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SAFETY REVIEW OF ALUMINIUM LASER WELDING AND INSTRUCTIONS FOR DESIGNING A SAFE WORKSTATION IN VALMET AUTOMOTIVE

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TIIVISTELMÄ

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Alumiinin laserhitsauksen turvallisuuskatsaus ja ohjeet turvallisen työaseman suunnittelemiseksi Valmet Automotivella

Diplomityö

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135 sivua, 23 kuvaa, 6 taulukkoa ja 9 liitettä

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Hakusanat: alumiini, Al, alumiinin laserhitsaus, laserturvallisuus, alumiinin terveysriski, alumiinin pölyräjähdysriski, työaseman suunnittelu, työturvallisuusvaatimukset

Tämän diplomityön tavoitteena oli selvittää, millaisia työturvallisuusriskejä liittyy alumiinin laserhitsaukseen ja kuinka näitä riskejä voidaan hallita. Työn toimeksiantaja Valmet Automotive harkitsee tulevaisuudessa ottavansa käyttöön alumiinin laserhitsausprosessin. Työturvallisuuden huomiointi ja työntekijöiden turvallisuus on työnantajan vastuulla. Alumiinin laserhitsauksen turvallisuuteen vaikuttavista seikoista on hyvä saada kattavaa tietoa jo suunnittelun alkuvaiheessa, jotta varmistetaan turvallinen työasema ja työprosessi.

Alumiinin laserhitsauksen työturvallisuushaasteisiin perehdyttiin laajan kirjallisuuskatsauksen menetelmien avulla. Käytettävänä kirjallisuusmateriaalina käytettiin pääosin erilaisia vertaisarvioituja aiheeseen liittyviä tieteellisiä artikkeleita ja tutkimusraportteja, käsikirjoja ja oppaita. Tutkimus kokoaa yhteen pakettiin lukuisten tutkimusten sisältämän erillään olleen tiedon.

Alumiinin laserhitsaukseen liittyy kaikki laserlaitteiston ja lasersäteen aiheuttamat turvallisuusriskit, ja lisäksi alumiini materiaalina aiheuttaa lukuisia terveyshaasteita ja turvallisuusriskejä. Alumiinin aiheuttamat terveyshaasteet ja turvallisuusriksit johtuvat pääosin hitsauksen aikana ilmaan vapautuvasta hienojakoisesta alumiinipölystä. Terveyshaasteiden ja turvallisuusriskien hallitsemiseksi on esitelty teknisiä ratkaisuja ja työn organisointiin liittyviä ohjeistuksia. Tämä tutkimus on tarkoitettu soveltuvaksi oppaaksi tuleville työasemien suunnittelijoille. Tämän avulla he osaavat ottaa riittävällä laajuudella ja vakavuudella alumiinin laserhitsauksen turvallisuuden huomioon, ja tietävät keinot ja ratkaisut, joilla turvallinen työ varmistetaan. Vaikka alumiinin laserhitsaukseen liittyy useita vakavia turvallisuusriskejä, sitä voidaan suorittaa täysin turvallisesti, kun työasema ja työprosessi on suunniteltu ja toteutettu oikealla tavalla.

ABSTRACT

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Safety review of aluminium laser welding and instructions for designing a safe workstation in Valmet Automotive

Master's thesis

2020

135 pages, 23 Figures, 6 Tables and 9 Appendices

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Keywords: aluminium, Al, aluminium laser welding, laser safety, health risk of aluminium, aluminium dust explosion, workstation design, occupational safety requirements

The aim of this master's thesis was to detect what occupational safety risks are associated with laser welding of aluminium and how these risks can be managed. Valmet Automotive as client, is considering implementing laser welding process for aluminium in the future. Consideration of occupational safety and safety of employees is responsibility of the employer. It is appropriate to offer comprehensive information on the factors that affect the safety of laser welding of aluminium at an early stage of design to ensure safe workstation and work process.

The occupational safety challenges of laser welding of aluminium were studied using the methods of an extensive literature review. The literature used was mainly various peer-reviewed scientific articles and research reports, manuals and guides. This research brings together in a single package of relevant information contained in numerous studies.

Laser welding of aluminium involves all the safety risks posed by laser equipment and the laser beam, and in addition, aluminium as a material poses numerous health challenges and safety risks. The health challenges and safety risks caused by aluminium are mainly due to the fine aluminium dust released into the air during welding. To manage health challenges and safety risks, technical solutions and guidelines related to work organization have been presented. This research is intended as appropriate guide for future workstation designers. This allows company to evaluate the safety of aluminium laser welding with sufficient scope and severity and to know the means and solutions to ensure work safety. Although there are several serious safety risks associated with laser welding of aluminium, it can be performed completely safely when the workstation and work process are designed and implemented correctly.

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LIST OF SYMBOLS AND ABBREVIATIONS

A	Absorption coefficient
K_{ST}	Deflagration Index [bar-m/s]
P_{max}	Maximum pressure [Pa]
R	Reflection coefficient

A1AT	Alpha-1-antitrypsin
AC	Aluminium Cast
Al	Aluminium
AlMP	Aluminium microparticle
AlNP	Aluminium nanoparticle
ALO	Adaptive Laser Optics
ANSI	American National Standard for Safe Use of Lasers
Ar	Argon
ASTM	American Society for Testing and Materials
ATEX	EXplosive ATmosphere
ATP	Adenosine triphosphate
AW	Aluminium Wrought
Bi	Bismuth
BMP-2	Bone morphogenetic protein 2
BPP	Beam Parameter Product
bw	body weight
BZ	Brennzahl (In English: Burning number)
CMT	Cold Metal Transfer
CO_2	Carbon Dioxide
Cr	Chromium
CRP	C-reactive protein
Cu	Copper
CW	Continuous Wave
DT	Destructive Testing
EA	Explosible at ambient temperature

EH	Explosible at high temperature
EN	European Standard
FFP	Filtering facepiece
FSW	Friction Stir Welding
GMAW	Gas Metal Arc Welding
GTAW	Gas Tungsten Arc Welding
HAZ	Heat-affected zone
HBM	Human biomonitoring method
He	Helium
HTP	Haitallisiksi tunnetut pitoisuudet (In English: TLV)
IEC	International Electrotechnical Commission
IgE	Immunoglobulin E
ISF	Welding and Joining Institute
ISO	International Organization for Standardization
ITEM	Fraunhofer-Institut für Toxikologie und Experimentelle Medizin
LBW	Laser Beam Welding
LD	Laser Diode
M	Magnification
MAG	Metal Active Gas
ME	Manufacturing Engineering
Mg	Magnesium
MIG	Metal Inert Gas
Mn	Manganese
MPE	Maximum Permissible Exposure
N_2	Nitrogen
NCS	Neurocognitive system
NDT	Non-Destructive Testing
NE	Non-explosible
NFPA	National Fire Protection Association
NIR	Near Infrared
O	Oxygen
OSHA	Occupational Safety and Health Administration
Pb	Lead

PEL	Permissible exposure limit
PFO	Programmable Focusing Optics
PSD	Particle Size Distribution
PTH	Parathyroid hormone
PW	Pulsed Wave
ROS	Reactive Oxygen Species
RWTH	Rheinisch-Westfälische Technische Hochschule
SET	Speedy Esplosibility Test
SFS	Finnish Standards Association
Si	Silicon
SUV	Sport Utility Vehicle
TGF-β1	Transforming growth factor β1
Ti	Titanium
TIG	Tungsten Inert Gas
TLV	Threshold Limit Value
Tukes	Finnish Safety and Chemicals Agency
UAl	Urinary Al
UV	Ultraviolet
Nd:YAG	Neodymium-doped Yttrium Aluminium Garnet
Zn	Zinc

1 INTRODUCTION

The use of aluminium (Al) alloys is increasing all the time. The reasons for this are especially its particularly effective lightness and strength properties. In current and future passenger cars, fuel economy is one of the most important criteria of the material selection. The use of Al instead of traditional steel produces passenger cars that are lighter and thus more fuel efficient. However, there are several serious health effects and risks associated with the use of Al, and especially when working with it. Most of the health effects and risk are related to occupational exposure to fine Al and the explosive properties of Al. The employer is responsible for health and safety of its employees therefore the health effects and risks of Al must be thoroughly considered, especially when designing new workstations and work processes. This research examines the various health effects caused by occupational exposure to Al and the explosive hazards of fine-grained Al dust. This research also presents practical technical solutions and lists issues to consider when designing the workstation to ensure safety when working with Al in all situations.

1.1 Background information and motivation

This research has been commissioned by Valmet Automotive Oy. The target company wants to map out the possibilities of performing laser welding of Al materials in foreseeable future, and the first of steps in such a survey includes making an occupational safety review. As a result of this research, Valmet Automotive Oy wants information and arguments concerning the occupational safety risks caused by Al material and especially on how these can be successfully managed. This research has been intentionally made as a guide for those designing workstations in the target company. This was especially emphasized in the section that goes through the issues to consider when designing a workstation. The motivations for the research are to detect successful results for Valmet Automotive Oy. In addition, increasing the occupational safety knowledge of researcher about Al laser welding and carrying out research that meets scientific criteria.

1.2 Research questions, framework and scope

Research questions are limited to the health effects and other occupational safety challenges posed by Al and their prevention. Firstly, the research needs to extensively examine and justify whether there are safety challenges and what challenges are involved in laser welding of Al. In addition, the research needs to examine on a practical level and with concrete examples how health effects and other occupational safety challenges in laser welding of Al can be managed. The solution to the first research question is sought mainly from scientific articles and publications. The research question reviews the effects of Al on human biology, and the effects of Al on the background of various health problems and diseases. The solution to the second research question is sought based on the findings of the first research question from scientific articles and publications, and also from various legal acts and guidelines, as well as specific examples. The second research question, above all, aim to clearly present the various actual solutions and issues that need to be considered in the design of a safe Al laser welding workstation. At the request of the target company, the aim has been to generate this research as an understandable and solution-oriented guide that future designers can use, even if the background information related to laser welding, for example, is incomplete. The aim is to find solutions to these research questions and to produce high-quality research, based on which Valmet Automotive can, if it wishes, move towards the introduction of laser welding of Al in production with considerations of broad focus on occupational safety.

1.3 Research methods

This research was conducted using a literature search as a method. The actual real-world practical contribution was not executed during current stage of this research. In the paragraphs reviewing the background and basics, the sources were primarily manuals and technical guides. Scientific publications and studies were mainly used as sources in the actual research on the same subject in the past. Only high-quality peer-reviewed scientific articles with extensive references were selected as sources. There exists a wealth of research on the subject, with a quick look at the contents of the studies and the selection of the most appropriate ones according to the topic and content were made. Most of the sources have been found through the LUT University Science Library LUT Primo, where technical publications from global databases are widely available. In addition, sources were searched online through various regulations and guidelines. The sources were sincerely widely used, and several different publications were sought as sources for many topics in order to obtain certainty as to the veracity of the matter presented.

1.4 Valmet Automotive

Valmet Automotive is a Finnish automotive contract manufacturer, a manufacturer of roof structures and kinematic solutions, a manufacturer of battery systems, and a provider of engineering services founded in 1968. Of these business lines, car contract manufacturing is currently the largest in terms of business and the production is performed at the Uusikaupunki car plant, where the head office of the company is also located. To date, about 1.7 million cars have been completed at the Uusikaupunki car plant. The production of car plant includes a body welding shop, paint shop, assembly, logistics and maintenance. Valmet Automotive has operations in Finland, Germany and Poland. Net sales of Valmet Automotive were EUR 652 million and the average number of employees was 4,812 in 2019. During 2017 and 2018, the company has grown significantly, hiring about 3,000 new employees, mainly for car production at the Uusikaupunki car plant. In the future, Valmet Automotive will invest even more in electrified transport. This strategic direction is aided by cooperation with the technology company CATL, contract manufacturing of batteries at the Salo plant, and a recognized Tier 1 level supplier of electric car battery systems. (Valmet Automotive 2020, pp. 3-5, 58; Valmet Automotive A, Nd; Valmet Automotive B, Nd.)

2 LASER WELDING

This chapter reviews the general principles of laser and laser welding in automotive field. Laser technology and laser welding processes are introduced, the strengths, opportunities, weaknesses and limitations of laser welding are listed. In addition, an overview of laser welding in the automotive industry is made, with explanation of how laser welding is performed at the target company Valmet Automotive.

2.1 General information on laser

Laser is an abbreviation that consist of Light Amplification by Stimulated Emission of Radiation. Laser radiation is optical radiation that, as its name implies, is generated by stimulated emission. Radiation is generated when the active laser medium is excited by an external energy source. The electrons excited in the medium return to the normal state and in this case send the photon on its way. Photons that have already been generated collide with other excited electrons and this causes the discharging of excitation and the formation of another similar photon. The process proceeds and eventually results in numerous completely identical photons moving in the same direction. The radiation generated is directed to the desired location by the optics. Laser radiation has three properties that distinguish it from normal light. Laser radiation is monochromatic, coherent, and in a same phase. Monochromatic indicates that the laser radiation contains very accurately only one specific wavelength of radiation. Coherence indicates that the waves of laser radiation are in the same phase and thus can interfere, in other words. amplify each other. Same phase indicates that the advancing laser beam spreads very little over a long distance. The laser beam thus has a small divergence, in other words. the angle of expansion. Composition of the laser light differs from normal visible light, which can be seen in Figure 1. (Ylianttila & Jokela 2009, pp. 42-44; Kujanpää, Salminen & Vihinen. 2005, pp. 34-36.)

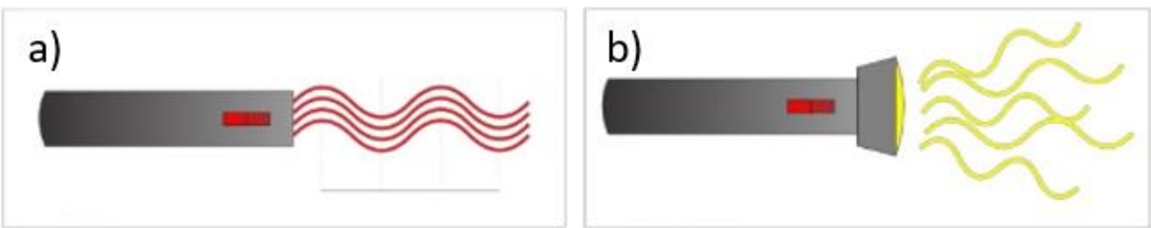

Figure 1. Difference between laser (a) and normal light (b) (Mod. Kosmala 2015).

Laser technology was developed 60 years ago in 1960, and in the beginning, there was a pulsed ruby laser. Since then, various technologies have been developed and for a long time the most popular model for high power lasers was the CO_2 (Carbon Dioxide) laser. The CO_2 laser has been followed by the optical fiber-guided Nd:YAG (Neodymium-doped Yttrium Aluminium Garnet) laser, and today the most popular high-power lasers are the high-efficiency diode laser or laser diode (LD), the high-quality disc laser, and the high-efficiency, compact-size fiber laser. High-power lasers can perform many traditional material processing operations with very high efficiency and accuracy. Methods for removing the substance include cutting and drilling. Methods involving joining of the substance include welding, brazing and soldering. Methods that change the surface of the workpieces include hardening, cladding and annealing. The power produced by high-power lasers is able to vaporize almost all known materials. Due to process accuracy, optics requirements and monitoring, virtually all laser technology processes are automated. (Katayama 2013, p. xxi; Billings 1992, p. 1-5.)

2.2 General information on laser welding

Laser welding is based on the high-power energy density of the laser beam. The high-power laser beam is focused on a small area, whereupon the power causes the material to melt and/or evaporate. A processing head that moves the beam relative to the object provides a smooth weld seam. In laser welding, the geometry/cross-section of the weld resembles that of electron beam welding in many applications. These two methods provide a very narrow but at the same time deep weld geometry. Electron beam welding requires a vacuum to operate and this limits the use of it compared to laser welding. Correspondingly, in arc and plasma welding processes, the geometry of the weld is considerably wider and weld depth is less. In laser welding, power and focusing can be changed very widely and a wide variety of metals and plastics, for example, can be welded with same equipment by using suitable adjustments. The thickness of the materials to be welded varies between 0.01 mm and 50 mm. Helium (He), argon (Ar) and nitrogen (N_2) are commonly used as shielding gases. Shielding gas protects the weld pool from oxidation and prevent the occurrence of welding defects. In addition, shielding gas prevents the beam from being absorbed or scattered into the plasma that is generated during welding. Laser welding can also be performed without shielding gas and in some applications, under vacuum. (Katayama 2013, pp. 3-4; Kujanpää, Salminen & Vihinen 2005, pp. 171.)

Laser welding can be performed in many different ways. The most used and well-known application of the laser welding is deep penetration welding, in other words known as keyhole welding, in which the laser beam is focused directly towards the surface of the object. Due to the energy density of the focused beam, an open hole caused by evaporation is formed in centre of the molten material. As the beam is moved relative to the surface of the object, the melt pool moves from the leading edge to the trailing edge of the hole and solidifies rapidly. The name keyhole comes from the cross-section of the weld, which is very narrow and vertical. For keyhole welding to be successful for steel, for example, the required energy density of laser beam must be above 10^4 W/mm^2 (Oladimeji & Taban 2016, p. 420). Required energy density is still highly dependent on the more specific properties of the material. The laser can also weld using a lower energy density of the laser beam, in which case the process is called conduction laser welding. This process is reminiscent of traditional arc welding methods. The laser beam is focused on the surface of the object, causing the surface to heat up and melt, and thermal conduction penetrates the melt to the required depth in the object. By moving the laser beam relative to the surface of the object, a smooth weld seam is created. In conduction laser welding, the cross-section of the weld is wide and low. In conduction welding, energy density of the laser beam is generally less than 10^4 W/mm^2 (Oladimeji & Taban 2016, p. 421). Pulse welding is when a focused laser beam is applied to an object with varying energy density over time. The goal of the pulsed mode is to produce short-term, high-power impacts of beam energy, resulting in deep penetration or, alternatively, very low heat input. When using pulsed mode, the laser beam is moved relative to the surface of the object and the pulses are struck at the appropriate rate on the surface of the object. Figure 2 shows weld profiles of conduction welding and keyhole welding and combination of these two methods. (Katayama 2013, pp. 7-11; Kujanpää, Salminen & Vihinen 2005, pp. 157-160; Dorn & Jafari 1996, p. 2.3.2-15.)

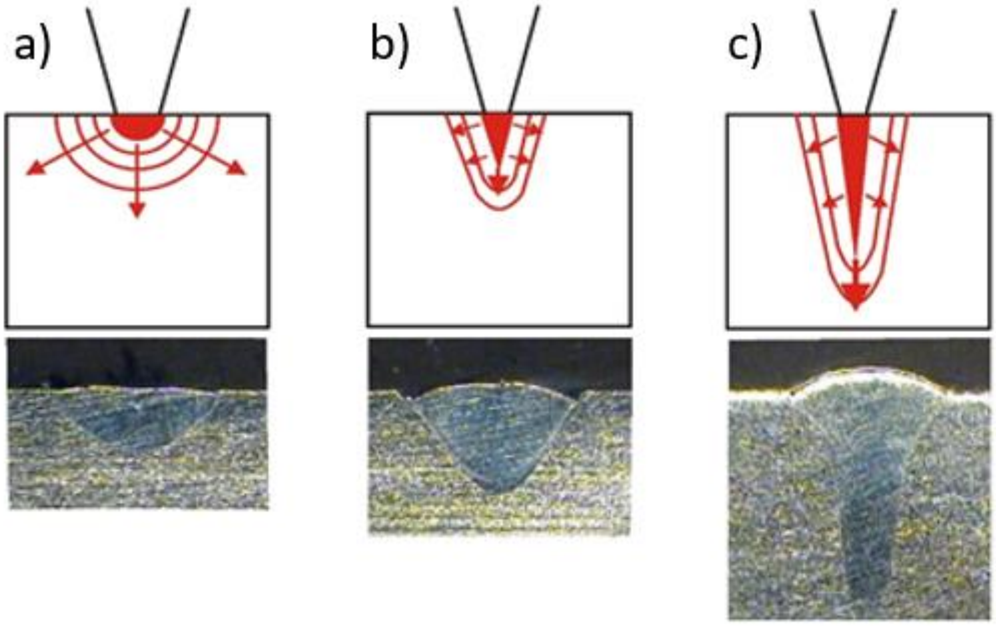

Figure 2. Difference between conduction laser welding, keyhole welding and combination of these two methods (Mod. Shannon, 2016).

As it can be seen from Figure 2, conduction laser welding (a) differs from keyhole welding (c) in terms of heat input and weld profile. Combination of these welding methods (b) is in the middle of the Figure.

Laser welding can also be performed with a filler material. The process can then be both, a keyhole or conducting laser welding. The filler material is most commonly fed in form of a filler wire to the front of the melt pool. In laser welding with filler material, the basic principle is that the laser beam melts the base material and at the same time the filler material is fed to the process. The application of laser welding with filler material can be done as a multi-run welding, in which a deep weld can be produced by several different weld runs, each performed over the previous one. Its own separate application in laser welding is the laser hybrid welding. In laser hybrid welding, laser welding is combined with an arc welding method in the same welding process. The arc welding methods combined with laser welding are, for example, TIG (Tungsten Inert Gas), MIG (Metal Inert Gas), or plasma welding. The basic principle of hybrid welding is to combine the deep and narrow penetration of laser welding with a traditional arc welding process that is easy to control and brings stability. Hybrid welding is used, for example, when the tolerances of the grooves to be welded alone are not sufficient for very precise laser welding or the aim is to increase the welding speed.

Laser brazing process is very similar to traditional soldering methods, but the heat source in this process is a laser beam. The Figure 3 shows four different applications of laser joining process. (Kujanpää, Salminen & Vihinen 2005, pp. 28-29, 161-163.)

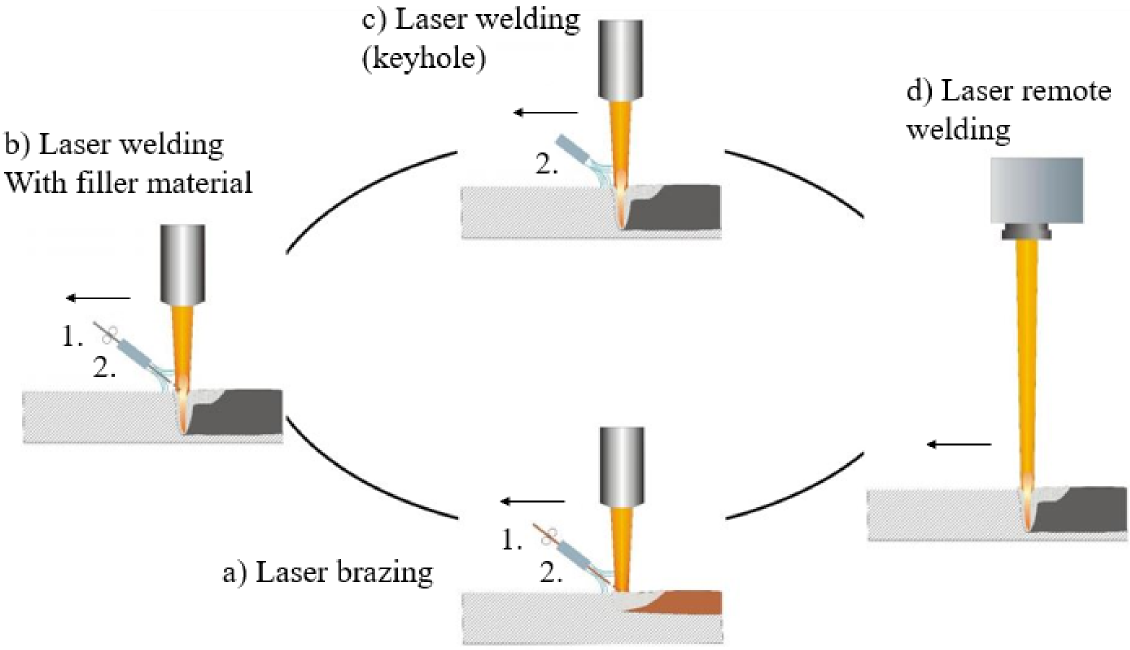

Figure 3. Four different applications of laser joining process (Mod. Alfamm, 2017).

As it can be seen from Figure 3, two of these laser applications (a) and (b) use filler material (1.) and three of these applications (a), (b) and (c) use shielding gas (2.). Remote welding (d) does not need filler material or shielding gas to operate properly.

2.2.1 Different systems for laser welding

Over the years, a variety of lasers have been developed to meet the current needs of the industry. The most common high-power lasers used industrially today are disk lasers, fiber lasers and diode lasers. Traditional CO_2 lasers and Nd:YAG lasers are hardly developed or applied anymore, as above mentioned laser types have outperformed them in terms of technology and performance. The beam quality of the CO_2 laser is good, but weaknesses of the CO_2 laser includes the incompatibility of its beam with the optical fiber to be used for beam delivery. The Nd:YAG laser beam can be transported by the optical fiber, but weaknesses of the Nd:YAG laser include poor efficiency and issues with stability of beam quality. (Katayama 2013, pp. 4-6.)

The most common lasers are named according to type of the active laser medium. The wavelength of the diode laser beam is 0.8-1.1 µm and the active laser medium is a suitable solid material. The diode laser is a semiconductor device similar which a diode pumped with electrical can create lasing conditions and laser beam. The special strengths of the diode laser are its very compact size, which brings ease in hardware design and handling as well as excellent efficiency. Diode laser weaknesses include a rather poor beam quality and for this reason it is now used as a pumping performer in the latest laser applications in fiber and disk lasers. LD pumped solid-state laser pumping is performed using the previously mentioned diode laser. Disk laser and fiber laser are technologies with similar characteristics. Both are high performance and high-quality high-power lasers. In both, high powers, excellent beam quality and excellent efficiency are achieved. Beam parameter products (BPP) for both technologies are less than 10 mm * mrad. Due to this excellent beam quality, both systems can be used in the most of technical applications of laser welding and remote laser welding. Table 1 summarizes the characteristics of the laser welding techniques reviewed. (Katayama 2013, pp. 4-7; Kujanpää, Salminen & Vihinen 2005, pp. 55-68.)

Table 1. Different laser types and properties (Katayama 2013, p. 5; Kujanpää, Salminen A. & Vihinen 2005, pp. 55-68).

Laser type	Wavelength	Laser media	Average power	Efficiency	Merits
Diode laser	0.8-1.1 µm	InGaAsP (solid) etc.	10 kW	20-60 %	Compact, high efficiency
LD pumped solid-state laser	1 µm about	Nd^{3+}:$Y_3Al_5O_{12}$ (solid)	6 kW (PW) 13.5 kW (CW)	20-25 %	Long service interval
Disk laser	1.03 µm	Yb^{3+}:YAG or YVO_4 (solid)	16 kW (CW)	15-25 %	Fiber optics, high power and efficiency
Fiber laser	1.07 µm	Yb^{3+}:SiO_2 (solid)	100 kW (CW)	20-30 %	Fiber optics, high power and efficiency

2.3 Advantages and opportunities of laser welding

Laser welding has numerous even unbeatable strengths compared to traditional welding methods. Laser welding is versatile process because it can be used to weld almost any materials and even join different types of materials. Laser welded seam is immediately ready for use and there is no need to finishing because of high accuracy in all situations. There is no actual tool wear with laser welding because laser beam itself is the tool. Laser welding is very rapidly process and has high productivity which makes it appeal especially in series production. There is low total heat input in laser welding process, thus the heat-affected zone (HAZ) is very small. Thin materials, heat-sensitive parts and micro-components can successfully be welded without risk of cracking or distortion. Laser welding process is easy to automate, and laser welding workstation can also work as a cutting station when equipped with a laser cutting head. Laser welding can be done in all positions because laser beam is able to reach difficult geometries and use of filler material is typically not required. (Mahamood & Akinlabi 2018, p. 142; Kujanpää, Salminen & Vihinen 2005, pp. 157-158; Scharfe 1996, p. 3.3.1-15.)

2.4 Disadvantages and limitations of laser welding

Laser welding also has certain limitations and weaknesses compared to traditional welding methods. Laser welding equipment investment costs are high and normally laser welding machine has high running costs as well (Mahamood & Akinlabi 2018, p. 142). Joints need to be dimensionally very accurate especially for non-filler laser welding and groove tracking system must be on at all times, especially with long seams. In laser welding, rapid cooling may cause cracking with some materials and some welding mistakes are very difficult to notice without x-ray test. Working with high laser power and reflective materials may damage sensitive and expensive optical components of the beam guidance system. In many applications there is need to redesign to products for laser welding. All welding parameters need to be precisely right for successful welding process. (Mahamood & Akinlabi 2018, p. 142; Kujanpää, Salminen & Vihinen 2005, p. 158; Katayama et al. 2019, p. 170.)

2.5 Laser welding in automotive industry

The first industrial applications of laser processing date back to the 70s. The automotive industry introduced laser welding at a fairly early stage in the 80s. Initially, laser welding has been used in the simplest of applications, but over time, it has spread into the manufacturing of many car parts. The automotive industry is one of the largest users of laser welding worldwide. The main reason for this is the excellent suitability of laser welding for the automatic production of large series. The shapes of car body parts, which are particularly well suited for laser welding, also are favourable for laser welding. Thin sheet metal parts, the required repeatability and, for example, joint types that are challenging for other welding methods are ideal for laser welding. Welds made in automotive factories are extensively tested with a large number of destructive (DT) and non-destructive testing (NDT) to ensure the quality of many different welding methods, and quality inspection of laser welding is part of this same process. Today, laser welding is used in the automotive industry in joining of:

- Car body and body parts including roof, C-pillar, doors, trunk door and car chassis
- Motor parts including valve parts and diesel chamber
- Gear parts including drive wheel and planet support
- Clutch parts and vibration dampers
- Gasoline and oil filters
- Different sensors
- Exhaust systems

(Kujanpää, Salminen & Vihinen 2005, pp. 17-18, 315-316; Barbieri et al. 2016, p. 1057; Scharfe 1996, p. 3.3.1-16.)

Currently made and future cars aim for suitable economic performance in terms of lightness, and at the same time solid and optimal durability in terms of crash safety. The car body is the largest single structure that affects these two effects. Today, the car body is increasingly optimised down to the smallest detail. One way to optimise is to use the right materials and structures at the right places in the body. High-strength steel and very light Al can be placed in places that receive the largest stresses and forces. Such challenging subassemblies can be welded together using laser welding. Laser welding can be used to join overlapping thin sheet sections together at a very high speed. Using laser brazing, different metals can be joined together and with the same laser device, the necessary cutting of sheet parts can also be performed in addition to welding. The most evident strength of laser welding in the automotive industry is its ability to weld without a filler material, making the structures optimally lightweight. Laser welding is performed as remote laser welding, especially in manufacturing of body parts. Remote laser welding is probably the most advanced and high-performance laser welding application at the moment, with very high welding speeds and repeatability. Figure 4 shows a typical laser welding system in the automotive industry. (Baur & Graudenz. 2013, pp. 555-562.)

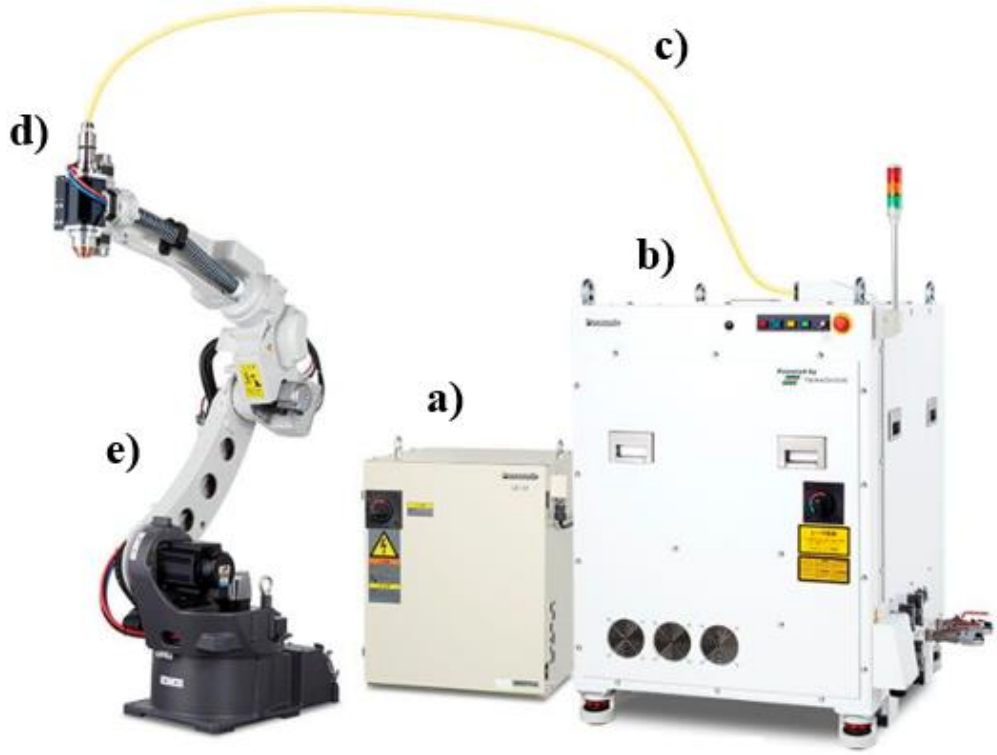

Figure 4. Typical laser welding system in automotive industry (Mod. Directindustry, Nd).

As it can be seen from Figure 4, the remote welding system consists of (a) controller of the laser system, (b) laser source, (c) optical fiber for beam transport, (d) welding head and (e) a robot.

2.6 Laser welding in Valmet Automotive

Laser welding is performed in a body shop at car plant of Valmet Automotive in Uusikaupunki. The body shop is the first department in the car manufacturing process, where the end product is the finished car body and the doors, hood and tailgate are set to place. The finished bodies then transfer to the body warehouse and from there to the paint shop. Body shop of Valmet Automotive manufactures two different car models. The Mercedes-Benz

GLC SUV (Sport Utility Vehicle) and the Mercedes-Benz A class compact car. Parts of the bodies of both cars contain laser welding and/or laser brazing. (Laihonen 2020.)

Laser equipment is normally used in the body shop by process operators who interpret and understand the messages given by the equipment when necessary. In the event of a fault, the maintenance team of Valmet Automotive body shop will be the first to arrive. They are able to perform simple maintenance and repairs on laser equipment. If the problems persist, supplier of the equipment will then be of assistance at least through phone support. Fixed annual maintenance for laser equipment is performed by professionals from supplier of the equipment. If changes are required to the products and movements or the quality of the work carried out by the equipment, the implementing them is the responsibility of ME (Manufacturing Engineering) department and the maintenance of the body shop. The biggest challenges in laser welding are related to the control of spatter generated in the welding process thus causing fast contamination of laser optic safety glasses. All laser welding processes of Valmet Automotive are carried out without shielding gas, which in turn causes spatter to be an issue. Efforts have been made to control spatters by optimising process parameters, enhancing lateral airflow (Crossjet system) and utilizing air vortex (TornadoBlade system). (Laihonen 2020.)

2.6.1 Laser equipment in Valmet Automotive

All laser sources used in the body shop of Valmet Automotive are either Trumpf TruDisk 4002 (maximum power 4,000 W) or Trumpf TruDisk 6002 (maximum power 6,000 W) models. 6002 models are used mainly for remote laser welding processes when 4002 models are used for laser brazing and welding processes. Scansonic ALO3 optic is used in laser brazing and conductive laser welding with filler material (ALO refers to Adaptive Laser Optics). In remote laser welding applications, the optics used are Trumpf PFO 3D (Programmable Focusing Optics). One laser source is used to manufacture the front wheelhouse, but two different working heads are alternated according to the work cycle. In other applications, one working head typically has its own laser source. Table 2 summarises the laser welding equipment used in body shop of Valmet Automotive. (Laihonen 2020.)

Table 2. Different laser systems in Valmet Automotive Oy (Laihonen 2020).

Car	Weldable object	Laser joining method	Laser source	Average power	Notes
A	Tailgate	Laser brazing	Trumpf TruDisk 4002	1,700-1,800 W	1.2 mm filler wire CuSi3
GLC	Door	Remote laser welding (keyhole)	Trumpf TruDisk 4002	4,000 W	Preparation for the next station
GLC	Door	Remote laser welding (keyhole)	Trumpf TruDisk 6002	5,800-6,000 W	Several thin seams
GLC	Front wheelhouse	Laser welding with filler material	Trumpf TruDisk 6002	5,800-6,000 W	1.2 mm filler wire G3Si
GLC	Front wheelhouse	Remote laser welding (keyhole)	Trumpf TruDisk 6002	5,800-6,000 W	Several thin seams
GLC	Internal side part	Remote laser welding (keyhole)	Trumpf TruDisk 6002	5,800-6,000 W	Several thin seams
GLC	Tailgate	Laser brazing	Trumpf TruDisk 4002	1,700-1,800 W	1.2 mm filler wire CuSi3
GLC	Tailgate	Remote laser welding (keyhole)	Trumpf TruDisk 6002	5,800-6,000 W	Several thin seams

As it can be seen from Table 2, there are a total of three different main types of laser joining processes. Laser remote welding is used in a total of five different locations: two different devices with GLC door production, one device with GLC front wheelhouse production, GLC internal side part production and GLC tailgate production. Laser brazing is used in two different locations: GLC tailgate production and A tailgate production. Conduction laser welding with filler material is used in one location, GLC front wheelhouse production. The power ranges of these applications range from 1,700 W to 6,000 W.

3 ALUMINIUM

This chapter explains what material Al is. It is presented what properties Al has and why Al is popular material today and in the future. In addition, introduces what Al alloys exist and how Al is used in the automotive industry.

3.1 General information on aluminium

Aluminium is the third most common element on earth after oxygen (O) and silicon (Si). The chemical designation of aluminium in the periodic table is Al and the sequence number is 13. About 8 % of the crust of earth is Al. Al never exists as a pure metal in the crust of earth, but has formed compounds with oxygen and other substances, and therefore exists as various oxides and silicates. Al is made almost completely by separating it from bauxite. Short description of the Al production process is presented in Appendix I. (Lukkari 2001, pp. 8-9; Baker 2018, pp. 5-9.)

Al includes a very hard and thin oxide layer (Al_2O_3) on top of the surface that protects Al from the effects of oxygen in the air. Thanks to the oxide layer, Al objects do not need to be painted or protected separately to increase corrosion resistance. Al is light material compared to steel, and it has effective electrical and thermal conductivity (Baker 2018, p. 6). Al has about one third of the density of steel, and for this reason it has long been used, for example, in aviation. Due to its electrical and thermal conductivity, Al has been used in many electrical applications and kitchen utensils. Pure Al is quite soft and that is why Al has been alloyed with many different substances to increase its strength and ductility. The famous Al alloy used in aircraft is duralumin, in which 4 % copper, 1 % manganese and 1 % magnesium are alloyed with the Al. It was developed in Germany as early as 1909 and is named after the locality of the invention, Düren. The production of the duralumin essentially involves the heat treatment process of precipitation hardening invented during the development of that material. Al alloys typically slightly degrade the corrosion resistance of the material, as the oxide layer does not develop to perfection. Today, Al alloys are divided into different series according to their applications. There is a total of eight different of these series, from 1xxx series to 8xxx series. The use of Al is growing all the time and the development of increasingly energy efficient and lighter cars will substantially increase the use of Al in the future. In 2016, global Al production is amounted to 58 million tonnes, of which China alone accounted for 31 million tonnes. Al has a low melting point of 660 °C, making it easy and economical to recycle. The Figure 5 shows the bauxite stone and Al profile. (Baker 2018, pp. 5-9; Polmear 2017, pp. 15-21.)

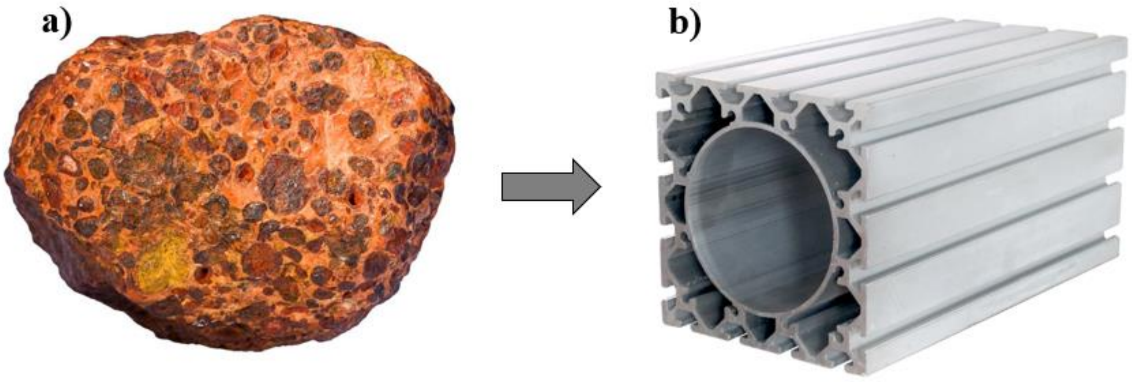

Figure 5. Bauxite stone and finished Al profile (Mod. Sandatlas, Nd & Shanghai Common Metal Products Co, Nd).

As it can be seen from Figure 5, Al in the bauxite stone (a) is processed by the manufacturing process into a complex Al bar profile (b).

3.2 Properties of aluminium

Al has several very useful properties that make its use very popular today in many different applications. Main properties that increase the use of Al are its effective lightness and strength properties and protective oxide layer. Al is the second most widely used metal in the world after iron. Comprehensive list of the properties of the Al material are presented in Appendix II. (Huhtaniemi 2006, pp. 8-12; Lukkari 2001, pp. 24-25; Kaufman 2018, pp. 31-42.)

Al is known as a common element and its properties are well known. It is appropriate to realize that Al is still quite rarely used in pure form. The main mechanical and physical properties of pure Al are summarized in Appendix III. (Lukkari 2001, p. 25; Baker 2018, pp. 5-9: Kaufman 2018, pp. 31-42.)

3.3 Aluminium alloys

All Al alloys are divided into wrought alloys and cast alloys. Wrought Al alloys are used for forgings, extruded profiles, sheets, strips and foils. Cast alloys are used to produce different types of castings. These include sand, die and pressure die casting. Completely pure Al is quite soft and has low strength. Its use is therefore limited for these reasons. However, high-purity Al is used, for example, as a reflective material and in electronic components. Al is alloyed with several alloying agents to increase the desired properties. When Al is required to be stronger, magnesium (Mg), silicon, copper (Cu) or zinc (Zn) are alloyed with it. If it is required to further improve its corrosion resistance, manganese (Mn) or chromium (Cr) are alloyed with it. Manganese as an alloying agent further reduces the grain size of the Al and thus prevents the effect of iron dissolved in the Al production step. If a particularly beneficial gloss is desired on the Al surface, copper can be alloyed with it. The surface properties are further improved by the alloying of titanium (Ti) with Al. If it is desired to improve the machining properties of the Al, lead (Pb) or bismuth (Bi) can be alloyed with it. When it is desired that the Al is not anodized, silicon is alloyed with it. (Huhtaniemi 2006, pp. 55-57; Lumley 2011, pp. 2-3.)

3.3.1 Categorization of aluminium alloys

The American Aluminum Association has published an international nomenclature system in which, using letters and a four-digit code, all Al alloys are divided into their own headings. In Europe, commonly agreed EN (European Standard) is used for Al alloys, according to which all Al alloys are marked EN at the beginning of the heading. The next symbol is the letter A, common to all Al alloys, which indicates that the alloy is an Al alloy. The second character is either W (Wrought alloys) or C (Cast alloys). The letter W indicates that the mixture is a modifiable alloy and the letter C indicates that the mixture is a cast alloy. After the letters, the heading has a dash and a four-digit code for the alloys to be modified or a five-digit code for the castings. An example of a perfectly presented marking method is EN AW-5754 for wrought alloys and EN AC-42000 for cast alloys. This numerical code indicates the main constituents of that alloy. All Al alloys can be divided into eight different main groups according to their alloying elements. In each group, the first digit of the code indicates the main component according to Table 3. A ninth group has been left separately if there is a need for it in the future. There may still be a separate letter at the end of this number chain to indicate a national deviation. (Lumley 2011, p. 3; Huhtaniemi 2006, pp. 62-63; Suomen standardisoimisliitto & Metalliteollisuuden standardisointiyhdistys 2014, p. 42.)

Table 3. Major alloying elements in different Al series (Lukkari 2001, p. 41; Huhtaniemi 2006, p. 62; Suomen standardisoimisliitto & Metalliteollisuuden standardisointiyhdistys 2014, p. 42).

1xxx(x)	Non-alloyed (pure aluminium)
2xxx(x)	Copper
3xxx(x)	Manganese
4xxx(x)	Silicon
5xxx(x)	Magnesium
6xxx(x)	Silicon + magnesium
7xxx(x)	Zinc
8xxx(x)	Others
9xxx(x)	In reserve

In group 1xxx, the last two digits indicate the minimum Al content as a percentage and reflect the minimum Al content to two decimal places. The second number of the group indicates the transformation in the impurity limits or in the alloying elements. If the second number is zero, indicates the purity of the alloy is unalloyed Al. In groups 2xxx-8xxx, the last two digits indicate the different Al alloys in each group without special significance. The second number of the groups indicates the mixture transformation. If the number is zero, it indicates that the alloy is original. If necessary, the numbers one to nine are used as the second number to indicate the alloy transformation. (Lukkari 2001, p. 41; Lumley 2011, pp. 3-4.)

3.3.2 Properties and using of alloys

There are numerous different types of Al alloys according to the requirements of different applications. All Al alloys are grouped according to the main constituents and all groups possess their own properties and suitable applications. Comprehensive list of the properties and applications of the main groups of Al is presented in Appendix IV. (Huhtaniemi 2006, pp. 67-71; Dutta & Lodhari 2018, pp. 122-124.)

3.4 Aluminium in automotive industry

Car manufacturing is a highly competitive industry, and modern customers considering buying a car value cost-effectiveness of the car, comfort and connectivity, while car manufacturers continue to develop car safety, fuel economy and vehicle performance to increase competitiveness. At the same time, many international regulations and obligations are driving the automotive industry to become increasingly safer, more economical and more environmentally friendly. There is a constant effort to reduce greenhouse gases and emissions from transport, and here the economy of the cars has a significant role to play. The bodywork of the car has a large impact on both safety and also to fuel consumption of the car due to weight. Al has been used in car body structures for a long time, but its use is expected to grow significantly in the next few years. Another growing phenomenon is the optimization body structure of the car, which combines several different manufacturing materials and connection methods, making the body structure more complex, but overall increasing its quality and performance in terms of durability and lightness. (Summe 2019, pp. 39-40; Vadirajav, Abraham & Bharadwaj 2019, pp. 89-90.)

The main construction material of the car has traditionally been steel. Indeed, steel has accounted for roughly about 60 % of weight of the car in North America on average until recently. In 2015, Al accounted for an average of 10.4 % of weight of the car in North America. Al was projected to account for 16 % of the average car weight in North America as early as 2028. Because Al is a lightweight material, its volume share will be clearly more than its weight share. The growing popularity of electric cars is one of the biggest reasons for the rise in the popularity of Al as a structural material for cars. The energy efficiency is a critical metric in the comparison of electric cars and lightening a car is one of the biggest factors affecting energy efficiency. It is estimated that saving 100 kg of weight in a car will reduce fuel consumption of the car by up to 6-7 % on average. (Summe 2019, pp. 40-50; Vadirajav, Abraham & Bharadwaj 2019, p. 91.)

3.4.1 Structure of car body

Modern car body structures consist of several pieces of different materials joined together for optimal durability and lightness. The lightness of the body structure brings large advantages in terms of fuel economy and therefore, where possible, light Al is used in the body. The durability of the body provides safety in crash situations and therefore ultra-strong steel grades are used at suitable points. The car body has traditionally been made of the same material throughout to simplify the manufacturing process, for example high-strength steel. Today, this manufacturing technique is seen as old-fashioned, and the modern car body is increasingly optimized and consists of ever smaller, individually designed parts. Each part is designed to meet the requirements of that little detail, and a large number of different fabrication materials and manufacturing methods are available. Modern car bodies use several different Al alloys, boron steels and other steel grades. When designers are free to develop the car body as a whole according to small different parts, the end result is the most optimal solution in terms of weight and durability. In the automotive industry, the Al alloys used as the body structure are mainly belonging to 6xxx and 7xxx series alloys. The 6xxx series alloys are used for applications requiring high strength and impact energy absorption, as well as to enhance the optimization of the closed structure. The 7xxx series alloys are used for very strong structures. In addition, other Al alloys are used in the surface structures of the body to improve design, joint structures, finish and durability. All of these can be used in a variety of body structures and weight savings compared to steel are 50 to 60 %, depending on the target. An example of weight savings in the car body is the difference between the Ford F150 model year 2015 and the model year 2014. In the 2015 car model, the body is made of Al and steel parts where possible. The weight savings of just over 200 kg have been achieved from the car body alone. Figure 6 shows the body structure of the Audi A8 in different material grades marked with colour codes. (Sierra et al. 2007, pp. 197-198; Summe 2019, pp. 47-52; Vadirajav, Abraham & Bharadwaj 2019, p. 94-95.)

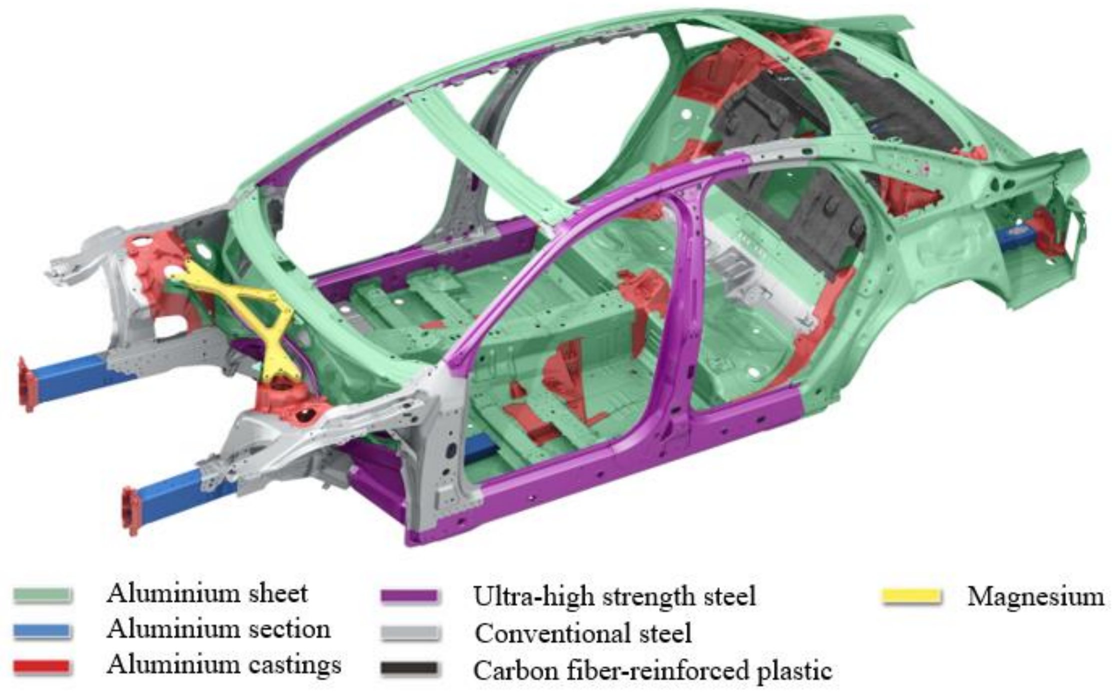

Figure 6. Picture of Audi A8 (2017) car body structure (Mod. Green Car Congress, 2017a).

As it can be seen from Figure 6, there are several different material qualities on display. Audi A8 is expensive price class car but it is a suitable example to illustrate the many different materials a modern car body contains and how versatile their use is. The side parts of the body, marked in purple and grey, are still made of steel and are designed to increase crash safety, but otherwise the body of the car in question is mainly made of the Al.

An essential part of a functioning optimized body structure is the interconnection of smaller subassemblies. Al parts and subassemblies can be joined using conventional resistance spot welding, conventional and remote laser welding, self-pierce riveting and flow drill screws. In addition, many of these methods use adhesive bonding to support the joints. Suitable connection methods must be considered in the design from the outset in order to create production as smooth and disturbance-free as possible. The structure of the bodies of modern cars is increasingly a hybrid body, which combines several different materials. Essentially, this denotes joining Al and steel parts together. Al and steel can be joined using methods such as mechanical clinching, FSW (friction stir welding), adhesive bonding and riveting. When joining Al and steel, the different properties of the materials must be considered in order to perform the joint as durable and even as possible to fuse. Studies have shown that using spot-welding for joints between Al and steel has stress level at its maximum and the rivet joint method has the lowest stresses at the joints (Long, Lan & Chen 2008, p. 491). Due to the slightly lower strength of Al, the thickness of the Al sheets frequently must often be dimensioned to be thicker than the steel sheets of the same joints. Figure 7 shows the amount of Al used in the surfaces of the 2013 Audi A8. (Summe 2019, p. 51; Long, Lan & Chen 2008, pp. 483-491.)

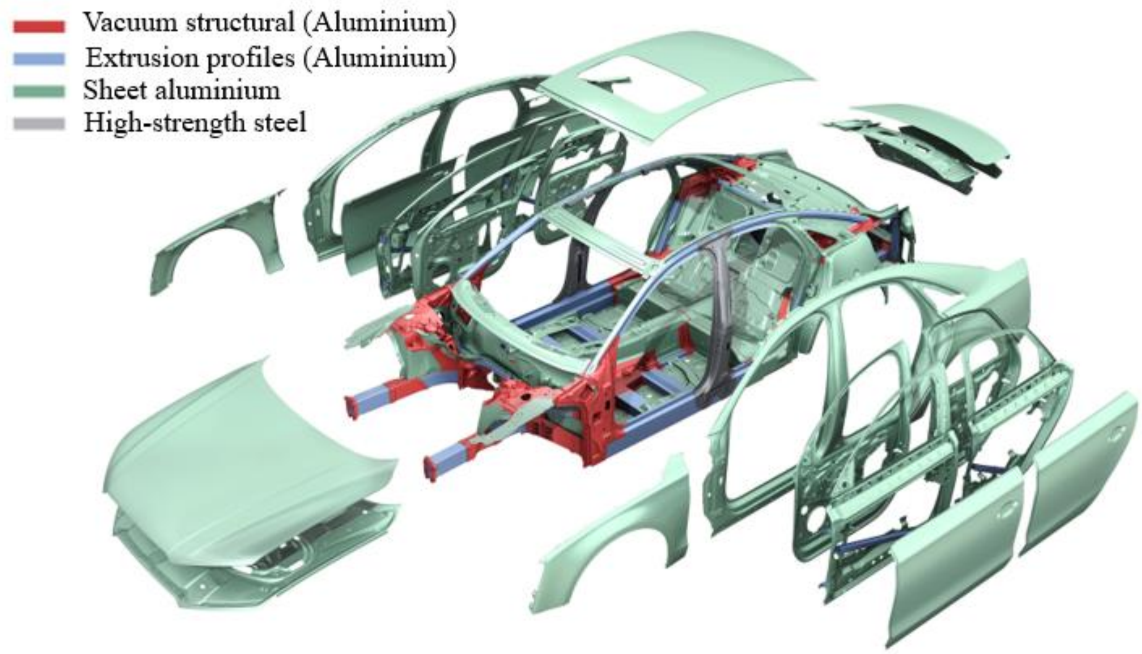

Figure 7. Picture of Audi A8 (2013) car body structure with all surface parts (Mod. Green Car Congress, 2017b).

As it can be seen from Figure 7, materials marked in light green are Al sheets, and virtually all surfaces on that car are made of this material. The car in question belongs to rather expensive price class, but the image conveys the idea of Al use in body structures, this trend will carry over to cheaper price class cars in the future as well.

4 ALUMINIUM LASER WELDING

This chapter presents laser welding of Al alloys in more detail. Basic principles of laser welding of Al and equipment for laser welding of Al are introduced. Strengths and limitations of laser welding of Al is considered, including the removal of the oxide layer and the bonding of different materials. The purpose for using of laser welding of Al is discussed, especially in scope of automotive industry.

4.1 General information of aluminium laser welding

The basic principles of laser welding of Al are very similar to normal laser welding of steel, with advantages such as precision, speed, low heat input, excellent quality and a very wide range of different joint types. Laser welding is mainly used for thin Al sheet parts with a thickness between 0.09 and 1.5 mm. Either argon or helium or a mixture of these are commonly used as shielding gases. All Al alloys can be laser welded, but the most common are 5xxx and 6xxx series alloys. The cross-sectional profile of finished laser weld is deep and narrow in Al as well, and the material is being subjected to a reasonably small heat load. If the aim is to further reduce the heat load on the material, a pulsed laser can be used. The laser welding of Al is extremely common in automotive industry, where this welding method delivers significant advantages over traditional arc welding. The advantages include high welding speed, low heat input and favourable shape of the weld cross-section, which together reduce deformations and residual stress. Al can also be welded by hybrid welding, by combing laser beam welding with traditional arc process such as MIG, MAG (Metal Inert/Active Gas), TIG welding or plasma welding. (Huhtaniemi et al. 2006, pp. 198-199; Lukkari 2001, pp. 100-101.)

Laser welding of Al involves some fundamental challenges caused by properties of the Al. These challenges are caused by effective thermal conductivity, high reflectivity and low viscosity of the Al. The purer the alloy, the better the thermal conductivity of the Al. The effective thermal conductivity causes the heat in welding process to spread beyond the targeted location into material to be welded, and thus more power is required for successful welding process. All Al alloys influence thermal conductivity to some degree, active substances being especially silicon, magnesium and zinc. An increase in the silicon content decreases the thermal conductivity in Al alloys thereby improving the weldability. Magnesium and zinc have lower melting points than Al and therefore improve the weldability of the Al, especially in keyhole welding. The absorption of laser radiation into Al depends largely on the wavelength of the radiation. Regardless of the laser type used, the reflectivity of Al is generally about 80 % and higher the more the purer the Al is. In addition, the practical reflection is also affected by the oxide layer on top of the material surface, possible pre-process surface treatments and surface roughness. It has been found that suitable surface treatments, such as grinding or darkening, increase the absorption and penetration depth of the weld by about 20 %. Regardless of the used laser system, the radiation reflection is more important in laser conduction welding than in laser keyhole welding, as the keyhole amplifies the effect of laser radiation that laser beam bounce around inside the keyhole with reflections and laser energy lasts longer. The low viscosity of the Al interferes with the welding process in the molten region, as it limits the expansion of the Al before the melt solidifies. Currently, there is no clear way to affect the viscosity of the Al in the molten region and therefore this challenge affects all Al laser welding processes. (Sánchez-Amaya, Amaya-Vazguez & Botana 2013, pp. 215-218.)

4.2 Used techniques and equipment

Laser welding processes used with Al can be divided into two different types: keyhole and conduction welding. The keyhole welding provides deep penetration and at the same time a very narrow weld, while conduction welding produces a wider and lower weld and is more stable as a process. In addition to the keyhole welding and conduction welding, there is a separate technique falling in between the two fore mentioned called the transition regime. It has features of both, keyhole welding (undercut, not flat top profile and small depression on the surface) and the conduction welding (low aspect ratio). The resulting weld shape depends not only on the power density applied to the surface but also on the welding speed and beam diameter. The keyhole welding mode can be switched to the conduction welding very quickly by defocusing or increasing the beam velocity. Each of these regimes can be automatically monitored by analysing optical and acoustic emissions and thus changing the input parameters in real time to produce the needed weld profile. In addition, outcome of laser welding Al strongly depends whether continuous or pulsed mode beam is used. The continuous mode produces uniform smooth weld seam and deep penetration, whereas in pulsed mode, heat input can be controlled with high accuracy to achieve fine welds with extreme precision. Shielding gases also have a major impact on the quality of weld when welding Al. Helium provides slightly better protection for the weld, argon on the other hand improves the beam absorption and thus is beneficial for higher depth/with ratio at lower power level (compared to unshielded process). The combination of these two gases achieves both advantages. However, the effect of shielding gas or mixture of thereof depends considerably on the laser source used and the Al alloy to be welded. Diode laser, fiber laser, disk laser, among others, can be used for laser welding of the Al with fiber and disk lasers being used most frequently. Both systems are capable of producing high brightness beams, at wavelength ~1,000 nm that is well absorbed in Al. (Sánchez-Amaya, Amaya-Vazguez & Botana 2013, pp. 218-226; Katayama et al. 2009, pp. 744-745.)

In keyhole welding, limit of energy density of the laser beam for ferrous metals is considered to be around 10^4 W/mm^2 and for Al materials, this required energy density limit is generally at least 1.5 x 10^4 W/mm^2 (Quintino et al. 2012. p. 43). If the process is to be as stable as possible, energy density limit of 2.0 x 10^4 W/mm^2 is recommended (Quintino et al. 2012. p. 43). Higher required intensities are due to the reflectivity of the Al. Depending on the alloy, the magnesium and zinc evaporates, and these fumes inhibit the absorption of the laser beam into the base material. In addition, magnesium and zinc create porosity in the weld. The possibility of beam back-reflection from workpiece to the optics must be considered and avoided. Optics must be protected by the necessary means and the position of the welding head must be adjusted, that the back radiation interfere with the beam guidance equipment as little as possible. (Quintino et al. 2012. pp. 39-45.)

Diode, disk and fiber lasers are excellent for all metalworking applications, including laser welding of the Al. The efficiency of the diode laser is at an excellent level (30-50 %) and radiation wavelength 800-900 nm is well absorbed into Al. Fiber laser and disk laser are suitable for laser welding of the Al very well and with correctly adjusted welding parameters the result is a flawless and even weld seam. The advantages of the laser welding include a very versatile adjustment of welding parameters. By adjusting these parameters, the errors commonly associated with Al welding can be largely reduced. For example, pulse lasers can be adjusted that the pulse does not start or stop unexpectedly but narrows, thereby reducing frequent cracking. In addition, the porosity frequently encountered in laser welding of the Al can be reduced by reclining the laser beam forward. Figure 8 shows the absorption rate as a percentage for a few different metals with respect to the wavelength of the radiation. (Quintino et al. 2012. pp. 43-50; Sasabe 2009, p. 335.)

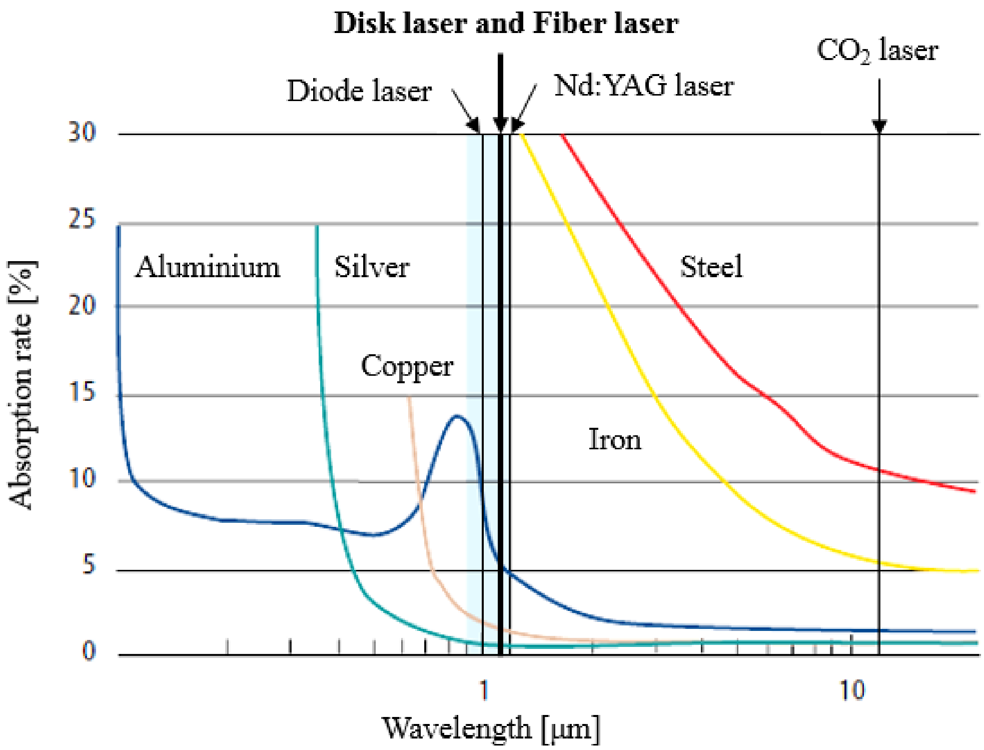

Figure 8. Absorption of different metals for laser radiation wavelengths of three most used laser systems (Mod. Fatoba et al. 2016).

As it can be seen from Figure 8, dark blue line depicts Al and it is shown that disk laser and fiber laser (bold text and line) absorption rate in Al ranges to about 5-7 % and a shorter diode laser wavelength has up to 14 % absorption rate.

4.3 Oxide layer of aluminium

Al is very easily oxidized and therefore a thin oxide film (Al_2O_3) is formed on the surface of the Al. The oxide layer is two-part, with a barrier layer 1-2 nm thick below and 5-10 nm thick a coat layer on top. If the oxide layer is removed from the surface of the Al, it will be about 2-3 nm thick after one day. If Al is stored in humid conditions or the storage temperature is too high, the oxide layer can grow considerably thicker. The oxide film is an excellent corrosion protection for Al in many different end applications, but at concerning welding, its presence complicates the process, as its composition, structure and properties differ significantly from the base material below the film. The oxide film is very hard and tough, it is slightly denser than base material and therefore the pieces detached from the oxide film sink downwards in the weld pool and cause defects such as oxide inclusions, porosity and incomplete fusion. The melting point of Al oxide is much higher than that of the base material (Al: 660 °C and Al_2O_3: 2050 °C) and this has traditionally been challenge in various welding processes, as Al oxide does not melt during welding. Al oxide is hydroscopic, or it absorbs moisture, which releases hydrogen during the welding process. The released hydrogen causes pores in the weld. The pore formation tendency is much higher for Al than for steel materials. Secondly, of Al gases, only hydrogen causes pores, while in steel, the most pores are caused by nitrogen and carbon monoxide. The oxide film acts as an electrical insulator that can interfere with traditional arc welding methods, and in all welding processes, it acts as an insulator and troublemaker that prevents the melt and groove surfaces from joining together to form smooth weld. Depending on the welding process used, the oxide film is typically removed before starting the actual welding. However with TIG welding, alternating current mode and helium gas and direct current mode and the electrode connect to positive can be used to remove the oxide film during the welding process. (Lukkari 2001, pp. 59-60, 102-104; Lohrey, Fuessel & Tuerpe 2014, p. 226.)

Many different methods can be used to remove the oxide film prior to the welding process. The methods are either mechanical or chemical: mechanical methods include brushing the joint area with a stainless-steel brush, scraping, or abrasive blasting, and other methods suitable for Al stored under optimal conditions and has adequate purity. When oxide layer is suspected to be thicker than usual (or the purity requirements are stricter), chemical cleaning can be applied. Then, the to-be welded pieces are first immersed in sodium hydroxide solution for 10-60 seconds to etch the oxide film, followed by another 30 seconds immersion in nitric acid solution (Lukkari 2001, p. 218). This chemical cleaning method is suitable for applications with very high purity requirements, but using this method is challenging in production terms, especially in serial production. Cleaning should be performed as close as possible to time of welding, so that oxide film does not have enough time to re-grow to a detrimental size. Using laser technology, the Al oxide layer can be removed using pulsed beam scanned over the area that needs cleaning. This pulse technique is very similar to laser marking or coating, in which high-power laser pulses are used to remove or treat the surface of a workpiece to produce desired properties. Using the appropriate laser intensities and the appropriate pulse frequency, a well-controlled and accurate removal of the oxide layer is obtained (Jha et al. 2007, p. 4725). The laser pulse hitting the oxide layer vaporizes and decomposes the oxide layer on the surface and the Al of the base material below become exposed. An example of suitable laser powers and pulse frequencies for removing Al oxide is 62-160 mW/cm^2 and 50 Hz using a 532 nm wavelength Nd:YAG laser (Jha et al. 2007, pp. 4725-4726). By removal of the surface layer, the weld porosity can be considerably reduced. For example, porosity of fillet edge welds after pulsed laser treatment was 0.5 % compared to the untreated surface, where it ranged from 10 to 80 %. The porosity of flange couch welds after pulsed laser treatment was 0.23-0.8 % compared to the untreated surface, where it was between 0.7-4.3 %. The reduction in porosity is resulting not only from the removal of the oxide layer, but also because the impurities are also being removed at the same time. Figure 9 shows oxide layer removing process with a pulse laser. (Lukkari 2001, pp. 104, 217-219; Jha et al. 2007, pp. 4725-4726; AlShaer, Li & Mistry 2014, pp. 162-163.)

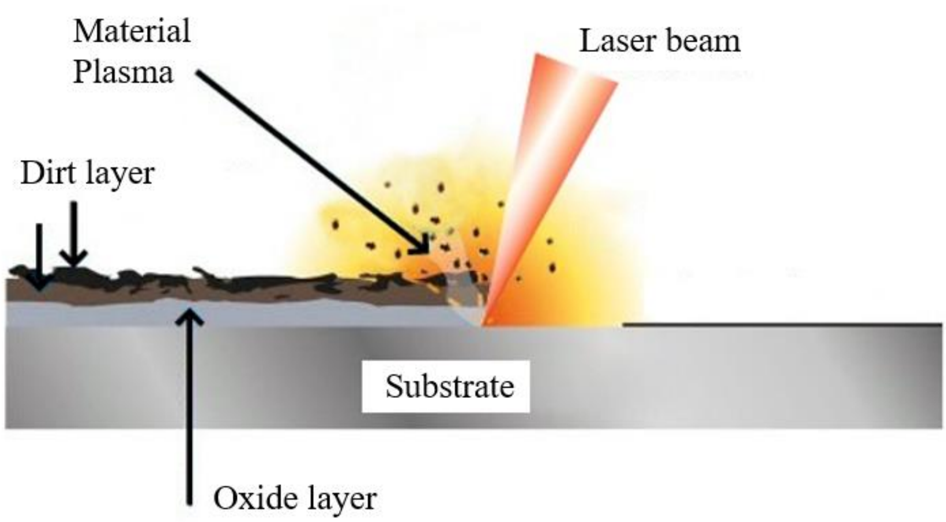

Figure 9. Al oxide layer removal by pulse laser (Mod. Eco laser clean 2019).

As it can be seen from Figure 9, dirt layer and oxide layer on the surface of the material are removed and released into the air, from where they are normally removed with a separate suction part (not shown in Figure 9).

4.4 Advantages and limitations of aluminium laser welding

The advantages of laser welding of the Al are very similar to those of laser welding of other metals. The strengths of laser welding of the Al and other metals include the optimal shape and depth of the weld, very high accuracy and excellent mechanical properties of the weld, high welding speed, low heat input during welding, high flexibility of the welding process and excellent suitability for automation and robotics. In addition, the finished weld does not need to be finished or machined with few exceptions. Common limitations and weaknesses of laser welding include high equipment costs, precise dimensional tolerances between the parts to be joined and critically fine-tuned welding parameters. The limitations of dimensional tolerances can be reduced, for example, by hybrid welding, automated seam tracking or beam wobbling and redesigning the product. The overall efficiency can be significantly increased by speeding up part processing time, reducing the amount of material, using more materials in the same process, increasing automation and optimizing the process. (Quintino et al. 2012, pp. 52-54; Sánchez-Amaya et al. 2009, pp. 9512-9513.)

As a material, Al introduces certain limitations for laser welding. In particular, keyhole welded deep penetration seams for thicker Al materials shall be approved and performed under the supervision of classification societies in accordance with applicable standards. The weldability of the Al varies largely between different alloys due to chemical variation. Used filler material typically changes the properties of the welded part and this can contain a limiting effect on the use of the finished products. Butt joint tap joint and flange joint are best suited for laser welding of the Al. The butt joint joints are successful with laser welding of the Al if the edges are rectangular and straight. Fit-up tolerance is recommended to be 15 % of the material thickness. To avoid misalignment of the parts, the flatness should be less than 25 % of the material thickness. When laser welding the Al, cracks in the round seams are not permitted unless the shielding gas can be directed to both sides of the welding process. The flange joint is ideal for laser welding of the Al, as the shrinkage rate of the Al is high. Precise fittings and straight surfaces are prerequisites for successful laser welding of the Al. When laser welding without a filler material, the gap between the Al joints must be 0.1 mm. When welding with a suitable filler wire, the gap between the pieces to be joined can be between 0.6-1.0 mm. (Quintino et al. 2012, pp. 53-54; Shiganov, Kholopov & Ioda 2012, p. 232.)

4.4.1 Joining aluminium and steel with laser welding

Traditionally, Al and steel parts are connected to each other mainly by mechanical joints. These methods include screwing, riveting and clinching. The main challenges in fusion welding of steel and Al are caused by differences between the melting points of these materials, poor solubility of iron in Al and the formation of brittle compounds such as Fe_2Al_5 and $FeAl_3$. The advantage that laser welding has over other welding methods its ability to create very fast exposure time between the parts to be joined. This limits formation of harmful brittle compounds. Laser welding can easily join overlapping sheets parts by forming a weld seam through the sheets with one-sided access from above with welding in a keyhole mode. In this way, the effect of large differences between the material melting points can be reduced. Thus, in lap joints metallurgically successful joint is obtained between Al and steel, provided that the gap between sheets that are welded remains at least 10 µm. In lap joints, the steel sheet is positioned on top of the Al sheet to avoid reflectivity issues and ensure successful fusion. If necessary, filler material can also be used, for example Al-12Si filler wire is well suited for this method. (Sierra et al. 2007, pp. 197-198.)

Al and steel do not normally mix with each other in the molten state and in welding this poses metallurgical challenges on top of the difference in melting points of materials. In addition, hot cracks, porosity and incomplete fusion are a problem in welding of Al and steel. Despite these problems, welding Al and steel together offers large potential for creating strong and lightweight structures and has been extensively researched and tested (Wang et al. 2016a, p. 3081; Torkamany, Tahamtan & Sabbaghzadeh 2010, p. 458). The laser welding has several advantages that produce it quite suitable for welding the Al and steel. The laser welding can be used to improve the microstructure and reduce the segregation tendency in the welding zone. The laser welding can also be used to control the formation of Fe-Al compounds that are brittle during welding. The same challenges posed by the mechanical and chemical differences between the Al and steel also apply to the laser welding, and the success of a fully functional welding process requires the right parameters and process conditions. There are other methods exists to join Al and steel. These methods are briefly described in Appendix V. Figure 10 shows the basic principle of joining Al and steel by laser beam. (Wang et al. 2016a, pp. 3081-3082; Meco et al. 2017, pp. 122-123.)

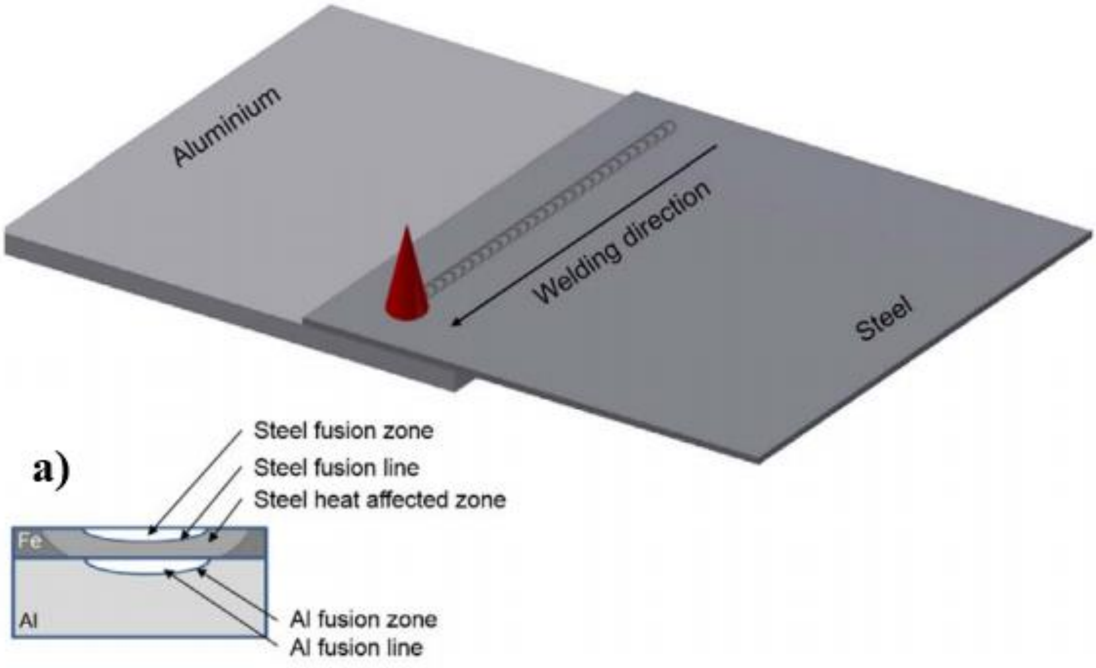

Figure 10. Joining Al and steel together using laser welding (Mod. Meco et al, 2017).

As it can be seen from Figure 10, the weld cross-section (a) shows that the Al and steel have not been in the molten state against each other, but the heated steel has conducted heat to Al so that Al has melted and the lower part of steel sheet has remained in a solid-state.

4.5 Application of aluminium laser welding

Laser welding of the Al is used in industry, especially in the automotive and the aerospace industry. Laser welding significantly reduces manufacturing costs compared to traditional joining methods, such as riveting. Largest aircraft manufacturers in the world, Airbus and Boeing, both have invested in laser welding equipment and are increasingly moving to laser welding, that is, away from gluing and riveting. In particular, multi-purpose and high-power fiber lasers and disc lasers have gained popularity in large production facilities. It has been estimated that replacing riveting with filler material free laser welding will reduce aircraft weight by about 5 % with the removal of the rivets and other materials. It has also been estimated that with better material optimization and joint structure design, aircraft weight savings through the laser welding can be as high as 15 % in the future. (Quintino et al. 2012, p. 54; Humberto Mota de Siquera et al. 2016, pp. 497-498.)

Although the laser welding of the Al mainly focuses on joining thin sheet parts together, laser welding can also join slightly thicker materials. For example, 10 kW disc laser or a fiber laser achieves a penetration of 13 mm in Al at a welding speed of 50 mm/s and a weld shape of a keyhole. Achieving a sufficiently deep penetration will also increase the popularity of the Al laser welding in the shipbuilding industry. Long and well-automated welds can be made quickly and efficiently by the laser welding. The laser welding is well suited for a wide range of manufacturing solutions, but its use is mainly limited by high investment costs, which require high manufacturing volumes and high equipment utilization. Therefore, laser welding is currently limited to high-volume or high-volume production, or the automotive, aerospace and shipbuilding industries. As laser equipment continues to evolve, it can be expected that the Al laser welding will become more common in the manufacturing industry in a number of different industries in the future. (Kawahito et al. 2012, p. 275; Quintino et al. 2012, pp. 54-55.)

4.5.1 Aluminium laser welding in Automotive industry

Conventional spot welding is still by far the most widely used in the manufacture of the car bodies. The spot welding is supported by the simplicity of its welding process and its suitability for robotics. On average, there are 2,000-5,000 individually made spot welds in a car body. The spot welding is well suited for steel materials, which have traditionally been used as a material in all parts of the car body. As car manufacturers strive for ever lighter and more durable car body structures, increasingly light metals have been adopted as manufacturing materials, and the Al is the most suitable of these due to its effective strength and lightness properties. The Al is not well suited for spot welding, as it requires about three times more electricity than steel, and at the same time the electrodes of the tips wear ten times more rapidly than welding steel. Instead of spot welding, the best option for automatic production of large volumes of the Al is the keyhole laser welding. The laser welding of the Al has many applications in the automotive industry. In addition to car body structures, the Al is also used in a wide variety of different components around the car. The modern light and strong car body is increasingly associated with extruded Al elements attached to each other and to other parts at special nodes. The laser welding, laser MIG/MAG hybrid welding in addition to traditional arc welding and soldering processes are used to create such a structure. Versatile process conditions favour compact, accurate and high-performance fiber lasers and disc lasers. The ever-increasing power of solid-state lasers and the improvement in beam quality bring a clear advantage and ever new possibilities, especially for welding light metals. Laser hybrid welding can further expand the versatility of the welding process and enable a very stable and high-quality joining process at suitable sites. (Quintino et al. 2012, p. 54; Hong & Shin 2017, pp. 46-49.)

Welding is by far the most important car body manufacturing technique. Successful welding guarantees a strong and durable structure for the car body, and on secondly, an efficient and rapidly manufacturing method guarantees competitiveness of the car manufacturer in relation to other manufacturers. The parts of the car body consist mainly of thin sheet parts and the residual stresses after welding are harmful. These stresses cause dimensional throwing and contain a detrimental effect on the strength and service life of the structures. A special feature of the laser welding is the very narrow and deep weld in keyhole welding, where the residual stresses due to heat are very low. The keyhole welding can be used to weld thin sheet sections in many different ways, for example several overlapping sheets together. Using appropriate welding parameters, welding can be done successfully and efficiently to a wide variety of car structure objects. The laser welding of the Al is considered to be a competitive and highly suitable manufacturing method for the needs of the automotive industry, especially when the limitations of the laser welding and the Al material are recognized and taken into account. (Siegele, Brand & Veneziano 2008, pp. 27-28; Hong & Shin 2017, pp. 47-49.)

5 GENERAL SAFETY ISSUES FOR LASER WELDING SYSTEMS

This chapter introduces the dangers and protection systems of different industrial laser equipment. The focus is on outlining the general safety risks that need consideration when by working with high-power laser systems. The hazards and risks originating from material properties of Al are discussed in more detail in chapter 6.

5.1 General information of work safety with lasers

In many applications, the energy of laser radiation exceeds the threshold for tissue damage to the skin and eyes. Tissue damage is caused by absorption of the laser radiation in substance. The electromagnetic energy of the laser radiation is converted into vibration of molecules and high energy causes mechanical damage to tissues in the form of an explosive rupture. The dangers of laser radiation have been recognized since the first laser development, and the first limits of exposure to have been set on the basis of extensive biological studies (Jokela et al. 2009, p. 76; Reidenbach 2007, pp. 1252-1253). Studies provide extensive knowledge base about exposure limits, and stages that cause damage to eyes and skin. The laser radiation differs from normal visible light in its properties that when ordinary light propagates evenly and dissipates as the distance increases, the laser light can be dangerous even over very long distances. An example of this is military rangefinders, which can contain safety distances of several kilometres (Jokela et al. 2009, p. 76; Titterton 2015, pp. 312, 314). Industrial laser processing with high-power lasers has risks from the safety point of view, as laser powers used are high. The laser safety risks can be divided into different types of risks, including but not limited to damage caused by beams, electrical equipment, gases and other substances involved and other secondary risks. The main principle in the laser safety is already accounted for at the design stage of equipment so that unintentional radiation is prevented and/or isolated. In other words, laser equipment must be surrounded by adequate protection means so that direct or indirect radiation does not cause any health hazards. In addition, all the necessary optical devices for monitoring and controlling the laser process must be installed in such a technique that the laser radiation does not escape the intended area. Figures 11 and 12 show an example of how to warn on lasers. (Jokela et al. 2009, pp. 76-77; Kujanpää, Salminen & Vihinen 2005, p. 327; Beier 1996, pp. 2.4.1-1 - 2.4.1-3.)

Figure 11. General laser warning sign without information on laser class (Mod. Safety Label Solutions, Nd).

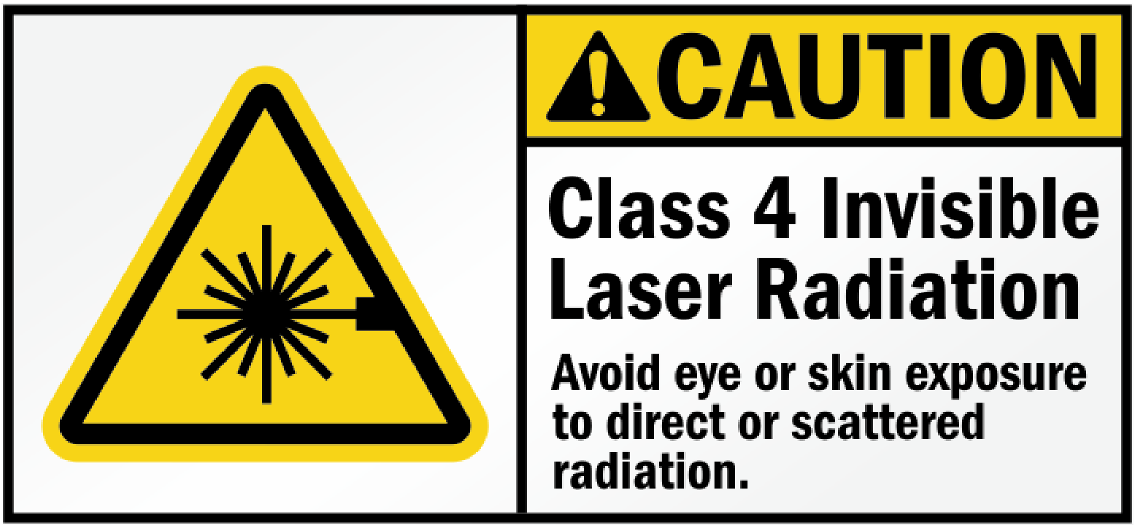

Figure 12. Laser warning sign with information on laser class 4 and invisible beam (Mod. My Safety Labels, Nd).

5.1.1 Laser safety standards

Laser technology differs very much from all other machining processes. For this reason, much attention has been paid to ensuring safety and developing the necessary standards for mapping and overcoming the hazards have been in use for decades. The standards for laser safety with SFS (Finnish Standards Association) and ISO (International Organization for Standardization), which focus on the various details of the laser work and the laser process, are listed and summarized below:

SFS-EN ISO 1 553-1

- Machine safety. Laser systems. Part 1: General safety requirements (2009).

SFS-EN ISO 11553-2

- Machine safety. Laser systems. Part 2: Safety requirements for hand used laser devices (2009).

SFS-EN ISO 11553-3

- Machine safety. Laser systems. Part 3: Noise reduction and noise measurement methods of laser processing machines (2015).

SFS-EN 12254 and SFS-EN 12254/AC

- Used screens for laser working places. Safety requirements and testing (2010/2012).

SFS-EN ISO 11145

- Optics and photonics. Lasers and laser equipment. Vocabulary and symbols (2018).

SFS-EN ISO 11554

- Optics and photonics. Lasers and laser equipment. Laser beam power, energy and time parameter measurement (2017).

(SFS 2019, pp. 6-13; Kujanpää, Salminen & Vihinen 2005, pp. 333-334.)

5.2 Classification of lasers

Laser equipment is classified into four main and all-together seven different safety classes according to the health risks they cause. Emission limits have been defined for the safety classes according to the wavelength and the time of exposure. The laser safety classes currently in use were revised in 2001 and are defined in the international laser safety standard IEC 60825-1. IEC is abbreviation from International Electrotechnical Commission. The corresponding European laser safety standard is EN-60825-1. There are seven different classes in this classification system currently in use and they are numbered that the hazard level of the laser device increases as the number increases. The classes are 1, 1M, 2, 2M, 3R, 3B and 4. The old classification, which can still be encountered in some contexts, has used classes 1, 2, 3A, 3B and 4. Lasers used for example in consumer electronics devices, generally fall into class 1-3. The laser used in them is almost typically encapsulated, that the enclosure itself acts as a shield against the radiation. All lasers that perform laser processing belong to the most dangerous class 4, which means their use requires protection. Regarding class 4 processing lasers, it should be noted that if the laser is a class 4 device, it must typically be encapsulated over the duration of entire process. This means that the laser device can be treated as if it were a class 1 laser when users located outside the enclosure. Such processing lasers are class 4 lasers inside the shields, but class 1 lasers outside the shields, and do not require separate shields from the user. If, for any reason, it is necessary to enter inside area of laser operation, class 4 protective equipment must be used. (Jokela et al. 2009, pp. 97-98; Kujanpää, Salminen & Vihinen 2005, pp. 327-328.)

Class 1 lasers are low power and contain wavelengths in the range of UV radiation, visible light and infrared. Class 1 laser equipment does not cause any risk and therefore does not require protection even over a long period of exposure. Class 1 also include devices in which the laser radiation travels enclosed inside the device. In some devices, the laser source may belong to a higher safety class, but due to the enclosure, the device as a whole is a class 1 laser. In automotive industry, class 1 laser are used as navigating tool when welding processes are changed, and work programs are revised. The beam of class 4 lasers is frequently strong enough that it burns the skin in an instant. Class 4 lasers damage the eye even through stray reflections and over very long distances. Class 4 lasers are used in processing lasers, laser surgery and public performances, among others. All lasers used in laser welding belong in class 4. Laser classes 1M, 2, 2M, 3R, 3B are presented in Appendix VI. Different laser classes maximum permissible power with continuous beam, wavelength with maximum permissible power and applications are presented in Table 4. (Jokela et al. 2009, pp. 97-106; Kujanpää, Salminen & Vihinen 2005, pp. 327-328; Barat 2019, pp. 2-4 - 2-7.)

Table 4. Laser classes maximum permissible power with continuous beam, wavelength with maximum permissible power and applications (Jokela et al. 2009, pp. 97-106; Kujanpää, Salminen & Vihinen 2005, pp. 327-328; Barat 2019, pp. 2-4 - 2-7).

Laser Class	Maximum permissible power (continuous beam)	Wavelenght with maximum permissible power	Applications
1	0.39 mW	500 - 700 nm	Laser printer, CD player, toys

Table 4 continues. Laser classes maximum permissible power with continuous beam, wavelength with maximum permissible power and applications (Jokela et al. 2009, pp. 97-106; Kujanpää, Salminen & Vihinen 2005, pp. 327-328; Barat 2019, pp. 2-4 - 2-7).

Laser Class	Maximum permissible power (continuous beam)	Wavelenght with maximum permissible power	Applications
1M	500 mW	300 – 4,000 nm	Wireless communication devices
2	1 mW	400 - 700 nm (Visible)	Laser pointer, bar code reader
2M	500 mW	400 - 700 nm (Visible)	Cross line laser
3R	5 mW	300 nm - 1 mm	Laser pointer, measuring equipment
3B	500 mW	400 - 780 (Visible)	Experiment and research lasers
4	-	180 nm - 1 mm	Laser machining, laser surgery

5.3 Laser beam hazard to eyes

Different human tissues are damaged in much the same way by laser radiation. What is essential in the occurrence of damage and the extent of damage is how much energy is absorbed into the tissue and what the wavelength of the incident laser radiation is. Energy density of the laser exposure and laser exposure limits are described using the energy density (J/m^2) and energy density of the laser beam (W/m^2) of the laser pulse hitting the tissue. The laser beam hitting the eyes is at its most dangerous at the wavelength of visible light (400-780 nm) and close to the wavelength of infrared radiation (780-1,400 nm). These wavelengths are the most dangerous, as the anterior parts of the eye do not attenuate these beams and all the radiant energy is focused through the lenses of the eye onto the retina in a very small area. How much the eye is damaged by the impact of the laser beam in each case depends largely on the pulse energy of the laser beam, the point of the impact, the position of the optics of the eye and on chance. Figure 13 shows how different radiation wavelengths affect the eye. (Jokela et al. 2009, pp. 77-78.)

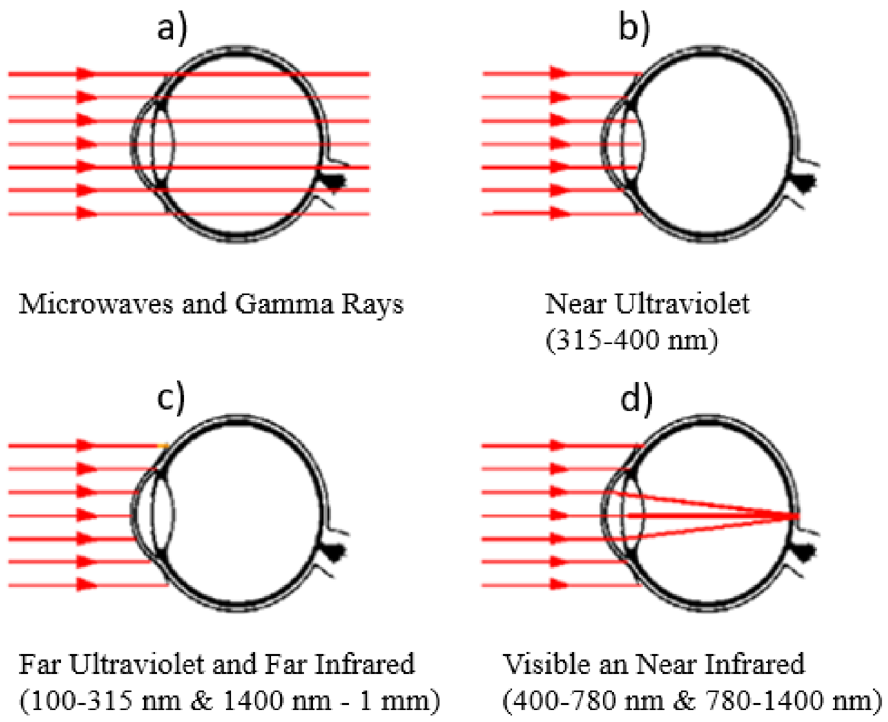

Figure 13. Wavelength of radiation effect to the eye (Mod. Oregon State University, Nd).

As it can be seen from Figure 13, the most dangerous wavelength of the laser radiation (d) is focused through the lens of the eye on a very small area to the retina. It can also be seen from the Figure that near ultraviolet wavelength (UV) (b), far ultraviolet and far infrared wavelengths (c) are absorbed into the surface layer and lens optics of the eye and thus damage the surface parts of the eye

In laser work safety, the most serious danger is considered to be eye damage, in which, at worst, vision is completely lost. When the focused focus point of the laser beam hits the eye, at least some permanent eye damage results. If the laser beam hitting the eye is a raw beam of a lower energy density of the laser beam, a scattered beam, or a reflection of one of these, it can be survived with good luck without permanent damage. Secondly, the energy density of the focused laser beam decreases rapidly as the distance increases, while the energy density of the raw beam remains at almost the same level even if the distance increases. For the same reason, the reflected raw beam is practically typically more dangerous than the reflected focused beam. The danger of reflected beam is also that they can hit the eye from unpredictable directions. Materials that appear rough at the wavelength of light visible to the human eye can be very reflective at longer infrared waves. The most dangerous situations for the eyes are frequently maintenance situations where the raw beam is exposed unprotected. In addition, in maintenance situations, it may be necessary to turn off some of the safety devices in use during normal laser operation. In such situations, it is necessary to stay very well informed throughout the maintenance process concerning where the beam is going at any given time and what the danger areas are at any given time. Major maintenance of laser equipment must be carried out on a suitable schedule and it must be ensured that no unauthorized persons enter the danger area at any stage. (Kujanpää, Salminen & Vihinen 2005, pp. 328-331; Ringelhan 1996, p. 2.4.2-6.)

5.3.1 Mechanism of eye damage and assessment of damage risk and MPE

Pulsed lasers cause usually worse eye damage than continuous laser radiation. The pulses contain a very large amount of energy for a short time and the pulse that hits the eye comes to the eye unexpectedly, that the eye does not have time to react to the pulse at all before the damage occurs. If the pulsed laser radiation hits the eye, the vision will be blurred immediately, and a bright flash will appear in the field of view. The laser beam focuses on the retina, where local damage occurs. A blind spot called a scotoma forms at the site of this lesion. If the beam hits close to the fovea, the result is permanent visual impairment. If the beam hits the edge of the retina, a blind spot results, which does not necessarily interfere with vision at all. If the laser radiation is high-powered and hits the retina, it can result in large destruction to the nerve connections between the optic receptors and the optic nerve. In this case, bleeding also frequently occurs between the retina and the vitreous. Bleeding blurs vision and nerve connections can be damaged more. At worst, the entire retina can come off completely. The detachment is caused by a shock wave caused by high-power lasers in the structures of the eye. The damaged retinal site does not repair on its own, but vision can frequently be significantly repaired as the leaked blood drains and the blind spot disappears from consciousness. (Jokela et al. 2009, pp. 78-80.)

Looking directly at the sun, the energy density on the retina of the human eye is about 10 W/cm^2. This also causes damage to the retina over time. Due to the difference in laser radiation, a 1 W argon laser produces the energy density of 10^4 W/cm^2 for the retina. Under suitable conditions, the retina can be damaged with as little as 1 mW of laser power, even if the eye closes with a reaction time of 0.25 seconds. If the eye is exposed to laser radiation above critical power intensities, it is typically recommended to arrange meeting with an ophthalmologist immediately. Although there is usually nothing to be done on the damage itself, but the damage can still be recorded, and a formal written statement can be given for further processing. (Ringelhan 1996, pp. 2.4.2-5 - 2.4.2-6.)

Damage to the eye caused by laser radiation has been assessed in animal tests. In the tests, the pulse energy of the laser radiation was increased until the smallest possible change in the retina was observed. Numerous similar measurements have been made, and these are used to determine the amount of energy that causes damage with a 50 % probability. From this amount of energy, an exposure limit is determined, which is generally ten times lower to create the necessary safety margin. The eyes of experimental animals and humans differ somewhat and for this reason the safety margin ratio may vary slightly, but in general it can be said that the risk of significant damage only begins to increase when the amount of energy is ten times the exposure limit. Such a limit is frequently referred to as MPE. MPE is made up of the words Maximum Permissible Exposure and describes precisely this maximum radiation level exposure to which a person can be exposed without causing any physiological damage. In the human body, the most sensitive areas to laser radiation are the eyes and therefore MPE is also defined according to them. MPE is frequently described in J/cm^2 or W/cm^2. That is, either the amount of energy caused by the laser beam or the amount of power per area. (Jokela et al. 2009, p. 79; Reidenbach 2007, pp. 1260-1263.)

5.4 Laser beam hazard to skin

When a laser beam or beam reflection used in laser processing hits the skin, it usually burns the skin. The severity of the burn depends on the energy density and exposure time of the beam. If the beam hitting the skin is focused, it will vaporize the skin. In this case, the injury is not actually a burn, but rather a hole or incision. In these cases, the focused beam vaporizes the nerve connections and blood vessels in the tissues and the injuries hardly hurt nor bleed. Most often, however, the beam hitting the skin is not focused, but is caused by beam reflections, and this results in varying degrees of burns. The sensitivity of the skin to laser radiation does not differ much from the eye if wavelengths are used to which the lens optics of the eye do not respond. While the wavelength of the laser radiation is in the range of visible light or near-infrared radiation, the sensitivity of the eye is much higher. This is due to the inherent action of the lenses in the eye, which focuses the laser radiation onto the retina of the eye. Subsequent problems in skin exposed to the laser radiation include abscessing, scarring, and pigmentation with UV lasers of various degrees of burns of the skin. (Kujanpää, Salminen & Vihinen 2005, p. 329; Jokela et al. 2009, pp. 86-87.)

The laser radiation affects the skin in many ways and the most significant effect is the thermal effect. Caused by laser and then resulted of the heat causes burns and they are divided into three categories according to the severity of the injuries. First-degree burns include reddening of the skin, second-degree burns include blisters that appear on the skin, and third- and most severe-degree burns include destruction of the entire outer layer of the skin. The energy density limit for first-degree burns is considered to be 12-24 W/cm^2. The intensities of the laser radiation in second-degree burns are in the range of 24-34 W/cm^2. The burn is the third-degree burn when the energy density of the laser radiation is more than 34 W/cm^2. Prolonged exposure to the laser radiation increases the severity of the skin injuries. (Zohuri 2016, p. 39.)

When using high-power lasers, the laser beam can also penetrate deeper into the tissue and cause damage elsewhere than in the skin. However, such accidents require that the laser beam is appropriately focused on the surface of the skin and much of the safety features of the high-power laser devices have been manually turned off. At wavelengths of UV and infrared radiation, the depth of the penetration into the skin is quite small. The maximum penetration depth into human skin and tissues is 700-1,400 nm. This is near infrared radiation (NIR). Such radiation at sufficiently high intensities can cause damage to the subcutaneous layers of the skin. It is also important to note that the skin of the eyelid is very thin and does not provide protection to the eye if the laser power energy density is high. In addition to burns caused by the laser radiation, the exposure limits for the UV radiation must be taken into account. The UV radiation causes skin redness, photosensitivity, aging and also skin cancer at high exposure levels. The UV radiation at a wavelength of about 300 nm is most dangerous to the skin. Some medications used can expose the skin and eyes to photosensitivity. Such drugs are commonly referred to as photosensitizers. Figure 14 shows how different radiation wavelengths affect the skin. (Jokela et al. 2009, p. 87; Ringelhan 1996, pp. 2.4.2-6; Barat 2019, pp. 3-8 - 3-11.)

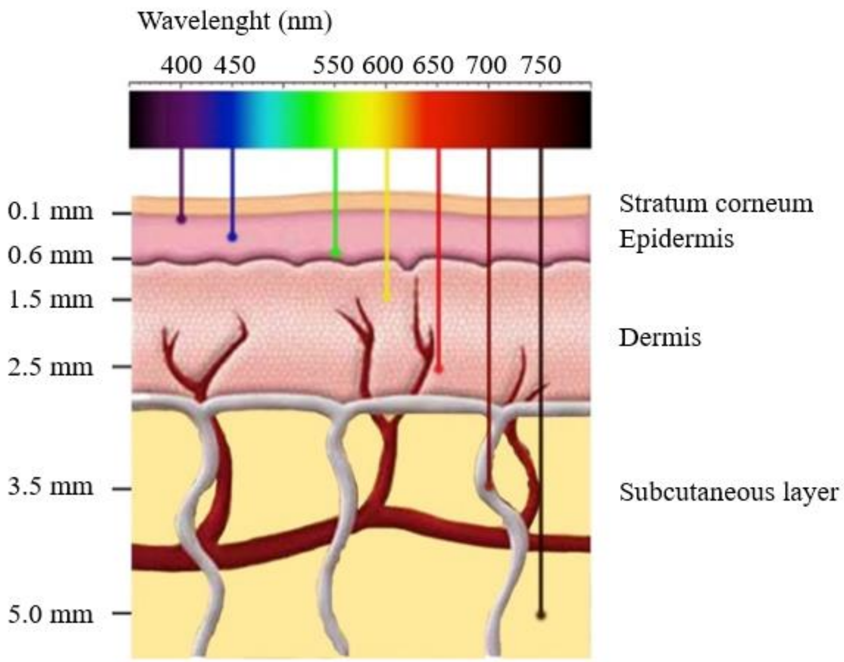

Figure 14. The penetration depth to the skin according to wavelength (Mod. Wang et al., 2015).

As it can be seen form Figure 14, the wavelength of the radiation greatly affects how deep the laser beam penetrates the skin and tissue. It seems that at a wavelength of 700-750 nm, the beam penetration is largest.

5.5 Non-beam hazards

Laser equipment also involves hazards other than those directly caused by the laser beam. Some of these are related to the secondary hazards caused by the laser beam, but some are related to the very essence of a laser device as a high-power electric machine. Not all imaginable risks and hazards are introduced in scope of the thesis, the focus is on the most common and dangerous ones.

5.5.1 Electrical hazards

The laser equipment is an electrical device and it typically carries the risk of electric shock. High-power industrial lasers use high-voltage circuits, with voltages up to hundreds of kilovolts in use. However, in terms of the risk of electric shock, the standards and regulations in use, laser equipment is similar to other machine tools using machine shops using high-voltage circuits. Maintenance and repair situations are the most dangerous situations in terms of electrical safety. Maintenance workers frequently touch the internal components of the equipment from which an electric shock can be received. For example, many high-power lasers use high-voltage capacitor systems that can produce a dangerous electric shock. In the situations of repair and maintenance, the correct grounding must be ensured in accordance with the device instructions of the manufacturer and it must be ensured that the device does not start up accidentally during the maintenance. (Kujanpää, Salminen & Vihinen 2005, p. 329; Barat 2019, p. 21-3.)

Almost all deaths in history related to laser technology have been caused by electric shocks. For example, typical CO_2 laser equipment uses a voltage of 30,000 V and a current of 400 mA. An electric shock from such a device is very dangerous. Laser devices capacitor circuit usually has large capacitors that can deliver a deadly electric shock even after the device is turned off. The general rule for high-power lasers is that access to the high voltage circuit should be protected by a lock. The most important object when working with laser and electrical equipment in general is to be aware of own work skills and ensure that the equipment is properly grounded. (Steen & Mazumder 2010, p. 525.)

5.5.2 Fume and gas hazards

Laser processing is based on a very high focused temperature and this temperature is able to vaporize the material. The vaporized material forms a fine cloud of fume and large number of small particles in the air, which are frequently toxic or at least harmful to human body. Some compounds are very dangerous and carcinogenic, in other words cause cancer at certain exposure levels. In laser processing, the formation of fumes released from the base metal is very similar to the formation of fumes released in conventional arc welding. The laser processing is frequently encapsulated to limit the laser beam, and for toxic fumes. The same enclosed space is individually ventilated, and ventilation is efficient. The necessary filters must be added to the ventilation to prevent harmful fumes from spreading into the environment. The resulting fumes mainly contain base metal chemicals when laser welding metals and alloys without filler material. When the filler material is used, the fume generated in the air also contains particles of the filler material. When the basic metal and the filler material metal are mixed with the prevailing air, various metal oxides are formed. When the welding parameters are set as close as possible to the optimal values, the generation of harmful fumes is usually as small as possible. Coating and alloying the base metal can significantly increase fume generation. For example, using the same laser welding parameters, unalloyed steel has a fume generation of 1.5 mg/s, while galvanized steel has a fume generation of 7 mg/s. (Steen & Mazumder 2010, p. 525; Spiegel-Ciobanu, Costa & Zschiesche 2020, pp. 32-48.)

Laser processing methods that release significant amounts of fumes and small particles into the air include laser cutting, welding, drilling, and marking. In the laser processing, the number of fumes and small particles released into the air are generally much lower than in similar conventional thermal methods. However, depending on the applications, clearly more fumes are released in laser cutting, for example, than in water cutting. Laser devices can themselves cause harmful gas emissions. Resonator gases can contain very dangerous elements and therefore damage situations are challenging situations. For example, some excimer lasers use fluorides, which are highly toxic. In CO_2 lasers, zinc selenide is commonly used as the material for permeable optics, which, when decomposed, releases a strong carcinogen into the air. The lens will break if the accumulated dirt causes the beam to focus on the lens and the lens to explode under the influence of heat. If such damage occurs, the room must be carefully ventilated, and the necessary maintenance performed using the correct protective equipment. In the special application of the laser welding, laser brazing, the melting temperature of the brazing material is much lower than the base material. The brazing materials are frequently some copper alloys. In the general CuSi3 brazing material, Si accounts for 3 %, Mn for 1 % and the remaining 96 % for copper. For this reason, laser brazing releases significant amounts of copper oxide into the air. In the laser brazing, little of the base material vaporizes into the air, but all of the vaporized material comes from the filler material. (Kujanpää, Salminen & Vihinen 2005, pp. 329-330; Spiegel-Ciobanu, Costa & Zschiesche 2020, p. 48.)

5.5.3 Reflected radiation

When performing laser processing, not all outgoing radiation is completely absorbed into the workpiece. In some applications, there are risks that radiation partially passes through the workpiece and/or is reflected into the environment in different directions. The reflections are particularly dangerous and challenging to control, as they can be invisible to the human eye and can head in very surprising directions. Most of the documented eye injuries have been occurred in a situation where the laser beam pulse has been reflected to the eye in a surprising direction and the use of goggles has been deficient at that very moment. At that very moment, the person may have corrected the position of the goggles or looked at something other than the actual work process from the side of the goggles. Because of these dangerous and inconspicuous reflections, it is essential that the entire operating range of the laser processing is encapsulated, and it is ensured that the dangerous reflected beam cannot hit a person at any stage of the process. If it is necessary to be able to monitor and control the work process, it is recommended to install a sufficient number of surveillance cameras in the workspace and monitors outside the enclosure. The laser beams passing through the part can damage the structures under the workpiece and cause different types of hazards when the structures break down. Reflected beams can damage the optics, resonator and other parts of the laser equipment. Particularly dangerous are situations in which the reflected beam can damage safety-related components of the equipment, such as safety switches. The reflected beams contain a large amount of energy, especially in high-power processing lasers, and can ignite materials in the proximity of the workstation to burn. Various explosions are also possible under certain conditions. For this reason, no flammable material should be left inside the enclosed workstation and the necessary cleaning of the workstation should be done regularly. (Barat 2019, pp. 6-4 - 6-5; Kujanpää, Salminen & Vihinen 2005, pp. 330-331.)

Depending on their chemical composition, different materials reflect radiation in different ways. The wavelength of the used laser also largely affects the absorption and the amount of reflection. At its simplest, the reflection coefficient R from an object is determined by the amount of total radiation applied to the object reduces the absorption coefficient A. Table 5 summarizes some of the laser processed material grades and their coefficients of reflectivity. These results in the Table 5 have been obtained using a 1.06 μm laser beam. As can be seen from the Table 5, different metals reflect radiation in very different ways, and this must be carefully considered when considering the operational safety of the equipment. (Steen & Mazumder 2010, pp. 89-90.)

Table 5. Reflection coefficients of different materials (Steen & Mazumder 2010, pp. 89-90).

Material	Symbol	Reflectivity R
Aluminium	Al	**0.91**

Table 5 continues. Reflection coefficients of different materials (Steen & Mazumder 2010, pp. 89-90).

Material	Symbol	Reflectivity *R*
Copper	Cu	**0.99**
Iron	Fe	**0.64**
Molybdenum	Mo	**0.57**
Nickel	Ni	**0.74**
Lead	Pb	**0.84**
Tin	Sn	**0.46**
Titanium	Ti	**0.63**
Tungsten	W	**0.58**
Zinc	Zn	**0.58**
Glass	-	**0.04**

5.5.4 Other risks

There are also indirect risks associated with the use of high-power processing lasers, which differ in some aspects from traditional machining methods. These indirect risks are called secondary risks. All laser processing are processes that heat the material in some way and therefore involve a risk of burns. The warming effect of the laser can be very local, and the same workpiece can be room temperature on one side and very hot on the other side. After laser processing, no ordinary traces of heat may be visible in the heated area. After laser cutting, the edges of the pieces can look very neat and smooth when viewed visually. In practise, they can be very sharp at the same time and cause severe incised wounds to those handling them. High-power lasers cause noise when operating in some applications, requiring noise sources to be encapsulated and/or users to properly protect their hearing. Frequently, the noise source is associated with, for example, high-pressure gas flow during process, whereby the enclosure of the workstation effectively isolates the noise source. A very essential part of laser machines is the control of excess heat in the laser source and optics. Cryogenic coolants are used for cooling, which cause burns on skin contact, the risk of explosion in the wrong type of piping, and insufficient ventilation can cause oxygen to dissolve dangerously in the air when the coolant vaporizes. (Kujanpää, Salminen & Vihinen 2005, p. 330; Niemz 2007, pp. 250-253.)

5.6 Protection equipment

In order to protect against the laser radiation, it is important to isolate the radiation by encapsulation, typically as a class 1 laser device. The lasers used for laser processing are, without exception, class 4 lasers in terms of power and performance, but with the help of a complete workstation enclosure, they are nevertheless classified as class 1 lasers. However, it is not typically possible to completely enclose, and in this case, it is essential to protect especially sensitive areas, or the eyes and skin, from the effects of radiation. Also, maintenance situations and various tests are frequently situations where the use of protective equipment is required of everyone in the exposure area of the laser device. It is essential for the laser safety to protect yourself with all the risks of the laser work with the necessary protective equipment. By encapsulating the laser processing, several benefits are achieved from a laser safety perspective. The reflections and radiation of the laser radiation do not hit people or combustible materials, and in addition, the right ventilation allows harmful gases and fumes to be sucked into the filters from inside the encapsulation. In addition, it is an appropriate a plan to connect all the necessary safety means to the enclosure, including interlocks, service access panel, master switch, key control, viewing portals, display screens and safe collecting optics. Frequently, laser sources and components of the laser system are positioned that they cannot be touched by outsiders, and thus the dangerous risks of electric shock are minimized. (Jokela et al. 2009, p. 107; Reidenbach 2007, pp. 1270-1272.)

5.6.1 Laser safety goggles

Eye injuries caused by laser radiation are avoided by using special laser safety goggles. Their operating principle is based on lenses that selectively filter the radiation of a certain wavelength and still allow as much visible light as possible to pass through. The same laser safety goggles contain multiple filters, allowing them to be used with multiple lasers of different wavelengths. When choosing the right type of laser safety goggles, the wavelength of the laser source must be considered first and foremost, but the power of the laser and the length of the pulses with the pulse lasers must also be taken into account. All laser safety goggles state which wavelengths are blocked and what their optical density is. The light transmission of the laser safety goggles should be at least 20 % and the colour reproduction of the lenses is often poor. The penetration requirements and selection instructions for laser safety goggles are presented in the standards SFS-EN 207 (Filters and eye-protectors against laser radiation) and SFS-EN 208 (Eye-protectors for adjustment work on lasers and laser systems). Laser safety goggles do not withstand all kinds of laser beams, especially when viewed directly, but dissipate the power of a sufficiently high-power energy density so that beam is absorbed into the goggle lens material. The lenses of laser safety goggles can also wear (saturate) when the exposure to radiation is increased enough. After the wear, the ability to absorb radiation decreases and protective effect cannot be fully relied upon. This wear (saturable absorption) of the goggles is a known phenomenon when using very dense pulse lasers, for example so called pico lasers or femto lasers (Barat 2019, pp. 6-2 – 6-4). If these very rapidly pulse lasers are used, it is recommended to use special M-class goggles. Figure 15 shows three different laser safety goggles. (Jokela et al. 2009, pp. 107-108; Barat 2019, pp. 6-1 – 6-5.)

Figure 15. Three different types laser safety goggles (Mod. requip medical, Nd).

As it can be seen from Figure 15, safety goggles are available variety of sizes and shapes, as some fit normal eyeglasses underneath and especially the lenses have different looks because they are designed for different lasers. When choosing safety goggles, the price, weight, shape and size of the frames must also be considered. It is also important to consider that they also protect as much as possible from the reflected radiation entering from the side of the goggles. (Laser Safety Industries 2020.)

5.6.2 Laser safety cabin

High-power processing lasers must typically be encapsulated within separate protective structures that are built around the workstation. The most important function of the protection structure of high-power lasers is the same as the enclosure of even low power lasers (for example, a laser printer or DVD player), to limit the laser radiation coming through the protection structure to the level of a class 1 laser device. Protective structures can be of the active or passive type. A passive protection is simply an enclosure made of sufficiently strong metal plates which, even in reasonably foreseeable failure situations, cannot be melted and thus decomposed by the action of laser radiation. The basic principle in an active protective structure is that the inner surface of the structure reacts to the harmful amount of radiation with the help of various sensors and cuts off the laser power supply in time, that the outer surface of the structure is not damaged and blocking the beam from escaping out of the enclosure. Requirements for laser radiation protection structures are listed in standards SFS-EN 60825-4 and SFS-EN 12254. Standard SFS-EN 60825-4 specifies exactly how the maximum possible radiation exposure to a protective structure is assessed. In normal operation of the device, possible fault conditions and their duration before the safety devices of the laser equipment switch off the laser power are taken into account. (Jokela et al. 2009, pp. 109-110; Barat 2019, pp. 19-1 - 19-4.)

The protections around the laser welding station, or the housing parts, are subject to several different regulations as well as the safety requirements described in ANSI Z136.1 (American National Standard for Safe Use of Lasers). Access to the inside of the enclosure is prevented in three general ways: by an entrance locking mechanism, by mechanical and electronic locks and by warning signs and/or light signals. Doorways must be provided with an electrical and/or mechanical identification system that immediately cut the power to the laser device whenever the door is opened and does not allow the laser device to start until the door is closed. Frequently, there are also a number of different sensors and scanners inside the workstation that do not allow the laser equipment to start if there is an object inside the protective structure, such as a human. In addition, the necessary number of warning signs must be affixed in front of all doorways to warn all necessary personnel about dangers of laser device inside. (Barat 2019, pp. 15-1 – 15-4; Steen & Mazumder 2010, pp. 525-526.)

The durability of the enclosure structure around the laser work welding station should be tested in accordance with EN 12254 and its structure should meet national construction guidance standards, such as NFPA 701 (National Fire Protection Association). The materials used in the laser enclosure must be clearly marked with radiation values and other necessary performance meters in order to make their use and selection as clear as possible. The recommended enclosure material is a suitable metal material, such as Al or steel, as they include a very effective level of radiation resistance. The surface of the enclosure should be as highly absorbent as possible, as it prevents the reflection of hazardous beam inside the enclosure. The enclosure should be able to withstand regular cleaning, as any waste material accumulated during Al welding must be removed from the enclosure at regular intervals. It is frequently desirable to install a separate viewing window in the enclosure, but this is frequently the weakest point of the enclosure. Its necessity needs to be considered and also whether it could be replaced, for example, by a live surveillance camera and a suitable display outside the enclosure. In connection with the enclosure separately, it is appropriate to consider ensuring adequate lighting also inside the workstation, as in maintenance and fault situations, it is necessary to work inside the enclosure from time to time. Similarly, the outlets from the inside of the enclosure to the outside should be as unobstructed as possible in the event of a sudden emergency. Figure 16 shows an example solution for a functional laser workstation enclosure. (Barat 2019, pp. 15-4 – 15-9.)

Figure 16. Laser safety cabin (Mod. Directindustry, Nd).

As it can be seen from Figure 16, the left wall of the enclosure has the control panel (a) and the two walls are separated by large doorway (b) and (c) leading inside the enclosure.

5.6.3 Issues to consider in training for high-power lasers

High-power lasers, when misused, are very dangerous and must therefore be controllable and safe to use both in normal operation and in failure situations. Properly conducted comprehensive training for the laser operators is key to ensuring work safety. The following instructions regarding work with high-power machining lasers should be enforced prior to ensure safety at all times:

- When the laser device is not in use, it must be locked separately (with key) to prevent damage.
- Avoiding use of all reflective surfaces near lasers and taking into account the reflection of long-wave infrared waves, even from rough-looking surfaces.
- Persons working in the area where the lasers are used must be trained in the features of the laser device, safety precautions, warning labels and protection must be used.
- If a person is suspected of being exposed to laser radiation, the necessary medical examinations must be carried out immediately.
- Lasers are used only in the intended space designed for them and that the space is marked with all necessary warning signs.
- Whenever high-voltage equipment is touched, the person must know exactly what is being done.
- If the person must enter to the workstation of the laser device, one must be equipped with the necessary protective equipment.
- Laser equipment should, as much as possible, be remote-controlled in order to minimize unnecessary presence in area of the beam.
- All combustible materials must be removed from the laser workstation before the laser welding process is started.
- When working with laser equipment, employees must be aware of the dangers of laser radiation to humans and act accordingly at all times.

(Jokela et al. 2009, pp. 110-112; Reidenbach 2007, pp 1273-1274.)

5.7 Checklist for general laser welding safety requirements

The previous sections of this chapter include comprehensively reviewed requirements regarding general safety issues in laser welding. Six different topics were covered, all of them are essential to consider for ensuring work safety with laser welding machines. This research work reviewed these topics to offer guidelines for future workstation designers. Topics have been reviewed in the same order in which they have been addressed in past. Based on the results of previous sections, a compact and simple of checklist has been compiled for designers to follow. With that checklist designers can easily and quickly check or confirm details of interest if need arise. The full checklist is presented in Appendix VII.

6 SAFETY ISSUES FOR ALUMINIUM LASER WELDING SYSTEMS

This chapter goes through safety risks caused by laser welding of Al. The safety risks associated with laser technology have already been presented in previous chapter, current chapter focuses specifically on the safety risks caused by Al material. Health effects of Al especially those caused by occupational exposure are presented. Effects of Al on the human body and vital functions from Al exposure are presented. In addition, biomonitoring of Al exposure and Al dust explosion are reviewed.

6.1 General information on hazards of aluminium during laser welding

Al as a material poses various and, in some cases even serious hazards to human laser welding it (compared to steel). These hazards can be divided into three types: Firstly, there are particulate impurities released from Al or fumes; secondly, gaseous impurities, or gases from Al and the welding process, and lastly the ultraviolet radiation generated during the welding process. Ultraviolet radiation is not an issue in laser welding, as workstation is almost always encapsulated so that ultraviolet radiation does not reach outside the enclosure. Certainly, laser welding of Al includes all the other safety challenges associated with laser welding, but this section focuses solely on these three hazards, especially those posed by Al as a material. Generally, gases and fumes are absorbed into the human body, especially through inhalation. Generally, both gases and fumes are referred to as welding fumes. Welding gases and fumes contain particles of different sizes and for all airborne particles a fraction is separated according to ISO 7708: 1995;

Inhalable fraction

- Particles that are inhaled through the mouth and nose into the body and are 100 μm or smaller in size.

Respirable fraction

- Particles that can penetrate the alveoli, or pulmonary alveolus and are 10 μm or less in size.

Particulate matter generated during welding is in some cases very small in size. In general, the particle size is less than 1 µm and most frequently even below 0.1 µm. These particles are a respirable fraction and the air mixture formed from them is commonly called welding fume. According to morphological studies, the particles generated in welding do not have a completely homogeneous composition. The air at the welding station and its harmfulness are assessed using the TLV (Threshold limit value). In Finland, TLV is named HTP (Haitallisiksi tunnetut pitoisuudet). This TLV number is based on an occupational exposure limit value and the notion that there is a threshold below which there are no lasting effects on health. These values are given for welding fumes in mg/m^3 and are defined as eight-hour or 15-minute average concentrations. At the workplace, occupational hygiene measurements can be used to determine the peak concentrations of these concentrations and the longer-term average concentrations. The current TLV of Al welding fume is 1.5 mg/m^3 within eight hours of exposure. (Lukkari 2001, pp. 240-241; Spiegel-Ciobanu, Costa & Zschiesche 2020, pp. 1-3; Ministry of Social Affairs and Health 2018, p. 21.)

Particles of different sizes affect the human body in different ways as they travel and accumulate in different organs in the body. Many of the health effects caused by fine particles do not become apparent until several years later. Such are, for example, carcinogenic effects, and therefore no specific limit values have often been set for these, below which there are no definite health effects. In Al welding, the particles released into the air are mainly composed of Al oxide, or alumina (Al_2O_3). The Al oxide originates from the surface of the material to be welded and also from any filler material used in welding process. The Al oxide entering the body is harmful in many ways, the most well-known disadvantages of inhaled fine Al are lung diseases aluminosis, pneumoconiosis, and lung fibrosis. Another known health effect of Al welding is its effect on the neurocognitive system of the exposed person. However, the studies on neurotoxic effects of Al on humans have produced contradictory results. Some studies have found a clear causal relationship between individuals working in the area affected by Al particles and their neuropsychological and neurophysical changes (He, Qiao & Sheng 2003, pp. 141-143; Giorgianni et al. 2014, pp. 347-348). Other studies found no such causal relationship and some studies state that, for example, Al welders have been found to perform even better in psychomotor and reaction-testing tests than the control group. (Spiegel-Ciobanu, Costa & Zschiesche 2020, pp. 6, 20; Kiesswetter et al. 2007, pp. 50-62; Giorgianni et al. 2014, pp. 347-348.)

Laser welding in a keyhole mode involves material to be welded evaporating, during which at least some of the material is vaporised and forming the fumes, gaseous emissions and small particles. In laser welding without filler material, the amount of emissions released into the air is quite similar to that of traditional arc welding processes. When metals are welded, the particles released into the air contain alloying elements and there are differences in the resulting concentrations depending on the alloying of the material being processed. In laser welding with a filler, welding fumes also contain chemical mixtures of that. The use of a powdered filler material spreads additional dust from it to surrounding air without vaporizing it. According to experimental study done by ISF (Welding and Joining Institute) RWTH (Rheinisch-Westfälische Technische Hochschule) Aachen university with ITEM (Fraunhofer-Institut für Toxikologie und Experimentelle Medizin) Hannover, laser welding without filler material evaporates 2.6 mg/s when welding EN AW-6082 and 6.5 mg/s when welding EN AW-5454 (Spiegel-Ciobanu, Costa & Zschiesche 2020, pp. 52-55). For comparison, when welding DX53 (metal coated formable steel) with the same equipment and the same parameters, the material evaporation rate was 7.8 to 8.0 mg/s. The amount of vaporized material would thus appear to be the same between Al and steel in laser welding without the use of filler material. (Kujanpää, Salminen & Vihinen 2005, p. 329: Spiegel-Ciobanu, Costa & Zschiesche 2020, pp. 52-55.)

6.2 Exposure to aluminium

Human exposure to Al can be roughly divided into two different main types. These include exposure through normal daily consumer products and occupational exposure due to the handling of Al materials. Because Al is abundant in the soil and has many beneficial properties, it is found naturally in many fruits, vegetables, and grain products, as well as in many consumer products. Among other objects, several cosmetics, toothpastes, sunscreens and antiperspirants contain Al. In addition, Al packaging and Al containers dissolve at least some Al in the preservative contents. Such exposure through consumer products is daily and is not related to the occupational exposure identified in this study. In laser welding, the Al fume released into the air is part of the occupational exposure to which those involved and present in the welding process are exposed in addition to the normal exposure of Al through consumer products. The occupational exposure to Al is exposed to all workers who work in processes that fabricate or process Al. These include the Al powder industry, the Al metal processing industry and Al foundries. In such production facilities, most of the Al that ends up in the human body ends up in the air through respiration, either by being absorbed into the lungs or airways. The amount of Al absorbed through the skin and ingested orally can considered to be almost negligible compared to the amount of Al absorbed through inhalation. First objects exposed to Al in the air in the body through inhalation can be seen in Figure 17. (Tietz et al. 2019, pp. 3503-3504; Buchta et al. 2003, pp. 539-540.)

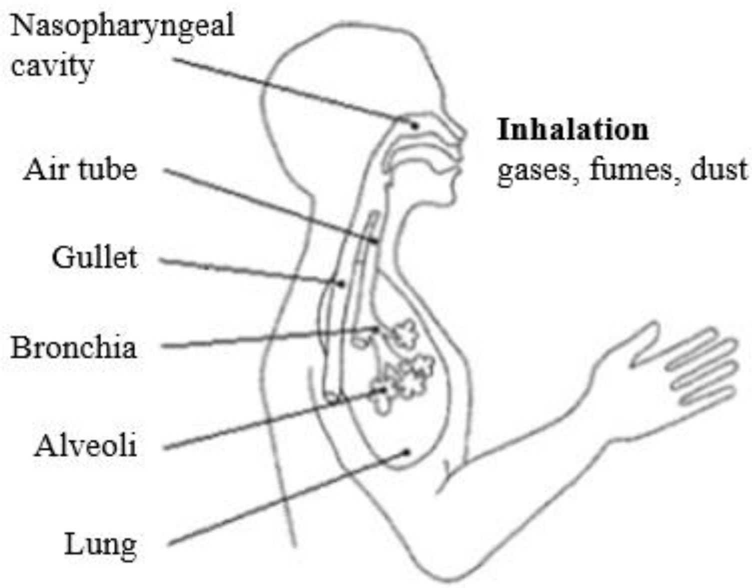

Figure 17. Inhalation of Al welding gases, fumes and dust (Mod. Spiegel-Ciobanu, Costa & Zschiesche 2020, p. 2).

The composition of the gas mixture released into the air during the welding process is studied by several different methods, as it is essential what particles the welding fume contains. This information is essential because different kinds and sized particles affect the human body in different ways. Welding fume is studied, for example, using photometer and powder and dispersion analyser, and these can be used to determine the size of the particles at unit density. In addition, secondary neutral mass spectrometer can be used to determine the compositions of successive layers of weld particles. Equipment used for laser welding all belongs to class 4 lasers and must be provided with a separate enclosure. Within this enclosure, the fumes of laser welding can be examined with reasonable accuracy. It has been found that in laser welding, in general, the fume particles are largely spherical, about micrometre in size and contain a composition exactly equivalent to that of laser cutting fumes. Laser welding processes are practically typically fully automated, that their processes can be adjusted to the optimum and the amount of flue gases can be kept as low as possible. It has been found that the fumes released into the air by laser welding without filler material are of the same level as metal active gas welding. When the filler material is used, the number of particles released into the air increases as there is more meltable material. Emissions are lower the better the welding parameters are adjusted. The optimally adjusted laser beam only melts the material in barely the right amount, that the amount of welding fumes released into the air is as low as possible. Similarly, the energy source of laser welding is important. When using traditional CO_2 laser welding, the emissions are higher than when using modern solid-state lasers. (Palmer & Eaton 1995, pp. 18-19; Warming et al. 2018, pp. 30-31.)

Al is generally considered to be a non-toxic and safe material in most everyday applications. However, fine Al that accumulates in the body has been found to be toxic in numerous animal experiments and is confirmed to cause dialysis encephalopathy, for example. The safe reputation of Al contributes to the fact that no separate legislation has been defined to limit the exposure to it. There are also no specific exposure limits in the legislation for the exposure through digestion, skin or inhalation. In normal daily life, Al accumulates in the body through digestion, among other objects, originating from wide variety of foods consumed. In case of laser welding, exposure does not happen through digestion, it accumulates in the body almost completely through inhalation.

Al can be absorbed into human body in four different ways

- Through skin
- Through respiratory tract
- Through lungs
- Through digestive tract

In laser welding, most of Al is absorbed through respiratory tract and lungs. Particulate Al that ends up in the airways initially ends up, at least in part, in the olfactory epithelium and further in nerve cells in the nasal cavity. Al particles can end up through the mucous membranes in the gut or along nerve connections even to the brain. The particulate Al that ends up in the lungs initially ends up in the lung epithelium and lung tissue. Of these, Al particles propagate mainly into the bloodstream and through it throughout the body. The health effects of Al released into the human body are manifold and difficult to elucidate. The effects of high Al levels have been studied in various animal experiments, and have been found to contribute to growth retardation, delayed development, impaired reproductive performance, and shorter life expectancy (Page et al. 2012, pp. 516-521). Some of these adverse effects have also been found to be inherited by the offspring. (Exley 2013, pp. 1807-1812; Page et al. 2012, pp. 519-521.)

6.3 Aluminium effects to metabolism

Al that ends up in the body accumulates virtually everywhere in the body. Particularly Al absorbed through the lungs, enters the bloodstream and through it all over the body. Although Al can accumulate in the human body along four different routes, only kidneys are able to remove the accumulated Al from body as part of normal functioning of body cleansing system. For this reason, the role of urine tests in determining human Al exposure is essential. When Al is removed from the human body, there are metabolic markers indicating presence of Al by half-life, which refers to the time it takes for certain amount of Al in the body to be reduced by half. The half-life of Al in the human body varies from days to months depending on the duration of exposure. Al is known to be involved in triggering several different health problems and diseases, but the actual molecular mechanisms and underlying disorders caused by Al exposure are still unclear. In humans, the accumulation of Al has been most abundant in the brain, bone, and liver.

Diseases associated with Al exposure in particular are:

- Encephalopathy
- Alzheimer’s disease
- Parkinson's disease
- Seizures
- Motor Neuron degeneration
- Osteomalacia

(Lemire & Appanna 2011, p. 1513; Bondy 2010, pp. 575-579).

The toxicity of Al has a versatile effect on the molecules of the human body and appears to impair the homeostasis of metals, calcium, magnesium and iron essential to the human body. Al moves at the cellular level to replace these three metals, thus causing a wide range of disturbances in various bodily processes. The cellular changes caused by Al in different parts of the body and the problems that result from them are rather complex. For example, in brain cells in Alzheimer’s disease, Al is thought to play a role in promoting tau-protein induction and phosphorylation as well as neuroinflammatory transcription. (Buchta et al. 2005, pp. 677-678; Lemire & Appanna 2011, pp. 1513-1514.)

The neurophysiological problems appear to be caused, at least in part, by decrease in the energy production capacity of cells essential for brain function, manifested as dysfunction of brain cell mitochondria as well as oxidative phosphorylation. When Al that ends up in cells replacing the metals in their normal state, energy production of the cells get impaired by blocking the activity of important ATP (Adenosine triphosphate) molecules. ATP is an important energy-transmitting and conserving molecule that is involved in many cellular functions. An association between increased Al exposure and decreased production of ATP molecules has been found (Lemire & Appanna 2011, p. 1515; Singh et al. 2009, pp. 4-8). The accumulation of Al in the liver interferes with its normal functioning in burning of lipids and fatty compounds. Excess lipids interfere with brain metabolism and this has been found to cause neurological effects. All in all, Al, when accumulated in brain tissue, disrupts cellular energy production in many ways, inhibits cell morphology and alters lipid metabolism. All of these are caused by on Al-induced astrocytic dysfunction, which frequently manifests as neurological problems. In the brain, the Al will eventually accumulate into a fairly restricted area of the hippocampus, as well as parts of the front side of the cerebral cortex. Al that ends up in high amounts in the body also enhances the formation of ROS (Reactive Oxygen Species) which leads to an inflammatory state of cells and cell death. The effects of Al, and especially the effects of the amount of Al in the body at the cellular level, are still quite controversial. Further research is needed to gain a more reliable understanding. The precise understanding of the effects of Al are disturbed by the holistic effects of Al and the disturbances to various processes and cellular functions in the body caused by other active substances, for example other metal materials. (Lemire & Appanna 2011, pp. 1514-1516; Maya et al. 2016, pp. 746-747, 752.)

6.4 Health effects of aluminium

The health effects of Al have been established through studying the effects of its absorption through respiratory system and in humans. Laser welding is not the only welding method in which welding fumes are formed. Welding fumes are generated in all welding processes where the metal melts and the metal are released from the fine material into the air.

The welding processes that produce welding fumes are:

- Shielded metal arc welding
- Gas tungsten arc welding
- Gas metal arc welding
- Flux-cored arc welding
- Submerged arc welding.

Welding fumes contain a wide range of different types of small particles and are generally hazardous to human health. Several studies show Al-containing welding fumes cause occupational asthma, bronchitis, fume fever, cardiovascular disease, and interstitial pulmonary fibrosis (Hartmann et al. 2014, pp. 160-162; Fang et al. 2009, pp. 850-854). In addition, there are several suspicions that Al-containing welding fumes would play a role in the mechanism of lung cancer. However, in real life, in the vicinity of a workplace welding station, the human body is also affected by non-welding fumes and gases. Many different processes are frequently performed in the same space, such as welding, grinding, soldering and use of chemical solvents. In addition, the effectiveness of ventilation, the susceptibility of individuals to disease, and the use of personal protective equipment complicate defining a straightforward an unambiguous assessment. High-quality research has taken into account the lifestyles that affect the health of all employees in the analysis of research results. The following subsections discuss in more detail the effect of Al entering the body on certain critical parts of the body. (Hartmann et al. 2014, pp. 160-162; Greenberg & Vearrier 2015, pp. 195-196.)

6.4.1 Effects on the lung health

When it comes to Al laser welding, the Al that ends up in the lungs comes mainly from welding fumes. The welding fumes consist largely of fine and ultrafine particles derived from the welded material and filler if it is used. The welding fumes contain very small particles of Al oxide. Welding gases typically also contain toxic gases such as ozone, nitrogen oxides, carbon dioxide and carbon monoxide. The use of shielding gases during welding reduces oxidation to some extent, resulting in less metal oxides in air. Secondly, the use of a shielding gas can enhance ultraviolet radiation, thereby increasing the amount of photochemical gases, ozone and nitric oxide. Level of lung damage is affected by the amount of inhaled welding fumes and the dose, the exposure time, and the composition of the welding fumes and welding gases. Welders generally possess a wide variety of respiratory diseases.

These are the respiratory diseases commonly found in welders:

- Metal fume fever
- Siderosis
- Pulmonary function abnormalities
- Infectious pneumonia
- Fibrosis
- Asthma
- Chronic bronchitis
- Chronic obstructive pulmonary disease
- Lung cancer

(Riccelli et al. 2020, pp. 1-2, 9.)

Al fumes undeniably cause damage to lungs and respiratory system and lead to a wide variety of respiratory diseases, but the mechanism of Al-induced pulmonary toxicity is not yet fully understood. Al that has entered the lungs is currently thought to potentiate oxidative and inflammatory stress leading to lung epithelial dysfunction. Studies have found that smoking Al workers have a higher Al load than non-smoking Al workers (Elserougy et al. 2012, p. 76). It can be assessed that as the Al load to humans increases, health problems became worse after long period. Thus, some studies have found that smoking or non-smoking is not directly related to work ability or risk of getting sick (Li & Sung 1999, pp. 226-227). Tobacco smoke contains quite a large number of Al, up to 0.37 % by weight, and more Al accumulates in lungs of smokers than in non-smokers. In one study for non-smoking Al workers the UAl (Urinary Al) is between 15.8 ± 4.6 mg/l and for smoking Al workers the UAl is between 20.5 ± 5.7 mg/l (Elserougy et al. 2012, p. 76). In addition to this lung study, it has been found that a decrease in C-reactive protein (CRP) levels and alpha-1 antitrypsin (A1AT) levels in the body are associated with an increase in Al levels and an increase in respiratory problems. Monitoring of the A1AT level has appeared to be a promising way to prevent more advanced Al-induced lung diseases. Individuals with deficient A1AT levels should move away from jobs that cause Al exposure and thus prevent more serious respiratory problems at a later age. (Elserougy et al. 2012, pp. 73-77.)

A particular disease caused by Al in the lungs is called aluminosis. These kinds of diseases are generally called pneumoconiosis and they are caused by fine dust in the lungs containing Al, especially Al oxide. Studies have been found that Al particles with a size between 0.5 and 5 µm are the most dangerous for aluminosis (Guidotti 1975, pp. 16-17; Smolkova & Nakladalova 2014, pp. 535-537). The first symptoms of aluminosis are dyspnoea on exertion and a dry cough. Aluminosis, if continued, leads to pulmonary fibrosis, where the lung surfaces scar and no longer function. The disease is serious, with deaths reported up to 3-5 years subsequent to the onset of symptoms. As with other pneumoconiosis, there is no effective treatment for aluminosis, and the resulting lung damage is permanent. Aluminosis is now a fully diagnosable and existing lung disease, although the pathophysiology of the disease has not been fully elucidated. Aluminosis has been observed most abundantly in persons working in the Al production involved with melting of bauxite, but also in abundance in those working with processing of fine Al powder and welding it. Aluminosis is currently a relatively rare disease, but due to the increasing use of Al, the risks leading to aluminosis must be considered and overcome. (Smolkova & Nakladalova 2014, pp. 535-537.)

The effects of Al fumes on the human respiratory system cause occupational asthma. Studies have been able to exclude the effects of general dust containing metal particles alone on the development of asthma, as no bronchial response was observed during mild steel welding, although the amount of respirable welding fumes has been significant (Vandenplas et al. 1998, pp. 1183-1184). A non-specific increase in bronchial hyperactivity has been observed with Al welding and such changes are frequently observed with asthmatic sensitivity. When comparing welding of steel to that of Al, it has been found that neither the fluorides in the welding gas nor the ozone created, neither chromium or nickel are expected to cause asthma symptoms. Moreover, the exact pathogens of work-related asthma are still unclear in welding, as the respirable welding gas contains such a wide variety of metal particles as well as a variety of gases and fumes. The IgE (Immunoglobulin E) -mediated mechanism of a specific antibody against allergic reactions in the body is thought to be involved in the pathogens of Al-induced asthma. A specific Al-induced asthma, called potroom asthma, is a disease observed in primary Al production workers as well as Al salt production workers, and Al welders are assumed to possess similar susceptibility and disease mechanisms to occupational asthma. (Vandenplas et al. 1998, pp. 1182-1184.)

6.4.2 Effects on the central nervous system

It has been long time known that Al accumulated in the body has effects on the human neurocognitive system (NCS). The first observations of these effects were made in 1976 in dialysis patients (Alfrey, LeGendre & Kaehny 1976, p. 184-188; Giorgianni et al. 2014, p. 347). In dialysis patients, all the problems caused by Al are increased because the removal of Al from their body is much slower. The partial reason for neurocognitive problems is considered to be the solubility of finely divided Al in the brain cells and the slow removal of the Al from the brain. Because of these, fine-grained Al accumulates especially in the brain and, with a long-term exposure, causes destruction of brain cells. The increase in Al in the body and thus in the brain has been found to lead to a wide range of neurocognitive problems, in particular to:

- Slowing down reaction times
- Impaired neuropsychological response
- Memory impairment
- Weaker coordination
- Impairment of abstract reasoning
- Decreased brain electrical activity in the anterior part of the brain

In addition, Al exposure has been found to be associated

- Irritability
- Difficulty concentrating
- Insomnia
- Depression

Numerous studies have found that the intensity of neurophysiological and neuropsychological changes strongly correlates with the dose and duration of Al exposure

(Riihimäki et al. 2000, pp. 124-129; Giorgianni et al. 2014, pp. 347-348). This has been concluded from the fact that people with longer occupational Al exposure perform worse on average in cognitive tests than those with less time of exposure. (Giorgianni et al. 2014, pp. 347-348, 354-355; Wang et al. 2016b, pp. 200-201, 205.)

Studies have shown that Aluminium nanoparticles (AlNPs) particles smaller than 100 nm in size affect oxidative damage more than aluminium microparticles (AlMPs). It is thought that smaller particles are likely to penetrate deeper into brain tissues and therefore cause wider and more severe damage. The ability of fine Al that accumulates in the brain to cause change and damage is based on its ability to alter cellular functions.

These cellular changes in the brain caused by Al particles are:

- Induction of ROS formation
- Lipid peroxidation
- Protein oxidation
- Glutathione depletion
- Mitochondrial dysfunction
- Gait abnormalities in a dose-depent manner
- Mitochondrial membrane potential reduction

Toxicity of Al exposure is particularly related to cell mitochondrial dysfunction and the ability of Al to impair the antioxidant defence system. Mitochondria are the main victims of cell damage caused by ROS, as they naturally lack protective structural proteins. Al that ends up in the brain causes electron transport chain dysfunction and increases ROS production and thus oxidation of mitochondrial DNA, proteins, and lipids. When the mitochondrial function of cells is significantly disrupted, cell deaths result. The accumulation of iron and the increase in ROS cause harm, especially in the brain. Al-induced oxidant-mediated damage is accentuated in the brain, as nervous system of the brain consumes a large number of oxygen, the meninges are highly oxidizing polyunsaturated fatty acids, the brain is high in antioxidant enzymes, and iron content of the brain is relatively high. Generally, all neurodegenerative diseases increase with human age. As the average age of a person rises, especially in developed western countries, various diseases of the nervous system will increase. Al exposure is also obtained daily with a number of consumer products, distinguishing central nervous system diseases caused by alone occupational Al exposure from this other Al exposure is challenging. (Mirshafa et al. 2018, pp. 261-262, 266-267; Bondy 2010, pp. 575-576, 579-580.)

6.4.3 Effects on the bones and aplastic anemia

Al that ends up in the body accumulates at certain sites in the body and bone tissue is most essential sites of accumulation. Prolonged exposure to Al reduces the amount of minerals and trace elements in the bones and leads to accelerated osteoporosis and osteomalacia. The accumulation of Al in bone tissue interferes with the deposition of essential minerals and trace elements (calcium, magnesium and phosphorus). Long-term Al exposure reduces the amount of zinc, iron, copper, manganese, selenium, boron and strontium in bone tissue and thus disturbs metabolism. Al is believed to affect bone mineralization by directly inhibiting the differentiation of osteoblasts and indirectly interfering with the synthesis and secretion of PTH (parathyroid hormone) and 1,25-dihydroxyvitamin D3. (Li et al. 2010, pp. 382-384; Li et al. 2015, pp. 166-167.)

Significant amounts of Al -induced bone injuries have been observed in those working in electroplating factories or Al mines. There, occupational exposure to Al is similar to that of Al welding. As in the brain, the different Al-induced mechanics of disease progression are also quite complex in the bones. Al in bone inhibits the expression of the cell growth-regulating protein TGF-β1 (Transforming growth factor β1) and the essential growth factor BMP-2 (bone morphogenetic protein 2), which reduces osteoblast activity and bone collagen protein synthesis. These cause disorders and defects in bone formation. As much as 58-70 % of the Al that ends up in the human body accumulates in bone tissue. Precise limit values for safe occupational exposure to Al cannot be set, as non-occupational exposure to Al varies much from region to region. For example, in France, the average Al exposure of a child to food is 40.3 mg/kg bw/day, where bw indicates body weight, while in China the corresponding Al exposure of child to food is as high as 471.7 mg/kg bw/day. (Li et al. 2015, p. 170; Sun et al. 2017, pp. 1-2, 5-6.)

Al accumulated in the body has been found to be associated with immune system changes and immuno-toxicity and further leads to autoimmune diseases. This is based on an increase in circulating immune complex and a decrease in erythrocyte immune function, leading to a decrease in immune complex capacity. Aplastic anemia is an autoimmune disease associated with abnormal proliferation and activation of immune cells and dysregulation of cytokines essential for immune function. High Al exposure has been found to lead to changes in various cytokine levels and thus has been interpreted as an association between Al exposure and aplastic anemia. Aplastic anemia refers to bone marrow loss, indicating that the bone marrow does not produce enough new blood cells (red blood cells, white blood cells and platelets). Aplastic anemia is a serious illness and if untreated, it often results in death in as little as six months. Al-induced blood system damage has also been observed in non-iron deficient anemia and renal anemia. The effects of Al on hepatic dysfunction also appear to be one of the causes underlying hypochromic anemia. Al accumulated in the liver triggers oxidative stress and depletes the biological portion of iron, disrupting the metabolic process of liver cells. Thus, liver heme degradation and iron accumulation are accelerated and this interferes with red blood cell production. The pathogenesis of autoimmune diseases is frequently very complex and therefore it cannot be directly said that just the right Al content is the cause of aplastic anemia but there may be other causes behind the disease. (Zuo et al. 2020, pp. 2, 8-9; Lin et al. 2013, pp. 225-227.)

6.5 Aluminium exposure assessment

Al that accumulates in the body is virtually eliminated only through the filtration of normal body waste products by the kidneys. Therefore, Al exposure can be assessed by separate urine tests, which detect well how much Al there is on average in the body. Fine Al is transported to different places in the body with the bloodstream and therefore Al exposure can also be measured through blood tests. In the urine test, a high Al content of 200 µg Al/litre is considered. Secondly, it is appropriate to remember that the health effects of Al appear very slowly. In one study, Al welders showed similar levels of Al in their urine, but at the same time no ill effects were observed over the four-year inspection period (Kiesswetter et al. 2009, pp. 1201-1206). The concentration of Al in the blood does not tell very precisely what the ratio of the measured value is to the amount of total Al and this has also been found to include poor temporal stability. The concentration of Al in the urine is not completely optimal measurement as it is sensitive affected by external variables. However, it appears that the urine test is currently the most accurate assessment of Al exposure. Over prolonged exposure, Al accumulated in the body is slowly eliminated and detectable in both urine tests and blood tests for a long time, even if there has not been an actual Al exposure for a while. Al exposure can also be assessed by performing various neurocognitive tests, but in practice these must typically include an unexposed control group, and the results of an individual subject can be affected by many other effects than Al exposure alone. Therefore, such neurocognitive tests are frequently performed on a larger group at a time to equalize individual aberrations and to better visualize the change compared to the control group. (Kiesswetter et al. 2009, pp. 1192, 1201-1203; Riihimäki et al. 2008, pp. 451-452.)

Changes in the amount of Al dust that is inhaled are best detected by a urine test that measures the ratio of Al to creatinine normally present in the urine (Al/g creatinine). In particular, small changes in the amount of respirable Al dust (0.4-0.8 mg/m^3) in the working space are not accurately reflected in the results of other urine tests. In one study a relatively low concentration of 0.80 mg/m^3 Al dust produces a creatinine test resulting in 40 µg Al/g creatinine and a high concentration of 6 mg/m^3 Al dust produces a creatinine test resulting in 140 µg Al/g creatinine (Kiesswetter et al. 2009, p. 1206). It has been found that the Al content of the daily human urine when working with Al welding can exceed up to 100 times the limit considered normal. Subsequent to accurately measuring the amount of Al in the air in the work area and estimating it for the Al content of urine tests in previously unexposed individuals, it has been estimated that approximately 1.2 % of the inhaled Al was absorbed into the lungs. Similarly, it is estimated that previously unexposed subjects excreted 0.1-0.3 % of their inhaled Al in the two next days following exposure. In other words, inhaled Al was absorbed much more efficiently into the human body than it dissolved from the human body. The amount of Al in the urine is assumed to depend on the current Al exposure and in part also on the previous prolonged duration of exposure. Among welders exposed to Al for less than a year, the half-life of Al was about 9 days, while among those exposed to Al for more than 10 years, the half-life was 6 months or longer. Studies have been shown half-lives of up to more than one year due to prolonged Al exposure (Riihimäki et al. 2008, pp. 458-461). The slowness of Al removal from the body is due to its accumulation in bone tissue and the slowness of bone tissue regeneration. For welders with 20 years of Al exposure, Al concentrations were measured four times over a nine-year period, including five years without exposure subsequent to completion of welding work. The results showed a change in the Al concentration in the blood of 4-53 µg/litre and in the urine of 107-351 µg/litre.

Thus, the percentage changes in Al levels in the blood are much larger than in the urine. (Kiesswetter et al. 2009, pp. 1201-1206; Riihimäki et al. 2008, pp. 458-461.)

6.5.1 Aluminium biomonitoring

The release of Al into the body during welding processes can be measured and detected by analysing the amount of Al in the blood serum or by implies of a blood test or urine by implies of a urine test. Such experiments and exposure assessment based on experiments are called the human biomonitoring method (HBM). This assay can be utilized especially in the introduction of various new welding processes and in ensuring safety. The functionality of respirators and ventilation can also be tested using these tests. Al levels of serum and urine are both equally valid measures for the assessment of short-term exposure. However, the urine test is more sensitive to indicating the amount of internal Al, as long-term exposure to Al is slowly excreted precisely through the kidneys and excreted in the urine. This is noticed in situations where welders possessed no Al exposure at all for months or even a year and their serum Al levels have been dropped to completely normal, but urine Al levels may still be elevated. In addition, it is important to remember that especially long-term Al exposure causes health problems and various diseases. Thus, Al levels in serum provide a more accurate indication of short-term exposure, while urinary Al levels provide a better indication of the amount of Al in the body and the duration of exposure. The Finnish Institute of Occupational Health has recommended a urine test action level of 162 µg/litre or alternatively 0.6 µmol/litre subsequent to an unexposed weekend. In Germany, the corresponding limit value for occupational exposure is 200 µg/litre. Similarly, a limit value has been set in Germany for urinary creatinine, which is 60 Al µg/g creatinine. In one study, 12 previously unexposed individuals were exposed to 2.5 mg/m^3 welding fumes (MIG welding) for 6 hours (Bertram et al. 2015, pp. 918-919). In this study, the blood Al level increased from the initial value by only 0.6 µg/litre. In the urine test, Al levels increased more (increases of 11 µg/litre and 8 µg/g creatinine), but still remained well below the limit of 60 µg/g creatinine, and, fell very close to pre-exposure values subsequent to one week. The health effects of Al are unlikely to be a problem if urinary Al levels are monitored for the required individuals and care is taken to maintain limit values. (Riihimäki et al. 2008, pp. 460-461; Bertram et al. 2015, pp. 913-914, 918-919.)

Biomonitoring of human Al exposure is still associated with some reliability and suitability issues that need to be considered. Most noteworthy are the following issues:

- The sample may be easily contaminated during the sampling and analytical process, as the overall Al concentrations in the samples are very low and even small impurities cause large discords in the results.
- Poor bioavailability of respirable Al and mostly unknown elimination of respired Al make occupational exposure assessment particularly difficult for workers who have long been involved in Al welding.
- A careful assessment must be made as to whether a normal level of urinary Al can be required or whether elevated Al levels can also be used to interpret the internal Al load.

In the urine tests of workers who have been exposed to Al for a long time, the Al levels are elevated, as the Al accumulated in the body, especially from the bone tissues, seems to dissolve very slowly and therefore the test results can vary very much. Because several HBM studies have been shown quite large variations in urinary Al concentrations among those who have performed Al welding for a long time, it is recommended that at least two urine samples be collected, one immediately subsequent to exposure and the other subsequent to exposure-free weekend (Bertram et al. 2015, pp. 920-921). In addition, it should be recommended to consider the creatinine-normalized result and also the not-normalized result. As mentioned above, Al HBM is a method that still involves some uncertainties and thus drawing conclusions is only indicative. Uncertainties are due to the high requirements of the method. (Bertram et al. 2015, pp. 918-921.)

6.6 Danger of aluminium dust explosion

Separate and especially risk associated with Al material is so called dust explosion. Such fine dust released from the material to be machined is frequently a by-product of the actual process and waste that is collected in abatement systems. The dust is collected mainly for health reasons. Al is one of the most challenging metals for explosions, as finely divided Al dust is generally quite reactive. Explosions of Al dust are particularly related to processes in which Al is ground or polished and a relatively large amount of Al dust is released into the air. Explosions of Al dust can be very serious and destructive. In 2014, an explosion caused by Al dust occurred at a car parts plant in China, killing a total of 146 people. The work process performed at the plant was Al alloy wheel hubs polishing. In metalwork processes where small particles are mechanically detached from the material, they retain essentially the same chemical properties. If the release involves a high temperature, the particles are partially oxidized and are less reactive. The size distribution of the particles also depends on the mode of operation of the process and this also has an effect on the reactivity of the dust cloud. Welding fumes from Al welding include spongy and porous aggregates, which are on the order of nanometres in size. The welding process itself is an effective source of ignition for dust explosion, and even fine dust on the surface of worktops can combust when it hits a weld. (Li et al. 2016, pp. 121-122; Danzi & Marmo 2019, pp. 195-198.)

There is no precise classification for the explosion hazards of dust generated by various metal works. The challenge in making such a classification is to characterize the dust sample. Frequently, metal dust is merely an unwanted by-product of the process and a waste that one wants to eliminate quickly and as easily as possible. The thermal processes of metalworking cause oxidation in the particles and, in addition, the size and shape of the particles vary very widely and frequently uncontrollably. Commonly, waste dust contains different metal dusts from many different processes and its analysis is therefore very challenging. Laser processes are quite easy to control in this regard. Due to the high heat generated by the laser beam, the particles released from the workpiece are mostly oxidized and, in addition, almost homogeneously spherical particles of the same size, and the risk of explosion in the case of such dust is quite small. The possible use of filler materials will somewhat mix the resulting particles and dust. Polishing and grinding, secondly, produce heterogeneously non-oxidizing elongated chips of different sizes and such dust is particularly dangerous to explode. For high-dust processes, it is necessary to add dust extraction system based on air flow movement. For less dust-producing processes, cleaning and removing dust from surfaces at suitable regular intervals is sufficient. Difference of composition between dust generated by laser cutting of Al and the dust generated by polishing can be seen in Figure 18. (Marmo & Danzi 2018, pp. 205-207.)

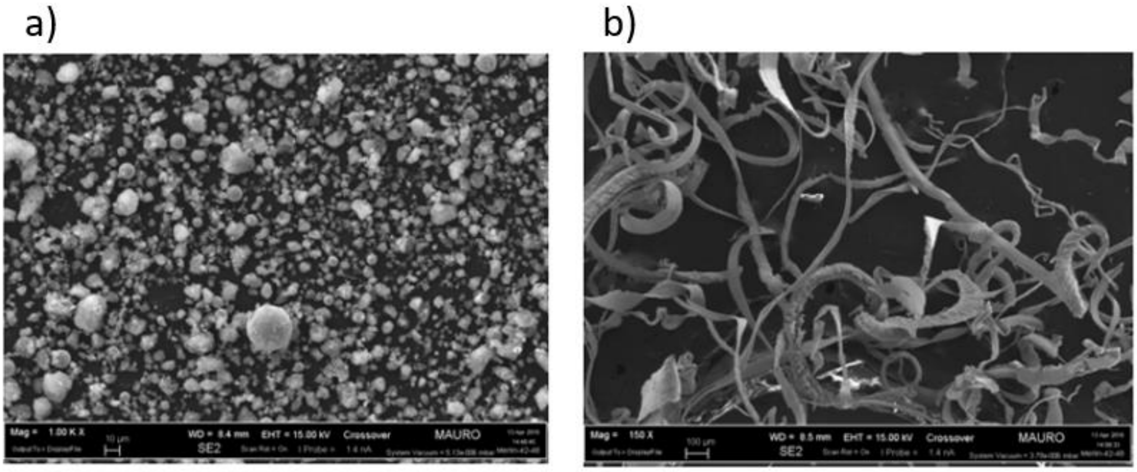

Figure 18. 1,000x magnification of Al dust from laser cutting (a) and polishing (b) (Mod. Marmo & Danzi 2018, p. 209).

The reactivity of metal dust would appear to be affected by three factors; the metal material in the dust, the size of the particles in the dust and the amount of oxide film and oxide present relative to the base material. Al and magnesium are among the most reactive metals in dust explosions. Less reactive metals include iron, steel and zinc. Among these, reasonably reactive metals include silicon. For comparison, the K_{ST} value (deflagration index which describing the intensity of the explosion) of Al is 515 bar m/s and the K_{ST} value of iron is 50 bar m/s. It has been found that very small metal particles with a size of less than 1 µm are even pyrophic, that implies they burn spontaneously when in contact with air. A special feature of metals compared to organic materials is their ability to oxidize in contact with air. This is significant because the oxide film formed on the surface of the metal particles is chemically inert and thus reduces the reactivity of the metal dust. Various protections have been developed for explosive metal dusts to avoid dangerous accidents. These protection techniques are:

Explosion venting

- In this technology, an explosive atmosphere has a panel or wall that gives in to the force of the explosion and the force of the explosion is directed in a safe direction, for example to the outside air.

Explosion suppression

- In this technique, a high-precision pressure sensor is used to bring an explosion-suppressing or repressing substance into the explosion area. Examples of such substances are sodium bicarbonate and calcium carbonate.

Explosion isolation

- In this technique, valves placed at suitable locations at the time of the explosion isolate the combustion chamber and the explosion does not proceed further, thus limiting the damage to the smallest possible area. Chemical explosion-proof barriers can also be combined in the same system.

(Taveau et al. 2019, pp. 7-11.)

6.6.1 Dust explosion hazard assessment

Tests can be conducted on metal dust produced in various metalworking processes to determine the risk of dust explosion. Such tests include, for example, the Speditive Explosibility Test (SET), which determines the P_{max} (maximum explosion pressure) and K_{ST} for each metal dust. The tests determine, among other items, whether metal dust can ignite at room temperature or whether hot ambient conditions (800 °C cloud auto-ignition and 400 °C layer auto-ignition) are required for ignition. Combustion tests are performed in small tanks and furnaces designed for them. The actual ignition is performed by an arc or a glowing wire. Depending on the flammability properties of the dust under study, it is classified into three different categories:

EA or explosible at ambient temperature

- Dust classified in this way is capable of combusting in room air
- The most dangerous type of dust and special attention must be paid to handling

EH or explosible at high temperature

- Dust classified in this way will only ignite in a hot environment

NE or non-explosible

- Dust does not ignite at all

K_{ST} value indicates the force of the explosion according to the rate of pressure rise, and the higher the value, the stronger the explosion. P_{max} indicates the maximum pressure produced by an explosion and can be used for example to compare the durability of structures. One study included nine different Al dust samples and, surprisingly, only two of these were classified as EA (Danzi & Marmo 2019, pp. 199-204). In the same study, the most reactive samples were generated as a result of brushing, grinding, sandblasting, and other finishing processes. During laser welding and laser cutting, the particles that end up in the air are frequently spherical and oxidized almost throughout. In the same study, the metal dust produced by laser cutting was classified as NE, or non-flammable. However, the process conditions for laser processing near the laser beam are very different from those a little further from the laser beam, therefore is no complete certainty on the level of reactivity of the metal dust. Mainly, the smaller the metal particles in the dust mixture, the more easily they ignite. Secondly, an increase in the oxide content significantly reduces the reactivity of the metal dust. Al-based dust can belong to all three different hazard classes. Speditive Explosibility Test in practice can be seen in Figure 19. (Danzi & Marmo 2019, pp. 199-204; Marmo & Danzi 2018, p. 207.)

Figure 19. Speditive Explosibility Test in practice (Mod. Foodengineering 2012).

According to several studies, Al particles generated in laser processing are surprisingly very poorly reactive and this is thought to be due to the very high oxidation of the particles (Danzi

& Marmo 2019, p. 199-204; Marmo & Danzi 2018, p. 207-210; Gascoin, Gillard & Baudry 2009, pp 348-349; Baudry, Bernard & Gillard 2007, pp. 330-336). In laser processing, the detachable Al particles contained at least 50 % Al oxide. Metal oxide even acts as a cooling element in combustion reactions and reduces the overall reactivity of metal dust. It would seem that laser welding of Al does not require special measures to avoid dust to explode, but only to ensure proper ventilation of the workstation and cleaning of the dust at suitable regular intervals. With the right cleaning, the workplace is kept hygienic, functional and safe. Certainly, in laser welding, the process conditions vary using many different welding parameters and for this reason it would be appropriate to ensure the safety of the process before large-scale deployment. Ensuring of the safety includes an extensive assessment of metal dust at the workplace in accordance with applicable standards. Metal dust characterization tests include moisture parameter evaluation according to ISO 562: 2010, PSD (Particle Size Distribution) by sieving, PSD by laser diffraction according to ISO 13320: 2009 and BZ (Brennzahl/Burning number) flammability class parameter evaluation according to VDI 2263- 1. These assessments provide certainty as to whether or not the air-miscible dust mixture during laser welding of Al is explosive. If the Al dust produced by that process is explosive, the entire work process will must be rethought. It is not possible to talk on the actual explosion-proof space at the laser welding station because the high-power laser beam can easily combust different materials and gases. (Danzi & Marmo 2019, pp. 198-204; Marmo & Danzi 2018, pp. 207-210; Ebadat 2009, pp. 35-36.)

6.7 Checklist for aluminium laser welding safety requirements

The previous sections of this chapter contain comprehensively reviewed the requirements of Al laser welding safety issues. In this chapter the focus has been on the safety challenges and different hazards caused by Al material. There have been six different topics covered, all of which are essential to consider for ensuring full understanding of the safety issues caused by Al material. This research work and these topics have been reviewed as a guidance for future workstation designers. Topics are reviewed in the same order in which they were presented and reviewed in the past. Based on the results found in previous sections, a compact and simple of checklist was compiled for the designers. With that checklist designers can easily and quickly look over or confirm some detail if needed. The full checklist is presented in Appendix VIII.

7 WORKSTATION DESIGN GUIDELINES FOR ALUMINIUM LASER WELDING

This chapter goes through the sections that workstation designers need to consider one by one. The topics themselves are not in any order of priority, all are emphasized as equally important to ensure work safety. Information on the health risks of Al is reviewed, with warning signs, training and exposure assessment. Technical protections and structures are presented, which include the workstation enclosure, a suitable ventilation system and personal protective equipment. Al dust explosion safety requirements and cleaning and maintenance of the workstation are introduced.

7.1 Workstation information

In industry, the Al laser welding is almost invariably performed in a separate workstation that is shielded from surrounding environment. This insulation is due not only to the welding fumes and radiation present in process, but also to limit the dangers of laser beam exposure. In addition, warning signs and the necessary information are attached to workstation in accordance with regulations. It is therefore reasonably easy to provide information on safe laser welding of the Al, as in principle it is sufficient to affix warning signs and the necessary data warning of the dangers of Al exposure accompanying the laser welding warning signs. The necessary warning signs must be affixed in as visible place as possible near the entrance to the workstation and in the immediate vicinity of the corridors. A study of the Al welding at the dockyard revealed that with and without the use of a respirator, the difference in respirable Al content is as much as 100 times bigger between two working days (Riihimäki 2008, pp. 454-455). In this study, the average concentration of welding fumes in the workplace was 3.5 mg/m^3, of which Al averaged 1.1 mg/m^3. According to findings, it is justified to include in the set of necessary warning signs instructions on the use of a suitable respirator if there is a need to enter inside the workstation (especially immediately subsequent to the end of the laser welding process). (Barat 2019, pp. 19-3 - 19-4; Riihimäki 2008, pp. 454-455.)

Almost all high-power laser workstations involve a sort of ventilation system that absorbs and cleans the gaseous compounds and shielding gases released during processing. Inside the enclosure of the laser welding cell, there may be a local exhaust ventilation in the vicinity of the welding point, or the entire safety cabin may be part of a ventilation system. In practice, the enclosure and the reliable operation of the ventilation system together prevent leaking of fumes and gases outside the enclosure. In this case, there is no need for using special protective equipment outside the safety cabin or to paying special attention to avoiding these dangers. Thus, with the equipment operating normally, almost all of the occupational safety risks associated with the material properties of Al are managed by workstation and the ventilation system inside the enclosure. Workstation operator or process controller usually do not need to interfere with the operation of the ventilation system, but maintenance personnel, for example, this may be part of their tasks. There have been numerous serious accidents around the world in situations where an unnecessarily large amount of fine Al dust has accumulated in the ventilation system and then exploded due to electrical short circuit, for example. If the fine Al dust from laser welding is found to explode in laboratory tests, it is essential to install warning labels and information labels on the properties exposed to Al dust in connection with the service hatches associated with all ventilation systems and cleaning. (Kujanpää, Salminen & Vihinen 2005, pp. 329-330; Going & Lombardo 2007, pp. 164-165.)

An essential part of ensuring safety is handling information flow and communication by compulsory training of workers. The laser welding process is in itself is technically challenging, so those working with it need to be equipped the necessary know-how on safety and the correct operating instructions. In addition, it is appropriate to provide the necessary training on the safety aspects of the Al material, especially for workers going inside the workstation or working with the ventilation system. With enclosed workstation and functioning ventilation system, training of the staff is relatively straightforward. If the process works normally, there is virtually no need for other people working in the vicinity of the workstation outside the enclosure to have knowledge about the safety challenges of laser welding or Al material deeper than on a general level. However, it is appropriate to provide all workers, including those outside the workstation, with concise training on how to act in possible emergencies, caused for example by process disruptions. Such training, secondly, is normally a part of all jobs during job orientation. More comprehensive training for those working inside the workstation enclosure and/or with ventilation system should be passed to review a wide range of safety threats posed by Al, its health hazards from fumes, welding process gases, radiation, and the explosiveness of Al. In addition, the suitable actions must be defined and taken to manage these safety risks and make daily work as safe as possible. Procedures for dealing with unexpected emergencies must be reviewed to the required extent and, in addition, the biomonitoring and necessary periodic health inspections and the grounds for these should be defined. (Lukkari 2001, pp. 240-247; Palmer & Eaton 1995, pp. 18-19; Danzi & Marmo 2019, pp. 195-196.)

7.1.1 Exposure assessment and the need for health surveillance

Al in the human body is virtually eliminated only in the urine. Exposure to Al can be assessed by a urine test or blood test. Various exposure assessment methods and their properties are described in more detail in section 6.5. Urine test has been shown to be of better quality, for in addition to the short exposure, the urine test also reveals the amount of Al in the body, especially in workers who have been exposed to Al for a longer period of time. This is due to the slow removal of Al from, for example, the bone tissue into which it has accumulated over a long period of time. The Finnish Institute of Occupational Health has recommended a urine test action level of 162 µg/litre or alternatively 0.6 µmol/litre (relative density corrected 1.024) subsequent to a weekend not exposed to Al. Exceeding the action level indicates too high Al exposure and changes must be made to working methods or, alternatively, an individual employee with high action level must be transferred to other tasks for at least some time. If the Al exposure of people who normally work into contact with Al welding is monitored at appropriate intervals and care is taken to keep the limit values, the health challenges posed by Al will not be a problem. (Riihimäki et al. 2008, pp. 460-461; Kiesswetter et al. 2009, pp. 1201-1206.)

In countries that assess Al exposure, urine testing is an established way to perform Al biomonitoring. The most important function of Al biomonitoring is to prevent the development of a load that endangers health, as the health effects of Al almost typically appear after a long period of time. Subsequent to use of a reasonably high Al-containing heartburn drug, antacid, a minimum of three days must be allowed in order to provide a reliable sample for Al biomonitoring. There is no specific action limit value for serum Al in a blood test, as serum Al is not as sensitive an indicator of workload Al load as urinary Al. (Työterveyslaitos 2015, pp. 5-8.)

For the designer, the control of Al exposure requires only the necessary contact with occupational health. Occupational health institutions around Finland know what tests need to be performed to determine Al exposure and how frequently. It is recommended that two urine tests are performed on all those working under Al exposure, especially when introducing a new work process. The first urine test is taken immediately subsequent to exposure to determine short-term exposure and the second urine test is taken subsequent to work-free weekend to determine long-term exposure. Health problems and various diseases due to Al exposure frequently only appear after long-term exposure, and for this reason regular monitoring is frequently an appropriate way to prevent problems from occurring altogether. Certainly, it is possible that the planned workstation and work process will be exposed to Al only to a very small extent, and then the necessary sampling for biomonitoring can be further reduced. However, this requires verification through properly performed tests, for it is challenging to assess Al exposure only simply by familiarizing yourself with the work process. (Työterveyslaitos 2015, pp. 5-8; Bertram et al. 2015, pp. 918-921.)

7.2 Workstation isolation with protective enclosure or safety cabin

The laser welding itself requires very strict safety requirements for the equipment, as all equipment capable to weld belongs without exception to the most dangerous laser class 4. The requirements for all manufacturers of machinery are such that operating it is as safe as possible for all users. In laser equipment, the most important consideration is when the laser beam hits the most easily damaged body part, and that is eyes. All laser equipment and laser workstations must be designed and manufactured so that the laser beam which causes the damage cannot under any circumstances strike the user or an unauthorized person. The easiest way to eliminate this safety risk is to install a suitable enclosure or safety cabin around the laser processing workstation that prevents direct and reflected laser beam from passing outside the hazardous work area. For more specific information on enclosing a suitable laser process workstation, has been introduced previously in subsection 5.6.2. Laser safety cabin. (Zohuri 2016, pp. 35-41; Steen & Mazumder 2010, pp. 519-522.)

In principle, the hazardous Al fumes and gases emitted from the laser welding workstation could be isolated from the rest of the surrounding space by almost any airtight wall material. However, the tight workstation enclosure frequently required for laser welding serves this insulation purpose succesfully, eliminating the need for a second insulation. The insulation of the Al laser welding workstation does not need to be completely airtight, as a properly functioning ventilation inside the enclosure creates a vacuum, that the fumes and gases emitted from the Al do not escape outside the enclosure at all. Essential in the insulation of the enclosure is therefore effective ventilation and a vacuum in the working space compared to the space outside the enclosure. In order to create a successful vacuum, at the bottom of the enclosure close to the floor, it is appropriate to build exhaust air hatches that allow replacement air to enter the enclosure, that hazardous fumes and gases generated in the centre of the workstation are absorbed into the ventilation system. (Steen & Mazumder 2010, pp. 525-526; Barat 2019, pp. 15-1 - 15-4.)

7.3 Workstation ventilation system

In practice, all occupational health hazards caused by Al are related to the respiration of fine Al fume in the air. Once the Al laser welding station has been successfully enclosed and a working vacuum has been established inside it, it can be ensured that, with the ventilation operating properly, Al vapours cannot escape from the enclosure. A very essential way to prevent occupational health hazards from Al is to ensure that the ventilation system works properly in all situations. During welding, the fumes and gases released into the air can be removed either by a smaller local exhaust ventilation or the whole enclosure can be a part of the ventilation system like a large laminar flow cabinet. Both methods can also be used at the same time. It is also essential to clean the removed air with the right type of filters to prevent harmful emissions from entering the environment. In the optimal situation, the ventilation system would be effective enough, that in the event of a sudden fault situation, one could enter inside the enclosure immediately without wearing a personal protective equipment. The TLV figure for Al welding fumes for an 8-hour exposure of 1.5 mg/m^3 as defined by the Finnish Ministry of Social Affairs and Health. The TLV of ozone released in Al welding is 0.2 mg/m^3. (Lukkari 2001, pp. 240-243; Kujanpää, Salminen & Vihinen 2005, pp. 329-330; Singh 2014, p. 94.)

The clear advantage of automatic robotic welding is that a person does not need to be in the vicinity of harmful welding fumes and gases during welding and thus Al exposure is significantly reduced. Secondly, the efficiency of robotic welding is at a very high level, due to which significant amounts of harmful welding fumes and gases are formed and it is important to ensure adequate ventilation efficiency. In addition, the amount of welding fumes and gas released into the air is largely influenced by the welding parameters used, the use of any filler material and shielding gas. Making an accurate estimate of the amount of welding fumes and gases in advance is very challenging. It is therefore recommended to adjust the process parameters for a successful weld joint and to estimate the amount of welding fumes and gases thereafter. The amount of welding fumes and gases can be measured using a photometer and an electronic particle counter. These methods can be used to determine particle size at unit density. Very accurate results are given by a special mass spectrometer which can be used to determine the compositions of successive welding layers. When the amount of welding fume generated in a particular welding application is known in more detail, ventilation and its efficiency can be optimized. Certainly, existing studies can be used to create a rough initial estimate, where laser welding without filler material has produced emissions when welding EN AW-6082 2.6 mg/s and EN AW-5454 6.5 mg/s. When MIG laser hybrid welding was used as the method, emissions were generated when welding EN AW-6082 1.2 mg/s and when welding EN AW-5454 4.3 mg/s (Spiegel-Ciobanu, Costa & Zschiesche 2020, pp. 52-55). In another study, laser beam welding (LBW) emissions without filler material are between 1-2 mg/s and laser beam welding with added filler material are between 6-25 mg/s (Singh 2014, p. 93). Thus, these estimates suggest that ventilation should be rated for emissions of at least 10.0 mg/s for laser beam welding without filler material and for emissions of at least 30.0 mg/s for laser beam welding with added filler material. Ventilation efficiency should be scaled as too efficient rather than barely sufficient for possible process changes. In this way, the efficiency of ventilation can be ensured if the emissions in future processes change radically and over-efficient ventilation does not in itself contain any detriment to a functioning laser beam welding process. (Palmer & Eaton 1995, pp. 19-20; Spiegel-Ciobanu, Costa & Zschiesche 2020, pp. 52-55; Singh 2014, p. 93.)

The different functions of the laser welding station are connected to the same control circuit with the actual laser equipment with different safety switches. This suggests, for example, opening the door of the workstation enclosure will immediately and automatically turn off the laser equipment and no more laser beam will be generated. Such safety switches and the proper functioning of the control circuit ensure the safety of people in almost all situations where the user may not be aware that one is making a dangerous mistake. One such essential detail, especially in connection with laser welding of Al, is to connect the operation of the ventilation to the same control circuit as the laser equipment. In practice, this system works in such a technique that when the control equipment is informed that the ventilation system is not working as it should, it stops the laser welding equipment immediately. This safety system ensures that a significant amount of Al welding fumes and harmful gases do not accumulate inside the workstation in the event of a ventilation failure. In the absence of the vacuum created by the ventilation system, these same emissions can also travel outside the enclosure and pose a danger to many people. The proper functioning of the ventilation is therefore an absolute prerequisite for the laser welding process to start and remain on. (Barat 2019, pp. 17-1 - 17-2.)

7.3.1 Necessary filtration systems

All welding processes that release significant amounts of harmful emissions into the air must use filtration as part of the ventilation system. Fixed filtration systems are particularly well suited for welding processes performed at the same fixed location. These include laser welding processes in the automotive industry as part of mass production. The actual welding fume or gas is not much different in laser welding compared to traditional welding methods and therefore the filters required are also very similar. The aim of filtration is to collect as much of the harmful substance as possible in a separate filter as efficiently as possible. The choice of the filter system used depends largely on the chemical composition of the hazardous substances. For example, in Al welding, it is recommended to collect harmful Al dust released into the air with self-cleaning surface filters. Al particles cannot be filtered with magnetic filters specially developed for welding steel. The filtration of gases released during welding is very challenging and their filtration must be designed to suit each process. In Al welding, such a challenge is especially with ozone. If several different welding fumes and gases are filtered with the same filtration system, it is appropriate to consider a separate pre-filtration, in which, for example, oily particles can be dried with the aid of a pretreatment material. This keeps the actual filtration system in operational for longer. Regardless of the composition of the metal particles released into the air, the filter should efficiently collect all particles of at least 0.5 µm in size. (Spiegel-Ciobanu, Costa & Zschiesche 2020, pp. 82-85; Weber 2003, pp. 28-30.)

There are two different ways to control welding fumes with a ventilation system. In one way, the impure air is filtered, and clean air is recirculated inside the plant. In another way, replacement air is retrieved from the outside and, after cleaning, is directed back out. When air is recirculated only indoors, it must be taken care to keep the permissible exposure limit (PEL) within the permissible level. When the air is led out of the plant after filtration, the current environmental emission requirements must be carefully observed. In either way, the best solution for filtering welding fumes and gases is to use high-efficiency cartridge filtration. If the filters do not filter the particles properly or require frequent replacement, it may be due to excessive airflow in the filtration area and the solution is to equip the ventilation system with larger cartridge filtration. Secondly, too low a compressed air pressure interferes with successful filtration. Moisture problems in the compressed air system interfere with the operation of the filters and this problem occurs especially during the cold seasons. Self-cleaning filters automatically pulse the dirt out of the filters, thus significantly increasing the service interval and replacement interval. However, it is appropriate to perform a regular maintenance check on the filters to check that all panels are in place, check the operation of the valves, test the pulse cleaning system and the pressure drop, check the compressed air header, check for compressed air header up. Figure 20 shows various cartridge filters for Al welding. (Ladwig 2018, pp. 47-48.)

Figure 20. Various cartridge filters (Mod. Ladwig, Nd).

As it can be seen from Figure 20, there is different cartridge filters with which welding fumes and gases from Al laser welding can be successfully filtered.

7.3.2 Use of respirator

Some studies have been found that workers with repeated but short-term exposure to welding fumes include experienced adverse health effects (Pelclova et al. 2018, p. 16; Leso et al. 2019, pp. 4-10). For this reason, the enclosure of the workstation and effective ventilation cannot completely eliminate the disadvantages of exposure, as the workstation usually has to be visited a few times during the shift. The reasons for the visits are either routines related to daily maintenance or the investigation of various fault situations. Because Al fumes have been shown in several studies to cause long-term health effects, including severe neurological damage, lung damage, and bone disease, it is recommended that, despite ventilation, to wear a respirator with suitable protection level when going inside the enclosure (Rechtman 2020, pp. 202-207; Pelclova et al. 2018, pp. 2-3; Mirshafa et al. 2018, pp. 261-262). A suitable respirator must be scaled for laser welding in accordance with the fine welding fume emitted from the Al. Similarly, one must remember the TLV value for Al, which is eight hours at an exposure of 1.5 mg/m^3. Commonly, visits inside the enclosure are short-term and quick maintenance situations that last from about 15 minutes to one hour. If one needs to stay inside the enclosure for longer maintenance, for example due to some seasonal major maintenance, it is recommended that one allows the ventilation to clean the workstation air for some time before entering the enclosure. (Pelclova et al. 2018, pp. 14-16; Mirshafa et al. 2018, pp. 261-262.)

The Finnish Institute of Occupational Health recommends using either a positive pressure respirator (combination of a positive pressure respirator and a welding mask), a supplied-air respirator (compressed air from the compressed air system and a welding mask) or a self-contained breathing apparatus (compressed air from the cylinder and a welding mask) to protect against fumes from Al welding. However, all these three means are quite cumbersome and are designed primarily for spaces where welding fumes and gases are very abundant, where may not be ventilation at all, and the exposure time is estimated to be a regular eight hours a day. Certainly, if, for example, the ventilation breaks down for one reason or another, and the Al content in the air becomes high, it is appropriate to involve at least a few of these heavier protection methods in place for maintenance. The most convenient of these is probably the positive pressure respirator, where the combination of air blower and filter blows clean air inside the welding mask or clear mask. The efficiency classes of the shield depend on the filter and are TH1P, TH2P and TH3P. Of these, a sufficiently effective shield is selected according to the particle concentration. In the efficiency classes of filterable fan guards, the protection factors with respect to the TLV number are 5 (TH1P), 20 (TH2P) and 100 (TH3P). If the use of the respirator is occasional, it needs to be replaced every six months, in order to verify the reliability of the respirator. When visits inside the enclosure are occasional, of short duration and ventilation is working properly, the use of a filterable half mask can be considered as an adequate of protection. Otherwise, for longer-lasting maintenance situations, a filterable half mask may be sufficient, especially when allowing ventilation to clean the air before entering the enclosure. To filter out harmful and small Al particles, the respirator should be rated FFP3, which filters more than 99% of airborne particles larger than 0.3 μm. FFP is an abbreviation from filtering facepiece. FFP3 classified respirators are recommended for use, for example, when working with harmful and toxic compounds, for example in the chemical and construction industry. Other filterable half masks are FFP1 and FFP2. In these filterable half masks, the protection factors with respect to the TLV number are 4 (FFP1), 10 (FFP2) and 30 (FFP3). However, to ensure occupational safety, the Finnish National Institute of Occupational Health recommends contacting a professional protective equipment salesperson who has attended protective equipment sales training provided by the National Institute of Occupational Health. The vendor is able to map more precisely the classification of the required shielding for each application and thus help ensure a safe work process in a relatively challenging Al laser welding. Figure 21 shows an example of the positive pressure respirator and Figure 22 shows FFP3 classification half mask. (Työterveyslaitos A Nd.; Työterveyslaitos B Nd.; Breul et al. 2020, p. 234.)

Figure 21. Positive pressure respirator with TH1P-TH3P filter (Mod. Safetecdirect, Nd).

Figure 22. FFP3 respirator mask with valve (Mod. Lyreco, Nd).

7.4 Explosion hazard management requirements

Previously, the explosion hazards of Al were reviewed at a general level quite comprehensively in the section 6.6 Danger of dust explosion. In that the chapter, Al was concluded to be generally challenging material because fine Al dust is generally very reactive. Al dust explosions are generally very destructive and mainly pose danger in Al grinding and polishing processes, where fine Al is abundant in the air. In metal processes where fine particles are mechanically detached from Al, they retain the same chemical composition and are thus highly reactive. If the release of the fine particles is associated with a high temperature, the released particles are partially oxidized and are therefore less reactive. The welding process itself is an efficient ignition/combustion source for dust explosion, in which case the welding workstation cannot be an ATEX safe workspace. ATEX is the legislation and standardization governing the design of potentially explosive atmospheres and comes from the words EXplosive ATmosphere. Explosive substances, gases, dusts or other equivalent are deliberately handled in ATEX-classified rooms, and all activities and equipment in the rooms are designed, that no spark, heat or open fire/flame required to start an explosion can be generated. (Danzi & Marmo 2019, pp. 195-198; Jespen 2016, pp. 1-3.)

In laser welding, the laser beam generates very high local heat and as a result, the particles released from the Al are mostly oxidized and spherical particles of the same size. Such fine Al dust released from laser welding would appear, surprisingly, to be poorly reactive and explosion-proof, according to studies (Danzi & Marmo 2019, p. 199-204; Marmo & Danzi 2018, p. 207-210). Correspondingly, the grinding and polishing of Al releases non-oxidizing elongated chip-like particles of different sizes into the air, and such Al dust is particularly dangerous to explode. The use of a filler material during the welding process alloys some of the particles released into the air. For processes that produce a large number of Al dusts, it is necessary to combine a well-functioning ventilation system with either local exhaust ventilation or workspace vacuum system. If Al dust is generated only moderately, regular cleaning and tidying of the workstation will suffice. Certainly, it is beneficial to perform the regular cleanings in addition to using ventilation. (Marmo & Danzi 2018, pp. 205-207.)

7.4.1 Explosion hazard assessment and classification

In general, the reactivity of metal dusts or explosiveness, is affected by three different factors; the metal dust material, the size of the particles in the metal dust, and the amount of oxide film and oxide in the metal particles relative to the base material. In addition to magnesium, Al is one of the most reactive metal materials. The smaller the particles the metal dust contains, the more sensitive it is to explode. For metals, the oxide and oxide film formed by the action of air include a large effect on the explosion sensitivity, since the oxide and the oxide film are chemically inert and thus significantly reduce the reactivity. It is assumed that Al fume released into the air during laser welding of Al and other laser processing is not explosive, as such results have been obtained in several studies (Danzi & Marmo 2019, p. 199-204; Marmo & Danzi 2018, p. 207-210). This is due to the large amount of oxide contained in the Al particles in laser processes and the inert property of the oxide

(Gascoin, Gillard & Baudry 2009, pp 348-349; Baudry, Bernard & Gillard 2007, pp. 330-336). The largest effect here is the oxidation of the Al particles, since, for example, in the case of laser cutting, the proportion of Al oxide in the particles has been found to be even more than 50 %. The different laser processing methods for melting the material are similar to each other, as they are based on the warming effect of the energy generated by the laser beam and the melting of the base material. Al oxide acts as a cooling element in combustion reactions and significantly reduces the overall reactivity of metal dust. (Taveau et al. 2019, pp. 7-11; Danzi & Marmo 2019, pp. 198-199; Marmo & Danzi 2018, p. 208.)

Occupational Safety and Health Administration (OSHA) regulations and NFPA standards classify combustible dusts based on two parameters, flammability and explosion intensity. Flammability and explosion intensity are determined according to ASTM (American Society for Testing and Materials) test methods in the United States. Based on the flammability of the dust and the intensity of the explosion, combustible dust is classified into different categories according to their risk of explosion. According to the NFPA definition, class I includes flammable gas, class II includes combustible dust, and Class III includes combustible fiber or combustible flying present. The class II combustible dust is further subdivided into three groups according to their nature. These groups are E, F, and G. The properties of the groups are listed below;

Group E

- Dusts are a variety of combustible metal dusts.
- For example, Al, magnesium and their alloys belong to this group.
- Other metal dusts whose properties and particle size allow similar explosions also include into this category.

Group F

- Dusts are a variety of carbonaceous dusts.
- For example, coal, carbon black, charcoal and coke dust belong to this group.

Group G

- Dusts that do not belong to the two previous groups.
- For example, flour, grain, wood and plastic fall into this category.

(Myers 2008, p. 73; NFPA 2015, pp. 8, 11, 33.)

When examining explosion assessment, it is appropriate to ensure above all whether the generated metal dust is explosive or not. This assurance is very essential, as its outcome will guide the design progress of the entire workstation in the future. Explosion sensitivity can be tested by various tests, including the Speedy Esplosibility Test (SET), which determines, among other items, whether metal dust is explosive at room temperature or whether hot ambient conditions are required for explosion (Marmo, Riccio & Danzi 2017, pp. 69-75). The tests are carried out in specially designed tanks and ovens and the ignition is carried out by an arc or glowing wire. Based on the tests, metal dust is classified as either combustible at room temperature, combustible only in hot environments, or completely non-combustible. Studies have been found that Al dust can belong into all three different categories (Danzi & Marmo 2019, pp. 199-204). Metal dust that can combust at room temperature is the most dangerous of these. The size and chemical properties of metal fume particles can be determined using various tests. These tests are governed by various regulations. The designer does not need control the performance of these explosion tests or be the one to determining the ignition/combustion likelihood of Al dust. To perform this, it is enough to master the basics of explosion tests and contact companies that perform explosion tests professionally. These consulting companies know with certainty concerning the risks of explosion, their results can be relied on and the work process can be planned on the basis of this information. (Marmo & Danzi 2018, p. 207; Danzi & Marmo 2019, pp. 199-204; Tukes A Nd.)

7.4.2 Explosion hazard warning and prevention

It is essential to prevent explosions in general that the risks of an explosion are widely taken into account as part of risk management at the design stage of the process. The necessary changes and updates to the risk management must be made immediately if any changes to the process or regulations are coming. The risk management involves assessing the probability and destruction of a dust explosion and taking the necessary action to proceed. According to research, a large proportion of dust explosions occur in some way in special working situations, such as maintenance situations (Paltrinieri et al. 2014, p. 670). It is paramount to train and instruct all employees on the dangers of a dust explosion and to place comprehensive training on maintenance workers. It has been found that while many workers know that fine iron dust is combustible, but in their practical work they do not take this into account at all and are not aware of the possibility of devastating explosion (Paltrinieri et al. 2014, p. 677). All necessary warning signs, information, warning lights and audible signals must be activated if an explosion hazard exists. An example of a dust explosion hazard warning sign is shown in Figure 23. (Paltrinieri et al. 2014, pp. 669-671, 674-677.)

Figure 23. Dust explosion hazard warning sign (Mod. MySafetySign, Nd).

Various practical protection levels have been developed for explosive metal dusts to avoid dangerous accidents. The most essential protection of all is the efficient collection of dust that it does not float uncontrollably in the air. Where possible, filtration systems for dust collection should be located in places where they are not in danger of exploding, for example, completely out of the space with a source of the dust. Special attention must be paid to dust accumulated on the surfaces of the process rooms, which must be cleaned out frequently enough. Surprisingly, dust accumulated on surfaces can be released into the air due to, for example, a strong air flow or a mechanical collision and cause a dangerous dust cloud. The operation of the dust collection system must be particularly reliable. If a fault occurs in the system, there is a high risk that the dangerous cloud of dust will expand rapidly and explode unexpectedly. If an explosion occurs in spite of preventive measures taken, there are various technical solutions that aim to curb and suppress the explosion. These solutions include explosion venting, explosion suppression and explosion isolation. The explosion venting is a panel or wall that easily gives up the force of an explosion and directs the force of the explosion to the open air, for example. The explosion suppression is a technique in which a precise pressure sensor is used to direct an explosion suppressing substance to the explosion area. The explosion isolation is a technique in which, in the event of an explosion, valves placed in suitable locations isolate the combustion chamber and the explosion is limited to a small area. (Paltrinieri et al. 2014, pp. 674-677; Taveau et al. 2019, pp. 7-11.)

The employer must compile a separate ATEX-compliant explosion protection document for all workplaces where there is a risk of explosion. The Explosion protection document must be kept up to date whenever changes are made to a process or regulation. The Explosion protection document must be prepared before a new process or workspace is deployed. The purpose of the Explosion protection document is to provide an overview of the risks associated with the workspace or process and the actions to be taken to manage them.

The Explosion protection document must include:

- The names of the persons responsible for working in potentially explosive atmospheres.
- Number of workers working in potentially explosive atmospheres.
- The information of potentially explosive substance.
- Conditions where an explosion is possible.
- Sufficient risk assessment and assessment methods.
- Floor plan of the hazardous area and all escape routes.
- Zoning of hazardous areas.
- List of all electrical and mechanical machines in potentially explosive atmospheres.
- Explosion safety inspection by a qualified person.
- Explosion protection document author and person responsible for updating.
- Sufficiently broad description of technical and organizational explosion protection measures.

In Finland, occupational safety authorities generally monitor the safety of employees in accordance with the Occupational Safety and Health Act, also in premises where there is a risk of explosion. In Finland, Tukes (Finnish Safety and Chemicals Agency) supervises facilities that handle and store chemicals that require a permit in accordance with either authorization of dangerous chemicals or explosive substances. In Finland, regional rescue authorities supervise small-scale handling and storage of chemicals. There may be some differences between countries in how the Explosion protection document is drafted and who controls explosion safety. (Tukes B Nd.; Achillides, Gecelovska & Gehre 2010, pp. 18-19.)

7.5 Workstation cleaning

Workstation cleaning is especially important when working with fine Al dust that is hazardous to health and safety. Although fine Al dust does not float in the air, it can accumulate on surfaces in abundance over time. Sudden mechanical movement or strong airflow may lift this fine Al dust into the air, making it very dangerous to health and safety. There have been some accidents in processes that produce or process fine metal dust, especially in situations where fine metal dust that has accumulated on surfaces suddenly rises into the air and explodes devastatingly. In 2011, two separate explosion accidents occurred at a company called Hoeaganaes, in which iron dust on surfaces was released into the air by the force of mechanical motion and exploded shortly thereafter. The first time the dust was released into the air by the vibration of the bucket elevator motor and the second time by the vibration caused by the hammer used by the operator in the maintenance work. The first accident killed two people and the second seriously injured one person. The cleaning of fine dust on surfaces cannot be postponed but must be carried out at regular intervals with sufficient frequency. NFPA regulation 654 unequivocally requires that all surfaces that may accumulate hazardous dust be designed and constructed to minimize dust accumulation and cleaning as easy as possible. On a practical level, such solutions include tilting the edges of interior windows, placing self-adhesive lids in boxes and painting rough concrete walls smoother. In addition, spaces that cannot be cleaned will be tightly closed. (Paltrinieri et al. 2014, p. 670; Frank 2004, p. 182.)

The amount of Al dust released into the air, and especially on surfaces, over a period of time is essential when assessing the need for cleaning. This need for cleaning cannot be estimated very accurately in advance. Due to sufficiently efficient ventilation, much of the Al dust released into the air can be collected, leaving only a small proportion of it on the surfaces. When introducing a new laser welding process, the amount of dust accumulating on the surfaces can be monitored and further it can be decided how often the surfaces of the workspace need to be cleaned. Fine Al dust released into the air during laser welding later accumulates on surfaces and is dangerous to human health, especially during cleaning, when a respirator with high protection level must be worn. For example, the positive pressure respirator with TH1P-TH3P filter presented in the previous section is a useful protection for cleaning. From point of view of the designer, it is essential to assess the need to clean the workspace and how frequently the cleaning needs to be repeated, and to create clear instructions to employees and management as needed. When cleaning up explosive dust, the brushes must be soft natural fibre brushes or squeegees that do not pose a risk of static sparking. Ordinary vacuum cleaners must not be used to clean combustible dust but must be a vacuum cleaner for vacuuming combustible dust in accordance with NFPA 484. It is recommended to use an external company for the cleaning of explosive dust, which knows the properties of explosive dust and is able to perform the work with sufficient professional skills. (Barrett 2010, p. 8; The Aluminum Association Nd. pp. 6-7.)

7.6 Workstation maintenance and maintainability

The numerous safety challenges encountered in laser welding of Al impose certain limitations and considerations on equipment maintenance procedures. First of all, it is essential for safety that the equipment works properly in all situations. However, if something very exceptional occur, the maintenance must be aware of the measures to achieve safe management. In laser welding of Al, the safety challenges are, above all, Al fumes and other hazardous welding fumes that are dangerous to humans. If the Al laser welding equipment and process work properly, it can be assumed that Al fumes that are hazardous to human health will remain inside the enclosed workstation and ventilation system. In this case, the health challenges and personal protection caused by Al fumes are only relevant when entering this confined space. Maintenance personnel must be able to enter the confined space at least periodically at regular intervals. When entering a confined space, they must use appropriate protective equipment to protect themselves from adverse health dangers. It can be assumed that a positive pressure respirator with a TH1P-TH3P filter is sufficient to protect against hazardous Al fumes if longer exposure times are required in the area affected by the Al fumes. If visiting the area affected by Al fumes is a quick procedure, it can be assumed by that the FFP3 respirator mask is sufficient for protection (Rechtman 2020, pp. 202-207; Työterveyslaitos A Nd; Työterveyslaitos B Nd). The health effects of fine Al fume do not directly affect the maintenance itself, but appropriate protection must be provided and training and familiarization of all persons with the health risks of Al must be ensured. (Rana et al. 2019, pp. 142-143; Spiegel-Ciobanu, Costa & Zschiesche 2020, pp. 5, 32-33.)

If studies show that fine Al dust released into the air by laser welding of Al is explosive, the maintenance personnel must be aware of the requirements and the requirements must be taken into account. The assumption, certainly, is that this dust is not explosive, and this problem does not need to be considered separately. Reliable ventilation and the maintenance and cleaning of all parts of ventilation systems with sufficient frequency are essential for explosion safety. The maintenance personnel must periodically carry out inspections and maintenance of the ventilation system and must possess precise information on how to proceed in order to be able to carry out the work safely at all stages. In challenging situations, such as extensive dust cleaning, it is an appropriate to contact an outside company that can perform the work in complete safety. The actual maintenance is otherwise done normally, but the risk of explosion must be taken into account at all stages of the work. (Barrett 2010, p. 8; Danzi & Marmo 2019, pp. 195-198.)

Due to the different technology, laser technology and laser welding equipment themselves pose some challenges for maintenance and service operations. Managing disturbances in laser welding are very challenging unless the operation of the equipment and the basic principle of laser welding are fairly well understood. Certainly, all suppliers of laser welding equipment offer their own services to provide assistance around the clock either by phone or by requesting a qualified service technician on site. However, this alone cannot typically be resorted to, as frequently in large-scale series production, every moment that the laser welding equipment is at a standstill costs money. Not only does the rest of the process chain wait for one device to start up in place, the planned production and quantity has to be done at another time, such as overtime on weekends. From perspective of the designer, the laser welding equipment and laser welding process must be reasonably familiar, as a company frequently appoints a person as a contact person for laser technology challenges and frequently this role falls on the designer of that workstation. However, it is not necessary to possess a thorough knowledge of the equipment or process, but frequently the basic knowledge of laser technology and the management of the necessary contact information are sufficient, from which real expert help is available for certain challenges. The designer must ensure that the maintenance personnel of the equipment and process know to a sufficient extent what technology is involved in laser welding and also take these requirements into account. This is closely related to the sufficiently extensive training and familiarization of employees and maintenance personnel involved in laser welding. (Barat 2019, pp. 8-4 - 8-5, 10-1 – 10-5.)

7.7 Checklist for workstation design requirements

The previous sections of this chapter contain comprehensively reviewed the requirements of an Al laser welding workstation from a safety perspective. There have been six different topics covered, all of which are essential to consider ensuring work safety. This research work and these topics have been reviewed as a guidance for future workstation designers in industry. Topics are reviewed in the same order in which they were presented and reviewed in chapter 7. Based on the findings described in previous sections, a compact and simple checklist was compiled for the designers. With that checklist designers can easily and quickly look over or confirm some detail if need arises. The full checklist is presented in Appendix IX.

8 DISCUSSION

This thesis was carried out as a literature review. Because of that, the actual results of the experimental tests are not to be presented and discussed. However, numerous different findings were made with literature review and these findings are discussed in this chapter. In this chapter, is introduced how this study succeeded in solving the problem, what and what kind limitations were associated with the chosen research method, how the study increased knowledge in the study area, what extent the findings can be generalized, and what and how the research findings can be utilized at the theoretical and practical level. Challenges for further studies and proposals for further studies are discussed in its own chapter 10.

8.1 Characterization of the workplace requirements

The main findings of this study are presented in detail in chapter concern with the general safety of laser welding, and, especially in chapter with the safety challenges of laser welding of Al and the chapter guiding the design of the workplace. General understanding of laser safety is already well established among those responsible for it in the target company, as laser welding has been performed using various technologies for six years. However, the topic was included in this research as a separate chapter, as designers of workstations may not possess previous experience or knowledge of laser welding, or, laser technology. Actual data that collects or compiles new information includes information on the health challenges posed by Al laser welding and general guidelines for designing a safe Al laser welding workstation. As many sources were found during extensive literature review, they were compiled into separate checklists in the appendices. A checklist of general safety challenges related to laser welding is presented in Appendix VII. The safety challenges due to the material properties of Al is presented in the checklist in Appendix VIII. The safety considerations to be considered in the design of an Al laser welding workstation is presented in the checklist in Appendix IX. These found key points were collected as checklists to make reviewing them easy and quick to understand. In the future, checklists can be used as a tool by designers to quickly review a topic that is currently being addressed. The review of the findings will focus on solutions of the research questions presented in the introduction. Each research question is reviewed in its own subsection.

8.1.1 Which safety challenges are present in laser welding of Al

The research question is twofold and on the based on the research it can be said with certainty that laser welding of Al involves numerous different safety challenges. Safety challenges are created by laser welding equipment and a high-power laser beam, but especially by the fine Al dust released into the air during laser welding. The safety challenges related to laser welding equipment and the laser beam have been reviewed in chapter 5 and a separate checklist has been compiled based on the chapter, which is presented in Appendix VII. Dangers associated with laser equipment include, for example, the risk of electric shock and the risk of especially to the eye - loss of vision. Fine-grained Al dust is a poison that affects the functions of body in many ways when it enters the body through respiration and accumulates in tissues. Known health effects due to long-term Al exposure include central nervous system disorders, lung diseases, bone diseases, and various anemias. In addition, fine-grained Al dust has caused numerous devastating dust explosions around the world, however studies show that Al dust released into the air during laser welding does not appear to be explosive due to its high oxide content. The safety challenges arising from Al as a material have been reviewed in chapter 6 and a separate checklist has been compiled based on the findings, which is presented in Appendix VIII. The aim of the study was to provide extensive information on safety challenges in laser welding of Al based on scientific articles and manuals. However, not all potential risks and threats have been presented in this study but limited to most relevant and dangerous risks.

8.1.2 Avoidance of health hazards and management of safety challenges

Because of the many different health risks and safety challenges associated with laser welding of Al, workstation design and work control design must be carefully planned. As the target company already has experience in laser welding of steel for several years, this research focused primarily on detecting ways to manage the safety challenges posed by Al material. As a finding of this research work, a few practical level technical solutions and conclusions related to the guidance of the personnel performing the work emerged. Practical technical solutions concern the insulation of the workstation by means of enclosures, the handling of ventilation requirements, the use of suitable respirators and warnings. With these means, airborne Al dust, can be isolated from people and no health effects can arise. The instructions may include the training of the persons performing the work, the biomonitoring of Al, and the review of the cleaning and maintenance included in the work. These tools guide the work process and ensure that no health effects arise even if something unexpected occurs during the work process. Explosion safety and related issues were discussed separately, although studies show that the Al released into the air during laser welding of Al is not explosive. The factors to consider in the design of the workstation have been reviewed in chapter 7, and a separate checklist has been compiled based on the findings, which are presented in Appendix IX. Summarizing the requirements of this workstation were intentionally intended to be written as clearly as possible for future designers to gain a good understanding of the safety requirements for Al laser welding and the important workstations to be considered separately.

8.2 Analysis of research method and findings

This research sought to detect solutions to research problems and argumentation for the solutions by reviewing related publications. The aim was to produce research data based on scientific publications in order to offer as much argumentation and factual basis as possible for the findings. The health effects and safety risks of Al were studied mainly through various medical scientific articles. Many of these publications initially included some form of experimental section in which, for example, a number of experimental animals were fed or watered with Al-containing food, and their behaviour was studied, and final results were made based on the results of the autopsy. There are many such articles, as the Al load from food has been widely talked in the recent years. These publications were hardly selected for this research, as the aim was to select from the articles only those in which Al exposure enters the body by inhalation of fine-grained Al dust. Some publications related to occupational exposure were detected to some extent and were widely used in the research. Such a large sample sought to confirm certain hypotheses related to the subject and was not satisfied with the absolute and only truth of the information in the individual study. The aim of the design of the workstation was to take advantage of the findings already detected on the health effects and safety risks of Al, and to detect ways to manage these. In addition to presenting the data and findings, this also sought to provide the rationale behind the data, that designers had a clear understanding of the existence of a solution.

The research method was extensive literature research, in which related articles and publications were reviewed and the suitable ones were selected for use. The selected articles and publications were used in the research as factual and background information to argument the findings. Limitations due to the chosen research method, literature review, did not appear much, as publications were found to be available and information could be collected extensively. However, one of the problems with this study was the lack of precise parameters, material knowledge, and similar details. These are due to that Valmet Automotive does not yet have opportunity to perform welding tests and the study has therefore been conducted at a general level and different recommendations had to be made that would be appropriate to implement in different situations to find the safety issues before starting the actual tests. In the design of the workstation and in the control of the work, the instructions have been given to suit certain limit values, and the designer can find the solution that suits each situation.

Laser welding of Al materials as a method is quite new and research adressing it is only a fraction compared to the most of traditional laser welding applications in steel or TIG/MIG/MAG welding of Al. No actual studies have been found that went beyond the safety aspects of laser welding of Al alone, but safety issues were frequently a smaller part of some larger study and the data had to be compiled by combining these. In further studies, it would be useful to know more on the characteristics of the equipment and the information related to the work process already at the beginning of the research. This would make it possible to exclude certain aspects from the outset and create the work instructions that are more specific to a process. In this research, it was initially planned to contact and inquire concerning recommendations for work safety from companies performing laser welding or supplying laser welding equipment. However, this was relinquished as there was a lack of concrete information on the upcoming process, leaving inquiries and responses at a very general level. The same data and findings, as well as the rationale behind them, were obtained through review of various scientific articles and publications.

This research sought solutions from several conceptually different sources on described topics and to validate the information using know how provided in them. The aim was to increase the reliability of the findings. In addition, efforts were made to use, where possible, only peer-reviewed strong sources as the sources of the research. Overall, the findings of the research can be considered reliable. A wide variety of materials was used, and sought to generalize the findings well, as more detailed information on future Al welding processes in Valmet Automotive, for example, was not a common knowledge. However, certain challenges were related only to addressing the health effects of Al material. Certainly, the health effects of Al on central nervous system effects appeared to be contradictory based on previous studies. Therefore, the findings obtained for this research are not highly specific, and, it is mentioned that available research on these topics is still ongoing. Because laser welding of Al is a challenging and complex process, it is very possible that some of the less known safety issues have not been addressed at all. However, throughout this work, efforts were made to gather and present all safety challenges and risks that are likely or contain a high impact at some level.

The aim of this study was to produce and categorize information that is especially relevant for the needs of the client Valmet Automotive. This goal was met successful because the target company did not have any experience with laser welding of Al. This study provides extensive and appropriate information on the safety risks associated with laser welding, the safety risks caused by Al in laser welding, and the means by which the laser welding process of Al can be executed safely. This information has already existed as such but so far it has been fragmented in various publications and studies. Now, findings were compiled into a single study and discussed by substantiating and compiling, based on the findings, compact checklists of the main points to be considered in the design and implementation of a safe Al laser welding workstation. Laser welding as a process is itself already challenging and poses clear safety challenges, but with the right practices and following the guidelines, its use can be considered almost completely safe. Laser welding of Al in addition, involves several elements that are hazardous to human health, but with the appropriate workstation design and work process control, these effects and risks are very well manageable.

Findings obtained during the research can be generalized to other situations and processes involving laser welding or laser welding of Al. The part that reviews the general safety challenges of laser welding can also be generalized to laser welding of other metals and laser welding of various plastics. In these applications, the laser equipment and the actual laser beam which melts the material, are similar to laser welding of Al. The health effects and safety risks caused by Al dust have been presented at a general level that the process that produces them into the air is laser welding. Similar high oxide fine Al fumes into the air are also produced by other high heat import Al processing processes. These include other laser processing methods; laser cutting, laser marking, laser coating, 3D printing, laser soldering, laser drilling, laser hardening and various hybrid welding applications. In addition, the traditional welding processes based on high heat input, arc welding and gas welding, also produce fine oxide-containing Al fumes in the air if the welding material is Al. Different processes produce different amounts of fine Al fume, but in the same way, based on the findings, the health challenges and safety risk of these processes can also be managed. Explosion safety was also addressed at a general level, as there was no complete certainty concerning the explosive properties of Al dust present in Al laser welding. If necessary, the challenges and practical solutions in explosion safety can be easily generalized to other work processes that produce fine Al dust.

The findings of the research contain a clear usability perspective at both, the theoretical and practical level. From the very beginning of the research, there was a clear goal to produce not only scientific research on the safety aspects of Al laser welding, but at the same time compose a guide for future workstation designers. The usability of the theoretical level is emphasized in order to gather a large amount of information in one publication and by producing a clear informative set, which provides information on the safety of Al laser welding. At the practical level, usability is emphasized by checklists produced for future workstation designers, see Appendices VII, VIII and IX. By going through checklists, it is easy to recall which were the most important points to consider in certain work processes. The research itself has been compiled in a method that the sections presenting its basic information serve as an in-depth guide to the topic, especially for those who are not already familiar with laser processing or Al as material. After reviewing this basic information, it is natural to present the pieces that present the actual research problems and their findings. In particular, the work that presents the design of the workstation has been aimed at making practical solutions and various constraints of the process. All tracks and checklists that presents the research problems are structured in a method that they provide strong theoretical and practical recommendations and guidance on how to perform certain work processes in order to maintain a high level of occupational safety.

8.3 Significance and further use of the findings of research

With the findings of this research, Valmet Automotive can continue the possible introduction of Al laser welding. With these findings, designers of Valmet Automotive know to consider occupational safety in workstation design with the requirements of laser welding of Al. Numerous different weld tests must be conducted to ensure a functioning work process and to achieve the required final quality. These tests must also consider occupational safety as seriously as it would be considered in serial production. In association with these tests, it is possible to verify at a later stage with the necessary measurements and surveys, whether the selected practical solutions to be considered in the design of the workstation are sufficient, or whether some details or guidelines require more clarification. Especially, this must be considered when the final laser welding parameters and other process-dependent variables are known. In that time, it is necessary to contact the necessary experts in order to be able to measure and estimate, for example, the demand for correct ventilation and possible explosion safety. At this point, it is appropriate to remember that any experimental tests were conducted, and all the information of this research comes from other studies and handbooks, so there is no complete certainty about any practical details. All critically dangerous details must be tested separately to ensure occupational safety.

The significance of these findings of this research and research itself for the reader is, above all, to serve as the guide and the source of information on the occupational safety of Al laser welding. This wish was already expressed at the beginning of the research for Valmet Automotive, and this has been the case during the research. Because the research has been done at a general level without process-dependent details, the research can also serve as a source of information for other readers interested in the topic. Occupational safety and its importance will probably be emphasized more and more in the future. None company can afford to carry a reputation as a dangerous workplace, and good level of work safety will be a competition for companies. The use of Al is expected to increase in the future, and it is possible that future researchers, such as Master's thesis workers, will also have the opportunity to continue to view the safety challenges of Al laser welding. It would be highly desirable for this research to provide an opportunity as a preliminary guide or aid for further researches.

9 CONCLUSIONS

In the introduction, research questions were used to describe the research problem and to limit the scope of the research. Research client, Valmet Automotive, want to learn about the potential health effects associated with Al laser welding. In addition to identifying these health effects, the focus is on assembling practical solutions and means to safely perform laser welding of Al. The aim of the research is to detect solutions to the research questions and to produce high-quality research, based on which Valmet Automotive can, if it wishes, move towards the introduction of Al laser welding with a broad focus on occupational safety. The aim is to find, through literature review, the most comprehensive information on the safety challenges of Al laser welding and their management, as well as the reasonings behind this information.

This research was conducted in an employment relationship with Valmet Automotive. Remote connections have made it possible to successfully communicate with Valmet Automotive research supervisor and university staff. The research materials used in the work have been found mainly in the collections of scientific publications available online (for example LUT Primo, Google Scholar, and Springer Link). Various guidelines, standards and regulations of institutions and organizations were also used online.

Al material undoubtedly causes various health problems through occupational exposure. Particularly fine-grained Al dust or Al fume floating in the air is dangerous because it enters the body efficiently through the respiration. Fine Al dust accumulates in the human body and causes many different and serious problems and diseases related to metabolism and cellular functions. Almost all the health problems and diseases caused by fine Al frequently appear slowly even subsequent to years. Most of these slow-onset health problems are due to long-term exposure to Al and the slow removal of Al from the body. Although, the health problems and diseases caused by Al has been studied widely, there is still some controversy in the results of the studies and there is no complete certainty concerning the role of Al as a pathogen. However, it can be said with certainty that fine-grained Al dust or Al fumes cause serious health effects and diseases through long-term exposure. There is a known risk of a serious dust explosion when handling fine Al dust. Studies have been shown that the Al particles released into the air during laser welding are almost inert due to the high oxide content and there is no risk of explosion.

The responsibilities of employer include ensuring the safety and health of workers, and therefore the health effects and safety challenges posed by Al must be considered with the appropriate seriousness and precision at the design stage of the work process. Naturally, laser welding involves all the safety risk caused by the most dangerous class 4 laser equipment, which must be considered separately. The new work process and workstation must be designed in a technique as to prevent or control all serious health problems and safety challenges with a reasonable probability. These means shall include technical solutions and structures as well as protective devices for the isolation of human and fine Al dust or Al fume, as well as appropriate attention to laser and explosion safety. In addition, the means include warnings, information, work instructions, training and exposure assessment in support of technical solutions to ensure the correct operation and control of workers to maintain a high level of safety.

The health, laser and explosion safety risks of occupational exposure posed by laser welding of Al, and the concrete management of these risks, do not appear to have been studied previously to this extent. Although the actual new data were not produced by various experiments or measurements, there can be new data of this research, in which the separate data were aggregated. The research has provided a wealth of new information on issues that are important to occupational safety for the client Valmet Automotive. With this information, Valmet Automotive can plan the work process of a possible future Al laser welding workstation and the workstation with work safety first. However, occupational safety is the basis of all well-being at work and all work must be done as safely as possible.

The main conclusions of this study are that there are undoubtedly numerous issues that are dangerous to human health in laser welding of Al, but awareness of them is the key to controlling the issues. Hazardous issues are managed through a number of practical and organizational means, which are already implemented by several industrial plants in their own production. The most important thing in management is to isolate the work process and the safety challenges and people in it to the necessary extent. Isolation is even quite easy due to the automatic work process. It is sufficient that the work process is allowed to operate in its own isolated space inside the enclosure and that emissions are controlled by the necessary means and that workers are outside the enclosure. Challenges to this are brought about by maintenance situations and malfunctions that occur in addition to the normal work process. Comprehensive training and information play an important role in their management. Employees must always be openly informed about the risks of the work process and how the employer has considered the risks. In this way, employees also have confidence in safe work and are also able to address any safety deficiencies that may arise.

10 FURTHER STUDIES

The lack of detailed information (for example welding parameters, exact material properties, or equipment) shaped the format of the research into an overview and guidance could only be provided at a general level. In any further research on the subject, it would be appropriate to identify safety challenges and their solutions in a specific way. By doing so, this research can be used as a basis and a part to look over the basics, and the new research will focus entirely on examining and reviewing the details for a piece of equipment, and process. In this way, concrete tests could be carried out to show unequivocally whether the selected data are at risk of being subjected to excessive Al exposure if one enters an enclosed work area without a respirator immediately after the welding process.

In many situations that depend on certain parameters or processes, it is advisable to contact professional companies for assistance if necessary. This ensures that the final work process is safe, even if the parameters or the operation of the equipment are unexpected. These critical parameters depend on ensuring explosion safety, selecting the right type of respirators, and performing Al biomonitoring. Clarifying and verifying these safety-relevant details with assistance of professional companies could also be appropriate topic for further research.

The health risks of Al to human in the short- and long-term exposure are still partly unknown. This is due to the complexity of human biology and the metabolism of the body and the potential health effects of other metal particles in addition to Al. If something new becomes apparent about the health risks of Al to humans later, or if, for example, some new technology is used to manage already known health hazards, it would be good to continue research on the basis of this information. In any case, in a future study, it would be useful to review the latest scientific articles on the health effects of Al and update the information in this regard.

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APPENDIX I, 1

Aluminium production process

Bauxite is a type of rock formed as a result of weathering that is widespread in the warm zones of the earth. The susceptibility of Al to oxidation and mixing with other substances is the reason for the late discovery of Al. Al was first separated in 1825 by the Danish scientist Hans Christian Oersted. Oersted used the reaction of Al chloride by combining a mixture of potassium and mercury and heating this mixture under reduced pressure. Today, the so-called Hall-Heroult method is used to separate Al, in which Al is separated by electrolysis from alumina/bauxite dissolved in molten cryolite (Na_3AlF_6). This method was invented in 1886 and at the same time the price of Al in metallic form was reduced to a usable level. As an example, in 1856 the price of Al was 200 $/kg and in 1888 the price of Al was 0.65 $/kg. (Lukkari 2001, pp. 8-9; Baker 2018, pp. 5-9.)

APPENDIX II, 1

Properties of the aluminium material

Light weight

- The density of pure Al is 2.7 kg/dm^3. This is about three times less than with iron or copper, for example. Al, like magnesium and titanium, is classified as light metals.

Weldability

- Many Al alloys contain an excellent level of weldability. The competitiveness and versatility of the metal will increase if the weldability is at an excellent level.

Strength and durability

- Al can be alloyed with several different alloying elements and thus largely changes the strength properties of Al. The tensile strength of Al alloys varies quite considerably, most frequently in the range of 70-700 MPa. Many Al alloys are as strong as structural steels. Al does not become brittle at low temperatures, but remains tough even at -200 °C.

Corrosion resistance

- The corrosion resistance of Al is based on the oxide layer formed on its surface by atmospheric oxygen. The Al oxide layer is very thin and dense and protects the base material below against corrosion by water and chemicals. If, for example, the oxide layer is mechanically damaged, it is immediately re-formed at the site of damage by oxygen. The oxide layer can be further grown by various surface treatment methods.

Electrical and thermal conductivity

- Al conducts electricity and heat well. The electrical conductivity of pure Al is about 60 % of the electrical conductivity of copper. The thermal conductivity of pure Al is about 30-50 % of the thermal conductivity of copper. Al reflects light and heat radiation well.

Hygiene

- Al, when used correctly, does not smell or taste at all and is therefore commonly used in food and medicine packaging as well as in household items.

Formability

- Al can be treated mechanically in many ways. For example, Al can be rolled into a thick sheet or into a very thin foil, it can be extruded with different profiles and made into various wrought pieces, it can be deep drawn into cans or drawn into a thin wire.

Workability

- Al can be successfully forged, bent and deep drawn. Al can also be machined by any cutting method.

Low modulus of elasticity

- The modulus of elasticity of Al is about one third of the modulus of elasticity of steel. Al is therefore well suited for impact loads. The relatively large deflection of Al can be compensated by optimizing the shape of the profile used.

No sparks

- Due to its composition, Al does not spark at all on impact and is used in suitable applications, such as kerosene tanks.

Connectivity

- Al can be connected in many ways. Common joining methods include welding, brazing, riveting and gluing.

Economical manufacturing technology

- Al is very easy to adapt to the diverse needs of customer. In the production of Al profiles, properties can be made to the profiles that facilitate the production of structures made of profiles.

Recyclability

- Al is a particularly easy material to recycle and the popularity of recycling is growing all the time. The recycling rate of different Al products from the finished product to recycling varies largely, but all Al recycling is recommended, as in recycling the production of a new Al product takes 5 % of the amount of energy required to produce primary Al.

(Huhtaniemi 2006, pp. 8-12; Lukkari 2001, pp. 24-25.)

APPENDIX III, 1

Table 6. Mechanical properties of Al (Mod. Lukkari 2001, p. 25; Baker 2018, pp. 5-9; Kaufman 2018, pp- 31-42).

Chemical symbol	Al	-
Atomic number	13	-
Chrystal structure	Face centred cubic	-
Density (20 °C)	2.6989	kg/dm^3
Density (660 °C and solid)	2.55	kg/dm^3
Density (660 °C and fluid)	2.37	kg/dm^3
Density (990 °C)	2.30	kg/dm^3
Coefficient of thermal expansion	23.6×10^{-6}	1/K
Modulus of elasticity	6.66×10^4	N/mm^2
Shear Modulus	3.5×10^4	N/mm^2
Poisson's ratio	0.33	-
Melting temperature	660.2	°C
Heat of fusion	390	J/g
Boiling point	2,470	°C
Heat of vaporization	1.14	J/g
Specific heat capacity (20 °C)	0.9	kJ/Kg K
Specific heat capacity (100 °C)	0.96	kJ/Kg K
Specific heat capacity (500 °C)	1.11	kJ/Kg K
Specific heat capacity (660 °C)	1.24	kJ/Kg K
Electrical conductivity	37.67	$m/\Omega\ mm^2$
Resistivity	0.02655	$\Omega\ mm^2/m$
Thermal conductivity	235	W/m K

Properties and applications of the aluminium alloys

1xxx series alloys

- Low strength, softness, suitable formability, very effective corrosion resistance, suitable weldability and coatability, effective electrical conductivity and thermal conductivity.
- Used in foil materials, ceiling structures, parts of machines and equipment, electrical conductor material, traffic sign material, light advertisements. Non-hardening alloy.

2xxx series alloys

- High strength and suitable machinability, poor corrosion resistance and poor extrudability, not suitable for MIG and TIG welding, Pb and Bi alloying improves machinability.
- Used in structures requiring strength, such as airplanes. Hardening alloy.

3xxx series alloys

- Better strength but poor formability compared pure Al, effective corrosion resistance.
- Used in facade structures, interior and exterior roof material, heat exchangers and car radiator material. Non-hardening alloy.

4xxx series alloys

- Silicon as an alloy material strengthens and smoothes the Al alloy.
- Used in soldering wire, welding wire, plywood material, heat exchangers and car radiator material. Non-hardening alloy.

5xxx series alloys

- Good strength and at the same time suitable formability, effective corrosion resistance and suitable weldability.

- Used in a wide range of applications due to its versatility, for example welded structures requiring strength, tanks, boats and ships, truck platforms, bus and train body structures and parts for the electronics industry. Non-hardening alloy.

6xxx series alloys

- Quite effective strength, suitable machinability and suitable weldability.
- Used widely as profile material for example in windows, doors and facades, furniture material, balcony material, fence structures, ladders and car structure parts. Hardening alloy.

7xxx series alloys

- High strength, poor extrudability, susceptibility to stress corrosion, suitable weldability.
- Used widely in high-strength structures such as demanding welded structures, bridges, cranes, automotive parts, and aircraft parts and the aerospace industry. Hardening alloy.

8xxx series alloys

- The properties of the alloys depend largely on the alloying elements and for this reason there are numerous using applications.

(Huhtaniemi 2006, pp. 67-71; Dutta & Lodhari 2018, pp. 122-124.)

Various methods of joining aluminium and steel

Various experimental welding methods included friction stir welding, resistance welding, explosion welding and ultrasonic welding. The problem with these methods is their suitability only for certain types of seams and this limits their versatile use. Using vacuum brazing, furnace brazing and CMT (cold metal transfer) techniques, the joining of the Al and steel is successful, but the resulting joint is brittle. The best methods for joining the Al and steel are gas tungsten arc welding (GTAW), gas metal arc welding (GMAW), electronic beam welding and laser welding in the light of current knowledge. All these methods are also used in the actual production in different applications. (Wang et al. 2016a, pp. 3081-3082; Meco et al. 2017, pp. 122-123.)

Laser classes 1M, 2, 2M, 3R, 3B

Class 1M lasers, the laser beam is not narrow, but has spread over a wider area, for example by using of optics. Only a small part of the wider beam can hit the eye, in which case the exposure limits for unprotected eyes or skin are not exceeded. The letter M in the classification indicates Magnification. Magnification, on the other hand, indicates that class 1M lasers must not be viewed through an optical magnifying aid. These include binoculars or a magnifying glass. Class 2 lasers are low power and eye closure reflex of 0.25 seconds has been considered to adequately protect the eyes when using class 2 lasers. However, class 2 lasers can cause damage to the eye in a completely direct orientation and if looking into the beam is intentionally prolonged. For class 2M lasers, the power exceeds that of class 2 lasers, but the laser beam is propagated in the same way as for class 1M lasers. Class 2M lasers can cause damage to the eye if viewing the beam is intentionally extended or the beam is viewed through an optical magnifying aid. Class 3R lasers emit five times the emission limits of the class 1 and 2 lasers. With class 3R lasers there is the power limit 5 mW. This is the safety margin that prevents damage from occurring. Beam that hits the unprotected eye directly or is reflected from a smooth surface can still cause permanent damage to the eye. The radiation of class 3B lasers exceed the emission limits of class 3R lasers. The direct or reflected beam of class 3B lasers is dangerous to the eyes in all situations. (Jokela et al. 2009, pp. 97-106; Kujanpää, Salminen & Vihinen 2005, pp. 327-328; Barat 2019, pp. 2-4 - 2-7.)

Checklist for general laser welding safety requirements

General information of work safety with lasers

- In laser processing, safety risks can be divided into different types of risks, which are the risks caused by the laser beam, the risks caused by electrical equipment, the risks caused by gases and fumes released into the air during laser processing, and secondary risks.
- Laser equipment must typically be provided with appropriate warning signs.

Classification of lasers

- Laser equipment is completely controlled by its own instructions and regulations, as laser technology differs considerably from traditional machining methods.
- All laser beam generating equipment must be classified according to its hazard and all laser welding equipment, without exception, belongs to the most dangerous class 4.
- The beam of class 4 lasers can burn the skin in an instant and is able to damage eye through stray reflections from up to a hundred meters away.

Laser beam hazard to eyes

- Eye injury is the best known and most common serious accident related to laser technology.
- The eye is the most sensitive point in a human body to damage caused by a laser beam, as the optics of the eye focus the laser beam hitting the eye on the retina of the eye.
- In practice, there is typically at least some damage to the eye when a high-power laser beam hits the eye; at worst, vision can be lost completely.
- The beam of lasers used in laser welding is not typically visible to the human eye, and the beam can be dangerously reflected from surfaces that are very hazardous to the human eye.

- Whenever class 4 laser beam is suspected to hit the eye of a person, an ophthalmologist must examine the injury immediately.
- All laser eye injuries that have been occurred, must be reported forward, that it can be recorded to the system and safety can be improved for the future.

Laser beam hazard to skin

- Class 4 laser beam causes varying degrees of burns, scarring, and pigmentation of the skin when it hits human skin.
- Skin damage can occur even if the laser beam hitting the skin comes through reflections.
- The focused laser beam penetrates deeper into the skin tissues and causes deep surgical wound-like injuries.

Non-beam hazards

- Laser processing equipment typically carries a dangerous risk of electric shock, because the equipment contains high voltage circuits and the electrical currents are high.
- Electric shock can occur even if the equipment is no longer connected to the mains, as the equipment uses high-power capacitors.
- Electric shock is most commonly caused by contact with electrical components inside the equipment during maintenance situations, and therefore the opening of service hatches and access to the equipment must be prevented by appropriate locking.
- During laser welding, harmful gases and fumes released into the air from the welded part or any used filler material, must be removed out with reliable ventilation and filtered with the correct type of filters.
- Hazardous emissions can also be released if laser equipment breaks down, in which case the emissions are frequently very dangerous fluorides or carcinogenic fumes.
- In laser welding, some of the radiation is reflected from the welded part and is directed to the environment quite randomly, and such reflected radiation is called reflected radiation.

- The danger of reflected radiation is based on its potential invisibility and the direction of reflection in a surprising direction.
- There are some secondary risks associated with laser welding, due to a lack of training of workers.
- The secondary risks include, for example, burns due to contact with hot objects, cuts caused by sharp edges, hearing damage due to the loud process, and injuries caused by cryogenic coolants.

Protection equipment

- Laser safety is fully managed through certain safety equipment and operating principles.
- The most essential safety equipment is the enclosure or insulation of the laser equipment and the area affected by the laser beam, which ensures that no dangerous laser beam can cause any damage outside the enclosure or insulation.
- The structure of a reliably enclosure is guided by certain standards and guidelines, but in practice, at its simplest, an enclosure consisting of metal plates is sufficient enough for enclosure.
- It is appropriate to install the necessary interlocks, service access panel, master switch, key control, viewing portals, display screens, and safe collecting optics in connection with the enclosure of the laser equipment to ensure work safety in all situations.
- If during maintenance or various faults, it is necessary to enter the enclosure or insulation, and there is uncertainty on the operation of the laser beam, special laser goggles and protective clothing must be worn.
- All persons working in the area affected by the laser beam must be given adequate training on the safety and operating principles of laser radiation, for example procedures in emergency situations.

Checklist for aluminium laser welding safety requirements

General information on hazards of Al during laser welding

- Al as a material causes various safety hazards during laser welding compared to steel.
- The hazards posed by Al are certainly caused by the fine fumes released from Al material, gases released into the air during the welding process, ultraviolet radiation generated during the welding process, and potentially explosion risk of fine Al dust.
- There is no need to be caution concerning the dangers of ultraviolet radiation in laser welding of Al, as the installed enclosure for protection against laser radiation also protects against ultraviolet radiation.
- In laser welding of Al, Al based welding fumes released into the air during welding cause different health hazards.
- This research has shown that the amount of welding fumes released into the air in laser welding of Al is in the same range as in laser welding of steel or MAG welding of Al.

Exposure to aluminium

- Exposure to Al distinguishes occupational exposure from normal daily exposure to Al, which occurs, for example, through digestion.
- In the case of laser welding, the exposure to Al occur entirely from the inhalation of air containing fine Al fumes.
- Threshold limit value for working in the area affected by Al fumes has been defined separately for 15 minute and eight-hour exposures.
- In Finland, this threshold limit value is known as the HTP value and is 1.5 mg/m^3 at eight hours of exposure.
- Al that ends up in the respiratory system passes through the olfactory epithelium and mucous membranes either to the digestive system or through nerve connections to the brain, for example.

- Al that ends up in the lungs enters the blood circulatory through the lung epithelium and lung tissue.

Metabolism and aluminium

- In laser welding, fine Al dust consists mainly of Al oxide and different size Al particles, end up in different places in the human body and act in different ways.
- Al particles that end up in the body during welding processes are frequently less than 1 µm in size and most frequently even less than 0.1 µm.
- Through inhalation, Al that accumulates in the body ends up everywhere in the body, but most of the Al accumulates in bone tissue, brain tissue, and liver.
- Only kidneys can filter Al out of the body as part of a normal body filtration system and the Al accumulated in the body is excreted in the urine.
- Al is slowly eliminated from the body and the half-life of Al in the human body can be up to more than a year subsequent to prolonged exposure to Al.
- At the cellular level, the effects of Al are not yet fully understood, but the hazardous of Al seems to be related to its ability to take the place of other metals essential to the function of body, and thus interfere with the normal functioning of cells.
- At the cellular level, disturbances occur especially in energy and mitochondrial function.
- Al accumulated in the liver interferes with the normal functioning of the liver and fatty compounds, or lipids, end up in the brain to interfere with normal brain function.
- Especially in brain cells, Al causes an increase in ROS, which sets the cells in an inflammatory state and the cells can die.

Health effects of aluminium

- The assessment and management of the health challenges posed by Al is difficult by the slow emergence of concrete problems, as health problems due to Al frequently do not occur until several years subsequent to the exposure.
- The health effects of Al are especially evident in various lung diseases, central nervous system diseases, bone diseases, and various anemias.

- In the lungs, Al causes a special lung disease, aluminosis, in which the lung tissues are scarred and no longer function, work-related asthma, and even lung cancer.
- Al ending in the brain has been found to be associated with a variety of central nervous system problems and diseases, such as encephalopathy, Alzheimer’s disease, Parkinson’s disease, seizures, and motor neuron degeneration, but several studies have been found these connections to be partially contradictory and open to interpretation.
- Completely reliable results are disrupted by other Al exposure of workers, exposure to other harmful metal particles, susceptibility to central nervous system diseases, and the ability to perform individually in tests measuring central nervous system function.
- Al accumulated in bone tissue causes various bone tissue regeneration problems and bone diseases as osteoporosis and osteomalacia.
- Al accumulated in the body has been found to cause autoimmune diseases as aplastic anemia, non-iron deficient anemia, renal anemia, and hypochromic anemia.

Exposure assessment and need for health surveillance

- The health effects and their severity are particularly affected by the duration of Al exposure, and the amount of Al accumulated in the body; therefore, it is appropriate to monitor the amount of Al in the body regularly through biomonitoring of Al.
- There are some methodological weaknesses associated with Al biomonitoring, but it is still the most suitable indicator of the risk of developing Al-related health challenge or disease.
- Al exposure can be performed with a urine test or a blood test, and the urine test is generally considered to be the most suitable option.
- The kidneys continuously remove the Al that has accumulated in the body, and therefore the urine test shows not only the amount of short-term Al exposure, but also the amount of Al that has accumulated in the body over a longer period.
- The Finnish Institute of Occupational Health has recommended the urine test action level of 162 µg/litre subsequent to an unexposed weekend, and action should be taken if this limit is exceeded.

Dangers of dust explosion

- Fine Al dust is highly explosive in its normal state, and there have been numerous devastating explosions around the world, including in connection with Al grinding and polishing processes.
- In such mechanically executed processes, the Al particles retain their normal chemical composition but, for example, in welding, where the releasing method is high heat, the Al particles are strongly oxidized.
- The oxide has been found to contain a chemically inert property and is effective in reducing the reactivity of the dust.
- Several studies have been detected that Al particles released into the air during laser processing of Al are poorly reactive and the dust has not been explosive at all.

Checklist for workstation design requirements

Workstation information

- Clear warning texts must be installed in the vicinity of the workstation concerning Al fumes that are hazardous to health inside the workstation and instructions on the use of a respirator if one must enter inside the enclosure surrounding the workstation.
- Sufficient training must be provided for employees involved in laser welding of Al, covering the safety aspects and operating instructions for Al in different situations.
- Adequate training must also be provided for other workers working nearby on how to deal with emergencies and unexpected disturbances.
- Especially when introducing new work processes that cause Al exposure, the necessary human biomonitoring test must be used.
- Al biomonitoring can easily be arranged together with occupational health care and it would be advisable to take two separate urine tests, the first taken directly at the end of the shift for short-term assessment and the second subsequent to work-free weekend to assess longer-term exposure.

Workstation isolation with protective enclosure or safety cabin

- If possible, the laser welding workstation must be encapsulated, that the dangerous laser beam cannot escape from the enclosure under any circumstances.
- Laser welding workstation enclosure requirements are governed by several standards and regulations.
- At the same time, the enclosure around the workstation acts as a effective insulator and a reliably operated vacuum created by ventilation ensures that no Al fumes dangerous to health can escape from the workstation at all.

Workstation ventilation system

- Reliable ventilation system controls Al fumes that are hazardous to health and, together with the enclosure, ensures that Al fumes do not escape from the enclosure.

- Ventilation can be provided with a wider vacuum solution in connection with the enclosure or with a smaller local exhaust ventilation system, or a combination of these.
- The efficiency of ventilation should only be assessed when the parameters of a functioning laser welding process are known, and the quantity of fumes released into the air can be estimated with accurate measuring equipment.
- If the ventilation is stopped for any reason, the automation must stop the laser welding process, that no further harmful emissions occur and spread outside the workstation.
- An essential part of the ventilation system is a functional filter that filters Al fumes, the reliability of which must be ensured by correct inspections carried out frequently enough.
- When entering an area exposed to Al fumes which are hazardous to health, the correct type of respirator must be worn. Especially maintenance situations and cleaning require the use of a suitable respirator.

Explosion hazard requirements

- Based on a few research results, it is assumed that Al fumes generated by laser welding are not explosive due to their high oxide content.
- However, the risk of explosion must be ensured at an early stage of the design, as if there is a risk of explosion, the entire work process will must be rethought.
- The risk of explosion can be reliably verified based on correctly performed tests.
- A workspace where laser welding is performed cannot be an ATEX safe space.
- If there is a risk of explosion, the workplace must create several different practical and organizational solutions to reduce and manage the risk of explosion.

Workstation cleaning

- Fine Al dust that accumulates on surfaces inside the workstation must be cleaned frequently and carefully enough to avoid dangerous health risks if fine Al dust suddenly rises into the air.

- It is possible to design and implement various technical solutions for the workspace to facilitate the need for cleaning.
- If Al dust from the Al laser welding process is found to be explosive, it is recommended that cleaning be performed by an outside professional company.

Workstation maintenance and maintainability

- To ensure safe operation, it is essential that the equipment operates reliably in all situations.
- If maintenance personnel must enter to an area where it is possible to be exposed to Al fumes that are hazardous to health, an appropriate respirator must be worn.
- Laser technology and laser welding equipment itself require the knowledge and expertise of maintenance personnel, and if additional information is needed in some challenging situations, it is available from the emergency services of equipment suppliers.