LUT UNIVERSITY
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Simulation of heat transfer in TIG welding torch

Examiner(s): D.Sc. (Tech.) Tuomas Skriko
M.Sc. Jarkko Malinen

ABSTRACT

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Simulation of heat transfer in TIG welding torch

Master's thesis

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63 pages, 29 figures, 2 tables and 3 appendices

Examiners: D.Sc. (Tech.) Tuomas Skriko
M.Sc. Jarkko Malinen

Keywords: TIG Welding, FE simulation, heat transfer

The purpose of this master's thesis was to find out whether temperatures of TIG welding torch during welding could be simulated. Simulations were done with Ansys simulation software and simulations were compared to experimental laboratory measurements. One aspect of the research was to find out whether simulation tool could be used as everyday tool for product development in Kemppi.

Research consists a literature review were heat transfer mechanics are presented. Structure of typical gas cooled TIG welding torch is explained along with standards related to the TIG welding torches. Required modifications and simplifications to 3D model are covered together with simulation setup and meshing. Material models are presented and thermal dependent models were used for copper, brass and tungsten. Results from laboratory measurements are presented and discussion of them follows.

Verification of the simulation model was done in three steps. In the first case only current was passing through the torch. This enabled to measure the effect of joule heating separately. In the second case shielding gas was added. Shielding gas is known to have effect on cooling of welding torches. The third case contained temperature comparison during welding. All three cases were repeated with 50 A, 75 A and 100 A currents. In the first two cases match between simulation and laboratory measurements was quite good. Comparison during welding in the third case showed more deviation.

It was pointed out that getting correct temperatures during welding is really challenging and would require much more complex simulation model. However, in simpler cases Ansys could be powerful tool for everyday research and development work. With Ansys it would be possible to compare different designs much faster than with actual prototypes. It would enable laboratory to focus only on best designs.

TIIVISTELMÄ

LUT-Yliopisto
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Paavo Sivula

TIG-hitsauspolttimen lämmönsiirtymisen simulointi

Diplomityö

2020

63 sivua, 29 kuvaa, 2 taulukkoa ja 3 liitettä

Tarkastajat: D.Sc. (Tech.) Tuomas Skriko
M.Sc. Jarkko Malinen

Hakusanat: Tig-hitsaus, lämmönsiirtyminen, FE-simulointi

Tässä diplomityössä tutkittiin, voidaanko simuloimalla laskea TIG-hitsauspolttimen lämpötiloja hitsauksen aikana. Simulaatiot tehtiin Ansys-ohjelmistolla ja niiden tuloksia verrattiin laboratoriossa mitattuihin lämpötiloihin. Osana työtä selvitettiin, voidaanko vastaavaa työkalua käyttää apuna tuotekehitysprojekteissa.

Työ koostuu kirjallisuuskatsauksesta, jossa esitellään lämmönsiirtymisen mekanismit. Kirjallisuuskatsauksessa esitellään myös tyypillisen TIG-hitsauspolttimen rakenne sekä sen rakenteeseen vaikuttava standardi. Tarvitut muutokset ja yksinkertaistukset 3D malleihin on käyty läpi, jonka lisäksi vaaditut valmistelut simulointiin on esitelty. Käytetyt materiaalimallit on esitelty, lämpötilariippuvaisia malleja käytettiin messingille, kuparille ja volframille. Tulokset simuloinneista ja laboratoriomittauksista on esitelty niiden vertailun lisäksi. Pohdinta-osiossa esitetään mahdollisia syitä eroille mittauksien ja simulaatioiden välillä sekä arvioitiin simulointimallin toimivuutta ja realistisuutta.

Simulaatiomallin verifiointi tehtiin kolmessa osassa. Ensimmäisessä tapauksessa polttimen läpi kulki ainoastaan virta. Tällöin voitiin mitata sähköä johtavien materiaalien lämpenemisen vaikutus erillään muista tekijöistä. Toisessa tapauksessa simulaatiomalliin lisättiin suojakaasun virtaus, jolla tiedetään olevan jäähdyttävä vaikutus polttimeen. Viimeisessä tapauksessa lämpötiloja vertailtiin hitsauksen aikana.

Työ osoitti, että lämpötilojen simulointi hitsauksen aikana on hyvin haastavaa. Tarkkojen tulosten saavuttamiseksi simulaatiomallin pitäisi olla paljon laaja-alaisempi ja monimutkaisempi. Tarkkojen tuloksien replikointi ei kuitenkaan ole aina tarpeellista. Ansys osoittautui hyväksi työkaluksi erilaisten rakenteiden vertailuun. Vertailu yksinkertaisissa tapauksissa voitaisiin tehdä huomattavasti nopeammin kuin laboratoriossa mittaamalla. Simuloimalla tehty vertailu antaa mahdollisuuden testata ainoastaan parhaaksi havaitut ratkaisut laboratoriossa.

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I would like to thank all the examiners of this thesis for their support. Especially support towards end of the project was important. My employer Kemppi has also been very supporting during my studies and during this master's thesis.

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Paavo Sivula

Paavo Sivula
Vicenza 20.11.2020

FIGURE OF CONTENTS

LIST OF SYMBOLS AND ABBREVIATIONS

A	heat transfer area
A_s	surface area of convection
h	convection heat transfer coefficient
k	thermal conductivity of material.
T_s	surface temperature
T_∞	temperature of the fluid far away from target surface
$\dot{Q}_{cond}$	Rate of conduction
$\dot{Q}_{conv}$	Rate of convection
$\dot{Q}_{emit}$	Radiation emitted
$\dot{Q}_{emit,max}$	Radiation emitted by black body
$\frac{dT}{dx}$	temperature gradient
σ	Stefan-Boltzmann constant
ε	emissivity of the surface
AC	Alternative current
CFD	Computational fluid dynamics
DC	Direct current
IEC	International Electrotechnical Commission
MAG	Metal active gas
MIG	Metal inert gas
TIG	Tungsten inert gas
WPS	Welding Procedure Specification

1 INTRODUCTION

Usage of modern simulation tools can provide many advantages to companies that are focused on research and development. Simulating different physical phenomena can lead to shorter testing periods or fewer prototypes. In best cases product development can be made using fewer resources and prototypes within shorter time. Usage of simulation tools also enables testing of much higher amount of different solutions than it would be possible using physical prototypes. Kemppi is a Finnish manufacturer of welding power sources and accessories. It is privately owned by the family of its founders. Kemppi OY has manufactured welding power sources and accessories over 70 years. Yearly revenue of Kemppi is around 150 million euros and over 800 people work for Kemppi. Manufactured products include welding power sources for manual metal arc welding, gas metal arc welding and for tungsten inert gas (TIG) welding. In addition, torches for these are manufactured along with protection equipment for welders. Kemppi has factory in Lahti, Finland. Main assembly of power sources and electronic circuit boards are made in Finland. Kemppi has also factories in Italy and in China. Kemppi has subsidiaries in 16 countries and products are sold all over the world.

1.1 Background

Main purpose of this master thesis is to test a modern simulating tool in practice. Usage of such simulation tool will be tested on TIG welding torch. This simulation case serves as case study of how well such tool would fit into research and development work. Specifically research will focus on temperatures of the TIG welding torch during welding. Parts that conduct current in welding torch are crucial. They play key role on arc formation and eventually in welding quality. Analyzing temperatures of those parts is crucial since material properties seldomly remain constant at higher temperatures. Weakened material properties can lead to shorter lifetime of TIG welding torch and customer dissatisfaction. Investigating existing situation closer can lead to some new discoveries which might lead to new business potential. When properly implemented, simulation tools can be a way to cut down research and development time when compared to conventional experimental methods. Simulation can eliminate several tests cycles and therefore save money and time. In best-case scenario, simulation tools can provide better products, generate competitive edge and save time and money in new product development process. Market for welding equipment is saturated and competition is tough. Bringing out new innovations can affect on company’s market position.

So far temperatures of TIG welding torch have always been measured in laboratory using thermocouples. During product development of new TIG welding torch, several measurements must be made. Setting the TIG welding torch for measurement includes many steps. One of the most time-consuming steps is the attachment of thermocouples which will be used to measure temperatures. Actual heat test may take around half a day, but all the steps included it takes one person at for least one workday to measure temperatures of the TIG welding torch. Given that project usually delivers several new products, total measuring time only for heat tests in one project is measured in weeks. Cutting down these measurements would bring savings. Savings alone can justify usage of simulation tools, but usage of simulation tools can bring other values as well. If simulations tools are applied with good success, it can provide reliable data and it can be used for design related decisions. Making simulations from different models can be quicker than actual heat measurements. This allows product development to analyze more options and search for optimal structure. However, simulation cannot alone act as a verification method for new designs. Testing of physical models is almost always needed in order to verify simulation results.

Concept of the simulation is not new. According to Goldman et al. (2009) first simulations were done in the late 18th century. Before the first computers were developed after World War II, simulations were statistical. After computers became more popular, variation of different simulation possibilities have increased exponentially. After 1980’s it can be said that simulation tools in different forms are used in every field (Goldman et al. 2009).

It can be assumed that spread of simulation tools have relation to the prototype cost. Larger and more expensive structures are among the first ones to use simulation tools to reduce development time. Welding torches are not particularly difficult to make prototypes. But usage of simulation tools does not always require expensive or large prototypes. Simulation tools can speed up and bring cost savings even when products to be developed are simple. Simulating welding torches will increase knowledge from physical phenomena related to the welding torches. The increase of knowledge is one of the most valuable resources that the research and development department and the whole company can have. When knowledge is on high level, product quality is also assumed to be high.

1.2 Research problem and approach

Welding is complicated physical phenomena which includes all four states of matter. Four states of matter are solid, gas, liquid and plasma. Welding arc is considered to be plasma. (Lu et al. 2004 p.2) Therefore, building of simulating model is expected to be challenging even though model is focused to temperatures of TIG welding torch handle and torch body only. Simulation model will be verified by temperature measurements made in laboratory. Simulation is interesting option to experimental measuring because those take a lot of time. Also, it is not possible to test all ideas in practice. Simulation in best case would speed up testing and provide possibility to test much more options during development projects. Simulation in this research done using Ansys 2020 simulation software. Ansys features many different modules for different applications. These simulations were done using Ansys Mechanical. In Ansys Mechanical this type of simulation can be done either in static-thermal or thermal-electric module. Thermal-electric module was used on this simulation. Shielding gas is needed during TIG welding and flow of shielding is known to have some cooling effect on welding torch. This gas flow will be part of simulation. Simulation model will consist of handle and torch body of TIG welding torch. Target is to simulate temperatures of TIG welding torch during welding. Before moving into simulating welding, simulation model is tested using two set of laboratory measurements. These measurements act as a verification before actual welding is simulated.

1.3 Research questions and target of research

This research aims to find answer to following questions:

1. Can modern simulation such as Ansys Mechanical provide appropriate information of TIG welding torch temperatures during welding?

2. Could such simulation tool be used as an effective tool for product development?

3. What are the most critical steps in accuracy of simulation and should one use thermal-electric model or static-thermal model of Ansys for simulations of this kind?

4. How much simulation can be simplified and still yield decent results; can thermal fluid flow be included in simulation without usage of computational fluid dynamics (CFD) analyses for example?

Answer for these questions are found out by simulating temperatures of TIG welding torch with Ansys simulation software and comparing results on laboratory measurements. Torch used in simulations is commercially available and it is gas cooled. Duty cycle for simulations was 100 % to avoid usage of transient simulations. Welding was performed with 50 A, 75 A and 100 A.

1.4 Research methods and delimitation of research

Research consists of the literature review of TIG welding and heat transfer mechanics. Also, standard related to TIG welding torch is presented in literature review section. Simulations were made using Ansys Mechanical software. Ansys used 3D models which were modified using the Solidworks software. Experimental measurements were made to verify the simulation results.

3D model of TIG welding torch will be used in simulation. Necessary modification will be done with Solidworks software before building of the simulation model. 3D models are provided by the Kemppi and it is representing commercially available gas cooled TIG welding torch. After simulation model is build, it is compared to the temperature measurements made in laboratory. Comparison is made in steps so model verification is more accurate. Simulation environment is based on the heat test described in the IEC 60974-7 standard. Simulation is done at static state, which means that temperatures represent static situation and the time to reach those temperatures is not part of study.

Simulation model will consist only model of the TIG welding torch and no weld pool will be simulated. Also, base material will not be part of the simulation model. TIG welding torch was selected from existing product portfolio and it is commercially available. Consumables were selected as they are in the factory installation. Simulation consist of the TIG welding torch handle and the torch body. Whole welding torch will not be simulated. Torch body will consist all the consumables that are needed for welding. Torch used in simulation is air cooled, which means that there is no water-cooling circuit present. Shielding gas is known to have some cooling effect on torch and it will be part of simulation model. Simulation is done using only the tools that are founded on Ansys Mechanical. Any computational fluid flow analyses will not be done in this research. Material data and used material models were based on data found on literature.

2 TIG WELDING TORCH AND HEAT TRANSFER MECHANICS

Literature review of this work consists short introduction to the TIG welding and typical construction of the TIG welding torch. Standard related to TIG welding torch is also presented. Standard defines procedures to measure temperatures of the welding torch. Heat transfer mechanics are also presented. In last section short introduction to the finite element method is presented.

2.1 TIG welding

TIG welding is arc welding process that uses non-consumable electrode. In the standard ISO-EN 4063 (2009) it is defined in category 14, gas-shielded arc welding with non-consumable tungsten electrode. Electrode material usually is tungsten and variation of tungsten alloys are used depending on welded material. Tungsten electrodes are defined in the EN ISO standard 6848 (2015). At first TIG welding was developed for aluminum welding applications before 1940's in USA. After World War II, first commercial applications become available also in the Europe. TIG welding in the USA started with helium as shielding gas because it was widely available and cheap. In the Europe, helium was expensive and therefore was not suitable option. In the Europe, usage of argon became more popular option for shielding gas. (Muncaster 1991, 1.)

In TIG welding, direct current (DC) and negative polarity is most often used. In this research, tungsten electrode is negative. It is also possible to use tungsten electrode as a positive electrode, but this is not as common. Positive polarity has very good ability to clean aluminum oxide that is formed on aluminum surfaces. This effect is called cathode cleaning. Positive polarity in the other hand heats welding torch radically more than negative polarity. DC TIG with negative polarity is most often used in welding of stainless steels. Alternative current (AC) applications of the TIG welding also exists. In the AC welding, polarity changes during welding and this creates some advantages of cathodic cleaning. Cathodic cleaning is helpful with welding of aluminum materials were oxidation layer is otherwise causing problems during welding. When TIG welding is compared to the metal inert gas (MIG) welding or to the metal active gas (MAG) welding, TIG welding is slower process, but cleaner and more precise. TIG welding does not produce any spatters and arc control is good. This of course requires skillful welder. (Muncaster. 1991. p. 1.)

In the recent years, materials and applications of MIG and MAG welding have increased. Nowadays it is possible to weld many different stainless steel materials efficiently with modern power sources. Same applies to aluminum and aluminum alloys (Weman K. & Linden G. 2006, 204 & 211). Although it is possible weld same materials with MIG or MAG welding, TIG welding is still preferred if quality demands are high. Welding Procedure Specification (WPS) or other standards might demand that welding is specifically done by TIG welding.
Welding arc is thermal plasma which includes multiple physics (Wendelstorf et al. 1996 p.4). It can be described as an interaction of electric and magnetic fields (Varghese et al. 2011). According to Murphy & Lowke (2018) the arc plasma can be modelled using computational fluid dynamics. Since thermal plasma also conducts electricity, model would have to include equations for current continuity and usage of Maxwell´s equations. It is also noted by Murphy & Lowke (2018) that different shielding gasses have effect on thermophysical properties of plasma. For example, ionization of helium occurs around temperature of 22000 K and same temperature for argon gas is around 15000 K. These differences must be taken into account in complete simulation model of welding arc.

2.2 TIG welding torch

Purpose of the TIG welding torch is to transfer power required for welding from the power source to the welded material. TIG welding torch will also transfer shielding gas to arc. Some of the welding torch have water cooling circuit to ensure higher welding current and higher duty cycles. Quite often welding torch will also have start switch which will guide power supply. When start switch is pressed, high frequency spark will ionize shielding gas between tungsten electrode and base material. This will ignite the arc. Arc can be ignited also by scratching electrode onto surface of the base material. Another option is supported by some power sources where electrode is first placed on base material and then lifted while power supply is raising voltage and arc is formed. This method is usually called lift-TIG, but some variations exists between manufacturers.

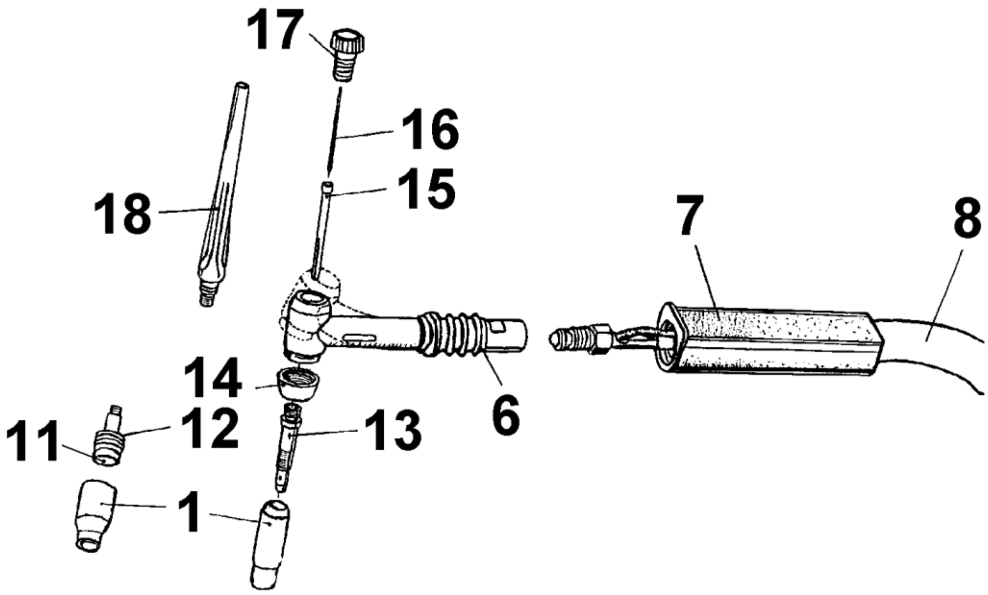

Figure 1. Construction of the TIG welding torch (IEC-60974-7. 2019. p25.).

Figure 1 (IEC 60974-7. 2019 p25.) presents typical construction of the TIG welding torch. TIG welding torch consists of handle and power cable (parts 7 and 8) and from torch body (part 6) and different consumables related to torch body (parts 1,11,12,13,14,15,16,17 and 18). Power cable is responsible from transferring the current needed in welding. In many cases, shielding gas is transported along with the same cable. This saves extra gas hose that would have been needed otherwise. Shielding gas is also known to have some cooling effect on welding torch so it is useful to cool down current transferring copper rope. According to the IEC 60974-7 (2019) outside of hose package can heat up to 40 K higher during welding than environment.

Handle is part of the TIG welding torch where welder usually grips during welding. Its purpose is to offer good ergonomics and protect user from high voltages present in arc formation of TIG welding. The role of handle and torch body ergonomics is to ensure that welder has best potential to produce high quality welds. Handle also protects user from hot power cable. Torch body is attached to the handle, usually allowing it to be rotated according to the welder's preferences. Torch body is attached to power cable, so it participates to transferring current and shielding gas. Torch bodies come in different angles and lengths. Some might be flexible allowing angle to be adjusted. Torch body is important factor regarding ergonomics, but it also has role on temperatures of TIG welding torch. Under scaled torch body will limit the performance of whole TIG welding torch. Consumables are also fixed to torch body. Most important consumable is the tungsten electrode which is the final connecting part before welding arc. Tungsten electrode must withstand temperatures over 3000 °C. Tungsten electrode is tightened into its place with help of collet, collet body and electrode cover. Collet body is attached into torch body with threads. Collet is usually made from copper and another end of it has longitudinal grooves. When electrode cover (part 18) presses collet against collet body, these grooves allow tungsten to be tighten into its place. Shielding gas is going through the torch body and will be forwarded towards arc. TIG welding usually needs good shielding gas coverage, especially if stainless steel or titanium is welded. Shielding gas flow needs to be as laminar as possible. For this purpose, different kind of consumables has been developed. When the collet body (part 12) is installed into TIG welding torch together with part 11 (gas lens filter), better gas shield can be achieved. In this research, standard consumables without gas lens filter are used in the laboratory measurements and in the simulation model.

2.3 IEC 60974-7

IEC 60974-7 is an International Electrotechnical Commission (IEC) standard covering torches for arc welding equipment. It also gives requirements for TIG welding torches. Heat test in IEC 60974-7 is done by welding with torch and measuring temperatures during the welding. Welding is done on top of copper block which can be water cooled. Usually water-cooled block is needed at higher currents. Table 1 describes gas flow and required distances for different welding currents.

Table 1. Test values for TIG welding torch heat test (IEC 60947-7 2019 p. 18)

Welding current A	Maximum gas flow l/min	Distance between nozzle and copper block ±1 mm mm	Distance between electrode and copper block ±1 mm mm
Up to 150	7	8	3
151 to 250	9	10	5
251 to 350	11	10	5
351 to 500	13	10	5
Above 500	15	10	5

According to IEC 60974-7, torch handle can heat maximum of 30 K above surrounding environment temperature. Handle is defined by the standard as a part where welder usually grips during welding. For torch body and consumables standard does not give any limits for temperatures.

During heating test, torch electrode is positioned perpendicularly to the top surface of copper block. Welding in heating test is continued at least 30 minutes or until temperature rise does not exceed 2 K/h. If torch duty cycle is not 100 %, each cycle length will be 10 min. For example, if duty cycle is informed to be 60 %, 10-minute cycle contains 6 minutes of welding and 4 minutes of cooling. Temperatures are measured from the middle of the last welding cycle. In IEC 60974-7 (2019) electrode material is specified as tungsten alloy. This leaves some room for different options to choose from, but usually ceriated electrode is chosen. Electrode polarity is defined to be negative and shielding gas to be used is argon. Welding current is specified by manufacturer and used current will be the rated current for torch when it is sold to customers. (IEC 60974-7 2019.)

2.4 Heat transfer mechanisms

Heat transfer occurs always from higher temperature to lower. Process continues until two bodies reach the same temperature unless the system is affected by outside heat flow. Heat can be transferred in three different modes, by conduction, convection or radiation.

2.4.1 Conduction

Conduction is heat transfer mode that occurs within solid, liquid and gasses. There heat is transferred between particles of material from more energetic towards particles that have lower energy. Energy in solids is transferred because of molecule vibration and movement of free electrons. In gas and liquids conduction occurs because diffusion and collision of molecules. Rate of the conduction depends on material properties, thickness, geometry and temperature difference. Rate of conduction is expressed as follows:

$$\dot{Q}_{cond} = -kA\frac{dT}{dx} \tag{1}$$

Where $\frac{dT}{dx}$ is the temperature gradient, A is the heat transfer area and k is the thermal conductivity of the material. (Cengel 2008, 374-375.)

In TIG welding torch, conduction is the primary mode of heat transfer. For example, when the copper cable is warming due to the joule heating effect, heat is transferred into surface of handle via conduction. Conduction also has its role when heat is transferring from the tungsten electrode into the torch body.

2.4.2 Convection

Convection is energy transfer mode that occurs between surface of solid body and gas or liquid next to it. Convection always requires motion of these gasses or liquids involved. Faster the movement of these liquids is, higher the convection heat transfer is. If there is no movement, heat transfer mode is conduction. Convection can occur naturally, or it can be forced conduction. Natural convection occurs when fluid motion is not alternated with any external force. Forced convection occurs when motion of fluid is somehow forced. Rate of convection can be expressed as follows:

$$\dot{Q}_{conv} = hA_s(T_s - T_\infty) \tag{2}$$

Where h is convection heat transfer coefficient, A_s is surface area where convection occurs, T_s is surface temperature and T_∞ is temperature of the fluid far away from the surface where convection occurs. Unlike in conduction, convection heat transfer coefficient is not a property of fluid or solid. It is usually measured or otherwise determined experimentally. Value of convection heat transfer coefficient depends on many factors, such as type of fluid motion, properties of that fluid, velocity of fluid and geometry of the surface. (Cengel 2008, 382.)
In TIG welding torch cooling of the torch is occurring because of the convection. If TIG welding torch has water cooling circuit, flowing water is cooling copper pipes inside torch body via convection. Also, at same time TIG welding torch outer surfaces are cooling down because of the convection. In this research only gas cooled torch is investigated. When shielding gas is flowing through the torch, it cools down the surfaces on its route because of the convection. During welding some fumes are always formed. These fumes are generally hotter than surrounding air and might have small effect on surface temperatures of the TIG welding torch.

2.4.3 Radiation

Heat transfer by radiation does not need any solid or liquid interaction because it is occurring via electromagnetic waves. It is also the fastest form of the heat transferring modes because electromagnetic waves are travelling at the speed of light. Because of the radiation, the Sun can heat the Earth. All bodies are emitting thermal radiation and it would only stop if the absolute zero point would be reached. Effect of the radiation can be neglected if forced convection is occurring or surface temperatures are relatively low. Perfectly black body emits radiation as follows:

$$\dot{Q}_{emit,max} = \sigma A_s T_s^4 \tag{3}$$

Where σ is the Stefan-Boltzmann constant, A_s is surface area where convection occurs, T_s is surface temperature. Equation 3 describes idealized situation, but in practice surface emissivity usually must be considered:

$$\dot{Q}_{emit} = \varepsilon \sigma A_s T_s^4 \tag{4}$$

Where ε is the emissivity of the surface. Value of ε ranges between 0 and 1. Idealized black body would have emissivity of 1. (Cengel 2008, 384.)

Regarding TIG welding torches, radiation might have some effect on the surface temperatures. Welding arc can have high temperatures, up to 21000 K (Goodarzi et al. 1997, p.2748). But arc and source of thermal radiation is not next to the handle for example and complicated geometries and presence of other physical phenomena are making it difficult to evaluate the effect of radiation alone in TIG welding torches.

2.5 Finite element method

The finite element method (FEM) is a numerical method to approximate solutions which have certain boundaries set. FEM is widely used across the field of engineering for solving variety of problems. Problems might include structural analyses, heat or fluid flow and many other applications. FEM is good way to find approximate solutions on problems where analytical and exact solutions would be impossible to find. It does not however neglect the need for experimental research. In FEM geometry is divided into finite number of elements. These elements have nodes which are used as a calculation point. Problems are solved at each node rather than trying to solve the whole model at once. Nodes also are connected to another elements and eventually whole geometry is connected to each other. Dividing geometry into elements is called meshing. Elements can have different size or shapes, but model made of elements is always approximation of the real geometry. How well it represents actual geometry indicates the quality of the mesh. Increasing number of elements increases number of nodes and calculation times as well. (Hutton 2004, 1-5).

3 SIMULATION MODEL

Simulation model was based on 3D model of commercially available TIG welding torch. Torch did not have additional water-cooling circuit. Rated current for this torch was 220 A at 40 % duty cycle. Model was first prepared using the Solidworks software. Material and contact definitions were made in the Ansys software. Ideal usage during the product development would require minimum amount of preparation work. This not however always possible and some modifications and simplifications to original 3D geometry had to be made.

3.1 3D model and preparations

Ansys software uses finite element method and some work was needed to be done in order to achieve reasonable mesh. Torch handle for example has a lot of small features to improve welders grip from it. These grip features caused issues when meshing was first applied and caused meshing to fail. If meshing would have succeeded, grip features would have still caused a lot more elements into the model. More elements increase the calculation time.

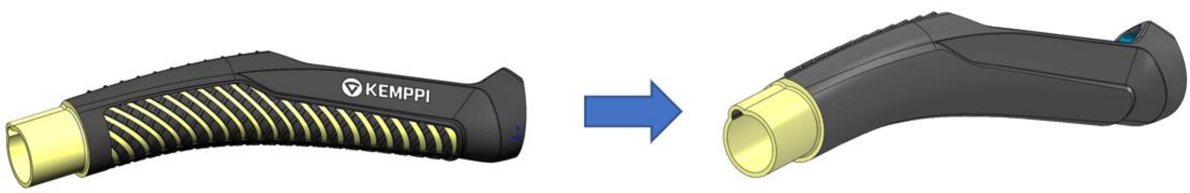

Figure 2. Silicone handle was modified to achieve simpler mesh.

In figure 2, modifications to handle can be seen. More modifications are made, more inaccurate results will be, but in case of the handle, it is believed that modifications made do not cause considerable error to the result.

Some other modifications were also made to the existing 3D model. Torches sold by Kemppi are usually 4 m, 8 m or 16 m long and original 3D model also has long power cable. This cable length introduces many unnecessary elements to the simulation model and therefore increases calculation time. Cable was shortened for the simulation model. This does not cause error in results, because thermal results are obtained only from the torch handle and neck.

3D model also had other features that needed modification. Torch body had very thin solid features that made mesh very complex. These features were in the model because modeling techniques used during design of the original 3D model.

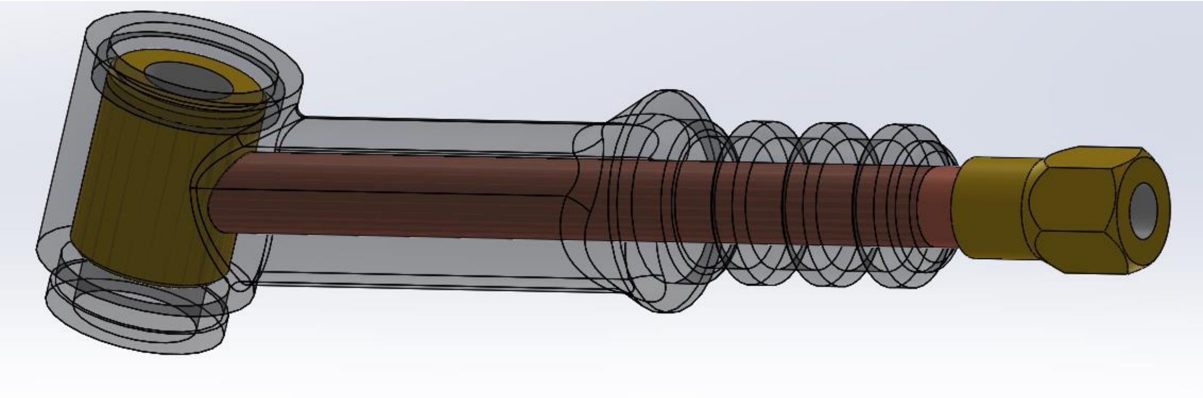

Figure 3. Torch neck is molded over brazed copper and brass parts.

In figure 3, torch body assembly can be seen. Torch body is manufactured by first preparing brazing assembly with copper tube and brass parts. This brazing assembly is then over molded with silicone rubber. When the 3D model was prepared, inner features of the silicone were made in Solidworks with cavity command. Cavity command has left some very thin solid features into model and those caused complex mesh features in the Ansys software. Thin features were removed from the 3D model.

Torch power cable is consisted of copper cable inside rubber hose. Shielding gas needed for welding is also transported inside this rubber hose.

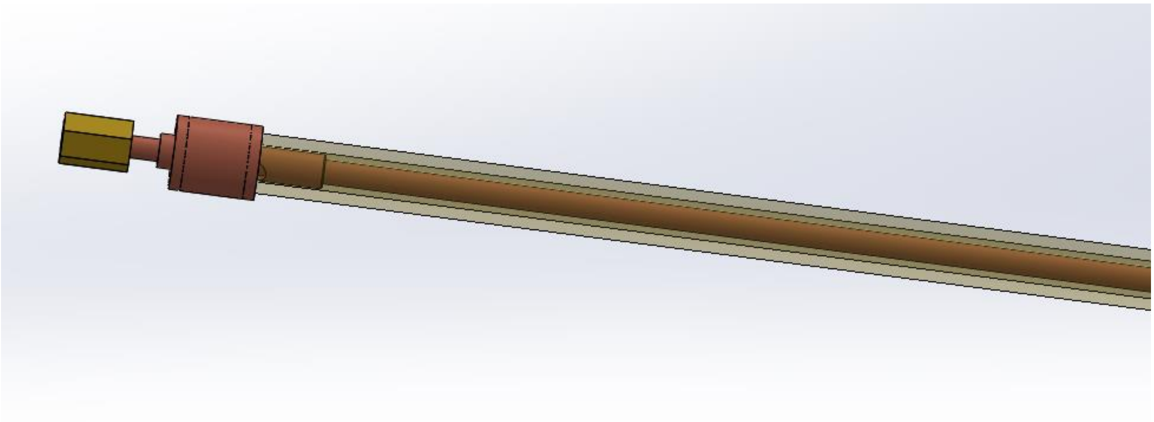

Figure 4. Power cable of TIG welding torch.

In figure 4, principle of power cable is presented. Rubber hose covering the copper cable is presented as transparent. Copper cable has connector pieces for connection to the torch neck. For simulation model, power cable was simplified to only consist copper cable. This was done to avoid excess of contacts that would have been present if accurate model were used. Once again, this should not cause big error on results, since purpose is to examine the temperatures of the handle and neck, not the hose package.

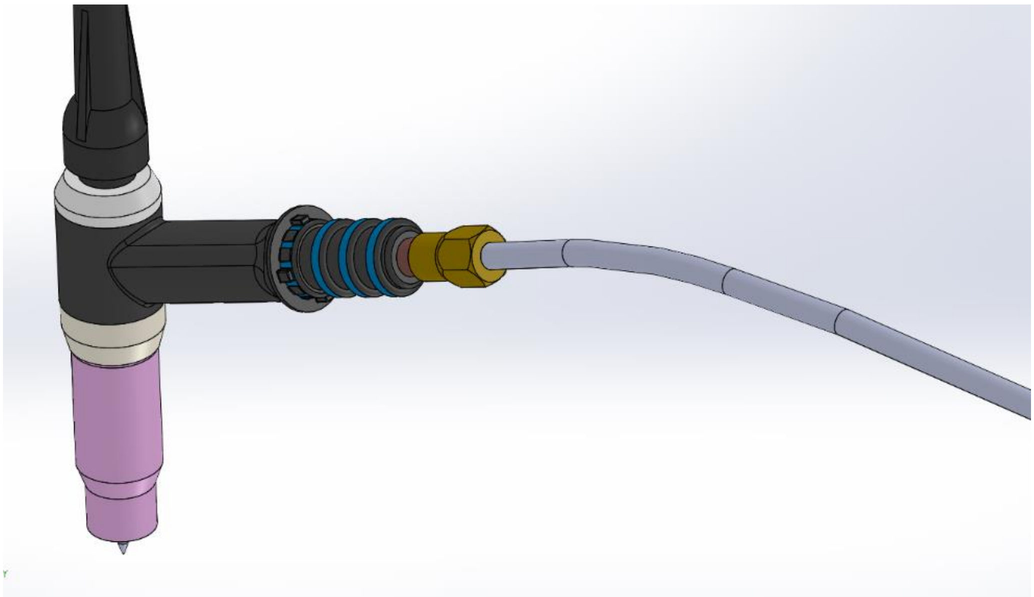

Figure 5. Power cable connected to torch body.

In figure 5, power cable is connected to the torch body. Contact area was approximately matched to the actual situation in the TIG welding torch.

Consumables in the simulation model represent standard construction in TIG welding torches. Current is transported from the power cable to the torch neck and finally made in contact with the electrode by consumables. Consumable parts are presented in figure 6. Electrode is in contact with part number 4 in figure 6, this collet part is in contact with part number 3, collet body. Collet body is in contact with neck part number 5. Electrode is tightened into its place with part number 6. Part number 2 is gas nozzle which directs the shield gas towards the arc. Electrode diameter (part number 1) used in simulation model was 2.4mm.

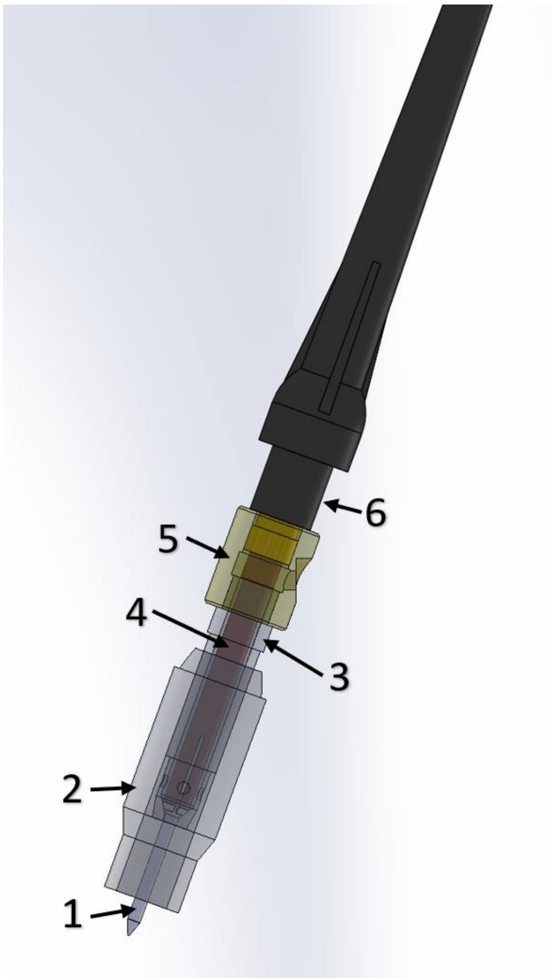

Figure 6. Consumables of typical TIG welding torch.

Accurate measurements of the contact area between collet, collet body and the electrode does not exist. Therefore, approximation of the contact area was used in the simulation model. Some simplifications were made on the consumables since original 3D models are modelled with nominal dimensions and direct contact is not present with nominal dimensions. This issue could also be dealt in the Ansys since contact distance can be defined.

Final assembly of the simulation model consisted total of 15 parts. Actual torch would consist around 40 parts, but most of the parts are irrelevant for getting the temperatures of the handle and neck. Final model for simulation can be seen in figure 7.

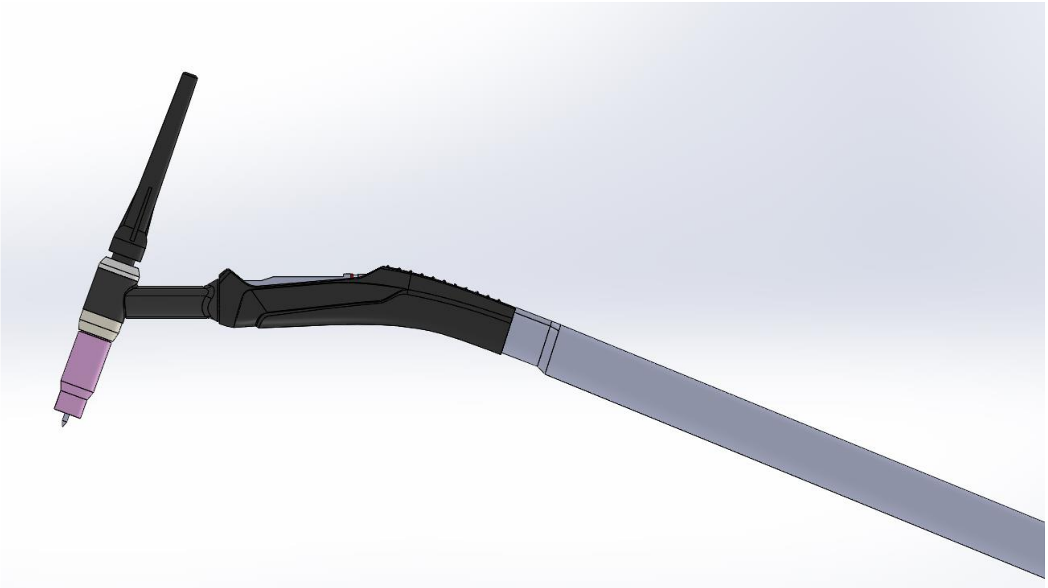

Figure 7. Final model of the TIG welding torch for simulation.

3.2 Materials and contacts in simulation model

Material data is perhaps one of the most important factors on thermal simulations. Materials have big differences on thermal conductivity and thermal conductivity depends on temperature in many cases. Ansys simulation software supports temperature dependent thermal conductivities. Such model was created for tungsten, brass and copper materials used in the TIG welding torch. For the other materials static value was used instead. Target of the simulation was to analyze temperatures of the handle and torch body only. For this purpose, only thermal conductivity and electrical resistance was needed. For simplicity, only general terms of materials were used. For example, material group copper consists a lot of different types of coppers and copper alloys, but those properties of each type are not relevant when thermal conductivity and electrical resistivity are selected correctly.

Thermal conductivity of tungsten varies a lot depending on temperature. During welding, tip of the tungsten can heat up to around 3000 °C. In these temperatures, thermal conductivity is only around half of the thermal conductivity in 0 °C. Figure 8 presents dependency of thermal conductivity of tungsten.

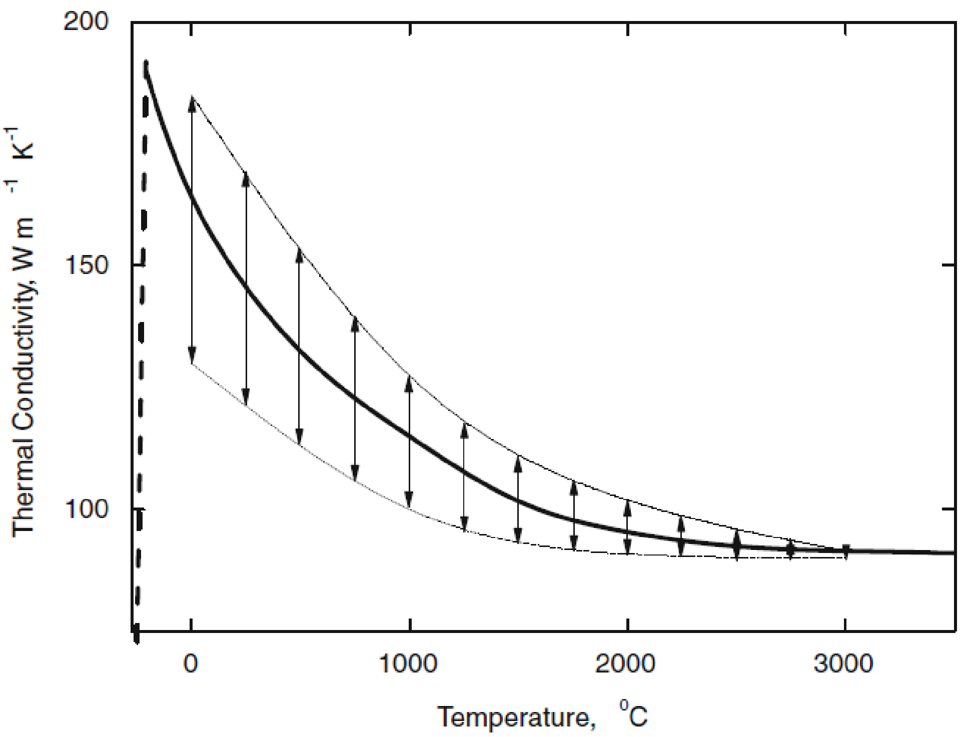

Figure 8. Thermal conductivity of tungsten in different temperatures (Shabalin. I. 2014, p.240).

Figure 8 also presents variation of the values in literature. Line in center is the average of these values and that was used in the Ansys simulation. Using temperature dependent thermal conductivities did not significantly increase simulation time.

Thermal conductivity of brass also depends on temperature. But opposite to the tungsten, thermal conductivity of brass raises when temperature rises. In figure 9, thermal conductivity of brass is shown. Thermal conductivity for copper and brass was plotted according to data provided by Touloukian et al. (1970). For copper thermal depended data was also used. Thermal conductivity of copper is plotted on figure 10.

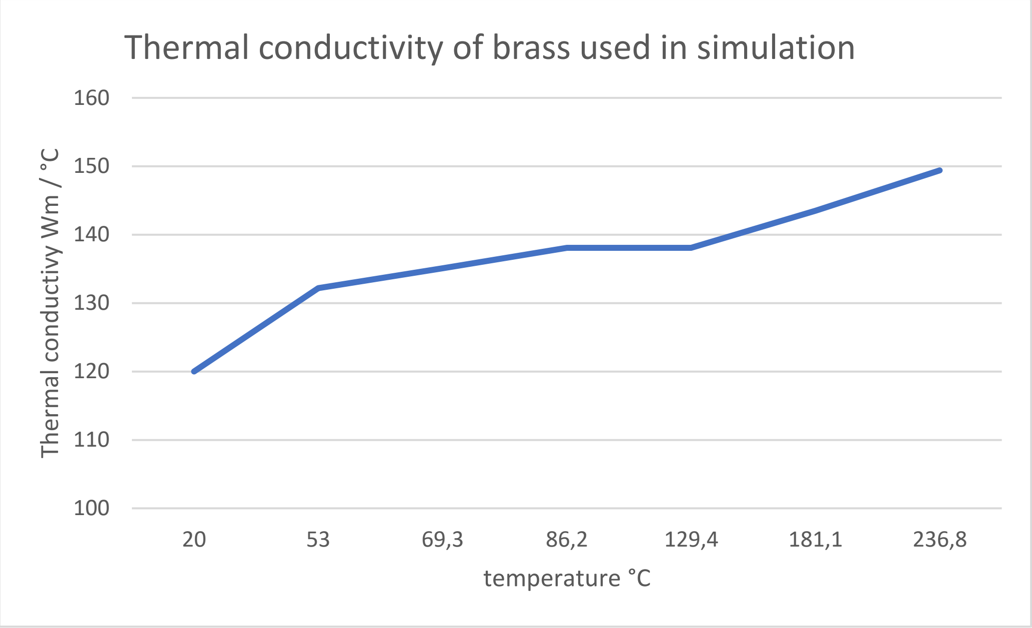

Figure 9. Thermal conductivity of brass used in simulation (modified from Touloukian et al. (1970).

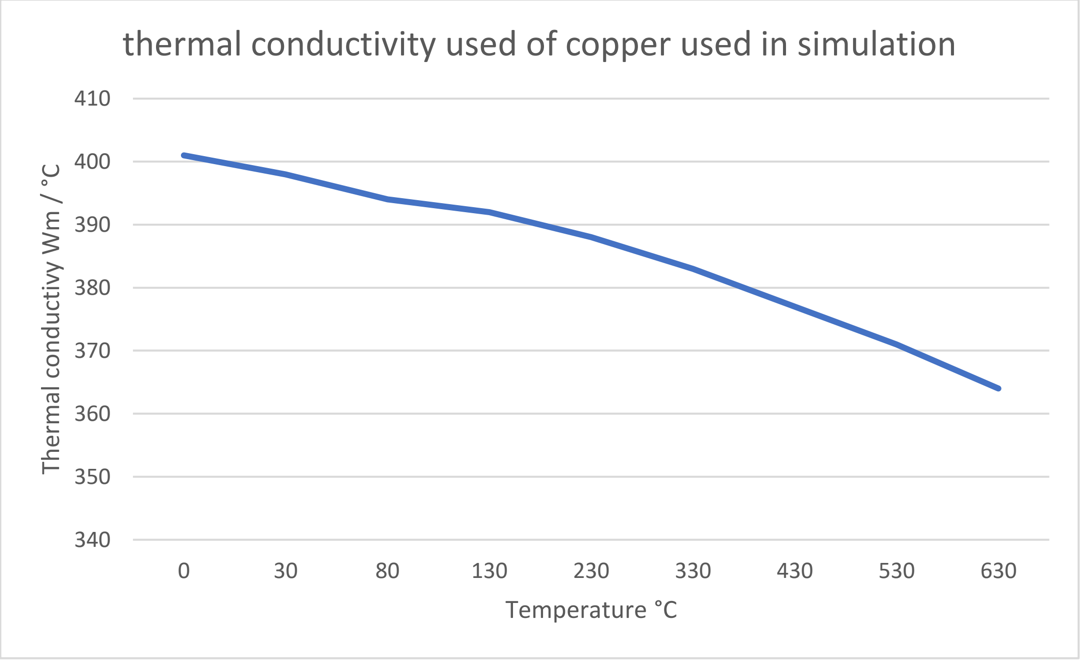

Figure 10. Thermal conductivity of copper used in simulation (modified from Touloukian et al. (1970).

On table 2, all the materials present in the simulation model are listed. Thermal depend material models were used on tungsten, brass and copper. Rest of the materials used static values. For parts that conduct current, electrical resistivity was set according to table 2. Parts that have no role on conducting current, value of the electrical resistivity was neglected.

Table 1. Material properties used in simulation.

Material	**Thermal conductivity (Wm/°C)**	**Electrical resistivity ohm*m**
Tungsten	Temperature depend	$5.6*10^{-8}$
Brass	Temperature depend	$7.8*10^{-8}$
Copper	Temperature depend	$1.7*10^{-8}$
AlO3	24	-
PA66	0.443	-
Phenolic plastic	0.308	-
Silicone	0.245	-
PTFE plastic	0.251	-

Contacts are necessary if thermal conductance is wanted to appear between different parts. Simulation model contains 15 parts, so contacts were created between them. Most of the contacts can be made automatically in the Ansys program, but all of them must checked and modified if needed. Automatic contact detection can extend the desired contact on to the surfaces nearby and these had to be removed. This was the case in about half of the contact pairs created automatically. For thermal analyses, only fixed contacts were used. This did not allow any movement or penetration between the contacts. Also, expansions due to changing temperatures was neglected, it should not have impact on the surface temperatures of the model.

3.3 Static-thermal method

In Ansys Mechanical it is possible to use static-thermal module for analyzing temperatures. In static-thermal, heat flow is possible to input in few different ways. These include internal heat generation and heat flow for example. Static-thermal does not allow direct input of the current and voltage. Might be that it could be done using commands, but this option was not further investigated. Static-thermal method was tried at beginning of the work, but results were not promising. Static-thermal method required measuring of the voltage loss over length of the TIG welding torch. Voltage loss for the power cable and for the torch body were measured separately. At 50 A it was measured that voltage loss was 0.32 V. For 75 A voltage loss was

0.050 V and for 100 A 0.675 V. Voltage losses for torch bodies were 0.15 V at 50 A, 0.023 V at 75 A and 0.032 V at 100 A. Voltage loss was measured with Fluke 287 true rms multimeter which is regularly calibrated. Voltage loss can be converted to internal heat generation when volume of the current transporting parts is known. This internal heat generation was inputted into the Ansys. Results however were not reliable, and this meant that another method would have to be find. Static-thermal method would have allowed configuration of the thermal fluid flow using graphical interface, but as results were not promising it was not wise to continue with this module.

3.4 Thermal-electric module

Static-electric method allows user to input voltage and current using graphical interface. This was simple and convenient when everyday use was considered. Effect of the joule heating will be calculated by Ansys software. In simulation model, same currents were used than in laboratory measurement. Thermal-electric module did not allow setting up the thermal fluid flow with using graphical interface. Thermal fluid setting was done using commands.

Some troubles were found at first when thermal-electric module was used. Solver stopped due to error. It was found out that software has some difficulties to solve analyses were parts have large differences in the electrical resistivity. In torch body for example outer layer is silicone rubber which has low electrical resistivity compared to copper and brass parts. Silicone is considered to be insulation layer and one of its tasks is to protect welder from touching the current conducting parts. Problem was solved by adjusting contact parameters between insulating and current conducting parts. Electrical conductance value was set to $1*10^{-8}$ S/mm^2 for all contacts like these. After this adjustment solver did not give error messages and analysis could be solved.

3.5 Convection, mesh and thermal fluid

When electrical loads were set in the thermal-electric module, it was time to introduce cooling for the simulation model. Without cooling in the model, it cannot reach stable state. Gas cooled TIG welding torch is cooled because of the convection. Convection was added on the outer surface of the 3D model. Convection In the laboratory measurements can be considered natural, since torch was held in normal room and no drafts were present.

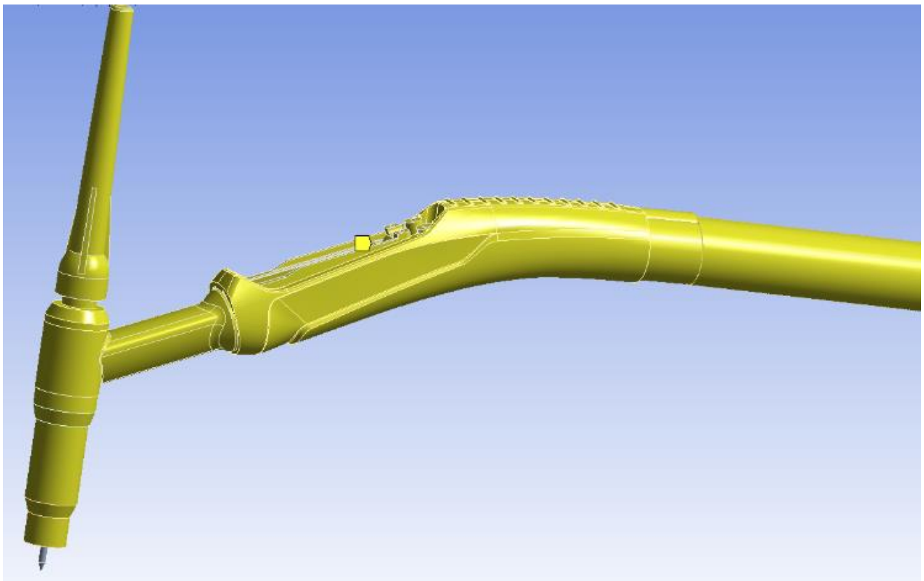

Figure 11. Convection was applied on the outer surfaces of the TIG welding torch.

On figure 11, surfaces where convection was applied can be seen. Value of the convection was found out experimentally by comparing temperatures of the simulation model for temperatures measured in the laboratory. Value of the convection coefficient used in all simulation analyses was $8x10^{-6}$ W/mm^2. This well in range with Yunus's (2007) table where typical values of the convection coefficient were listed. Free convection of the gasses was listed as 2-25 W/m^2.
Mesh for simulation model was made in the Ansys mechanical. 3D model was previously modified because meshing was impossible with the original geometry. Mesh consisted primarily of tetrahedron shapes elements. Maximum size for elements was set to be 5 mm and total number of elements was 71823 with 181679 nodes. Ansys has many tools for evaluating mesh quality. Tool used in this research provided visual presentation of the mesh overall quality. This tool compares ratio between element volume and edge length. This reveals if model has large amounts of wedge shaped long and thin elements. These can generate difficulties for solver and lead to inaccurate results. On figure 12, mesh quality of the simulation model can be seen. For the thermal fluid flow beam element FLUID 116 elements were used.

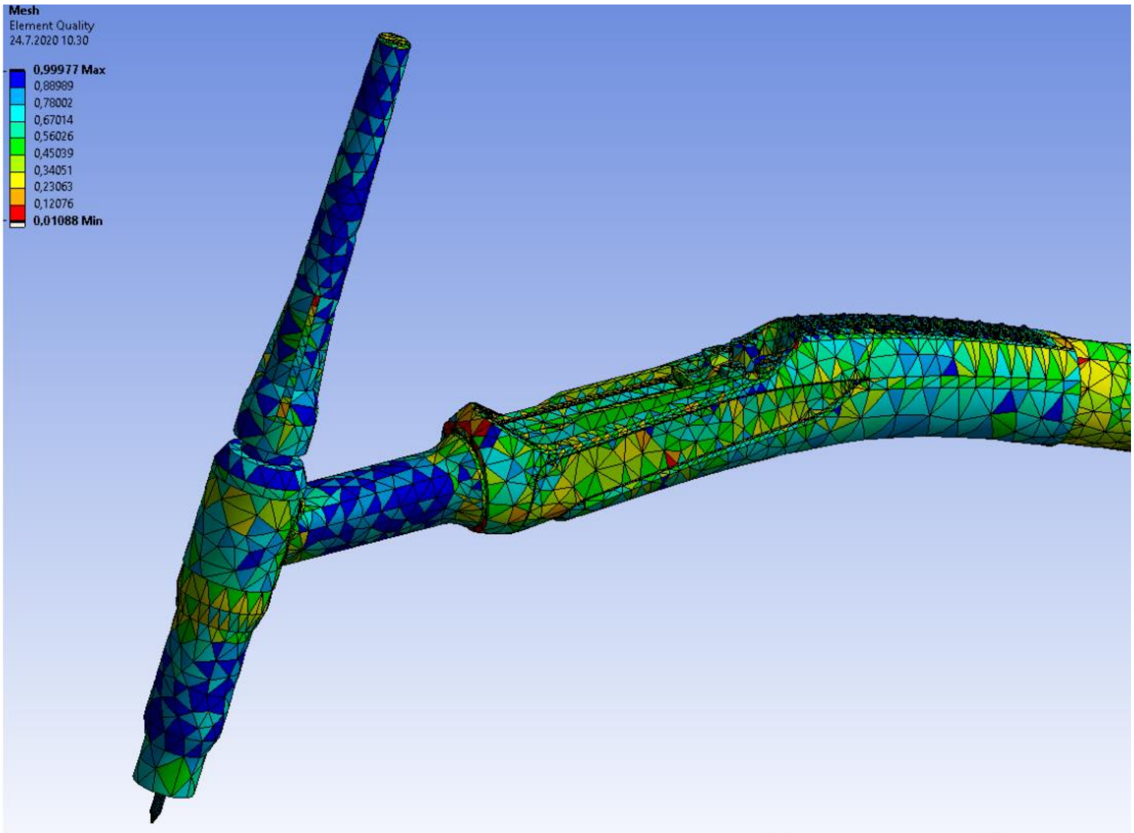

Figure 12. Screen capture from Ansys mesh quality analysis.

Shielding gas is known to have some cooling effect on the TIG welding torch, so it was included in simulation model. Simulation could have been done using CFD tools, but with thermal fluid flow it is possible to simulate thermal effects of fluid flow also using Ansys Mechanical. Thermal fluid flow is introduced into beam elements. To define beam elements, line representing the route of the gas flow was drawn in Ansys Spaceclaim and diameter was defined for that line. Thermal-electric module did not have option to use graphical interface for the thermal fluid definitions. Instead definitions were introduced as commands. For beam element density and specific heat capacity were defined. Gas flowing is argon, so density was set to 1.634×10^{-9} kg/mm^3. Also, diameter of beam was set in commands. Full details of beam commands can be seen in Appendix 1.

For solver some commands had to be defined. Adjacent surfaces for gas flow were defined in Ansys mechanical and in solver these commands were pointed out. Details of the solver commands can be seen in Appendix 2.

4 EXPERIMENTS AND VERIFICATION OF SIMULATION MODEL

To verify the simulation model, some laboratory measurements were done. Measurements were done without arc and shielding gas, without arc and finally with arc during welding. In the first measurement, when arc and shielding gas was not present, only current was passing through the welding torch. This way it was possible to measure effect from joule heating separately. In the second measurement, shielding gas was flowing through the torch. When comparing to the first measurement it was possible to evaluate cooling effect of the shielding gas. The third measurement was done during welding. Welding was done according to the heat test section of IEC 60974-7 (2019) standard. By verifying simulation model in three steps, only few variables could be adjusted at once during building of the simulation model.
In laboratory measurements, commercially available TIG welding torch was used. Same torch 3D model was also the base of the simulation model. Torch had standard consumables and the electrode diameter used was 2.4 mm. Rated current for torch was 220 A at duty cycle of 40 %. Electrode material was WCe20 according to the ISO 6848 (2015). All tests were performed with the same power source, Kemppi Mastertig MLS 2300 ACDC.

4.1 Temperature measurements

Temperatures were measured from the surface of the TIG welding torch from five different spots. Temperatures were measured with Yokogawa mv2000 monitoring devices where thermocouples were attached. Thermocouples were installed using heat conducting paste and tied in place with very thin steel wire. Two thermocouples were installed on the torch body and three thermocouples on the handle surface. Setup for thermocouples can be seen in figure 13.

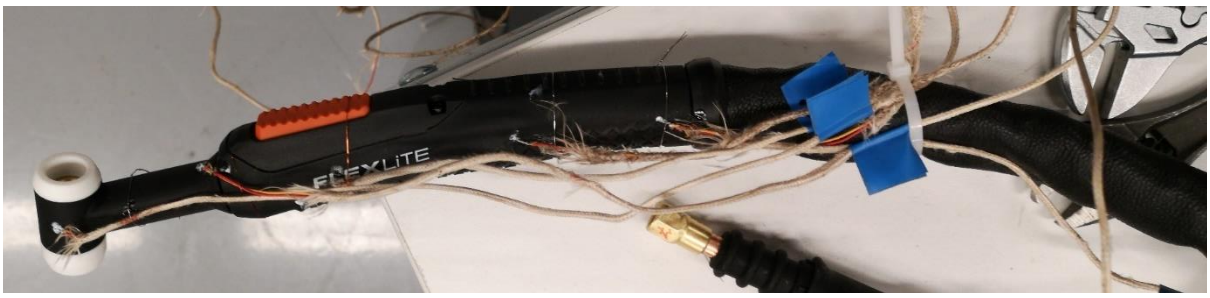

Figure 13. Thermocouples installed to the TIG welding torch.

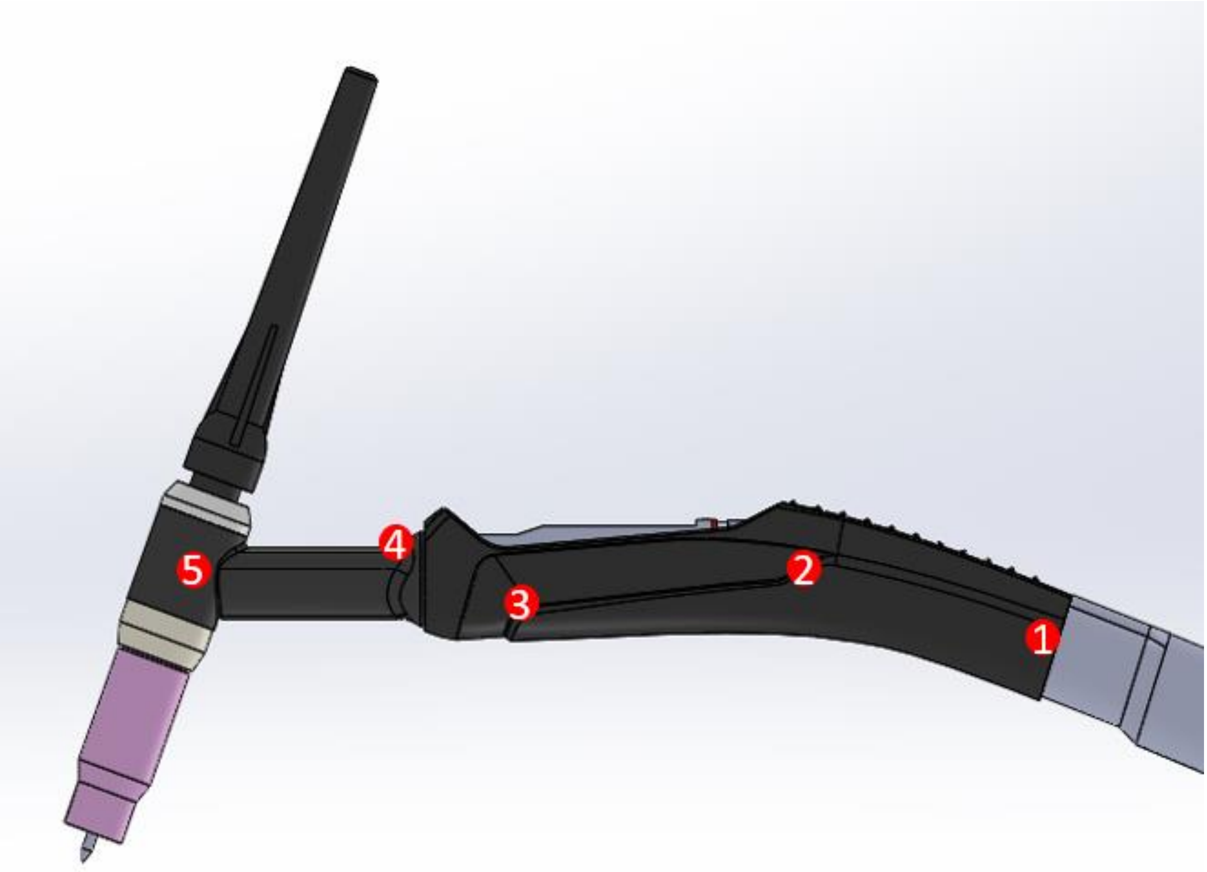

Figure 14. Temperature measurement locations.

Temperatures were measured only from the surface. In the IEC 60974-7 (2019) temperatures are only measured from surface of the handle. Measurements were made from torch body to ensure that the simulation model would give reasonable results also from this area. Inside of the TIG welding torch space is very limited. Therefore, with measuring system used, it was impossible to measure temperatures inside the handle or from the consumable parts. From figure 14 areas of measurements can be seen. Measurement points 1, 2 and 3 are placed into the silicone handle and points 4 and 5 into the torch body. With this selection of placement, whole construction is covered with 5 measurement point. Five thermocouples already take some space and if more is placed onto the torch, measurement wires can already effect on the results.

4.2 Temperature measurements without arc and shielding gas

In the first set of temperature measurements, no arc or shielding gas was present. Current was passing through the torch and into to the resistor unit. This enabled measuring only the effect of the joule heating. During the test, one connector was connected into the wolfram electrode and other one to the torch power connector. Currents used were 50 A, 75 A and 100 A. On figure 15, measured temperatures can be seen.

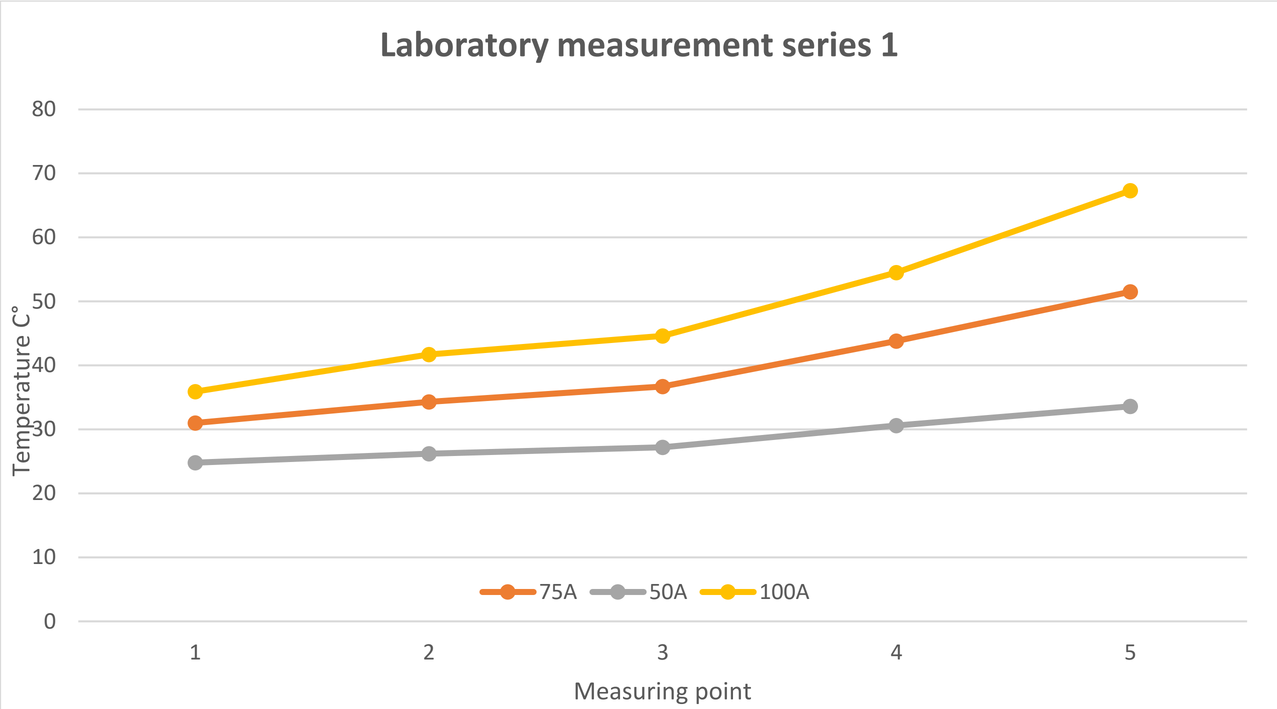

Figure 15. Measurements series 1.

Temperature is highest in the torch neck area. This is expected since electrode material wolfram has lower thermal conductivity than brass and copper and therefore it generates higher temperatures. Temperature of the surroundings was 21 °C during measurements.
Hottest point of the handle was measuring point 3 which was closest to the torch neck. At 100 A handle reached maximum temperature of 45 °C. Temperatures were lower in the back end of the handle. Temperatures in Figure 15 represent moment when temperature rise has settled. This turned out to take around 1.5 hours. Temperatures raised quite linearly in each measurement point when amperage was raised.

4.3 Temperature measurements with shielding gas and without arc

In the second measurement series, setup was like in the first measurements, but now shielding gas was flowing through the torch. Shielding gas is known to have cooling effect on the TIG welding torches. Measuring it together with the joule heating effect it gives simulation model more validation points. Shielding gas flow was set according to the IEC 60974-7(2019) heating test requirements and it was 7 l/min with all three current levels. In IEC 60974-7 this gas flow is used up to 150 A.

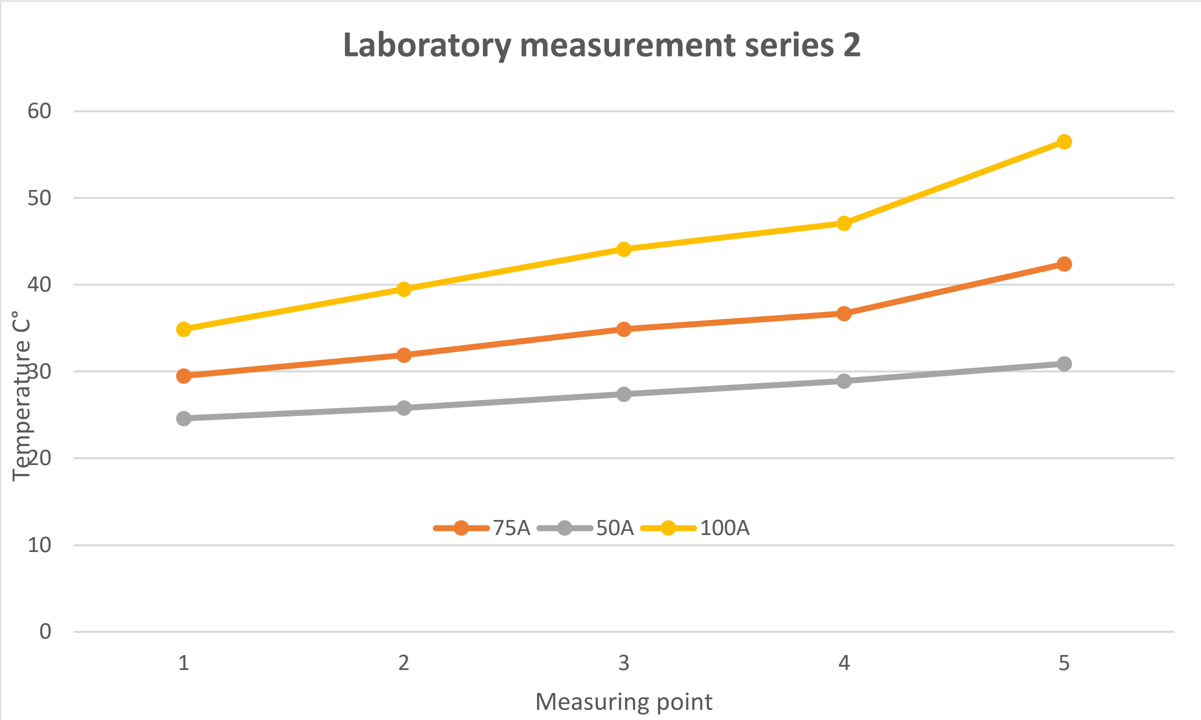

Figure 16. Measurement series 2.

Cooling effect of shielding gas can be seen when figure 16 is compared to figure 15. Temperature distribution is still same, hottest points being close to wolfram electrode and torch body and coolest points in the handle back end. At 100 A hottest point was 58 °C when shielding was flowing at rate of 7 l/min trough the torch. At figure 15, same reading was 69 °C.

Shielding gas was taken from centralized network and it was pure argon. Temperature of the shielding gas entering the torch was 10 °C. Room temperature was same 21 °C as it was in the measurement series 1.

4.4 Temperatures during welding

Welding was performed with calibrated Kemppi Mastertig MLS 2300 ACDC power source, the same one that was used in previous measurements. Welding in each case was continued until temperature raise had settled. This took 45 minutes of welding in each case. Duty cycle in the welding tests was 100 %, so welding did not stop during measurements. In figure 17, TIG welding torch can be seen in welding setup. Water cooled copper block is used so welding can continue for long periods of time. Torch is attached into fixture using thin steel wire. Large clamps would have some effect on the heat lost.

Figure 17. TIG welding torch during heat test.

Third and final laboratory measurement series was done during welding. Welding setup is described in the IEC 60974-7 (2019) in heat testing section. Welding is done stationary into water cooled copper block. Electrode distance from the copper block is 3 mm and gas nozzle distance 8 mm. Electrode stick out length was therefore 5 mm. Welding currents were same as in the previous tests: 50 A, 75 A and 100 A. Shielding gas flow was also same 7 l/min as in the measurement series 2. Temperatures measured during welding can be seen on figure 18.

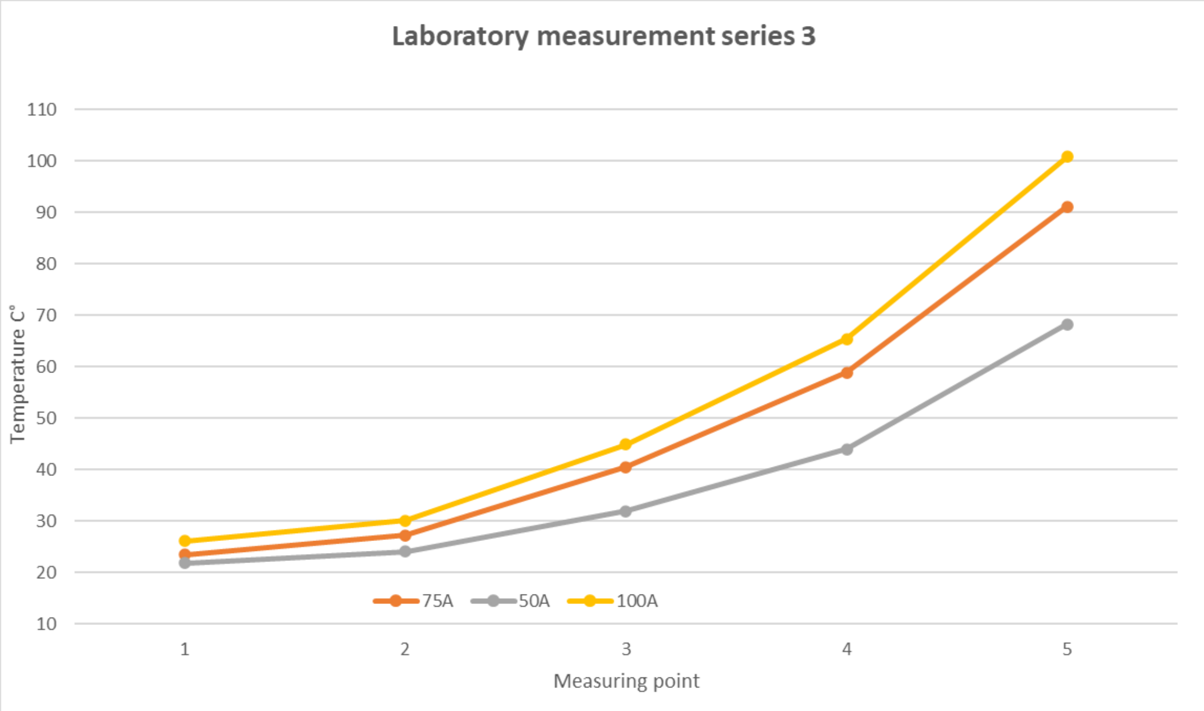

Figure 18. Measurements series 3.

Clear increase of the temperatures can be seen when figure 15 and 16 are compared. Hottest point of torch body measured 101 °C when welding was done at 100 A. It is notable that back end of the handle remained relatively cool during welding compared to other measurement points. At all current levels, measurement point 1 at the back end of the handle never exceeded 30 °C. Room temperature during measurement was same 21 °C as in the previous measurement series 1 and 2.

4.5 Comparison of simulation model without arc and shielding gas

Simulation model was compared to the laboratory measurement setup 1. In this case 1 only current was passing through welding torch. Current was introduced in Ansys software by using thermal-electric module which allowed inputting current straight to the 3D model. TIG welding torch in this case was cooling with the convection only. Convection parameter was set into the simulation software by using trial and error method. This was the only variable that could not be measured during the laboratory measurements. Measurement points were collected from simulation model using same location as heat couples were installed. On figure 19, simulation results are compared to the laboratory measurements.

At 50 A, simulation model measured within the limits of error same results on points 4 and 5 of the TIG welding torch. On measurement points 3,2 and 1, there is more variation between the simulation and laboratory measurements. On these points simulation temperatures shows higher results than laboratory measurements.

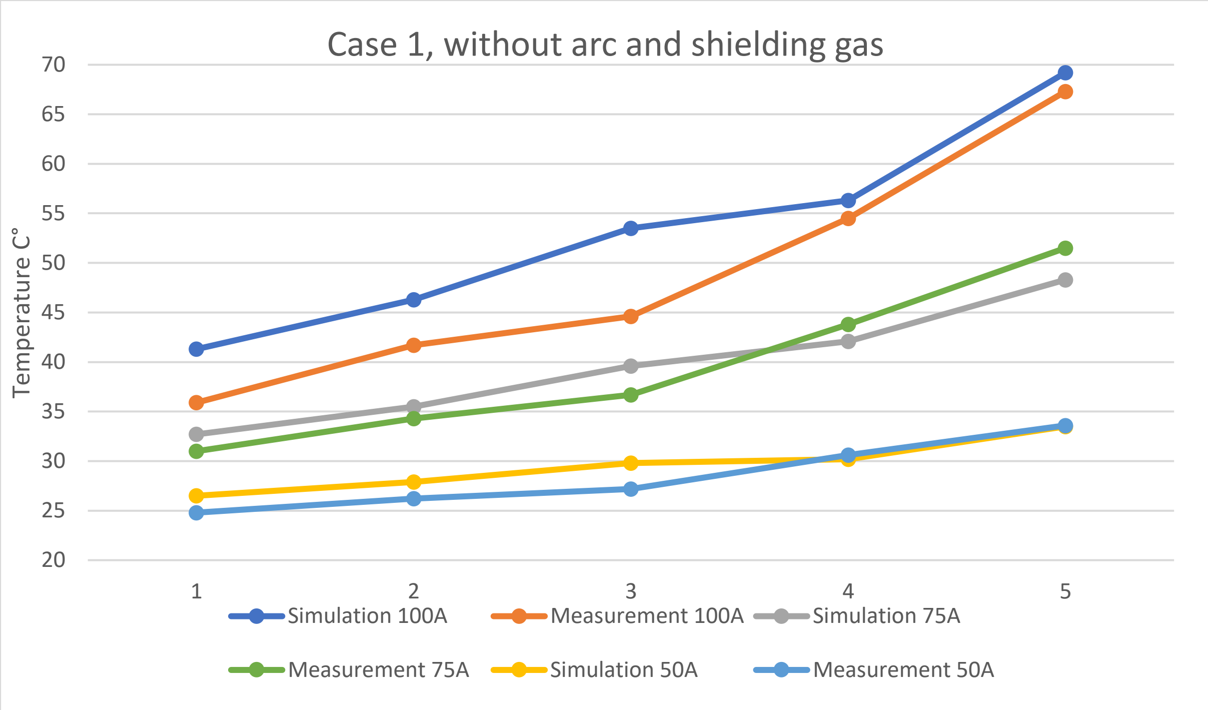

Figure 19. Comparison of the temperatures in case where no arc and shielding gas was present.

When current was set to 75 A in simulation model, temperatures vary slightly more than with 50 A. Especially measurement point 5 varied more than with 50 A. With 50 A, simulation showed slightly higher temperatures on the measurement point 4 and 5. Situation was same with 75 A and 100 A.

With 100 A the simulation showed higher temperatures in all measurement points. Temperature at the measurement point 5 was close to 70 °C. On the measurement point 3, simulation temperature was 54 °C and the temperature measured in laboratory was 45 °C. With 50 A and with 75 A simulation also showed higher temperatures, but variation was much lower. Error comparison of temperatures between simulation and measured was done and it can be seen on figure 20.

Figure 20. Error in simulation of case 1.

When 50A was used, error at measurement point 5 was -0.3 %. Error was small also on the measurement point 4 where it was -1.3 %. Error was larger in the other measurement points, largest error measured on the point 3 where it was 8.7 %. In the measurement points 1 and 2 error was 6.4 % and 6.1%. Average error with 50 A was 3.9 %.

Error calculation shows that the measurement points 1 and 2 had error of 5.2 % and 3.4 % when 75 A was used. Error is slightly smaller than when 50 A was used. Largest error at 75 A occurred on measurement point 3 again. In measurement point 3 error was 7.3 %. At torch body on measurement points 4 and 5 error was -4.0 % and -6.6 %. Average error when 75 A was used was 1.0 %.

Largest error occurred again on the measurement point 3 (16.6 %) when 100A was used. This error was the largest seen on these this comparison case. Error is more than twice compared to previous measurements with 50 A and 75 A. Measurement point 1 had error of 13.1% and measurement point 2 9.9 %. Torch body measurement points 4 and 5 had error of 3.2 % and 2.7 %. Average error with 100 A was 9.1 %, making it more than twice as big than average error with 50 A and 9 times bigger than with 75A.

4.6 Comparison of the simulation model with shielding gas and without arc

Next step in the verification of the simulation model was to introduce shielding gas flow into the simulation model. In Ansys simulation model this was done by introducing thermal fluid flow into model. Calculation is done using fluid elements, but this still is not considered as CFD calculation. Situation where gas flows through the TIG welding torch is straight forward and in simple cases, thermal fluid is more convenient than much more complex FCD calculations. Thermal fluid method can be used for example when the fluid is flowing in pipe which's cross section remains constant.

First comparison was done at 50 A. Simulation model shows slightly lower temperatures on each measurement point. Comparison of this setup can be seen on figure 21. At 50 A simulation showed lower temperatures in each measurement point. At the torch body in the measurement points 4 and 5 simulation showed temperatures of 29.3 °C and 27 °C. Laboratory measured temperatures in these points were 30.9 °C and 28.9 °C. At the back end of handle simulation showed temperature of 26.6 °C and the laboratory measurement 24.6 °C in the measurement point 1. At the measurement points 2 and 3 temperatures in the simulation were 23.8 °C and 26.3 °C while the laboratory measures were 25.8 and 27.4.

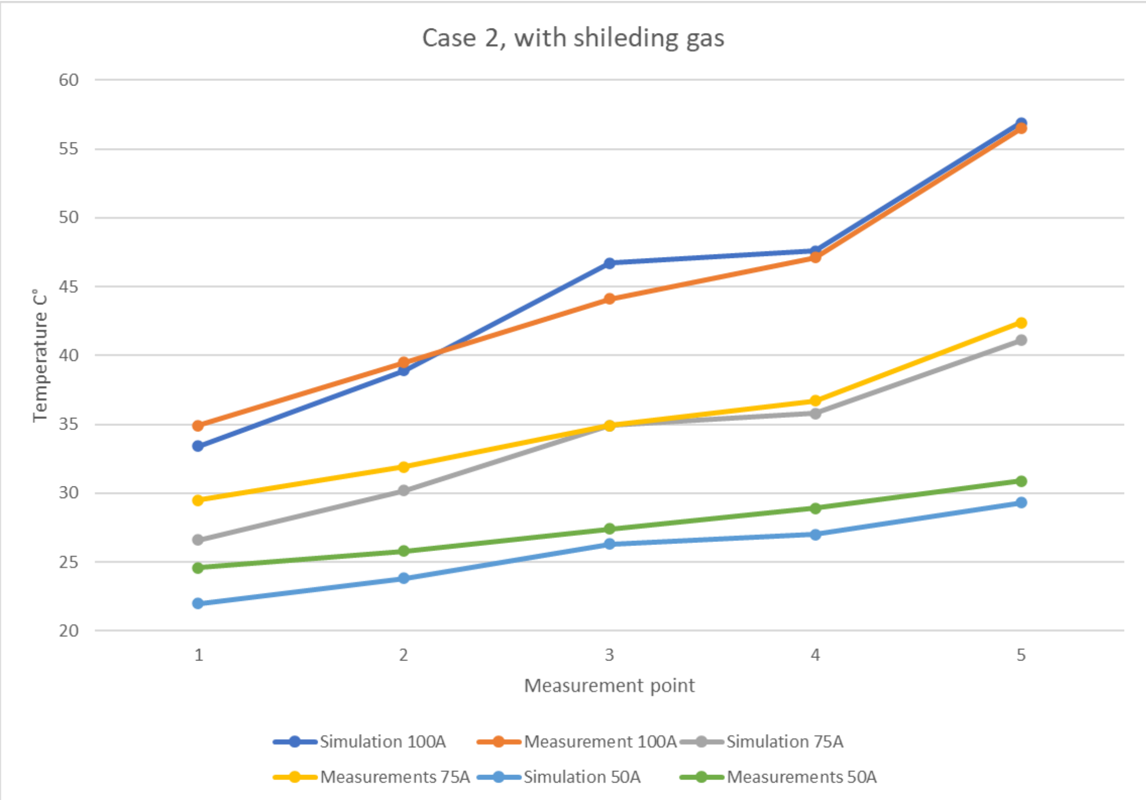

Figure 21. Comparison of the simulation model and laboratory measurements in case 2 where shielding gas was introduced to the simulation model.

In the next setup welding current was 75 A, all the other variables were kept same so results can be compared. Simulation model measured again lower temperatures than the laboratory measurements, except on measurement point 3 were exact match was found at temperature of 34.9 °C. At the torch body simulation showed temperatures 41.1 °C and 35.8 °C at measurement points 5 and 4. Temperatures in laboratory measurements were 29.5 °C and 31.9 °C at measurement points 1 and 2. Corresponding temperatures in the simulation model were 26.6 °C and 30.2 °C.

Final verification for this case 2 was done with 100 A. Again, no other parameters were changed than the current. Previously simulation results have been lower than the temperatures measured in laboratory. When 100 A was used, simulation showed higher temperatures on measurement point 3, 4 and 5. Lower temperatures occurred on measurement points 1 and 2. In previous cases simulation had shown higher temperatures in each case. Measurement point 5 and 4 measured temperatures 69.2 °C and 56.3 °C. In the laboratory measurements these measurements were 67.3 °C and 54.5 °C. With 75 A measurement point 3 had exact match but now simulation showed 53.5 °C and laboratory measurement 44.6 °C. measurement points 1 and 2 showed 41.3 °C and 46.3 °C in simulation and 35.9 °C and 41.7 °C in laboratory measurements.

Error calculations show that now largest error occurred on measurement point 1 where error was 10.6 % when 50 A was used. In the case 1 largest error occurred on measuring point 3, but now it measured lowest error (4.0 %). Close to wolfram electrode, errors were smallest in case 1. Now measurement points 4 and 5 measured errors of 6.6 % and 5.2 %. Errors seem to distribute more evenly than in previous setup. Error in the measurements point 2 and 3 were 7.8 % and 4.0 %. Average error with 50 A was 6.8 %. this is higher than in case 1. Error calculations can be seen in figure 22.

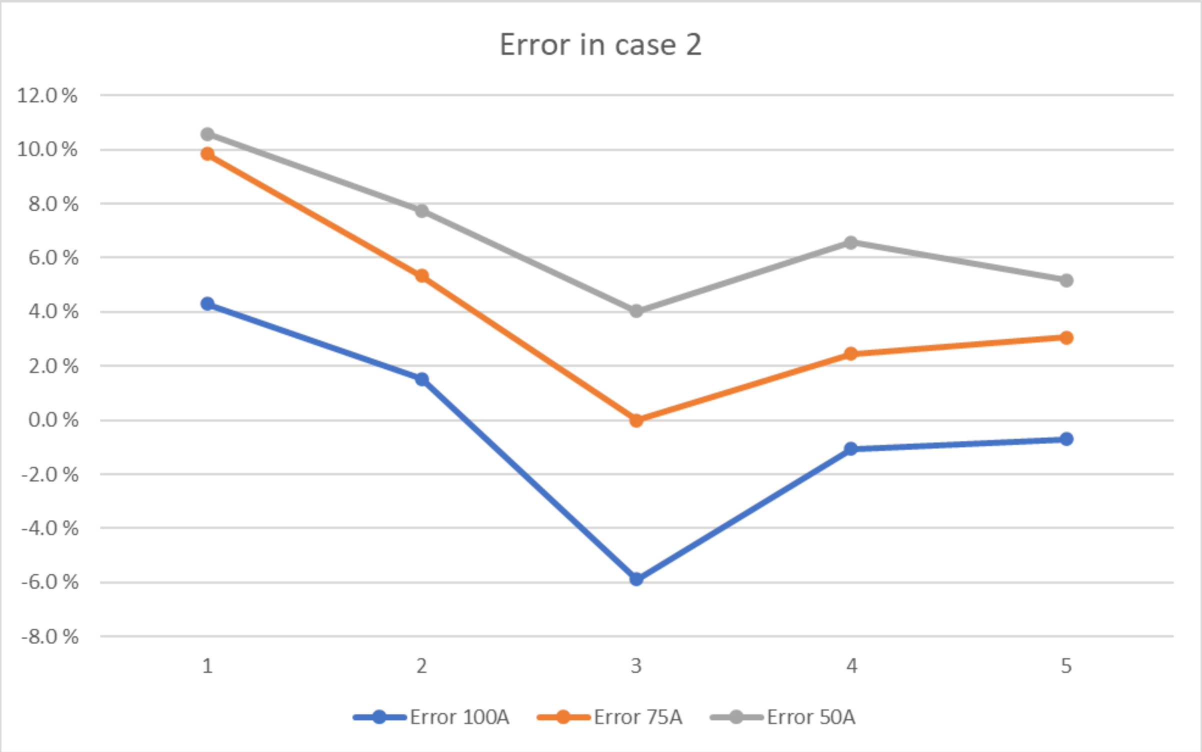

Figure 22. Error calculations in case 2 where shielding gas was present.

Measurement points 4 and 5 now measured error of 2.5 % and 3.1 % when 75 A was used. Error was smaller than with 50 A. On the measurement point 3, temperature was exactly same between simulation model and temperature measurement. Measurement points 1 and 2 in rear of the handle measured error of 9.8 % and 5.3 %. Results have same error distribution than in 50 A. Average error with 75 A was 4.1 %. This is again higher than in case 1.

When 100 A was used, good match can be found on measurement point 4 and 5. Error in these points was -1.1 % and -0.7 % In measurement point 3, error was largest (-5.9 %). On measurement points 1 and 2 error was 4.3% and 1.5%. Average error measured only -0.4 % and it was smallest in case 2.

4.7 Comparison of simulation model with arc

Final step of simulation model verification was to introduce heat flow from arc to the simulation model. This heat load simulated heat flow from welding arc to the torch. Shielding gas flow and current was kept as they were in the simulation model. Arc model was very simplified and did consider all the physical phenomena present during actual welding.

First comparison is again done with 50 A. Good match was found at measurement point 1, but everywhere else simulation model shows much higher temperatures. Temperatures in the simulation at measurement points 1 and 2 was 33 °C and 39.9 °C. Point 3 measured in simulation 51.7 °C and in laboratory 31.9 °C. Close to arc in points 4 an 5 temperatures measured in the laboratory were 44.0 °C and 68.2 °C. Simulation showed temperatures 53.8 °C and 67.9 °C in these points. Temperatures are plotted in figure 23.

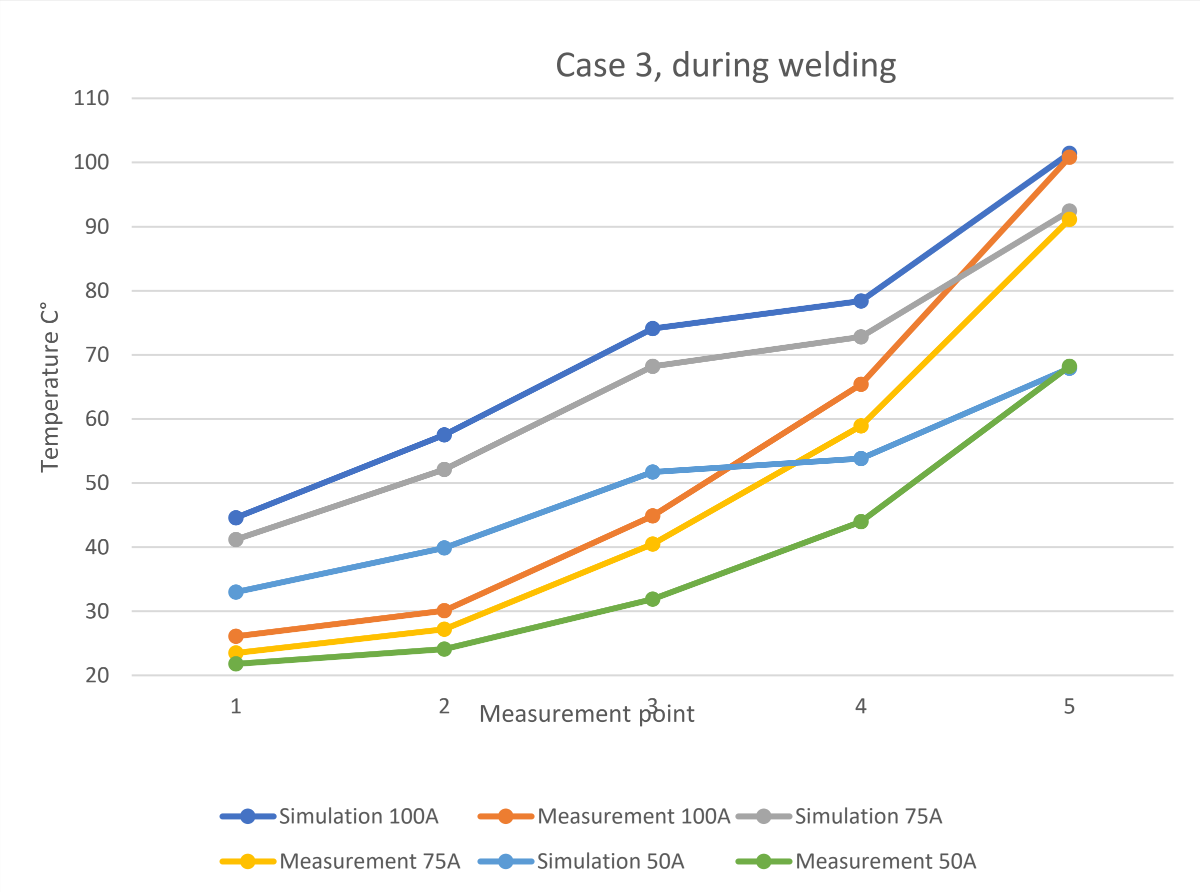

Figure 23. Comparison of simulation model and laboratory measurements.

Verification was continued on comparing simulation and measurement data at 75 A. At torch body in measurement points 4 and 5 simulation showed temperatures of 72.8 °C and 92.4 °C. Laboratory measured temperatures in these points were 58.9 °C and 91.1 °C. Already from figure 23 can be seen that temperatures match only at the measurement point 5. Measurement point 3 at front of the handle showed temperature of 68.2 °C in simulation and 40.5 °C in laboratory measurement. Points 1 and 2 measured 23.5 °C and 27.2 °C in the laboratory. Same measurements from simulation model were 41.2 °C and 52.1 °C.

With 100 A measurement point 5 measured 101.4 °C in the simulation and 100.8 °C in the laboratory. This was again best match in temperatures. Measurement points 3 and 4 measured 44.9 °C and 65.4 °C in laboratory and 74.1 °C and 78.4 °C in simulation model. Point 1 and 2 in the simulation model showed temperatures of 44.6 °C and 57.5 °C. Same temperatures in laboratory were 26.1 °C and 30.1 °C.

Figure 24. Error calculation of temperature measurements during welding.

Error calculations are presented on figure 24. Error was smallest on measurement point 5. In each case. With 50 A error was 0.4 %, with 75 A it was -1.4 % and with 100 A -0.6 %. With 50 A biggest error occurred on measurement point 2 where it was -65.6 %. Error in measurement point 1 was -51.4 %. In points 3 and 4 it was -62.1% and -22.3 %. Average error with 50 A was -40.2 %.

Largest error occurred on measurement point 2 and it was -91,5 % when 75 A was used. Error at back end of handle in measurement point 1 was -75.3 % and error in measurement point 3 was -68.4 %. At another measurement point at the torch body, point 4, error was -23.6 %. Average error was -52.1 %.

Biggest error with 100 A was calculated at measurement point 2 again. It was -91.0 %. Measurement points 1 and 3 had error of -70.9 % and -65.0 %. Measurement point 4 had error of -19.9 %. Average error at 100 A was -49.5 %. Error distribution between 75 A and 100 A was similar, but with 50 A error was much smaller in measurement points 1 and 2.

5 DISCUSSION

Simulation of the TIG welding torch offered interesting topic of research. Physical phenomena occurring during welding are rather complicated and simulating all of these on one simulation model proved to be very challenging. Especially the arc region during welding was one of the most challenging topics during research and eventually research did lack proper model of arc. Proper modelling of the welding arc would have required usage of CFD tools (Murphy & Lowke 2018). Many approaches for arc simulation was considered, but final simulation was done using simple heat load applied to the tip of wolfram electrode. This method did not yield satisfactory results, but otherwise in the first and second case results were on satisfying level.

5.1 Discussion on temperature comparison

Simulation model provided quite accurate match in the first two cases, without arc and shielding gas and with shielding gas. Arc model used on the simulation did not work very well when overall results are considered. During welding only the measurement point 5 was considered accurate. Arc model was kept simple as the purpose of this research was to find whether Ansys could be used as everyday tool during product development.

5.1.1 Simulation model without arc and shielding gas

Simplest case included only current passing through the TIG welding torch. Cooling occurred only by convection from outer surface of the TIG welding torch. In Ansys software effect of joule heating can be simulated using thermal-electric module for example. This allows to input used current simply by using graphic interface. This is quite convenient when everyday use is considered.

In overall, simulation results matched quite well against temperature measurements made in laboratory. Simulation model showed maximum error of 8.6 % when 50 A and 75 A current was used. When switched to 100A, maximum error was 16.6%. Average error of all the cases combined was 4.7 %. Error in the 100 A current is quite high, on average 9.1 %. This might cause problems if simulation results are used when decision about product structure is made during product development. Reason for much higher error at 100 A was not found. Only parameter that was changed was current. Laboratory measurement behaved quite linearly when current was raised from 50 A to 75 A and again to 100 A. Simulation model should behave similarly.

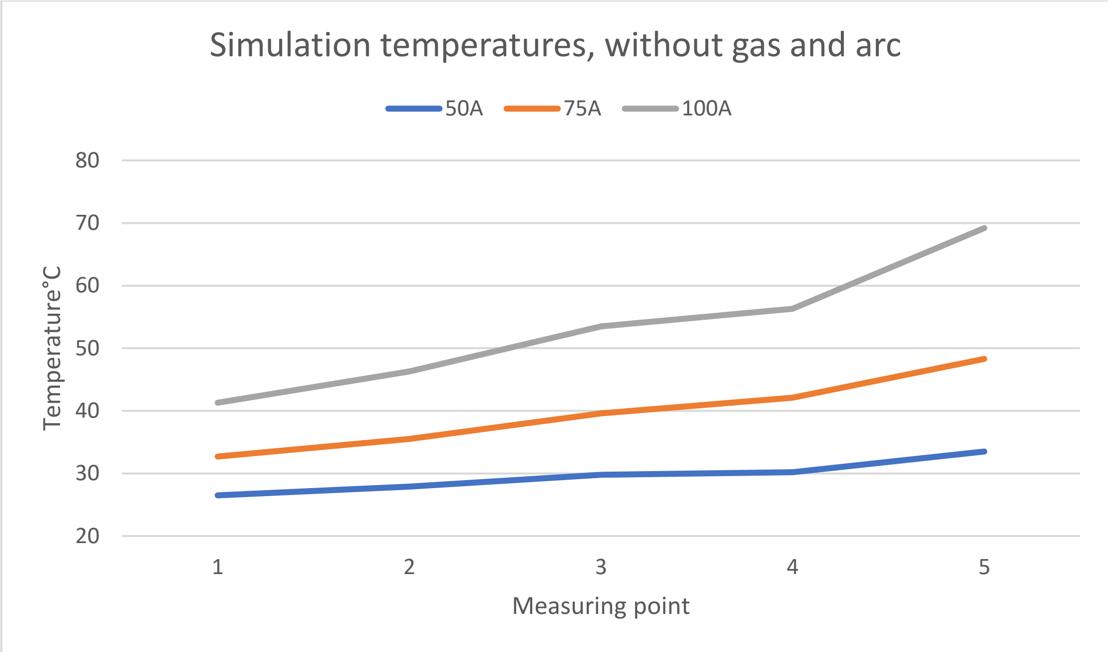

Figure 25. Simulation temperatures when only current was passing through the torch.

On figure 25, temperatures with all three current levels can be seen. Small nonlinear behavior can be seen when 75 A and 100 A measurements are compared.

5.1.2 Simulation model with shielding gas flow

Gas flow is known to have some cooling effect on TIG welding torches. Laboratory results provided way to measure this cooling effect. Shielding gas used was pure argon and flow was 7 l/min according to the IEC 60974-7 (2019) heat test requirements. At 50 A with shielding gas, TIG welding torch measured on average 1 °C lower temperatures than without shielding gas flow. At 75 A it was measured that temperatures were on average 4.4 °C lower and in 100 A same average of 4.4 °C was measured. On figure 26 cooling effect of shielding gas flow can be seen on each measurement point. Largest cooling effect occurred on the measurement points 4 and 5.

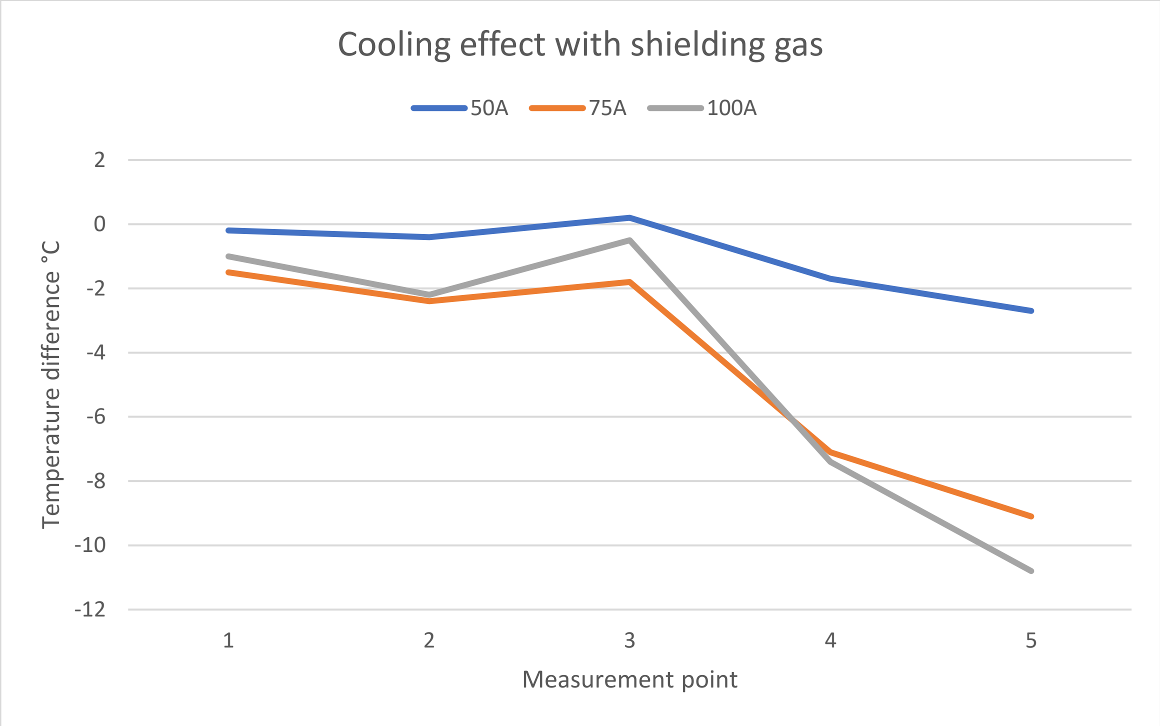

Figure 26. Cooling effect when shielding gas was flowing through the torch.

In simulation model shielding gas flow was introduced as a thermal fluid flow. Analysis uses fluid elements, but analysis can still be made on using Ansys mechanical. Thermal fluid flow had to be set using commands because thermal-electric module do not support usage of graphical interface on this case. Fluid convection parameter was set based on laboratory measurements. Full script used is presented in appendix 1. Fluid flow was set on beam element modelled in Ansys Spaceclaim. This beam was set to have a diameter of 4mm which was average diameter of the gas flow channel. Temperatures at 50 A are quite low, this might be the reason why shielding was does not seem to have such impact on temperatures.

When shielding gas was used at 50 A, average error was 6.8 % when simulation results are compared to laboratory measurements. At 75 A, average error of all the measurement points was 4.1 % and in 100 A it was 0.4 %. Total average error in this case was 3.5 %. Total average error can be considered quite good, even though must be remembered that individual measurement points still might have larger error.

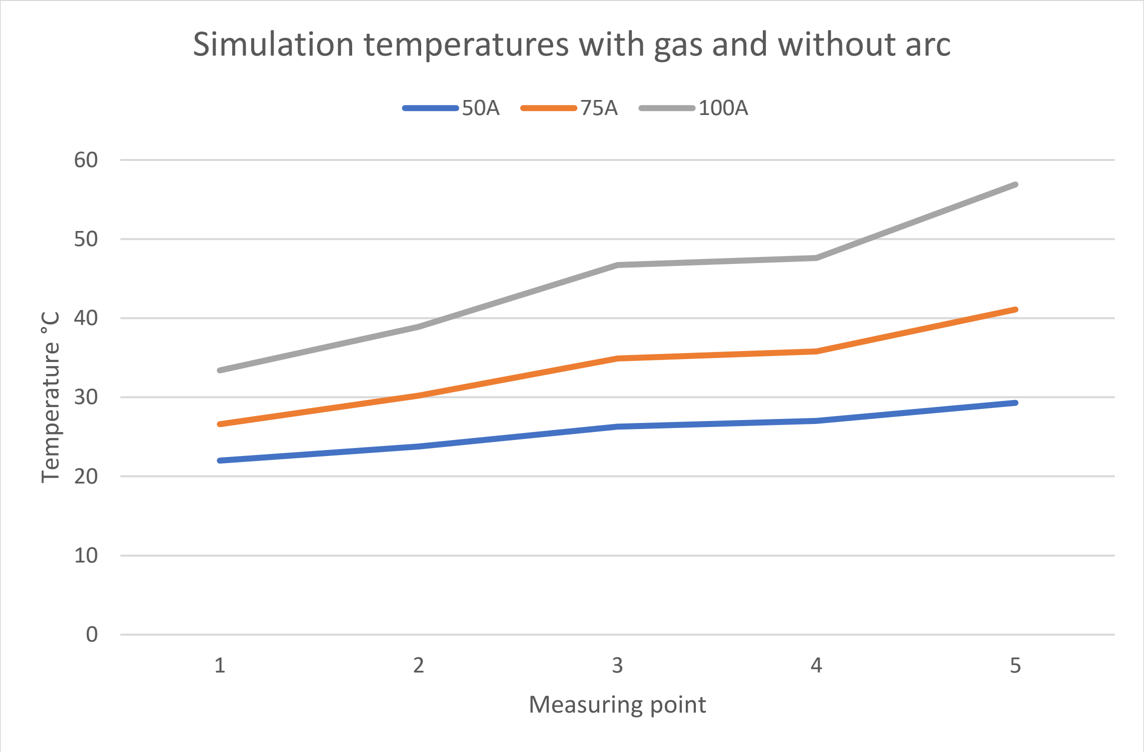

Figure 27. Temperatures from simulation when shielding gas was flowing and arc was not present.

On figure 27 simulation temperatures are presented. These follow same distribution as in figure 16 where laboratory measurements were presented.

5.1.3 Simulation model of temperatures during welding

Final step of simulation model verification was to introduce the arc model. Many approaches were considered, but eventually arc was simulated as a simple heat flow placed into tip of the electrode. This turned out to be very inaccurate. Simulation matched quite well on measurement point 5, but elsewhere simulated temperatures generally were much higher. One reason for this might be that simulation model did not consider the effect of radiation. During laboratory measurements, handle and its back end stayed relatively cool. Torch body measured much higher temperatures. Could be that the effect of thermal radiation is heating up front of the TIG welding torch body and effect gets weaker when distance form radiating source is higher. This could be measured in laboratory by blocking the thermal radiation close from the source. This would enable making estimation of how much of the heating is caused by radiation and how much by conduction. However according to Hälsig & Mäyr (2013) heat loss because thermal radiation in welding arc can be significant but is depended on welding current. Due to geometry of TIG welding torch, radiation reaches torch body easier than handle and especially back end of the handle.

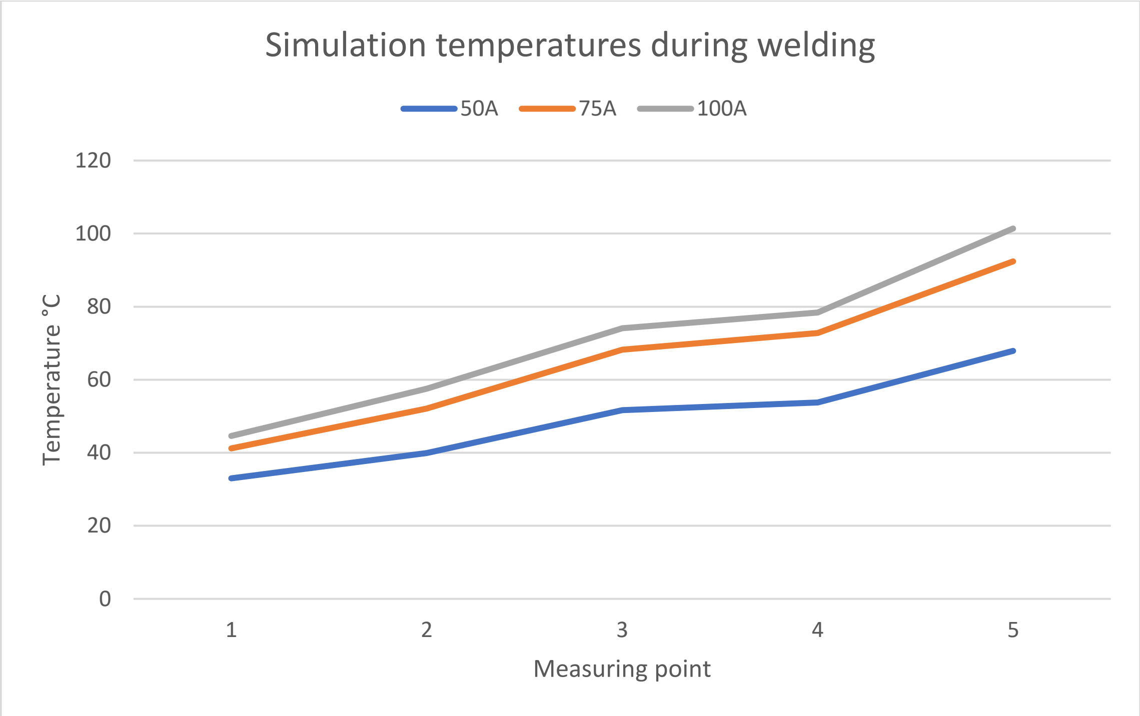

Figure 28. Temperatures of simulation during welding.

Temperatures of the simulation model during welding can be seen on figure 28. Model does not provide accurate results and it can be seen when it is compared to temperature measurements in laboratory in figure 18.

5.2 Improving accuracy of simulation

To improve accuracy of results, not much can be done in settings of the Ansys software. Increasing mesh density did not improved results. Even when the mesh density was increased so much that calculation times increased significantly, results were not any more accurate than results presented in this research. One option to improve result accuracy would be making 3D model more accurate. Especially current modeling of electrical connections can introduce some inaccuracy to the results. For example, connection between the gas-current cable and the torch body is now modelled as ideal situation would be. When gas-current cable is tightened to the torch body, connection surfaces deform and form the actual current transforming pair. Current is also passing through threads in the connection. If these connections would be modelled more precisely, some accuracy could be achieved. Threads are also present when the collet body is attached to the torch body. In 3D model, these threads are not present. Threads would increase mesh density quite significantly and in larger models it is assumed that advantage would be small compared to increased calculation time and higher work required to model accurate threads to each part. Ansys software provides option to set electrical conductivity to each connection pair. Setting this parameter right would require accurate laboratory measurements. This still could be better way to increase accuracy than modifying the 3D models. Problem is that for example this model consists already many connection pairs which each would have to be measured separately. For one simulation this would increase workload significantly and still there is no guarantee that results would be any more accurate. However, if such simulation software is adopted as a tool for product development, measurement work would be helpful. Measurements results could be used in many other applications when simulation software is used continuously.

Material data has its role when accuracy of the simulation is inspected. Thermal dependent models were used for tungsten, brass and copper. Some simulation runs were done using static values, but temperatures of the handle did not change significantly. Temperatures during simulation stayed relatively low so perhaps change in the thermal conductivity was not large enough to affect overall results. Material data reliability could be one topic of further research. Seems that there is a lot of data available, but some variation exists between sources. Best way would be to collect this data from different sources as it was done in the case of tungsten where Shabalin (2014) had made the recommendation based on information collected from different sources. In other aspect, results were generally most accurate in the area of torch body. Torch body had thermal dependent material models in brass, copper and tungsten. Handle area materials, silicone and PA66 had static values. Also grip surface was eliminated because meshing was not possible for that geometry. Grip surface increases total area of handle and might affect on convective cooling. Also, material models might have some role in inaccuracies present. If Ansys would be used in everyday work, collecting and creating this material data would have to be done only once. Similar raw materials are used trough the product portfolio, so data can be reused. This would encourage creation of thermal dependent material models for all commonly used materials. Ansys also provides some material data depending on licenses purchased.

Temperatures measured in the laboratory were done using thermocouples. Monitoring device is regularly calibrated. Measurements should be accurate, but reliability of the measurement system used has never been tested. In future projects reliability of measurement system used would be important to do. This would also serve future research and development projects.

Simulation results were picked from screen using probe tool. There is some degree of variation on placement of the thermocouples and point of probe tool. Some other method for this could be used. Surface temperatures in Ansys seemed to vary quite lot within short distance. Perhaps it would be best to select group of 10-20 measurements with probe tool and use average value of those measurements. This would reduce error of probe placement and even out temperature differences between measurement points. Variation of surface temperatures might be because elements created for simulation for some reason have some variation on temperatures. Usage of thermal camera help to evaluate deviation between simulation model and measurements.

6 CONCLUSIONS AND FURTHER RESEARCH

6.1 Ansys as product development tool

From the results of this research, it can be concluded that Ansys can provide relatively accurate information of the surface temperatures when the arc model is not present. Arc model could be topic for further research and it seems quite possible to produce arc model that could be utilized in all simulation where it would be needed. Calculation times do not seem to be problem with analysis of this scale. If model setup could be done quickly, analyses would be fast to produce once all material data and contact setup is done before hand. Making analyzes fast would be the key factor when Ansys is implemented in product development. If building of simulation model takes many weeks and months like in this research, it is faster to make physical prototype and do the measurements like they have always been made. It seems possible that analysis of torch body for example could be done in less than a day when all the preparations are done before hand and material data already exists. Making analyses at this phase, product development can test and optimize structure before any actual prototypes are made. In overall, despite quite large simplifications, simulation results were quite accurate when compared to the laboratory measurements. With better arc model even the third case would probably been successful.

So far, this research has only focused on simulation of temperatures. Ansys is however capable of other kinds of simulations as well, thermal simulations are only one part of different simulation types available. Many TIG welding torches have water cooling circuit to enable higher currents and duty cycles. In simple cases cooling effect can be simulated like in this work using thermal-fluid elements in mechanical module. If cooling circuit is more complex than simple pipe, CFD tools would come in handy. Usage of the CFD tools could also help to optimize water flow in torch body for example. Simulations would then be much more complex than just using the mechanical module, but if smaller entities are simulated, CFD tools could provide more useful information.

Best type of usage for the Ansys simulation tools seems to be comparison between two models. In the case of welding torches, it seems unnecessary to pursue same results that have been measured in laboratory. Welding torch standards require to make these measurements anyway and so far, simulation models have not proven to be so accurate that it could be used as decision maker. When several different structures are compared, best option would be identified quite quickly. Also, would be wise to split model into smaller pieces. Development of new torch body does not require handle or power cable in simulation model in order to identify optimal structures.

In other hand, complete and accurate model of the TIG welding torch would be helpful to have. If development job is done in smaller pieces, it would be then useful to combine best individual results into one larger model. This would ensure that these best individual solutions will work also together. Creation of this model would only have to be made once and the base of it could be used with different simulations. This would require much more accurate model of arc than used in this research. Result could still be useful.

Implementing Ansys into tool for product development does not happen in overnight. Training for users would take proximately few months to half a year depending how often trainings are organized. Basic usage would then be covered in around half a year. After that material data base would have to be created. Also, further investigation of brazed contacts would have to be made. Depending targets of the usage, first results could be expected after one year to one and half a year counting from start of the implantation project. True advantages of the simulation tools would take few years to show. Investment still can be productive even though implementation time seems to be long. Yearly license fee of Ansys software depends on licenses but can be said that it is around 50% of total salary cost for one employee of product development department.

When properly implemented it can cut down testing time in one project for around 1 month. Given that usually several projects are run at same time, yearly fees are covered with saved resources alone. This does not include benefits of the increased knowledge and better products that also can be achieved. These benefits might be crucial when welding markets are likely to tighten even more in future.

In order to maintain and gain market position in competitive market, product quality must be on excellent level. Quality of products is mostly decided during the product development. Manufacturing and testing are important factors, but do not save badly designed product. Usage of the simulation tools can help to increase quality and reliability of products as well. Simulation does not however eliminate the need for experimental measurements. In case of the welding torches experimental measurements are required if compliance with the standards is wanted to reach.

6.2 Further research

Lack of proper arc model is the biggest shortcoming of this research. Target was to achieve reliable results using methods that could be used on everyday work if such simulation tool would be used in product development. Oversimplified arc model did not yield accurate results and cannot be used for any decision during product development. Arc model could be created differently in Ansys. Instead of using simple heat flow, temperature model with gaussian distribution could be created. Issue that need to be solved is that arc column can reach temperatures up to 21000K (Goodarzi et al. 1997) p.5), but tungsten electrode only around 3000K. Including model with the arc column temperature only would probably introduce too high temperatures for tungsten electrode and therefore for the whole simulation model. Tungsten electrode stays relatively cool because thermionic boundary layer between tungsten electrode and arc column (Murphy & Lowke 2017. p. 36). This would be challenging to include in simulation, perhaps the best option would be to find out how much heat is transferring from arc to torch and configure simulation accordingly.

Simulation model did lack the effect of radiation. Ansys supports thermal radiation in simulations, but radiation would have to be included in arc model. This means that arc model would have to present temperatures that really occur during welding. Effect of the radiation could be evaluated during welding by measuring temperatures when source of radiation is blocked. These measurements could be compared to temperatures measured during this research.

Switching from mechanical module to CFD calculations would be interesting to test. CFD analyses would allow to include more complicated water circulation structures. CFD calculations are usually more demanding than analyses done using mechanical module. This still could be possible if simulation model is for example split into smaller sections. According to Lohse et al. (2015), welding arc model would require CFD analysis, this is because complex physics included. For everyday use, would be more practical to use only mechanical module. Further studies should be started with more research and trials of how to simulate the welding arc with radiation.

Simulating heat transfer of MIG/MAG welding torch would be interesting topic. More often higher currents are used during MIG/MAG welding and therefore temperatures can be higher. In MIG/MAG welding much of the heat transfer occurs when drops of wire are transferred into weld pool. Creating complete and accurate simulation model of MIG/MAG welding torch would even more challenging that with the TIG welding torch. However partial models could be simulated easier and comparison between different design would be possible. MIG/MAG torch bodies have different water cooling circuits than TIG welding torches. Optimizing these water flow channels in MIG/MAG welding torch would probably increase cooling and results better welding torch.

7 SUMMARY

Main purpose of this research was to find out whether modern simulation tool could provide sufficient data on temperatures of the TIG welding torch during welding. Research consisted literature review where mechanism of the heat transfer where explained. Literature review also consists information about TIG welding, TIG welding torch and standard regarding TIG welding torch. Before simulation 3D models needed some modification and some simplifications. Simplifications were needed for example because meshing was not possible to do with the original geometry. Other modifications consisted cutting the torch to only having 50 cm of hose instead of few meters and removing unnecessary parts. Some contact areas where modified to have actual contact, usually with nominal dimensions there is gap in 3D model. Simulation was done with the Ansys Mechanical. Simulation model consisted thermal fluid component which represented gas flow inside welding torch. This was based on the beam element model made with Ansys Spaceclaim. Otherwise simulation setup was made in the Ansys mechanical. In the Ansys Mechanical, two primary methods of performing the simulation was identified. First trials were done using static-thermal module, but quite quickly it was clear that this method did not lead to accurate results. Thermal-electric module was used instead of the static-thermal module. Thermal-electric module allowed user to input electrical current directly using graphic interface. When everyday research work is considered during product development, it is important that tools are easy to use.

Simulation model was verified in three steps. In the first case only current was passing through the torch. With this setup it was possible to evaluate effect of the joule heating alone. It also formed base of setting the convection parameter right. Convection was only mechanism that is cooling the TIG welding torch in this case. In the second setup, shielding gas was added to the simulation model. It is known that shielding gas has some cooling effect on the welding torch, but now it was measured in the laboratory. Simulation model was compared to these measurements. In the last case, simulation model was compared to the temperatures measured during welding. Simulation model was kept simple for two main reason. Every day usage must not be complicated, and simplicity was preferred over accuracy. Second reason was that accurate arc model would require usage of CFD tools which were not available for this research. In all three steps, three different currents were used. These currents were 50 A, 75 A and 100 A. Between these three steps with different currents, nothing else but current was changed.

Simulation results were evaluated based on the five measurement points. Two points were placed on the torch body and three on the handle. Error between measurement and simulation was also calculated. Simulation and temperature measurements had decent match on the first two cases. During welding results were inaccurate. Reasons for inaccuracy are discussed and several possible reasons were identified. It was stated that perhaps in the case of welding torch it is not wise to pursue exact same results that are measured in the laboratory. Best usage for simulation tool such as Ansys Mechanical could be the ability to quickly compare different designs. For example, comparing two assemblies were one part has different material is quite time consuming in laboratory, but in Ansys this can be done quickly and efficiently.

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APPENDICES

Appendix 1. Commands for beam element in Ansys.

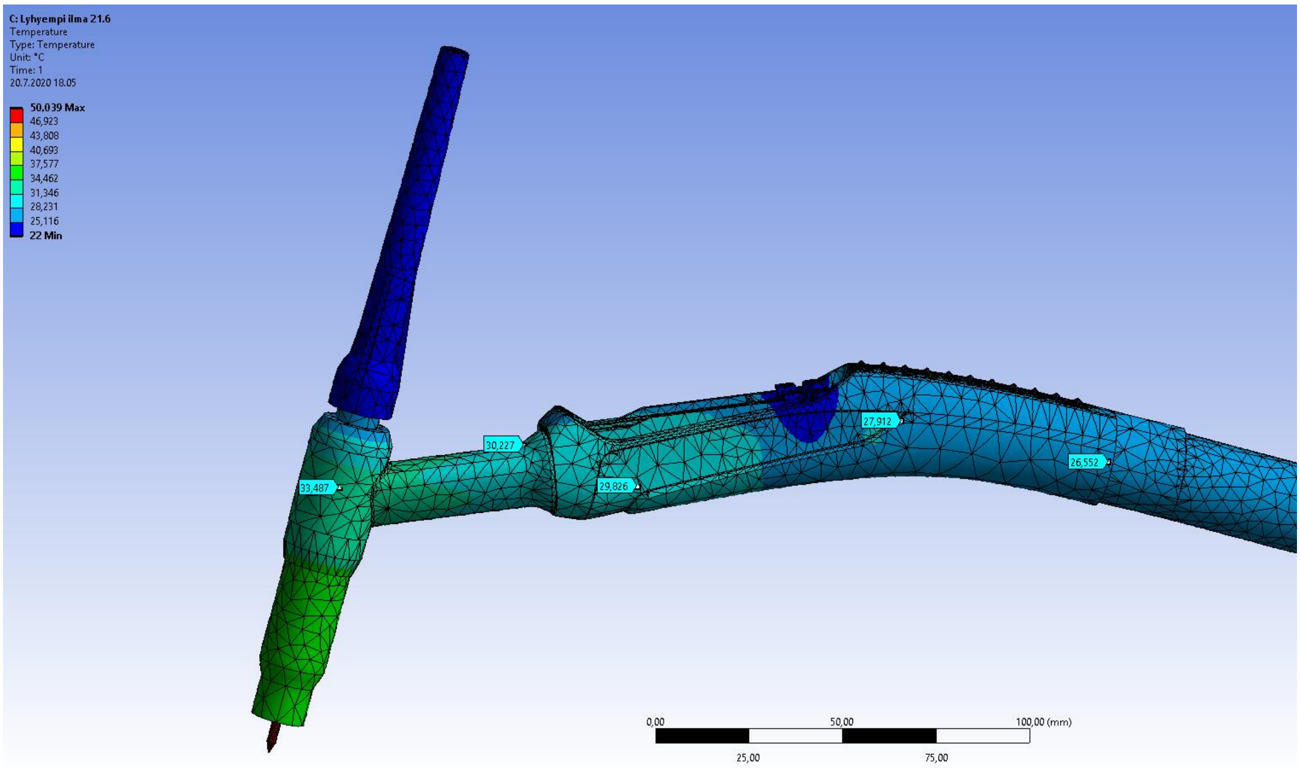
```
et,matid,116,1,1

keyopt,matid,1,1    ! Only TEMP dof
keyopt,matid,2,1    ! 2 nodes and convection information passed to SURF152
keyopt,matid,9,0    ! Fluid body discretization scheme
HD=arg1             ! Hydraulic diameter in mm
CS=3.14159*HD*HD/4  ! cross-section in mm
r,matid,HD,CS,1     ! r,matid,hydraulic diam,cross section,number of flow channels
! material data
mp,dens,matid,arg2  ! gas density in kg/mm^3
mp,c,matid,5.2e9    ! gas specific heat in mm^2/K/s^2


ARG1 7,0682
ARG2 1,634e-9
```

Appendix 2. Commands for solver in ANSYS.

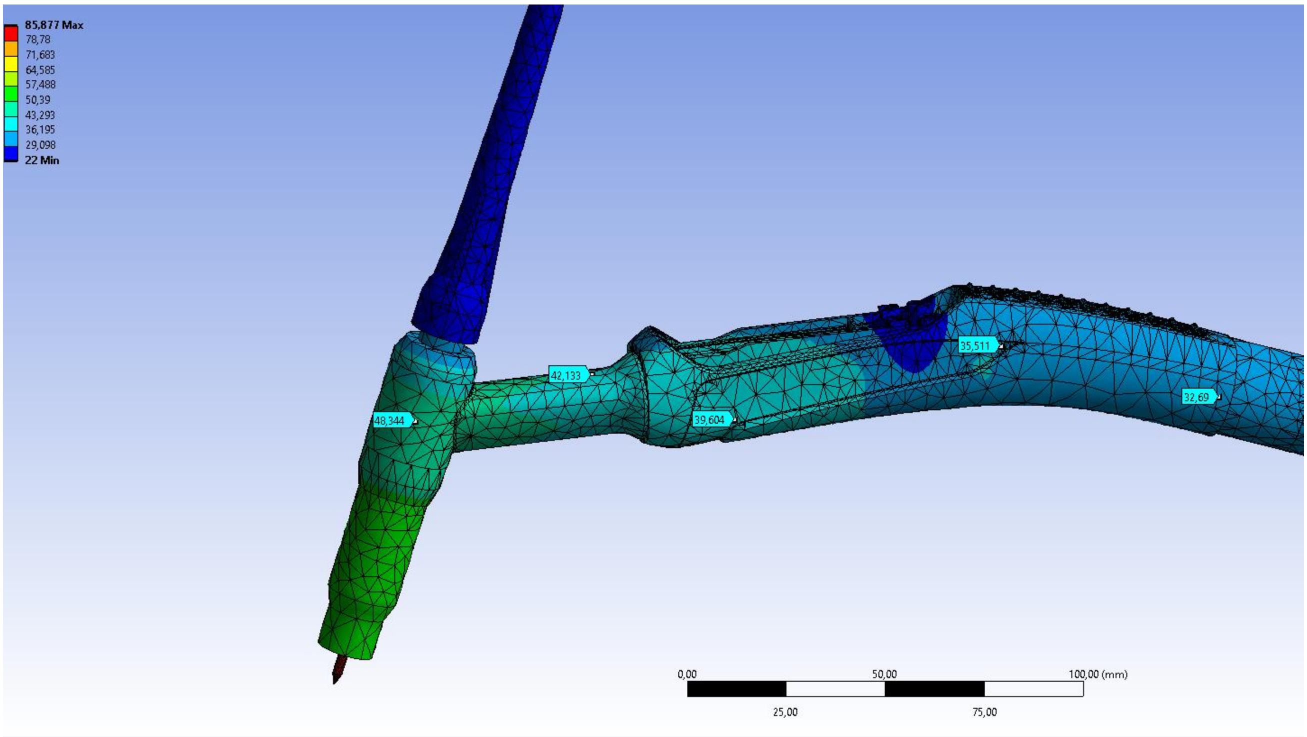
```
finish
/PREP7
!----
! surface effect elements
et,200,152
keyopt,200,8,2      ! Hf at average T
type,200
! generate surface elements on existing mesh of pipe with closest fluid element node
ndsurf,'convectionsurface','gas',3
!boundary conditions
cmsel,s,gas
sfe,all,,hflux,,2.5e-4 !mass flow rate in kg/s
esel,s,type,,200
sfe,all,,conv,,4        ! heat transfer coefficient in t/K/s³
!----
alls
fini
/solu
```

Appendix 3. Simulation results

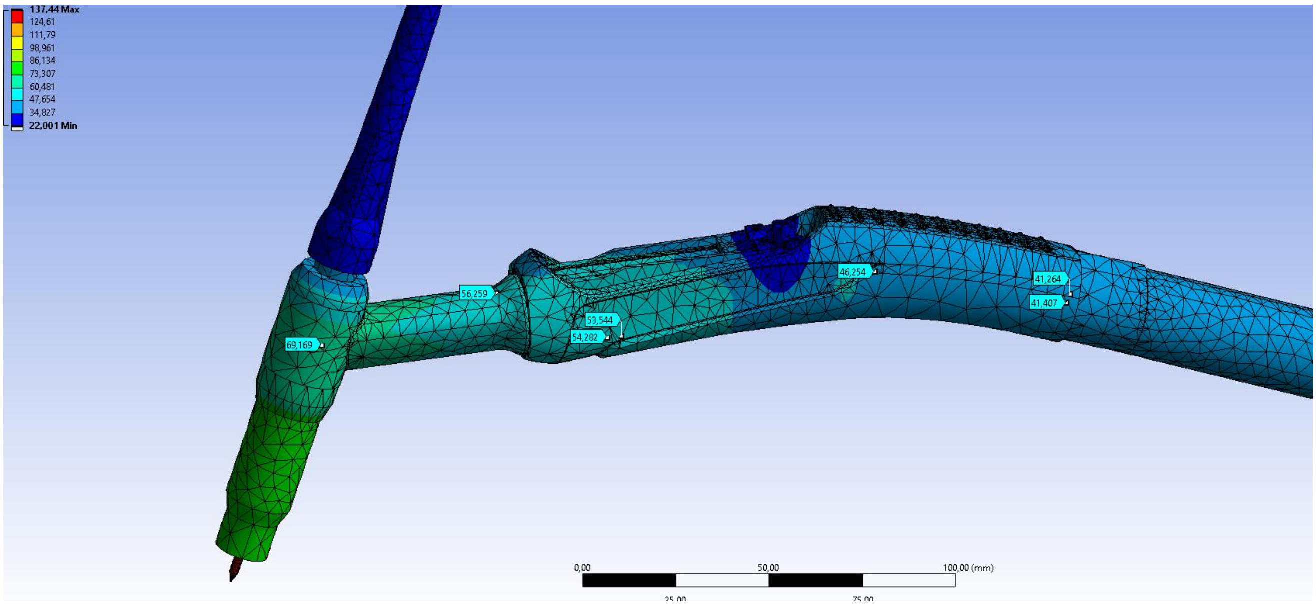
Case 1, 50 A



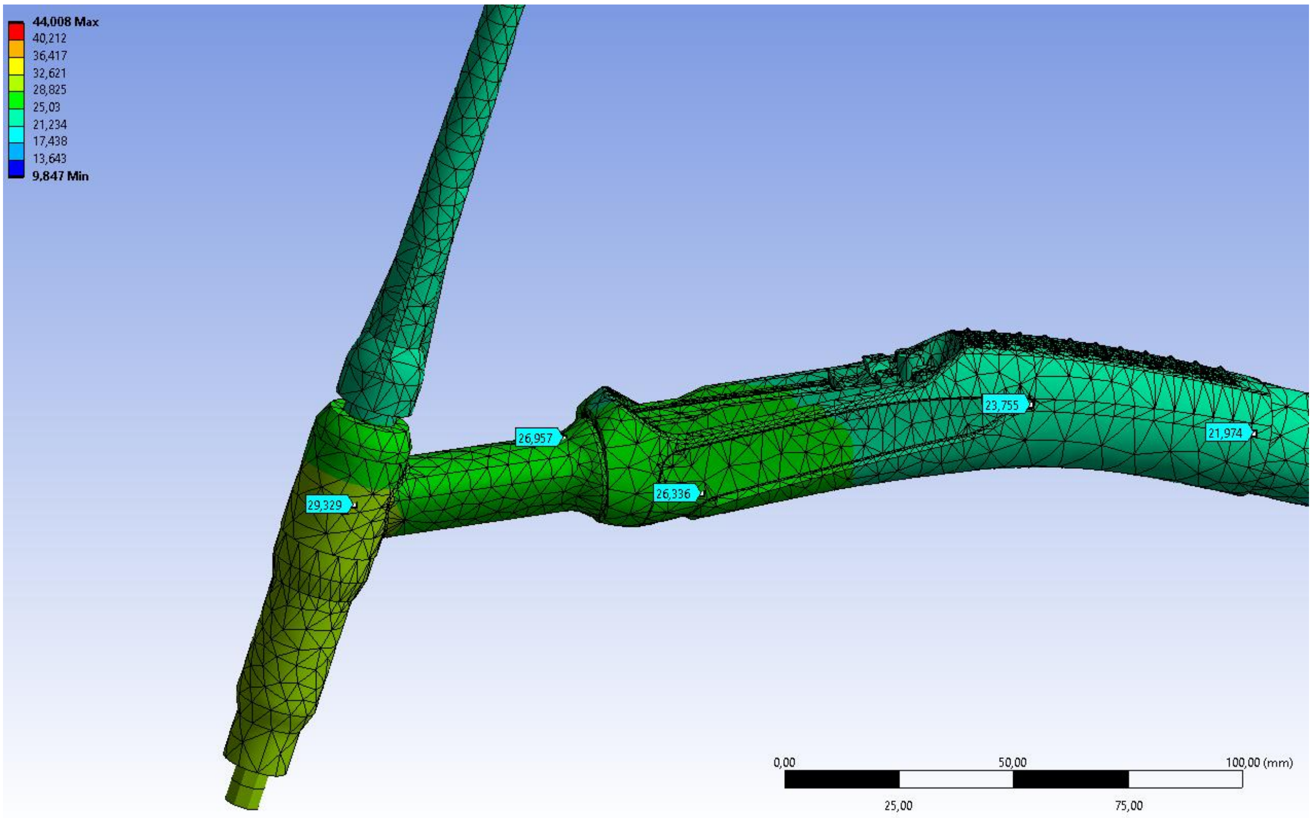
Case 1, 75 A



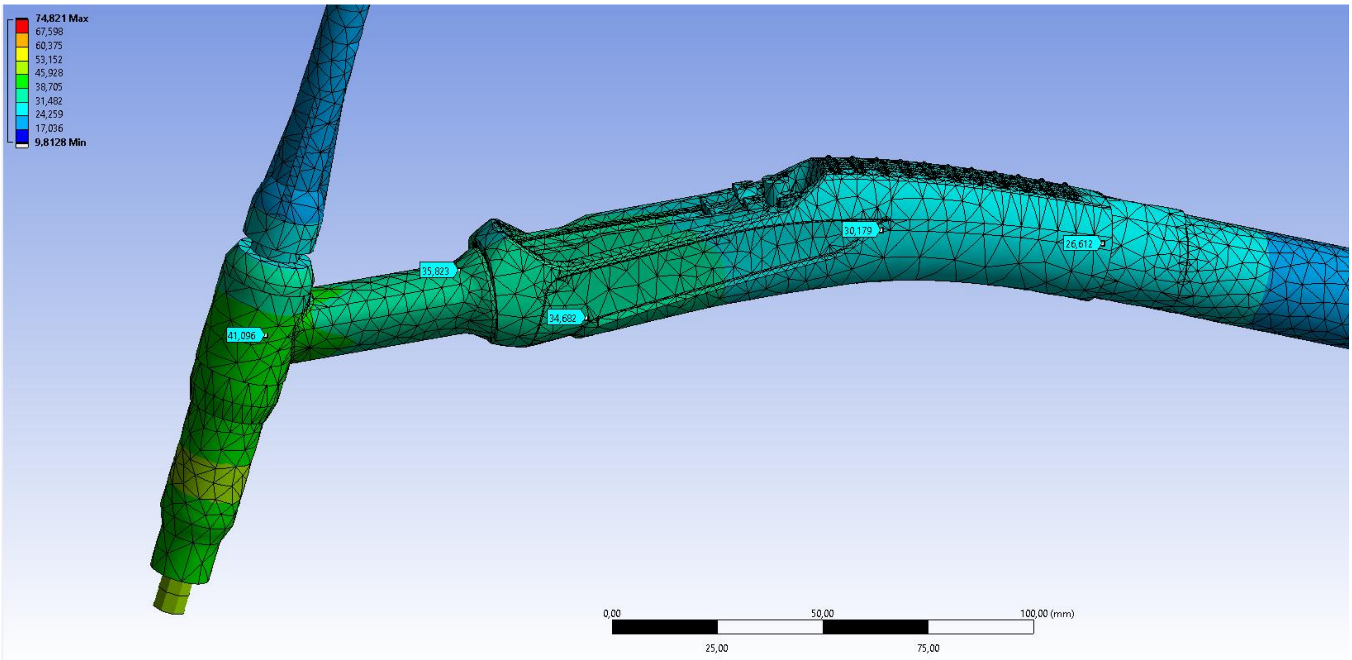
Case 1, 100 A



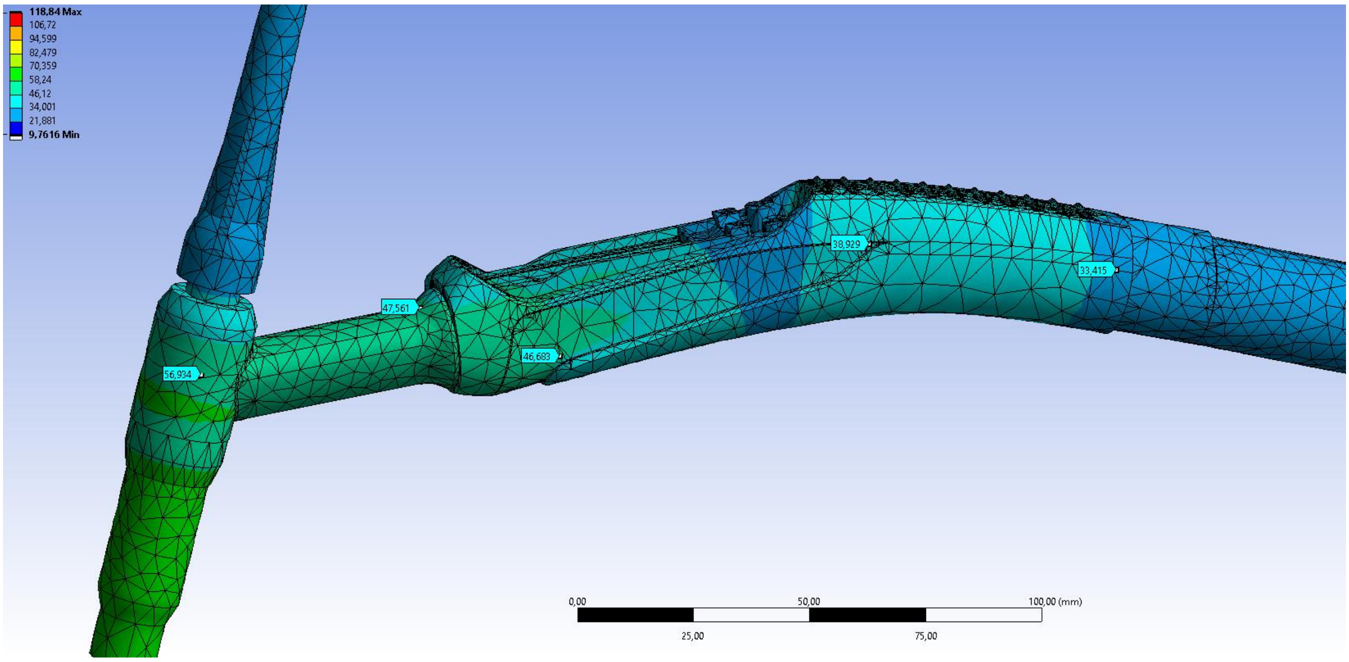
Case 2, 50 A



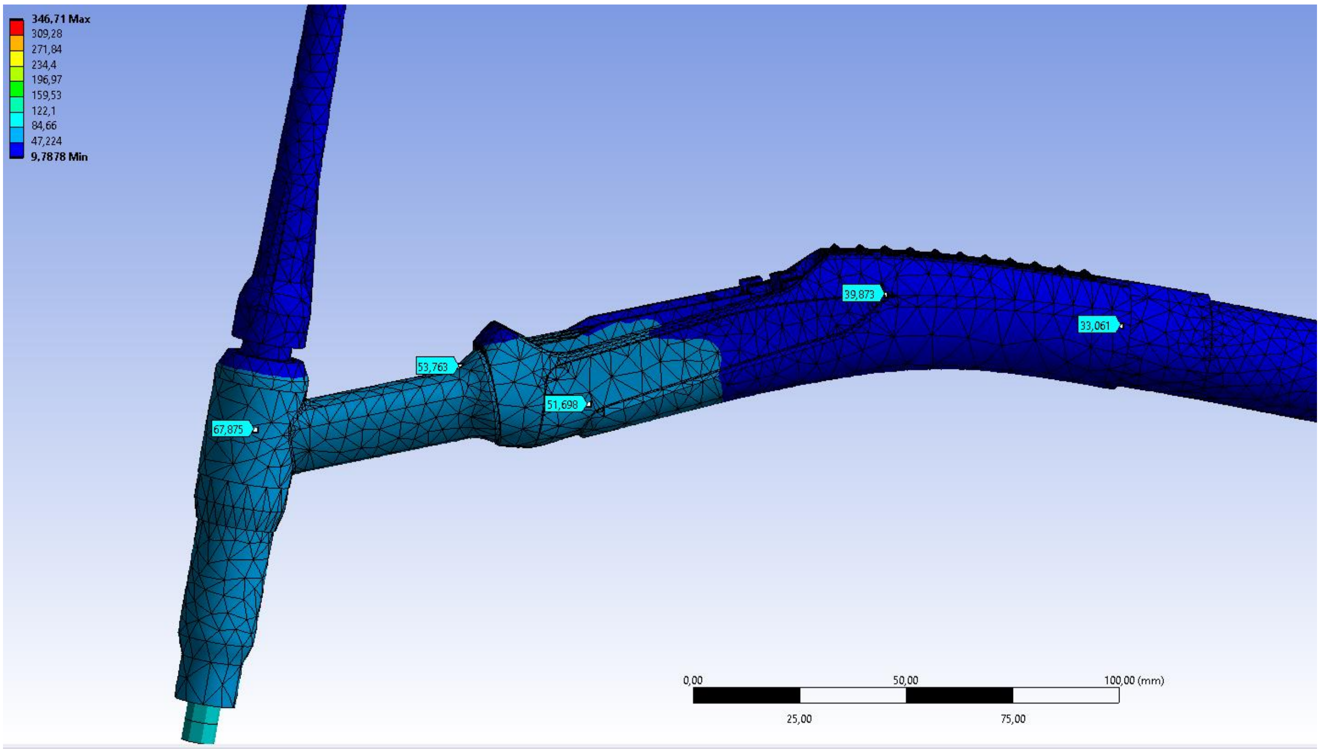
Case 2, 75 A



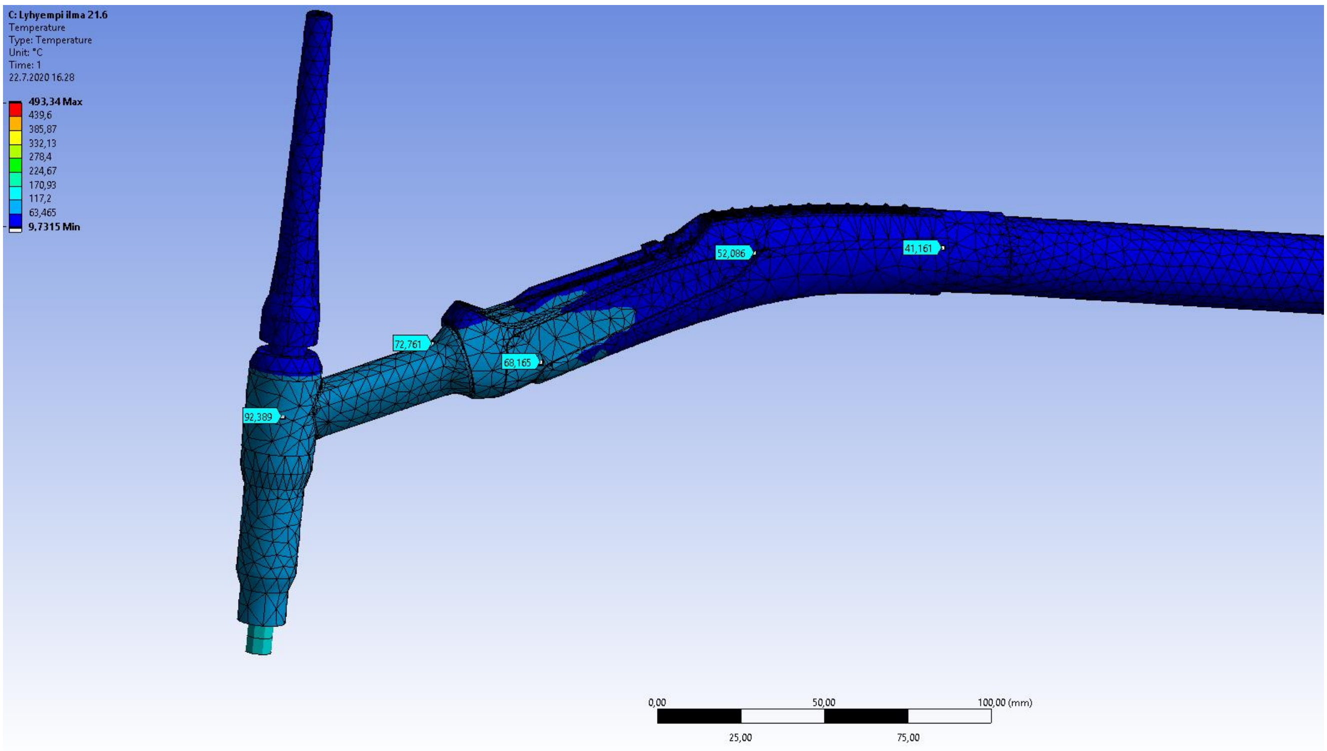
Case 2, 100 A



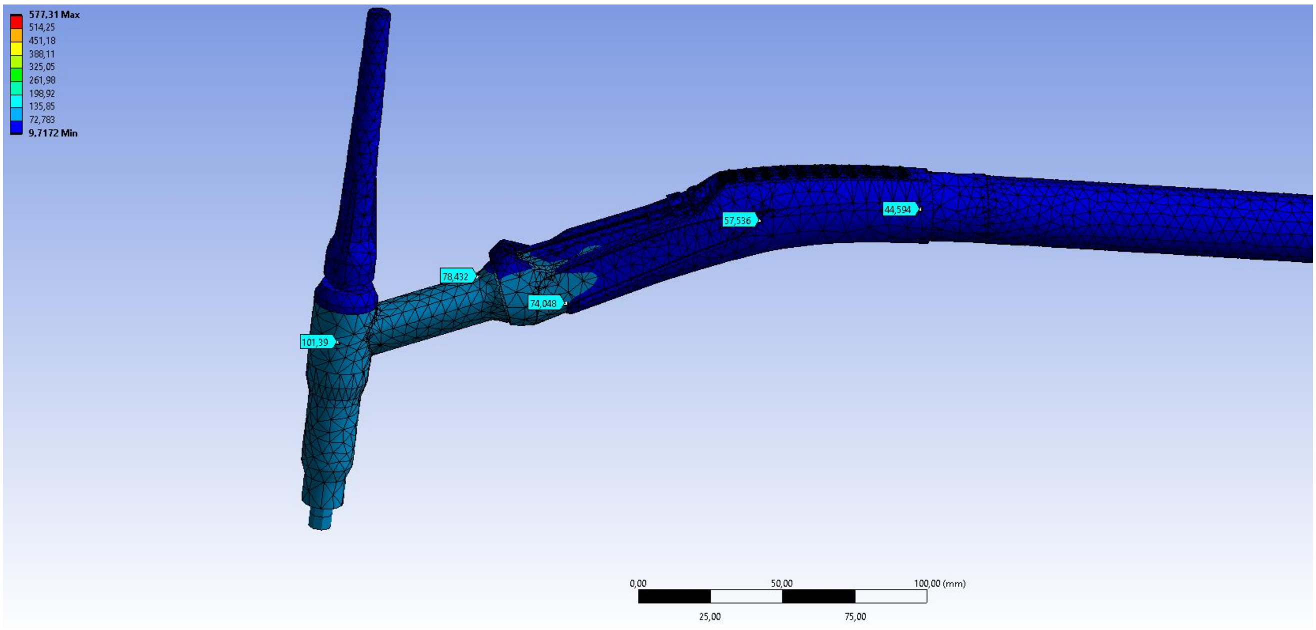
Case 3, 50 A



Case 3, 75 A



Case 3, 100 A



577,31 Max
514,25
451,18
388,11
325,05
261,98
198,92
135,85
72,783
9,7172 Min
78,432
74,048
101,39
57,536
44,594
0,00
50,00
100,00 (mm)
25,00
75,00