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IMPROVING CASTING TRACEABILITY IN IRON FOUNDRY BY LASER ENGRAVING OF MOULDS

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ABSTRACT

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The aim of this thesis is to improve casting traceability at Componenta Högfors iron foundry by laser engraving process of sand moulds. Different laser systems (CO_2, CW and pulsed mode fiber) were tested for engraving silica sand samples together with influence of laser process parameters to laser engraving process. Fiber laser in pulsed mode was used to engrave text markings into sand moulds which were casted to produce iron casting samples with raised cast text marking.

As a result of the study, a method for producing consecutive number marking for castings within the cycle time of automatic moulding line was presented. Unique marking in each casting produced by laser engraving of moulds would allow full traceability to foundry production parameters for individual casting improving internal quality level, production yield and quality assurance.

TIIVISTELMÄ

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LUT School of Energy Systems
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Diplomityö
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63 sivua, 30 kuvaa ja 7 taulukkoa

Tarkastaja: Professori Antti Salminen

Ohjaaja: DI Petteri Sirola

Hakusanat: Rautavalu, tuorehiekka, automaattikaavaus, laserkaiverrus, jäljitettävyyden kehittäminen

Diplomityön tavoitteena on kehittää valukappaleiden jäljitettävyyttä Componenta Högforsin valimossa kertamuottien laserkaiverrusmenetelmän avulla. Työssä tutkittiin erilaisten lasereiden (CO_2 sekä jatkuva ja pulssitettu kuitulaser) soveltuvuutta kvartsihiekka-näytteiden kaivertamiseen sekä erilaisten laserparametrien vaikutusta kaiverruksen lopputulokseen. Pulssitetun kuitulaserin avulla kaiverrettiin tekstimerkintöjä hiekkamuotteihin, jotka valettiin. Rautaisten valukappaleiden pintaan muodostui kohokirjaimin valettu tekstimerkintä. Työn tuloksena esiteltiin menetelmä, jolla voidaan tuottaa kertamuottimenetelmällä valettuihin valukappaleisiin juokseva numerointi automaattisen kaavauskoneen sykliajan sisällä. Laserkaiverruksen avulla tuotetun yksilöllisen numeroinnin avulla yksittäisille valukappaleille saadaan täydellinen jäljitettävyys valimon tuotantoparametreihin, jolloin voidaan kehittää valimon sisäistä laatua, tuotannon saantoa ja tuotteiden laadunvarmistusta.

LIST OF SYMBOLS AND ABBREVIATIONS

λ	laser wavelength	[nm]
f	focal length of optics	[mm]
Θ	opening angle of the laser beam	[deg]
K	beam quality factor	
BPP	beam parameter product	[mm mrad]
D_B	diameter of beam focal spot	[mm]
D_0	diameter of beam waist	[mm]
W_0	radius of beam waist	[mm]
NA	numerical aperture	[mrad]
F_0	absorbed power density	[W/m^2]
ρ	density of solid	[kg/m^3]
L	latent heat of vaporization	[J/kg]
C_p	heat capacity of solid	[J/kgK]
T_v	vaporization temperature	[°C]
T_0	temperature of the material at start	[°C]

CIM	Computer-integrated manufacturing
Nd:YAG laser	Neodymium-doped yttrium aluminum garnet laser
CO_2 laser	Carbon Dioxide laser
AFS standard	American Foundry Society standard
ERP	Enterprise Resource Planning

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1 INTRODUCTION

The purpose of this thesis was to find a solution for improving casting traceability in a serial production foundry producing cast iron components. Due to the nature of sand casting process, the part traceability is one key factor when internal and sometimes external quality problems are being solved in a foundry. In automatic sand moulding process during the mould shake-out and rinsing processes, castings in a production batch which are poured in exact order typically mix up. As a result, the link between an individual casting to its sometimes-unsteady manufacturing process parameters gets lost. Even though foundries usually collect a huge amount of manufacturing process data into their systems, such as sand and moulding parameters, melt chemical composition or pouring temperatures, due to the nature of foundry serial production process this valuable data cannot be easily linked to each casting.

If castings could be easily marked with unique part marking before shakeout process, the traceability problem could be solved allowing the variable process parameters to be linked into each casting, making it possible to recognize and correct the real root cause of a single defected casting.

1.1 Research problem

Iron castings are typically marked with raised or recessed cast text marking including information such as part number, casting date, iron grade or internal foundry markings which at the production plant can be used as a link between a production batch of castings to their production parameters in the computer integrated manufacturing (CIM) system. Even though recorded production parameters can be linked to a production batch of castings, the parameters cannot be linked to individual casting in a production batch due to the fact that all castings in production batch carry the same static marking.

Casting markings are typically static text which is either milled text plate or a changeable text tape attached to pattern forming recessed or raised marking on top of casting surface. In order to generate unique text or consecutive number marking for each casting, the static text in pattern should be changed before moulding each sand mould. What makes it problematic is the production speed of an automatic moulding line where typical cycle time for one mould may be only 12 – 60 seconds when sand moulds are produced with a speed of 60 – 300 moulds per hour and even faster. In order to produce unique text marking to each individual casting within the moulding line cycle time, a rapid and agile method for producing text marking without slowing down the production speed would be needed.

Vedel-Smith and Lenau released an article in 2011 where they studied the same traceability problem in foundry and described a method where “direct part marking using reconfigurable pin-type tooling based on paraffin–graphite actuators” was used to emboss data matrix symbols to mould sand (Vedel-Smith & Lenau 2011). In a mid-size series foundry where a variety of products are being produced with automatic moulding machine and patterns plates are changed frequently, the method was seen too complicated.

In this study solution for the same problem was looked from the side of laser processing. The idea was to solve the traceability issue by marking each casting via laser engraving process of sand mould cavities. This method would be more flexible for short and mid-size series production allowing non-pattern plate dependent online direct marking process which could be implemented to the foundry production line.

NASA technical handbook 6003-C also presents briefly a similar method for direct part marking by cutting symbols into sand moulds by neodymium-doped yttrium aluminum garnet (Nd:YAG) laser (National Aeronautics and Space Administration 2008). Unfortunately, the study has been presented on a very general level without any details. Therefore, this study aims on getting into the topic with hands-on attitude to clarify what is really needed in order to practically utilize laser direct part marking method in automated iron foundry.

1.2 Objectives and hypothesis

The objective of the study was to find a suitable laser type for laser direct part marking and to develop a laser marking system which would be suitable for marking iron castings via green sand moulds by means of laser engraving and could be implemented to automatic green sand moulding line at Componenta Högfors foundry in Karkkila.

By solving the traceability problem, internal quality level, production yield and quality assurance can be improved when exact production parameters recorded to foundry CIM system can be linked to each casting.

1.3 Research methods and contribution

The study consists of a literature review and an experimental part. In literature review the production process and material flow in iron foundry is briefly explained. Then the basics laser of processing, process parameters and interaction between laser beam and green sand are studied. Also, a plan about implementing the laser system to the automatic moulding line is presented.

The experimental part focuses in testing the suitability of different laser types for green sand engraving and the influence of laser process parameters to laser engraved sand samples. Second part of the experimental study focuses in finding suitable process parameters to actually laser engrave green sand and core sand samples with sufficient quality level to produce cast text marking. Finally, laser engraved core sand moulds are casted with molten iron to produce sample castings with text markings produced by laser engraving process.

2 IRON CASTING PRODUCTION PROCESS

Sand casting process consists from number of different tasks with an aim to pour molten metal into sand mould cavity to eventually produce shaped articles. Close to 70% of commercially produced castings are poured into green sand moulds as it is the most economical and rapid way for producing castings (Rao 2003, p. 49).

2.1 Green sand casting process and material flow in iron foundry

Iron foundry process begins from two main material flows. These are iron melting and treatment together with sand preparation and mixing simultaneously. Next, mixed green sand is moulded into desired cavity shapes using pattern plates. Then additional parts of moulds called cores are produced using core shooters and set into moulds to form any complex shapes which cannot be moulded into sand directly. Finally treated molten metal is poured into mould cavities. Molten iron which eventually solidifies inside the mould cavities results shaped metal articles called castings. After solidification, sand moulds are broken in the shakeout process and excess sand is cleaned from the surfaces of the castings by shot blasting. Figure 1 illustrates a simplified iron foundry production chain including the most significant process steps to produce cast iron brake discs.

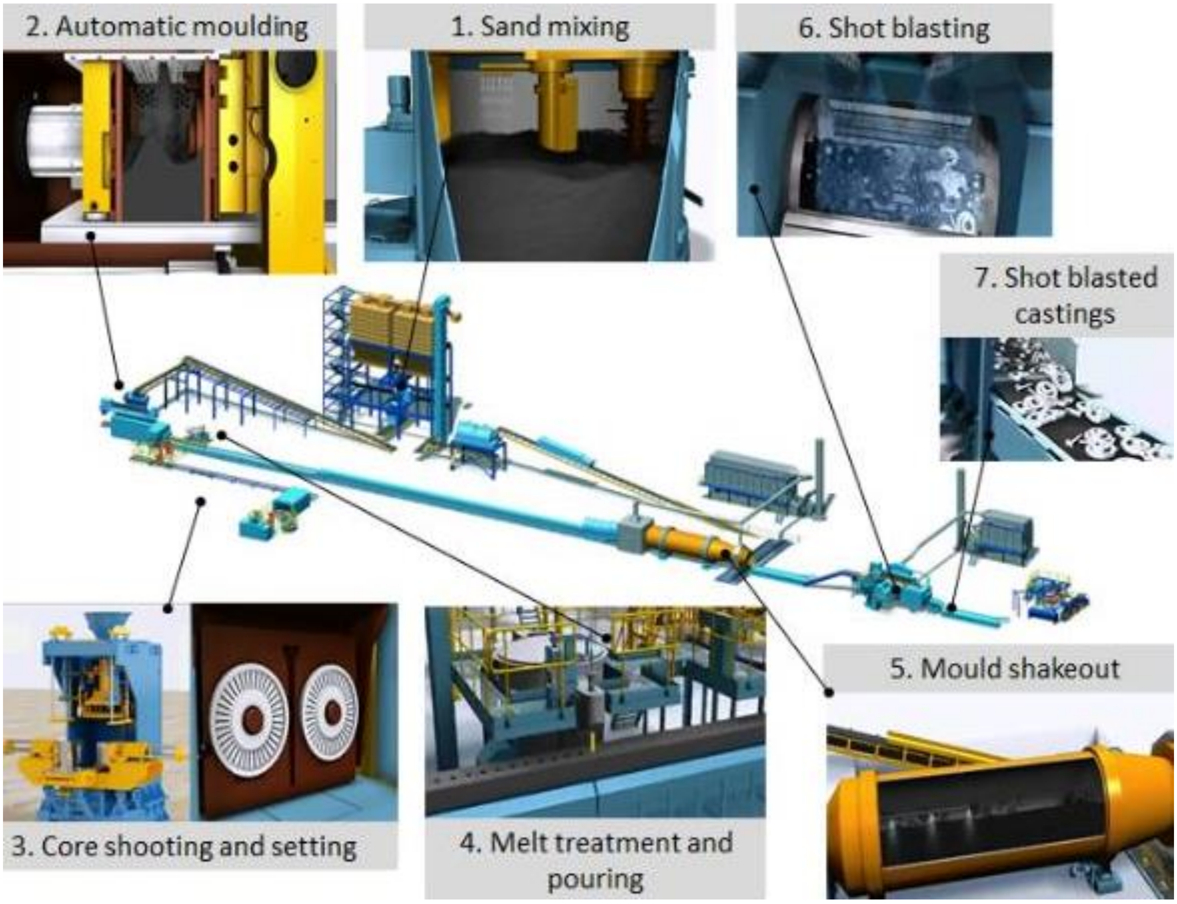


Figure 1. Simplified foundry process steps and material flow in cast iron brake disc production. 1. Sand mixing, 2. Automatic moulding, 3. Core shooting and setting, 4 Melt treatment and pouring, 5. Mould shakeout, 6. Shot blasting, 7. Shot blasted castings. (Disa Group 2016.)

2.2 Sand preparation and mixing

Moulding sand is mixed at sand mixing plant where partly new and reclaimed sand with bonding materials as well with water and special additives are mixed together. The intention is to mix all ingredients into smooth form, so that each sand grain is having a thin film of clay binder around (Beeley 2001, p. 202).

Green sand consists typically of silica or zirconium sand with suitable grain size and distribution. Sand grains which form the base of moulding material are bonded together with binders. The most common binder used in green sand foundries is bentonite clay. When bentonite clay is combined with suitable amount of water, it produces plastic mass bonding sand grains together and giving them high strength so, that moulds retain their shape under pressure, temperature and erosion during pouring of liquid metal. (Rao 2003, p. 22–23.) In order to improve casting surface quality, some additives are used in green sand as well. Iron foundries usually add 3-5% of coal powder into sand to improve casting surface quality. Coal decreases metal-penetration into sand and thus reduces sand burn on casting surfaces. (Rao 2003 p. 25.) Figure 2 illustrates sand mixing process where all green sand ingredients are mixed together.

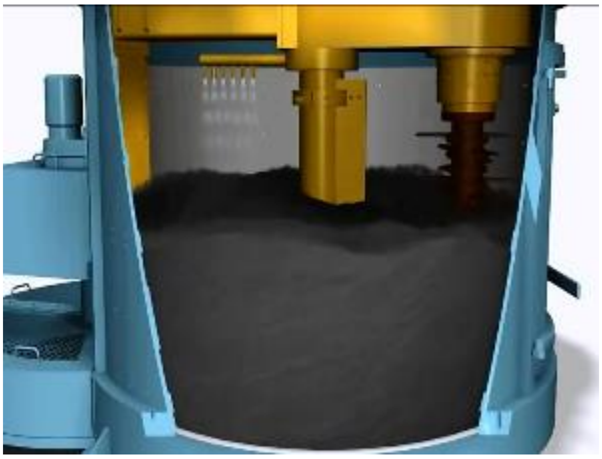


Figure 2. Mixing of green sand ingredients; silica sand, bentonite clay, coal powder and water into smooth form before moulding (Disa Group 2016).

2.3 Moulding

Moulding is a process in which sand moulds are created. Basically, green sand is packed into flasks around patterns to form a desired shape. Then patterns are withdrawn to form mould halves. Mould halves called drag and cope are finally assembled together and they form mould cavity or in other words a negative of the casting shape which is later filled by molten metal. High-pressure or high-density moulding methods are the most used moulding methods in automated foundries nowadays. Green sand may be moulded to flasks or moulds can be also made without flasks (Stefanescy 1998, p. 492). The orientation in moulds is according to the parting line either horizontally or vertically (Milne, Ritchie & Karihaloo 2008, p. 22). Figure 3 Illustrates flaskless Disamatic moulding where parting line is oriented vertically and finished moulds are pushed into a line to wait for pouring.

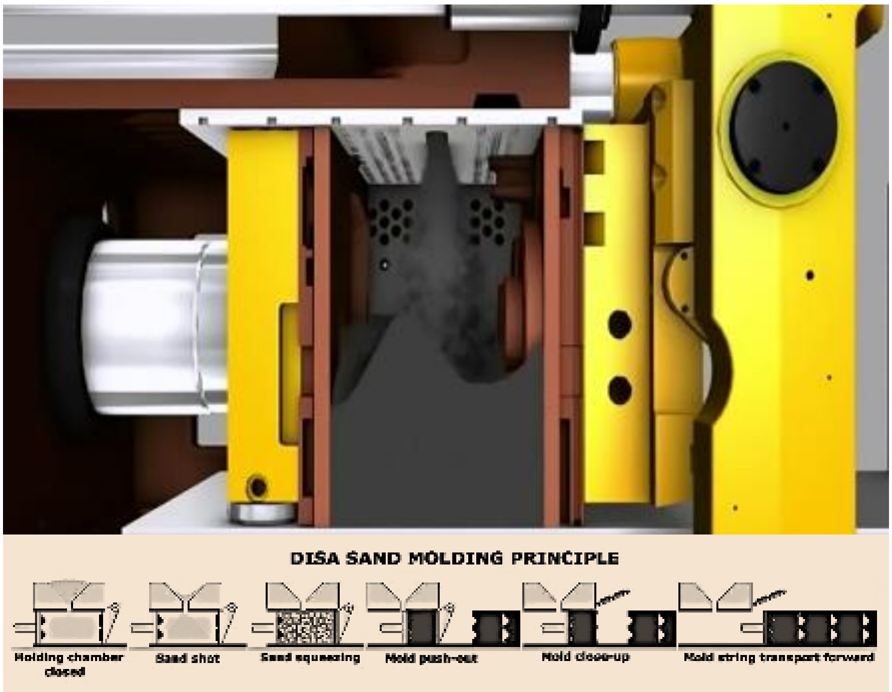


Figure 3. Automatic flaskless moulding with vertical parting line. 1. Moulding chamber closes and fills by a sand shot, 2. Sand squeezing, 3. Right hand side pattern plate swings away and finished mould is pushed out from moulding chamber. A string of moulds where casting cavities form between two molds, move forward ready for pouring. (Disa Group 2016.)

2.4 Core shooting and setting

Cores in moulding process are additional parts of the sand mould which are used to form interior parts of casting or otherwise complex shapes of mould which cannot be produced directly in the moulding process by packing sand around pattern plates. In metal castings, sand mould cavity is providing a space where molten metal can be poured, while core is used to keep metal from filling the entire space with melt. Sand cores can be produced manually or automatically depending from the application, but the material flow in core production remains the same. (American Foundry Society 2016.) In foundries with automatic moulding lines, cores are typically produced by cold box process where sand and liquid binder resin mixture is shot by core shooter into tooling called core box. Core box is usually a two- or three-part mould or box in which sand cores are moulded. Core production consists of following process steps: First a core box is set and fixed in a core shooter. Then by air pressure shot, the core box is filled by sand and resin binder. The sand-resin mixture is hardened by blowing amine gas catalyzer through core box. Core boxes are equipped with special air release vents which allow both air pressure shot and amine gas flow through box cavity freely without causing any unwanted pockets of trapped air or gas. After certain curing time which depends from the core size and shape the core box is opened and finished core is ejected. Then core is dressed by removing any additional burrs or fins from the core box parting line area and the core may be painted by a coating which improves the surface quality of the core and eventually the surface of the final casting (American Foundry Society 2016). Figure 4 illustrates a core shooter on the left and finished ventilated brake disc cores set into vertically parted green sand mould half.

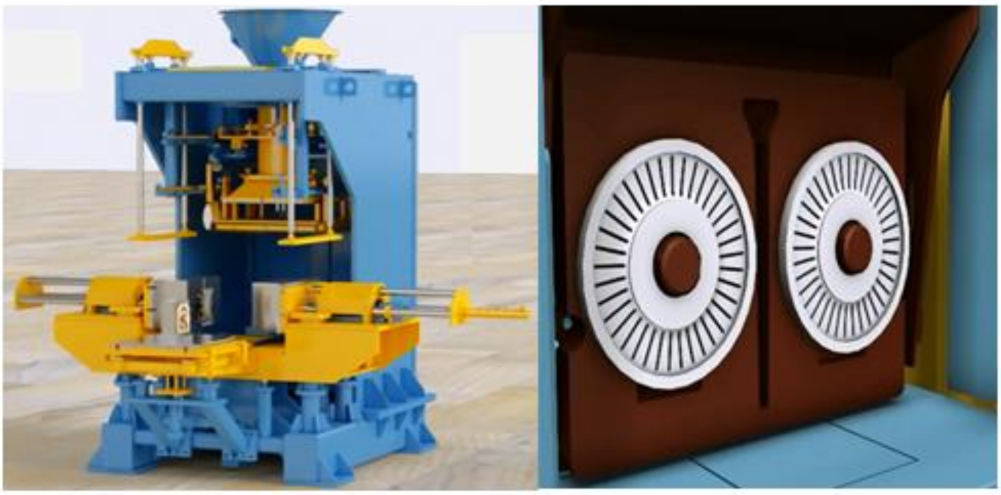


Figure 4. Core shooter used for automated core production on the left (Disa Group 2017). Finished cores with coating set into mould on the right. Cores on right side are used to produce internal shapes of ventilated automotive brake discs with cooling ribs. (Disa Group 2016.)

2.5 Melting, treating and pouring of iron

Cast irons are alloys with iron-carbon base that solidify close to eutectic point. In addition to iron and carbon content there are various amounts of other elements such as silicon, manganese, phosphor, sulfur, and trace elements such as titanium, antimony and tin. Iron properties may be widely varied by changing the balance between carbon, silicon and alloying elements. The properties can be changed also by different melting, pouring and heat treatment practices. (Stefanescu 1998, p. 1365.) Iron melting, treating and pouring are one of the most important parts of successful foundry process. The aim of melting is to reach desired metal composition without gas contamination in melt with low melting losses as possible (Beeley 2001, p. 508).

Melting furnace, typically an induction furnace is charged with pig- or ingot iron, steel scrap and returning scrap from internal fettling and machine shops. Pigs and ingots are chunks of melted iron ore which are normally supplied with certain chemical analysis, but especially iron and steel scrap require more exact control for melting charges so that desired melt composition can be reached. (Beeley 2001, p. 509.) By combining right amount of pig iron typically with high carbon content to a suitable amount of steel and iron scrap usually including some unwanted alloys and impurities, the chemical composition of the cast iron charge can be diluted to acceptable level to fulfill cast iron properties.

2.5.1 Cast iron nodularizing and inoculation

In order to reach the desired cast iron properties, some further melt treatments such as inoculation for gray iron and also nodularizing in case of ductile iron are needed. These processes adjust the microstructure of iron into correct form. Inoculation is a process which aims to increase the number of nuclei in molten iron. This is done to improve graphite precipitation and to avoid the amount of unwanted undercooling. When undercooling is minimized, there is lower tendency to form brittle white iron during the solidification. Inoculation can be done by adding the inoculant into the bottom of ladle before pouring melt from melting furnace or adding the inoculant into melt stream during pouring of moulds. Successful inoculation results uniform microstructure with small graphite flakes and thus improved machinability and mechanical properties. (Stefanescu 1998, p. 1385–1388). Nodularizing is a process to produce higher strength ductile irons. Nodularizing which changes the form of graphite into nodular form is done by additive including magnesium. The aim is to reach Mg level of 0.04–0.06% in the final alloy. Inoculation with FeSiMg is preferably done just before pouring of the molten iron into mould. This is done as the magnesium fades very quickly away in the melt. (Milne, Ritchie & Karihaloo 2008. p. 433.) High reactivity of magnesium causes fairly aggressive reaction which many foundrymen know as magnesium flash in the melting shop.

2.5.2 Pouring

When pouring of molten iron into moulds, there are few essential variables such as melt temperature, cleanliness and delivery technique or pouring speed which need to be controlled to reach decent quality castings. Melt temperature should be sufficiently superheated throughout the filling of the mould cavity in order to avoid any temperature-related casting defects. Superheat is the difference between melt temperature and the liquidus temperature of iron. The fluidity of gray iron is directly proportional to the temperature of superheat in melt. Due to this fact, thinner castings require higher superheat to successfully fill the mould cavity than thicker castings. The liquidus point of gray iron is determined by the chemical composition of cast iron alloy. Therefore, also higher strength gray irons with lower carbon content (hypoeutectic) require higher pouring temperatures than lower strength gray irons (hypereutectic) (Stefanescu 1998, p. 1390).

Molten iron with insufficient pouring temperature can lead to casting defects such as misruns, blowholes and chill. Too high pouring temperatures can lead to castings defects such as shrinkage, metal penetration, veining and scabbing. Typically, iron castings are poured in temperatures between 1315–1450°C. The correct superheat temperature depends on casting size, shape and chemical composition thus requiring experimental testing on each casting to find the optimal level (Stefanescu 1998, p. 1390). Equipment used for handling and pouring of melt is illustrated in figure 5.

Figure 5. A ladle used for melt handling (Moderneq 2016). A string of vertically parted green sand moulds poured by automatic pouring system (Disa Group 2016).

2.6 Mould shakeout

Shakeout is an operation where solidified and cooled castings are separated from mould and core sand. Shakeout process is done after certain time following pouring of moulds when the temperature of moulds has cooled down enough. Typically, the temperature of castings may be around 200 – 350°C during the shakeout process. It is important that shakeout temperature is controlled as it has significant effect on the final casting and its microstructure. Too early shakeout in too high temperatures may cause susceptibility for cracking and denting of castings or may lead to unwanted microstructure due to uncontrolled cooling speed. Required shakeout time and temperature depend on pouring temperature, casting size, weight, coring, and used sand mixture (Stefanescu 1998, p. 1097). Too early shakeout may also lead to unwanted residual stresses in casting.

Shakeout process can be carried out by different techniques and machines including vibrating conveyors, decks, shaker tables or rotational shakeout drums. In spite of the chosen technique or machine, the goal is to break the sand moulds and remove any lumps of excess sand inside the castings (Stefanescu 1998, p. 1097). From shakeout process mould and core sand is returned back to sand mixer by conveyer belts where the sand is reclaimed and cooled down for new moulding round. Castings and gating systems continue to de-gating and shot blasting processes. Figure 6 illustrates a rotational shake-out drum which is used for shakeout of brake disc moulds.

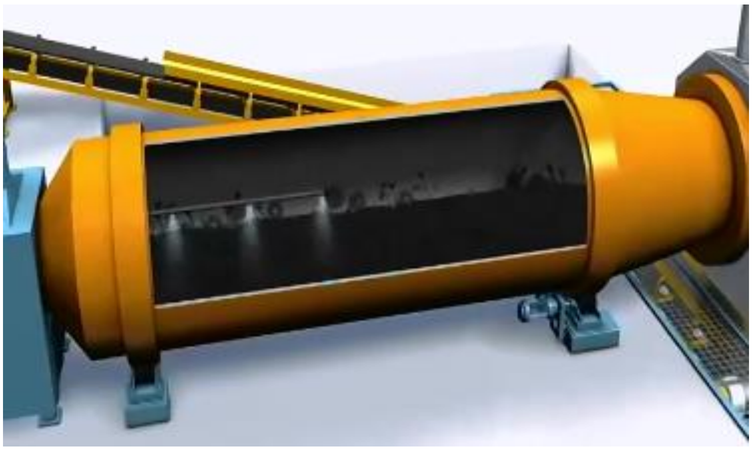


Figure 6. Rotational shakeout drum used for mould shakeout. The cooling effect can be intensified by spraying water in the shakeout drum during shakeout process (Disa Group 2016).

2.7 Casting cleaning by shot blasting

Shot blasting is a process which is required to remove oxide film and adhering or burned in mould and core sand from casting surfaces. Abrasive particle, typically steel shot or grit is propelled with high velocity to remove burnt sand or oxide film from casting surface. Shot blasting gives castings a nice clean and smooth finished surface. Steel shot or grit may be propelled to casting surface by centrifugal wheels or by air pressure nozzles. Used shot blasting equipment is dependent of casting size, shape and production size (Stefanescu 1998, p. 1103–1104).

Shot blasting is usually done in batch or continuous type of barrel-type tumbling machines or in rotating hanger type of blasting machines. Standard type of barrel tumbling machines are suitable for cleaning castings with mid-size and for simpler shapes which can stand the tumbling process. Rotating hanger-type shot blasting machines are suitable for bigger and more complex casting shapes which may be too fragile for tumbling (Stefanescu 1998, p. 1104–1108). Figure 7 illustrates two types of shot blasting machines which may be used for casting cleaning.

Figure 7. Shot blasting of brake disc castings in barrel type tumbling machine (Disa Group 2016) and rotating hanger-type machine (Wheel Laborator Group 2016).

3 CASTING MARKINGS AND TRACEABILITY

Iron castings are typically marked with raised or recessed text markings including different information such as part number, casting date, iron grade or internal foundry markings. Implementation of text markings in casting is agreed between the supplier foundry and customer.

VDA 5005 standard describes recommendation for processes and procedures for the traceability of vehicle components and the identifiability of their technical design. Supplier establishes a cross-reference to finished products quality and production data by a reference or a mark in supplied component which customer can use also as cross-reference for his end product. The reference or mark forms a reference between quality and production data of the products supplied by all suppliers in final products supply chain. Quality and production data may include batch of raw materials used, inspection results, settings, production site, equipment etc. The saved quality and production data should be retained by the supplier in compliance with agreement of supplier and customer (VDA 5005, 2005).

Due to the nature of sand casting process, casting markings are typically static text which is either raised or recessed text or changeable text tape on the pattern plates. Text marking on pattern plate is duplicated by negative recess on mould sand which appears as raised text on final casting after pouring. Casting markings can be also contrarily raised markings in mould sand which appears as recessed marking in the finished casting. Figure 8 illustrates a typical casting marking in casting and how it appears as a negative in sand mould half before assembly and pouring of moulds.

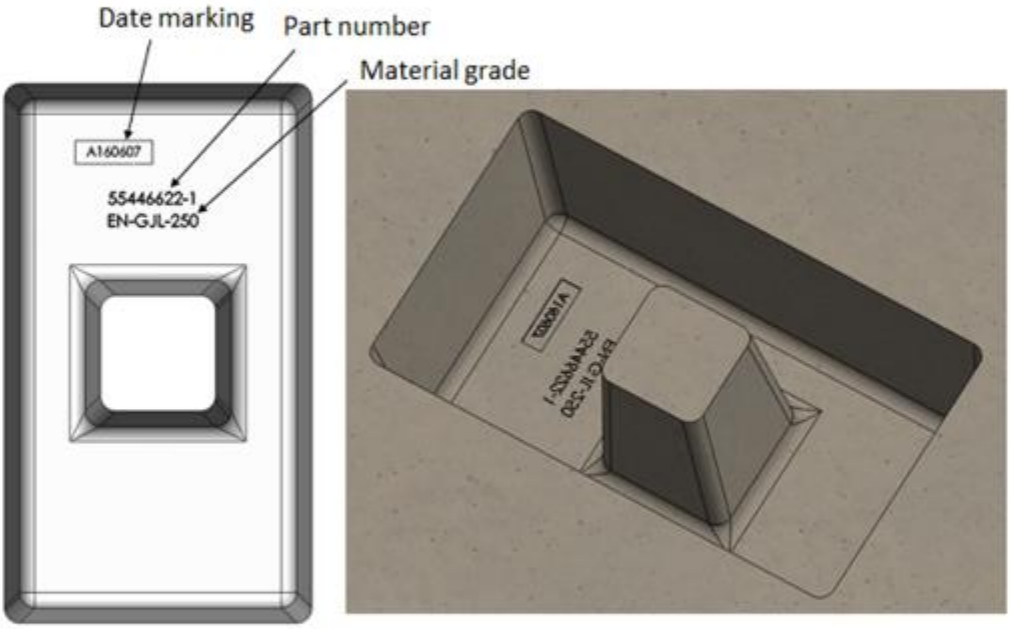


Figure 8. Casting text marking including manufacturing date, part number and material grade. Positive raised text on pattern and casting surface appears as negative recessed text on bottom of sand mould cavity.

The cross-reference marking at Componenta Högfors foundry which forms the reference of produced castings to their quality and production data at the moment is the static part number and manufacturing date marking. This particular reference is enough for tracing some production and quality data such as material test results for each melting batch, but is not always enough for tracing the root causes of some internal quality issues of individual castings.

Production parameters in foundry do vary during moulding, pouring and shakeout of each mould. The traceability to production parameters for each mould cannot be retained due to shakeout and other post processing operations. Figure 9 illustrates how the traceability of production data on each poured mould is lost during shakeout and post processing operations.

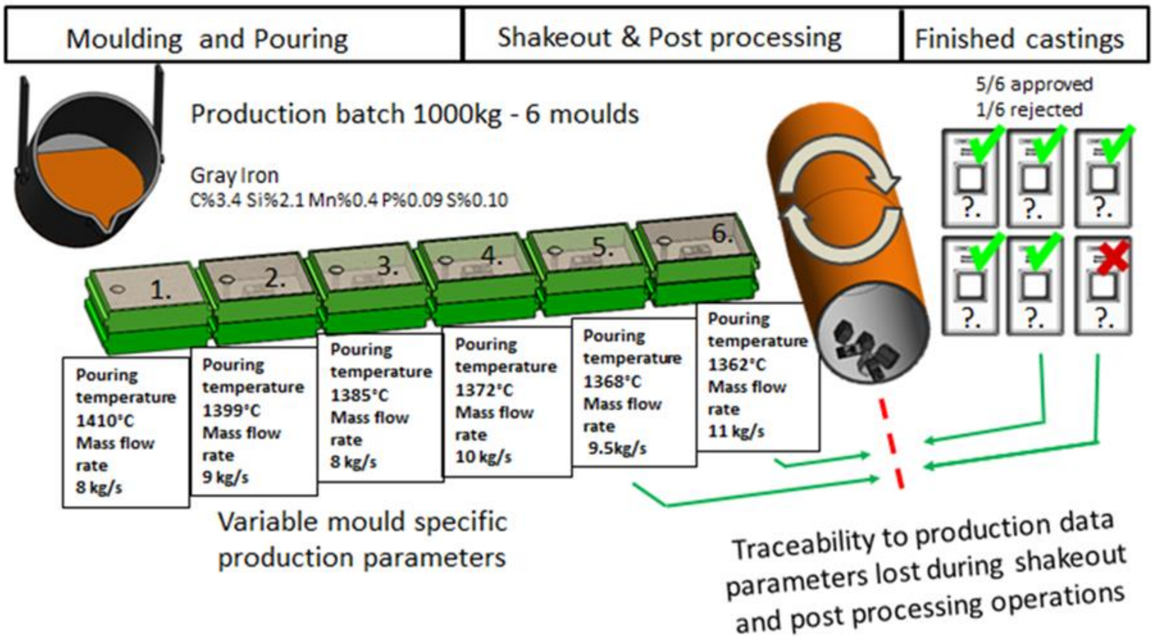


Figure 9. Traceability of castings gets lost during shakeout and post processing operations. Current reference mark between finished castings and poured moulds is part number and casting date which is not enough for finding critical process variables which lead to casting defects and eventually to rejecting of casting. Due to lost traceability, the critical process variable cannot be traced and cured.

In order to generate a unique text or successive number marking for each casting, the static text in patterns could be of course changed before moulding each sand mould, but problem with current solution lays in the fact that static markings cannot be manually changed fast enough for each mould cavity when the typical cycle time per one mould in automatic moulding line at Componenta Högfors may be only 15–22.5 seconds when sand moulds are produced with a speed of 80–120 moulds per hour.

The solution for the traceability problem is looked from laser processing. The idea is to solve the traceability issue by marking each casting by online laser engraving process during moulding via sand mould cavities. Laser beam would be used to engrave negative text to the bottom of each mould half which would appear as raised text on final castings. By online laser marking consecutive numbers could be engraved on bottom of each mould in addition to existing part number and casting date produced by conventional static text markings. By combining these three reference marks the traceability of each casting to their production data could be retained despite the shakeout and post processing operations. Laser engraving method was also seen to be fast enough method to mark each mould cavity with consecutive numbering within cycle time without slowing down the production line.

Laser engraving would be more flexible marking method than changing static text markings after each moulding cycle manually which would slow down the moulding line significantly. In order to reduce laser processing time and still maintain the traceability and handling of the pattern plates at foundry pattern shop, the idea would be to keep conventional static text for text markings for part numbers and pouring date. Laser processing would not replace the old marking method, but add the possibility for consecutive numbering within the cycle time of automatic moulding line. Figure 10 illustrates how consecutive markings would be applied on each mould half by laser engraving process after automatic moulding operation.

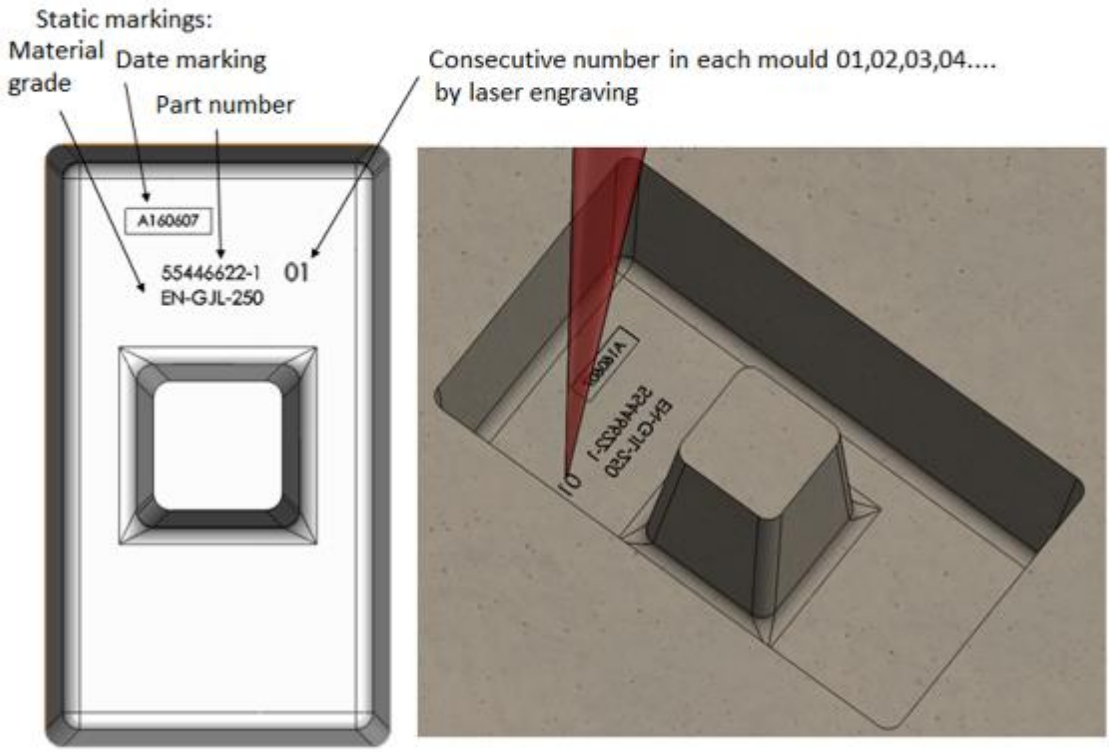


Figure 10. Casting and mould half with static text markings (part number, date marking and material grade) produced conventionally by pattern text plates and consecutive number (mould n. 01) produced by laser engraving process.

By applying online laser engraving method in foundry serial production, traceability of castings to their production and quality data can be significantly improved. Figure 11 illustrates an example how the production data of six poured moulds can be traced into six castings after shakeout process. From six castings, one casting is defected by blow holes which may be a result of pouring temperature related issue. By having consecutive numbers in castings, casting number six can be traced to mould number six which had the lowest pouring temperature of the production batch. Root cause for the pouring temperature related defect can be traced afterwards from foundry CIM system by time stamp. Gained information can be utilized to develop the foundry production process and for next production batch pouring temperature could be limited within margins which would reduce the susceptibility for blowhole defected castings.

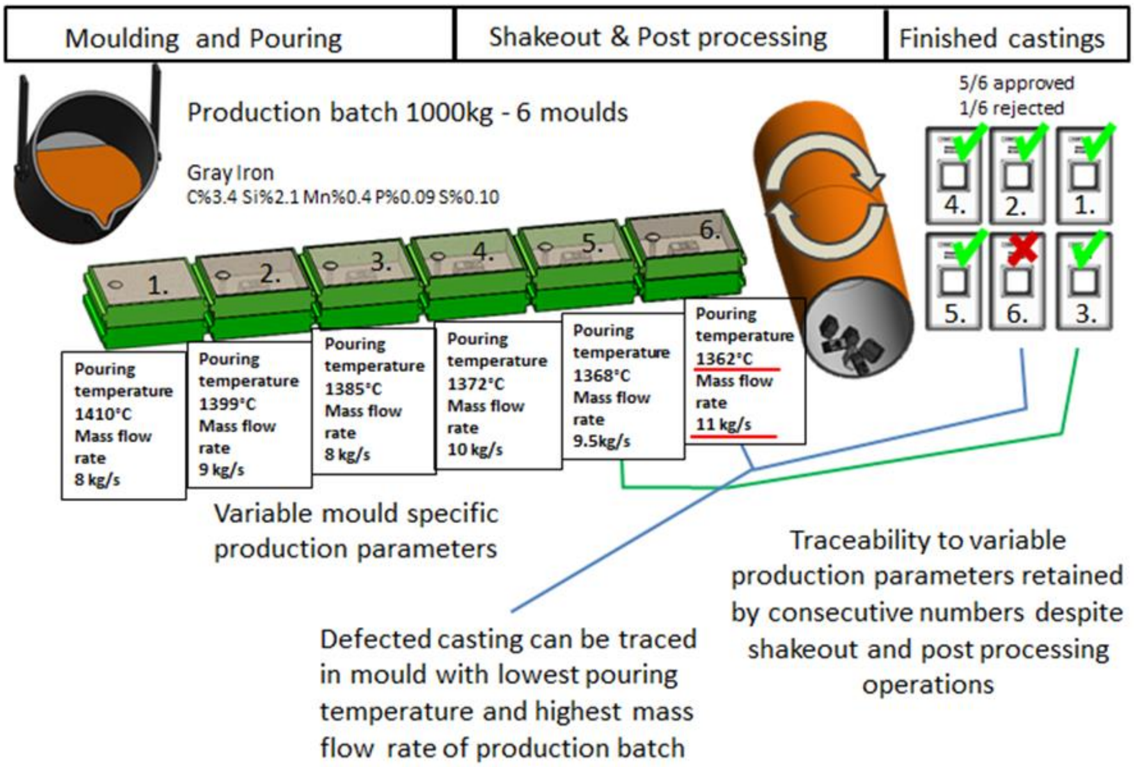


Figure 11. By laser engraving of moulds, consecutive number markings can be added in produced castings. Defected casting number six can be traced into mould number six which had the lowest pouring temperature in the production batch. Gained information can be used to develop foundry production process and reduce internal scrap rate.

4 LASER PROCESSING FOR ENGRAVING OF MOULDS

4.1 Laser beam and its characteristics

Laser stands for Light Amplification by the Stimulated Emission of Radiation. Three key components; an optical resonator, a pumping source and active medium are required to generate a laser beam. A pumping source is used to excite active medium to amplifying state and optical resonator with two parallel mirrors is used for providing optical feedback (Steen & Mazumder 2010, p. 11–12).

Normal lamp light and laser light differs in such way that laser light is collimated – in one direction, coherent – in one phase and monochromatic - in one wavelength. Figure 12 illustrates the difference between normal and laser light. Due to the characteristics of the laser light, laser beam can be focused on very small area which ensures high power density. High power density is one important factor in material processing (Dahotre & Mahimkar 2008, p. 29).

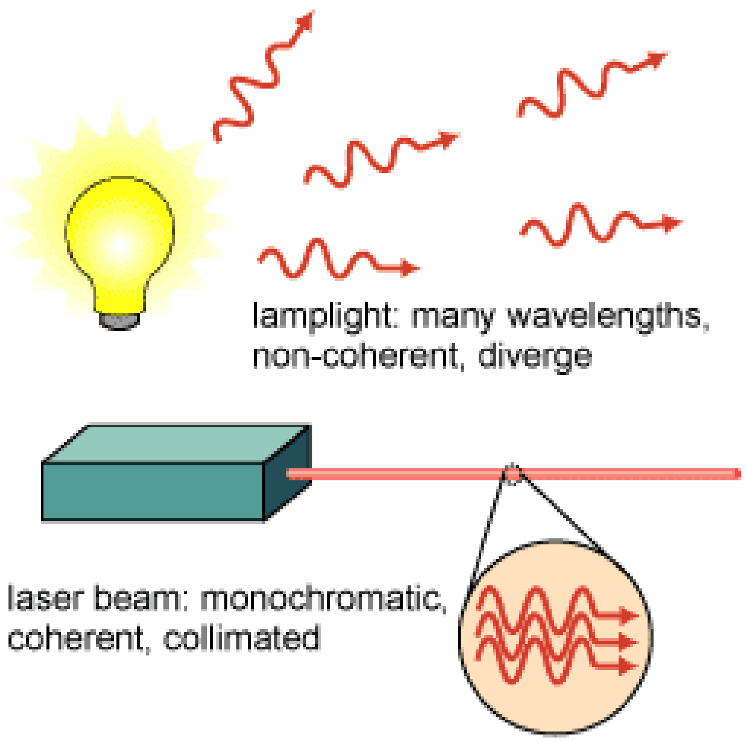


Figure 12. Difference between normal and laser light (Physics World 2016).

4.2 Principle of laser processing and laser engraving systems

In material processing applications the most popular laser systems are carbon dioxide (CO_2), Nd;YAG and fiber lasers with excimer and diode lasers which are also quickly becoming more popular (Steen & Mazumder 2010). Selection of lasers for application should be based on required power, beam quality, wavelength, energy efficiency and price of laser system. Often this leads to selection of fiber, diode and disc lasers.

For engraving of sand moulds no detailed documented studies about utilized systems were found. Only one reference mentioned direct part marking by cutting symbols into sand moulds using Nd:YAG laser (National Aeronautics and Space Administration 2008). As Nd:YAG laser systems are not anymore available as new and have been step by step replaced by other laser systems, this study concentrates into utilizing CO_2 and fiber lasers in laser engraving of sand moulds.

4.3 CO_2 lasers

CO_2 lasers use gas mixture where carbon dioxide in amounts of 1–9% acts as the active medium. Remainder of gas mixture consists from nitrogen (13–35%) and helium (60–85%) (Ion 2005. p. 74). CO_2 lasers typically emit light with wavelength of 10600 nm. Output power of commercial CO_2 lasers on market vary from few watts up to 20kW with electrical efficiency of 10-15%. Industrial CO_2 lasers are typically excited by direct or alternative current with high, medium or radio frequencies. Commercial CO_2 lasers are categorized by how process gas flows in the laser systems optics. Laser cavity may be totally sealed, it may be slow or fast axial flowing, transversely flowing or transversely excited atmospheric pressure type. (Ion 2005, p. 74–75).

CO_2 lasers like other lasers require high cooling. CO_2 lasers require cool gas mixture in order to work appropriately. Gas in slow flow lasers is cooled by conduction through walls of resonator. Fast axial flow and transverse flow CO_2 lasers which are able to produce higher powers are cooled by convection. (Steen & Mazumder 2010 p. 33.) Principle of CO_2 laser is illustrated in figure 13.

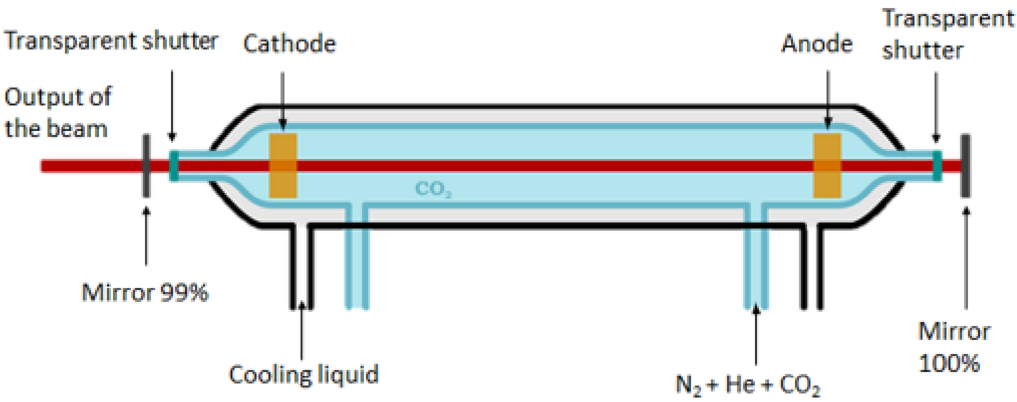


Figure 13. Diagram of a Carbon-Dioxide Laser (CO_2) (Brierre 2016).

Another CO_2 laser type is a pseudo-sealed design called diffusion cooled slab laser. Cavity in this laser is excited by two closely spaced water-cooled copper electrodes with large surface area. Very closely spaced electrodes dissipate heat generated to laser gas by diffusion cooling. Due to their special structure slab lasers do not require conventional gas circulation systems with complex blowers. The most significant advance of slab laser is that laser gas consumption is very low and gas doesn't need to be renewed or circulated permanently. This feature allows a very compact structure compared to conventional CO_2 lasers. Slab lasers are able to produce high quality beam with multi-kilowatt output (Ion 2005, p. 76) Figure 14 illustrates principle of a Carbon-Dioxide (CO_2) slab laser.

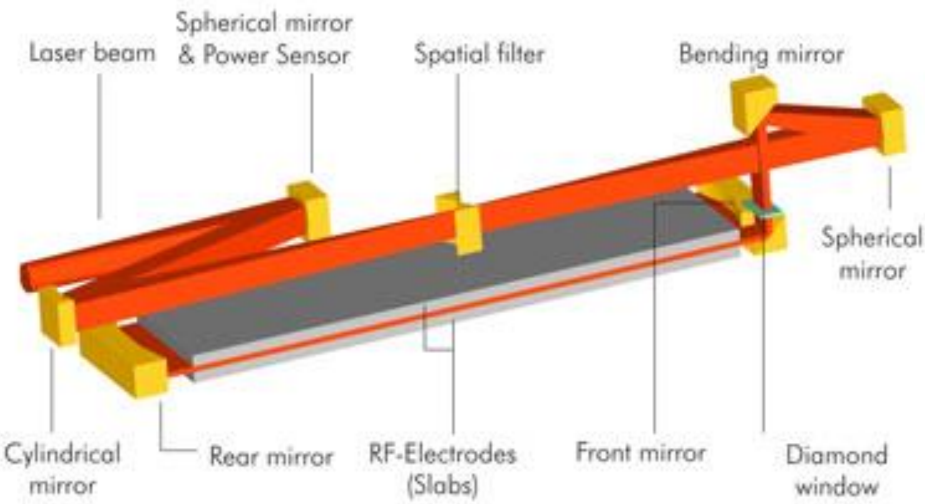


Figure 14. Schematics of diffusion cooled CO_2 slab laser (Kaast-CNC 2017).

4.4 Fiber lasers

A promising alternative to bulk solid-state laser systems such as Nd:YAG lasers is fiber laser. Instead of using a rod for gain medium with few millimeters in diameter and several centimeters long suffering from thermo-optical problems, fiber lasers use long and thin optical fiber as gain medium which has outstanding thermo-optical properties. This is due to large surface to volume ratio (Limpert, Schreiber & Tünnermann 2016).

In fiber laser both pump and laser radiation is guided in cladded fiber structure with active core inside. Dialect mirrors or fiber Bragg gratings are used in both ends of fiber to form the laser cavity. This type of structure is very compact and stabile without any fragile components (Limpert, Schreiber & Tünnermann 2016).

Pumping in fiber lasers is performed with diode laser. Fiber lasers typically emit light near infrared wavelength of 1070 nm and have excellent beam quality with output power up to 20 kW (Limpert, Schreiber & Tünnermann 2016). Figure 15 illustrates schematic diagram of fiber laser in its simplest form.

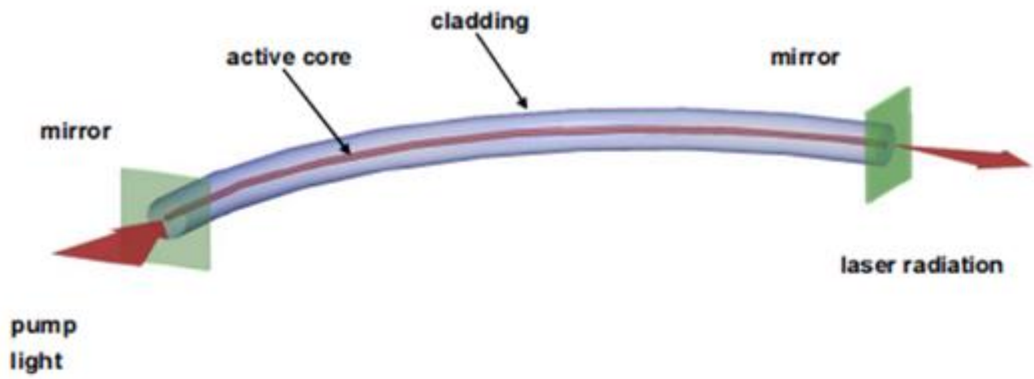


Figure 15. Schematic diagram of fiber laser (Limpert, Schreiber & Tünnermann 2016).

However, fiber lasers have one disadvantage: Power of single-mode pump diodes is limited to few watts. Fortunately, the limitation can be overcome by using spliced fiber design. By this way single mode laser can be multimode pumped to increase the laser power. Spliced fiber design allows amplification of single-mode fiber laser beam in multiple steps until desired laser power is reached (Limpert, Schreiber & Tünnermann, 2016). Figure 16 illustrates how single mode laser can be amplified by multimode pumping.

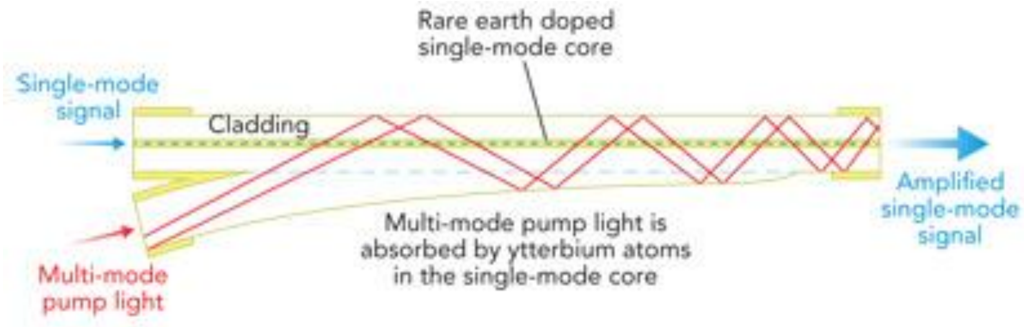


Figure 16. Multimode pumping to amplify single-mode signal fiber laser (Industrial laser solutions for manufacturing 2012).

Fiber lasers emit light on wavelength of 1070 nm close to infrared area in spectrum of light. Near infrared wavelengths absorb better into reflective metal materials, so they suit well for marking of i.e. stainless steel parts. Another benefit of shorter wavelength is that the beam can be focused on smaller spot, allowing higher power intensity and laser scanning resolution. Fiber lasers with near-infrared wavelengths are used for marking wide variety of both metal and non-metal materials (Industrial laser solutions for manufacturing 2012).

4.5 Beam focus and definition of beam quality

The raw beam emitted from laser resonator may be in diameter ranging from 15 - 70mm. As the raw beam cannot be utilized in its original state for material processing, different type of optics are used to focus to the laser beam into suitable form for material processing (Ion 2005. p. 104). The focal point diameter for example in laser cutting may be only 0.1–0.2 mm. Figure 17 and equation 1 describe how focal number, along with laser wavelength and beam quality affect to the laser beam focal point diameter.

The diameter of focal spot can be calculated from equation 1 (Ion 2005, p. 105).

$$D_B = \frac{4\lambda}{\pi} \frac{f}{K} \qquad (1)$$

where,

D_B = diameter of focal spot

λ = wavelength of laser

K = beam quality

f = focal number

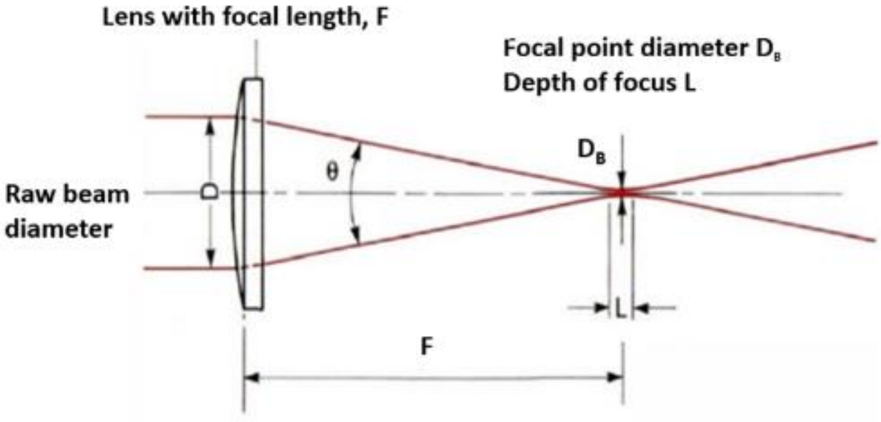


Figure 17. Laser beam focusing principle. Raw beam diameter D, focal length F and divergence angle Θ define laser beam focal point diameter D_B. L describes depth of focus.

Depth of focus measures change in the waist of beam. Depth of focus is proportional to square of spot size. As a rule of thumb, the depth of focus for a lens is about 2% of focal length (Ion 2005 p. 106). Equation 2 defines depth of focus.

$$L = \frac{4\lambda}{\pi K}\left(\frac{f}{D_B}\right)^2 \quad (2)$$

where,

L = depth of focus

D_B = diameter of beam focal spot

There are several definitions for laser beam quality such as M^2, K-value, or Beam Parameter Product (BPP). When comparing beam qualities between different laser wavelengths a definition called Beam Parameter Product (BPP) can be used. Beam Parameter Product considers the radius of beam and angle of divergence, but does not take into account laser wavelength. Equations 3 and 4 define Beam Parameter product (Primes 2017).

$$BPP = \frac{D_0\Theta}{4} \qquad (3)$$

$$BPP = W_0 * \mathrm{NA} \qquad (4)$$

where,

D_0 = diameter of focal spot

W_0 = radius of beam waist

Θ = full beam divergence angle

NA = numerical aperture

4.6 Pulsing of laser beam

Laser pulsing is a technique to create short high peak power laser pulses by different blocking, chopping or attenuation methods. Pulsing may be carried out by a shutter in laser resonator which closes and prevents laser action. During blocking the excitation energy continues to be absorbed. When shutter is opened, a large energy burst is released. Another way to produce temporal signal is to modulate the laser excitation signal. Laser beam can be pulsed down with different methods down to scale of femtoseconds (10^{-15} s). Laser pulsing techniques are commonly used in laser marking and drilling applications (Ion 2005. p. 61–62).

An article by Industrial laser solutions for manufacturing (2012) gives a good practical example about efficiency of laser pulsing. “One particular model available from the leading supplier delivers 18 W average power at 300 kHz with 1.5 ns pulses (60 µJ), an M2 of 1.3, and a peak power >40 kW”.

4.7 Laser engraving process

Laser engraving is a process where laser beam penetrates a surface removing material in lasers path. Laser beam increases the temperature of the surface locally above the melting point of processed material causing evaporation thus creating typically a readable high contrast marking (Joshi & Dixit 2014., p. 286–288). Lasers are suitable for marking or printing bar codes, matrix codes, universal product codes and serial numbers (Restrepo et al. 2006, p. 2272–2277). The main application of laser marking is for product traceability and identification purposes (Chen & Darling. 2005. p. 214–218). Productivity of laser engraving process is very high and it suits very well for short production cycles. Changes in engraved characters and figures can be changed smoothly through software changes. Laser engraving system can be easily integrated as a part of high speed production lines as on- the fly marking application. Investment costs of laser marking systems are typically high, but running costs of the system are low (Ion 2005, p. 386).

4.8 Interaction between foundry sand and laser beam

In order to engrave moulds at foundry, mould sand should be vaporized away from surface of sand mould in controlled manner to produce a clear recess which could be successfully later filled by molten iron to produce raised text marking. Laser engraving mechanism of sand mould is based on vaporization of sand grains and compounding bentonite clay from top of mould cavity surface. To vaporize silica sand very high discrete temperatures are required.

Most foundry sands are based on silica sand which can stand temperatures approaching 1700 °C (Beeley 2001, p. 199–202). Foundry green sand consists mainly of silica sand (SiO_2) which is a covalent ceramic. Si and oxide atoms share their electrons and achieve stable filled electron shells (Ion 2005, p. 141–142). Commonly silica sand grains are bonded together with bentonite clay. Bentonite clay with addition of water forms a bond between hydrated clay particles and silica surfaces. When temperature of bentonite clay is elevated to higher temperatures, chemically combined water vaporizes away weakening permanently the bonding capacity. Weakening of bonds begins approximately in temperatures of 400°C and is in all cases complete at 700°C (Beeley 2001, p. 199–202).

One way to estimate the rate of laser beam penetration to processed material is to use lumped heat capacity calculation assuming one dimensional heat flow. This calculation model assumes that all delivered heat energy is used for evaporation of material without any heat conduction. The volume of removed material per seconds of time is calculated from equation 5 (Dahotre & Hamirkar 2008, p. 146).

$$V = F_0 / \rho \, [L + C_p(T_v - T_0)] \quad (5)$$

where,

F_0 = absorbed power density (W/m^2), ρ = density of solid (kg/m^3); L=latent heat of vaporization (J/kg), C_p=heat capacity of solid (J/kg °C), T_v= vaporization temperature (°C), T_0= temperature of the material at start (°C)

To satisfactorily engrave sand moulds, high optical intensity (W/cm^2) from the laser beam is required. Depending if the laser beam is continuous wave or pulsed wave there are various other parameters in addition to laser average and peak power that effect the end result, such as energy by pulse, duration of pulse, repetition rate (Deprez et al 2012). Wavelength of the laser has significant impact on absorptivity (Spear & Scott 2016).

During laser engraving not all of the delivered energy is absorbed into processed material. Laser beam is partly reflected from the surface of processed material. In addition to laser beam properties also the processed materials properties affect the absorption of laser beam. Processed materials structure, chemical composition, mechanical characteristics surface quality with electrical, thermal and optical properties influence the effectiveness of laser marking (Deprez et al 2012). Ion has listed the principal process parameters of laser material processing. The following parameters presented in table 1 affect to the interaction between laser beam and processed material.

Table 1. Summarizes the key process parameters affecting in laser material processing (Mod. Ion 2005 p. 180).

Laser and scanning parameters	**Processed material parameters**
Laser Power	Composition
Beam Mode	Absorptivity
Laser wavelength	Thermal conductivity
Raw beam diameter	Specific heat capacity
Polarization	Latent heat
Depth of focus	Thermal expansion coefficient

Table 1 continues. Summarizing the key process parameters affecting in laser material processing (Mod. Ion 2005 p. 180).

Projected spot size	Initial temperature
Focal plane position	Transformation temperature
Transverse rate	Density

Absorption of the laser beam is also dependent from processed material and its thermodynamic properties. In addition to basic thermodynamic properties with bulk materials, surface roughness, particle shape and size distribution and packing density may affect to the absorption of light (Spear & Scott 2016). Same parameters are assumed to affect the absorptivity of laser beam to foundry sand. Figure 18 illustrates the heat transfer paths in laser processing of bulk materials such as green sand moulds.

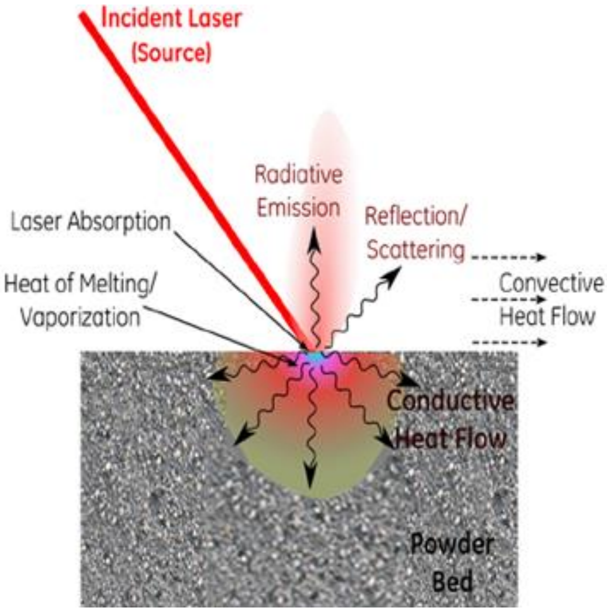


Figure 18. Heat transfer paths in laser sand mould engraving. Only part of the delivered laser energy absorbs into processed material. Rest of the delivered energy loses to conduction, reflection, convection and radiation (Mod. Spears & Scott 2016).

4.9 Laser scanner heads

Moving laser beam is one important part of laser processing. Laser beam focal point moving can be accomplished in several ways. Commonly laser scanners which may be pre- or post-objective are used to move laser beam by two X-Y or three X-Y-Z axes. Scanning mechanisms often use galvanometers with reflective mirrors which are able to form a working area either in two or three dimensions (Laser Focus World 2016). Figure 19 illustrates three-dimensional laser scanner head with its components.

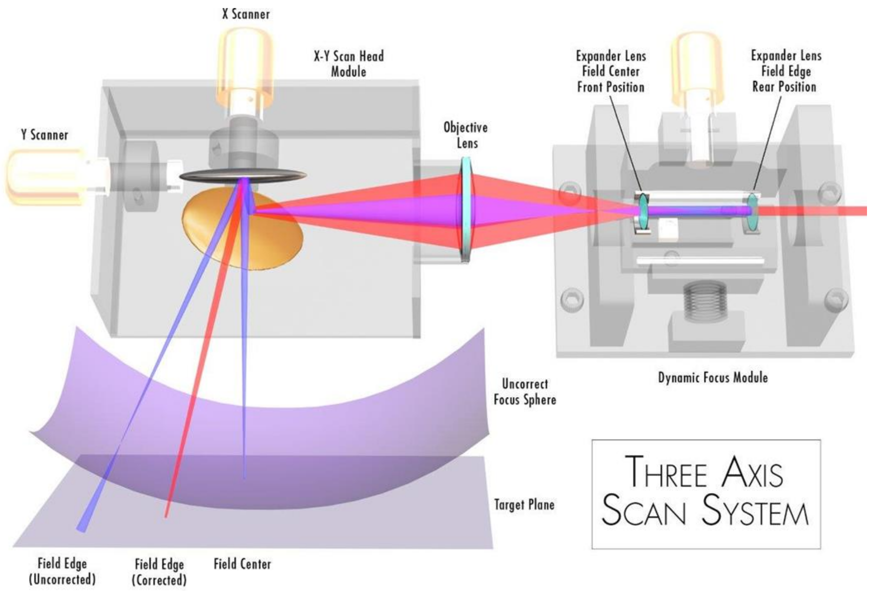


Figure 19. Schematic of a three-dimensional laser scanner head. Laser beam can be moved in X-Y-Z directions with high speeds by galvanometers with reflecting mirrors (Cambridge Technology 2017).

4.10 Implementation of laser engraving system to foundry production line

To implement a laser engraving system to foundry production line at Componenta Högfors the laser engraving system would be positioned over the string of drag side mould halves to area between automatic moulding machine before assembly of cope and drag side of moulds.

The challenge in implementing laser marking system to foundry moulding line is that the position of required marking changes with each produced batch of castings. Casting batch sizes in Componenta Högfors foundry typically vary from few moulds to several hundreds of moulds. Mould cavity size, position, depth and number of cavities per mould depend on the produced castings geometry and production method.

The flask size at Componenta Högfors horizontal moulding line is 1160x960x350+350mm. Practically this means that the required working area of suitable laser scanner head for laser engraving should be close the size of one flask. Three-dimensional working area of approximately 1000x800x300mm would be enough to sufficiently engrave drag side moulds for all required geometries in production. Figure 20 illustrates suggested position of laser scan head over horizontal moulding line at Componenta Högfors foundry and required working area dimensions for the laser beam.

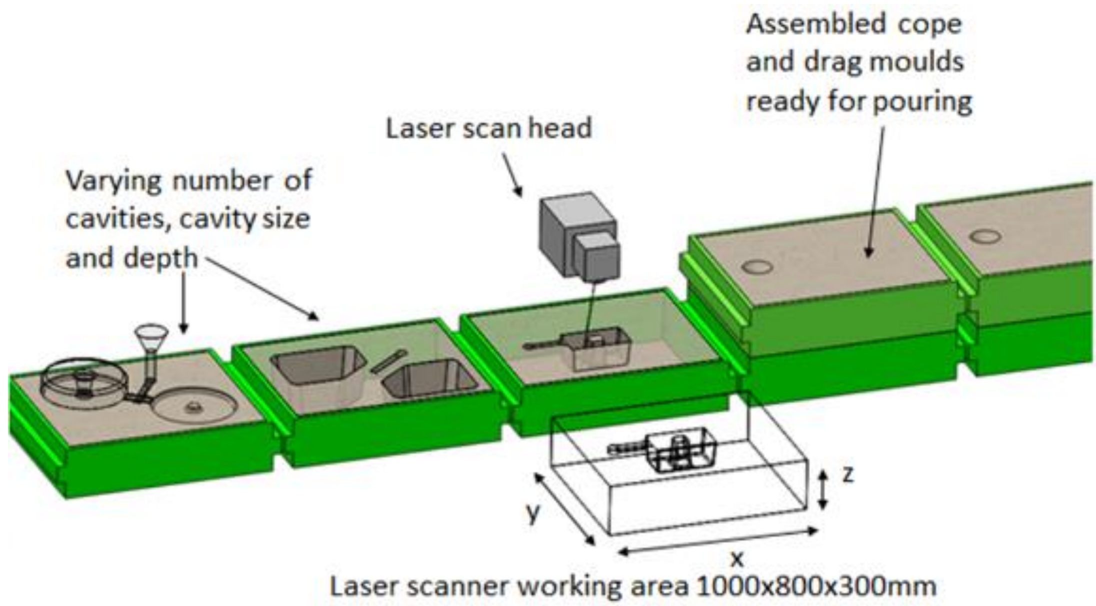


Figure 20. Imaginary laser engraving system implemented to horizontal moulding line at Componenta Högfors foundry. Varying number of mould cavities, cavity size and depth depend from the production batch. Different alternatives require relatively big working area for laser scanner.

As many of the laser scanner heads intended for laser marking on the market offer relatively small working areas. For instance, Trumpf Trumark 3130 has working area of 290mm^2 x 290mm, with f = 420mm (Trumpf laser 2016). Therefore, an auxiliary system would be needed to increase the working area. One possibility to increase the working area of the laser, so that it would cover the whole flask size area would be attaching laser head to robot arm or to X-Y-Z gantry table. Instead of using a statically positioned laser scanner, laser scanner could be attached to robot arm or gantry table allowing the movement of laser scanner head over mould cavities. Drawback of such applications is that the moving speed and positioning accuracy for laser beam may not be good as with plain static the laser scanner.

A laser system with auxiliary moving application would presumably lower the investment costs of laser scanner as a scanner with smaller working area could be used, but would require an investment for a robot system or for X-Y-Z gantry table with sufficient payload and reachability. The challenge in such setup would be finding a suitable software interface for positioning the coordination system of auxiliary movements with laser focal point to right position on mould cavity surface.

Most convenient way to realize the system is to use laser type where the laser beam can be delivered inside a fiber. Optical fiber allows the delivery of beam to laser head without disturbance in almost all required positions. CO_2-lasers operating in higher wave lengths require mirrors for beam delivery thus being more complicated in robot arm applications. With gantry table, also CO_2 laser could be used as the beam could be delivered by mirrors along straight moving axes. Figure 21 illustrates a robot arm and X-Y-Z gantry table based laser engraving systems over horizontal moulding line.

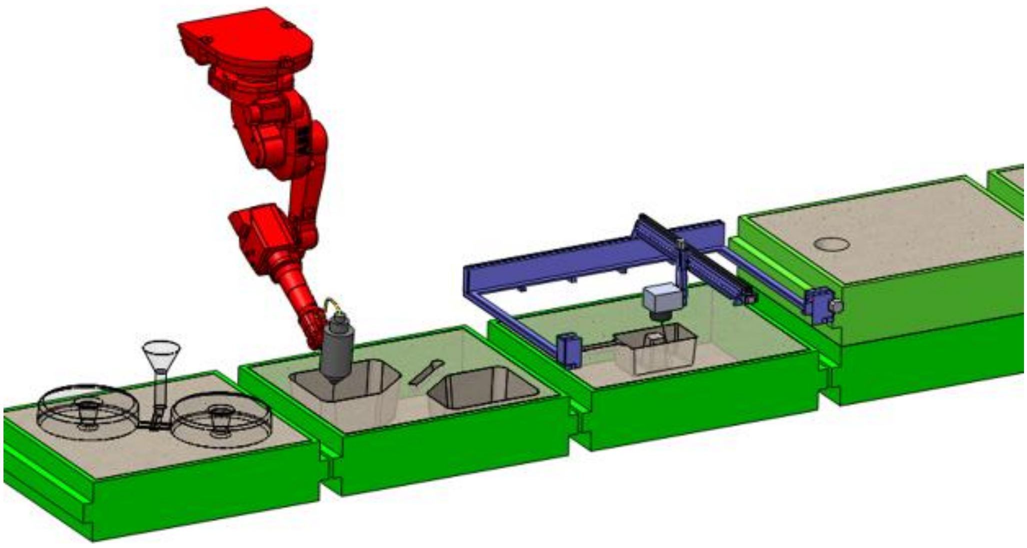


Figure 21. Upside down mounted ABB IRB 1600-robot arm and X-Y-Z gantry table moving fiber laser head over horizontal moulding line. These types of laser engraving applications could reach practically all required mould geometries at Componenta Högfors foundry.

5 EXPERIMENTAL PART

Experimental part of the study was carried out after literature review. From the literature review it was found out that laser engraving of sand moulds would be possible by melting and vaporizing desired areas from the compacted green sand moulds to form text markings shaped recesses on bottom of moulds which would appear in finished casting as raised text marking.

The experimental part of the study was carried out in two parts. In first part, the suitability of different lasers for sand engraving was tested at Lappeenranta University of Technology laser laboratory. Different tested laser systems were CO_2 laser and two fiber lasers with continuous and pulsed power.

In the second experimental part, the target was to get sufficient level laser engraving to a green sand sample that could be used to produce a casting marking. Additionally, the aim was to produce laser engraved sand samples which could be used for pouring actual sample castings. As it was not possible to use laser engraving at actual moulding line to green sand, two different type of sand core moulds were prepared and delivered for engraving to LUT laser laboratory and brought back to Componenta Högfros foundry for casting.

5.1 First sand engraving test

The aim of the first experimental test was to find out which type of laser would be suitable for engraving green sand moulds and what type of laser parameters would result a clear marking in sand moulds. Intention of the test was to find a suitable laser system which could replicate a typical foundry text marking, in this case three letters with 8mm font height as 1mm deep recess on surface of sand sample.

Engraving test was carried out at Lappeenranta University of Technology laser laboratory. The experimental setup consisted of three different types of laser workstations including CO_2 laser engraving and cutting station, continuous wave fiber laser and pulsed fiber laser systems which were tested for engraving foundry sand samples in different forms. Tested sand samples included a hand moulded green sand specimen, an American Foundry Society (AFS) standard 2x2 inch green sand compactibility sample and a cold-box core sand bar. Table 2 illustrates the details of tested laser workstations used for each engraved material.

Table 2. Tested laser workstation details and engraved materials

Laser workstation	**Power (Peak)**	**Beam type / Focal spot diameter Ø**	**Wavelength**	**Engraved material sample types**
CO_2 laser engraving and cutting station	120 W (135W)	continuous wave 0.15 mm	10600 nm	Hand moulded green sand specimen Cold box core sand bar
Continuous wave fiber laser	200 W (240W)	continuous wave >0.10 mm	1070 nm	Hand moulded green sand specimen
Pulsed fiber laser	20 W (10–15 kW)	pulsed wave 0.07 mm	1070 nm	Hand moulded green sand specimen AFS 2x2-in. specimen Cold box core sand bar

5.1.1 CO_2 laser engraving and cutting work station

First engraving tests were carried out with Bodor BCL-1309XU CO_2 laser cutting and engraving work station. The work station consisted of a programmable XY-table carrying a laser head with beam from a CO_2 laser power unit. Laser beam was produced in sealed, water cooled tube. The maximum continuous power of the system was 120W with peak power of 135W. Maximum processing speed of system was 60000 mm/min.

The working station was tested for hand moulded green sand sample and for cold box core sand bar. Several test runs were carried out with different engraving laser speeds, and powers up to maximum scale. Final test runs were done with high end power, lower engraving speed and repetition. Figure 22 illustrates sand core engraving with CO_2 laser cutting and engraving machine.

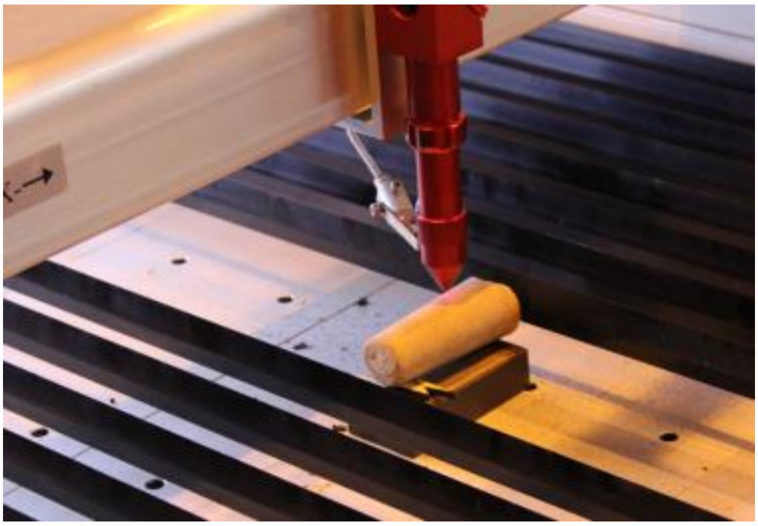


Figure 22. Bodor 120W CO_2 laser cutting and engraving system tested for laser engraving of a cold box sand core.

5.1.2 Continuous wave fiber laser

Second sand engraving test was carried out by a continuous wave fiber laser. This work station consisted of YLS-200-SM-WC ytterbium fiber laser unit with 200W power, a laser scan head and PC which was used to control the system. The wave length of the laser was 1070 nm. Maximum processing speed of the laser scan head was 2000 mm/s. The focal spot diameter was less than 0.1 mm.

Continuous wave fiber laser was tested for hand moulded green sand sample with different parameters. Several test runs were made step by step slowing the laser scanning speed and increasing the laser power up to high power range. Figure 23 illustrates engraving of hand moulded green sand sample with continuous wave fiber laser.

Figure 23. Continuous wave fiber laser tested for engraving hand moulded green sand sample.

5.1.3 Pulsed fiber laser

Last tested laser system which was capable of producing the highest peak power was a pulsed fiber laser. This laser workstation consisted of an IPG 20W fiber laser power unit with Q-switching feature for pulsing, laser scan head and a PC which was used to control the system. The wave length of the laser was 1070 nm.

The system was used in pulsed mode with different pulse lengths at high end power to engrave hand moulded green sand sample, AFS test sample and sand core bar. Peak laser power varied between 10 – 15 kW during the test runs. Figure 24 illustrates testing of laser engraving with 20 W pulsed fiber laser system.

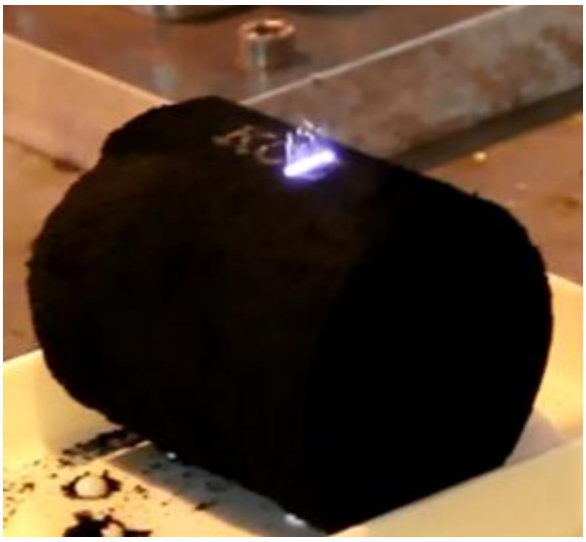


Figure 24. Pulsed fiber laser tested for engraving AFS 2x2-in. green sand compactibility test specimen.

5.2 Second sand engraving test

Aim of the second sand engraving test was to get better results for green sand samples and produce engraved sand samples which could be actually used for pouring actual castings. All laser engraving tests in second test round were carried out with 20-watt fiber laser in pulsed mode as it gave the most promising results of all tested laser systems during first test round.

What was learned from first trial round with green sand was that the tested samples were too soft and spongy and did not therefore resemble hard rammed sand moulds in a foundry produced with automatic moulding line. In order to replicate more the moulds at foundry environment, the idea was to build a manual press which could be used to produce harder sand samples at laser laboratory before laser processing. In order to validate the hardness of sand samples after pressing, a green sand compression strength gauge was used to validate, that the compression strength corresponded to average moulds at Componenta Högfors foundry. Figure 25 illustrates built manual press used for producing sand samples and green sand compression strength gauge used to validate foundry mould conditions.

Figure 25. Built manual press used for producing sand samples at laser laboratory and Georg Fischer green sand compression strength gauge used to validate foundry mould conditions.

5.2.1 Engraving test for compressed green sand sample

Aim of the test was to replicate the green sand mould conditions at Componenta Högfors foundry and engrave text markings with fiber laser to sand samples possessing similar features as green sand moulds in foundry environment.

Green sand moulds at Componenta Högfors foundry where moulds are produced by HWS automatic moulding line are typically quite hard rammed. In order to validate that sand sample conditions corresponded to automatically produced moulds, a Georg Fischer green sand compression strength gauge was used to validate sand sample properties. Typical green sand compression test values at Componenta Högfors foundry normally vary between 10-30 kN/m^2 depending from the measurement location. Measured values for green sand samples in laser engraving test were 10.5 and 11.2 kN/m^2.

After validation of sample compression strength, 20W pulsed laser was used to engrave text marking recess to green sand sample. Laser parameters were chosen to be similar as in the first test round. Engraved marking was text “KOE” with 8mm height and approximately 20mm wide with bolded font. Laser engraving test for manually compressed green sand specimen was conducted three times by changing the number of repetition cycles of lasers path. Figure 26 illustrates validation of green sand sample conditions and laser engraving of manually compressed green sand sample with fiber laser.

Figure 26. Testing green sand compression strength of sand sample to validate Componenta Högfors foundry mould conditions and laser engraving of manually compressed green sand sample with pulsed fiber laser.

5.2.2 Laser engraving of core sand samples for casting

One target of the second experimental test round was to produce laser engraved sand samples which could be actually casted to see if it would be possible produce a text marking into actual iron casting.

As the laser engraving tests were conducted at Lappeenranta University of Technology laser laboratory where it was not possible to melt iron for pouring, the sand samples had to be brought back for casting to Componenta Högfors foundry in Karkkila. Another issue was that green sand samples dry and degrade very quickly after moulding process so it would have been very difficult to deliver them back to foundry for pouring in good condition.

In order to get some results how laser engraved moulds would work in actual casting, the idea was to laser engrave tensile strength test bar moulds which were produced by core shooter. Samples produced with core shooter have amine-gas cured resin tying the sand grains together, which makes sand cores more durable and hence transportable between laser laboratory and foundry without degrading.

Again, 20W pulsed laser was used for engraving core sand samples, including several smaller cores and bigger core which is normally used for producing cast iron tensile strength specimens at foundry. Engraved marking was the same as earlier, text “KOE” 8mm height and approximately 20mm wide with bolded font. Also for sand cores laser engraving test were conducted for several times by changing the number of repetition cycles of lasers path to see how it affected the depth of engraved text recess. Figure 27 illustrates laser engraving of core sand sample.

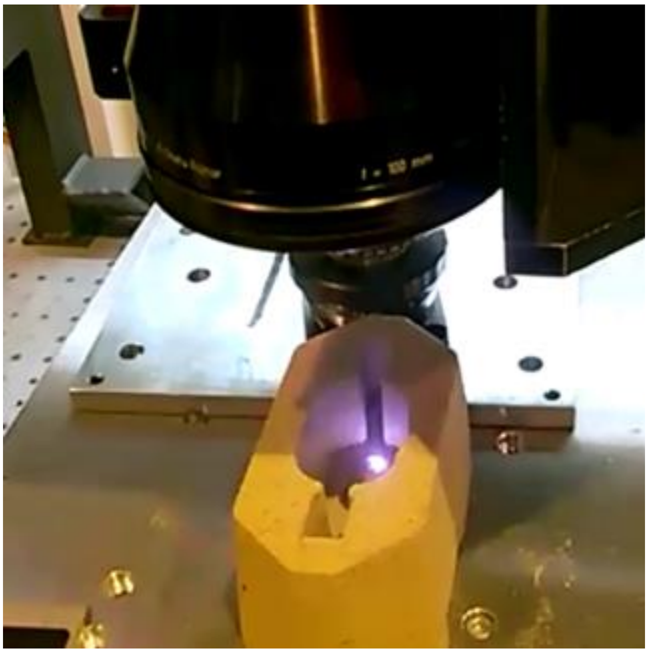


Figure 27. Laser engraving of a core sand sample for casting.

5.3 Pouring of laser engraved moulds

After successful laser engraving tests at laser laboratory core sand moulds with laser engraved text marking were delivered back to Componenta Högfors foundry in Karkkila. There moulds were poured with molten ductile iron at 1400°C temperature. After pouring of moulds they were left for cooling. Three hours later solidified casting samples were ejected from moulds. Finally, castings were cleaned in hanger-type shot blasting machine to remove burnt-on sand and oxide film from the casting surface. Figure 28 illustrates pouring of laser engraved core sand samples.

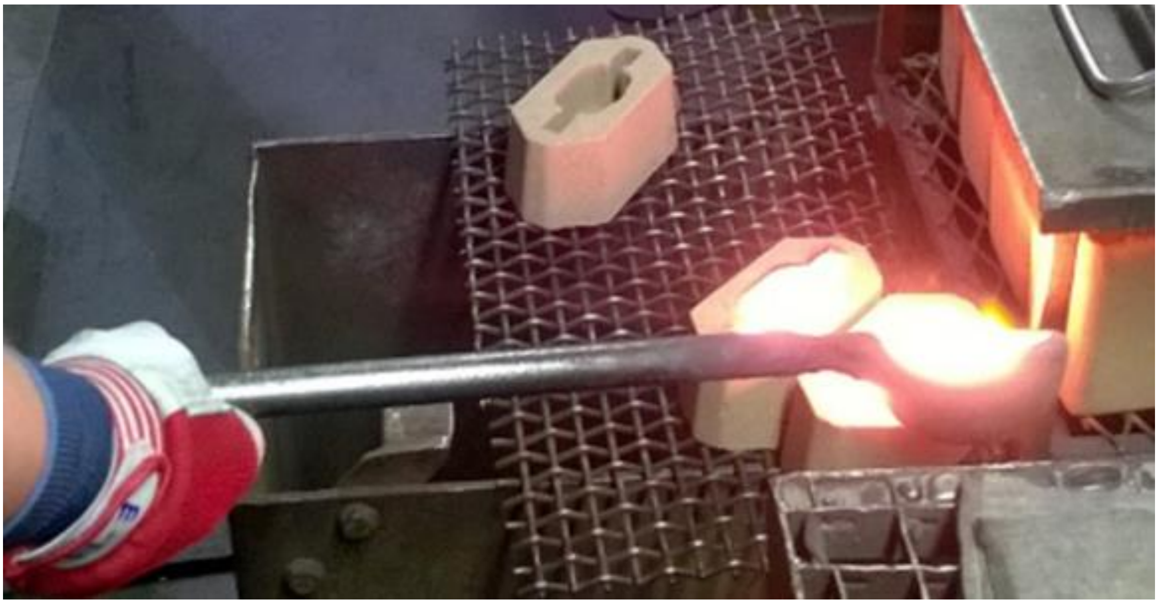


Figure 28. Pouring of laser engraved sand core moulds with molten ductile iron at Componenta Högfors foundry.

6 RESULTS

Results of the study have been divided into three parts. First part presents results from testing different laser systems and parameters to foundry sand. Second part presents results about laser engraving manually compressed green sand sample and core sand moulds which were later used for casting. Third part presents results about cast core sand moulds and finished castings with text marking produced by laser engraving process.

6.1 Results from first sand engraving test

In first sand engraving test three laser systems with different parameters were tested to foundry sand used at Componenta Högfors foundry including green sand and core sand samples.

6.1.1 CO_2 laser engraving and cutting work station

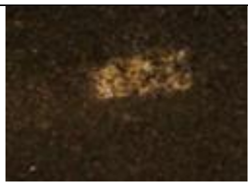
First tested laser, a continuous wave CO_2 laser was tested in to samples which were hand moulded green sand sample and core sand bar.

First results from trials with CO_2 laser to hand moulded sample were not that promising. Processed green sand only changed its color from black to white. Probably the carbon in foundry sand burned into gray ash, but no signs of melting or vaporization were seen. Furthermore, the pressurized air stream shielding the laser heads optics in CO_2 laser workstation pushed an unwanted hole into sand sample. As the focal length in the station was only 6mm, the decision was to continue only with more solid core sand sample where sand grains were tied by resin mixture.

Several test runs were made using different laser power and engraving speed. In general, more power and lower engraving speed than tested would have been required to get more visible results. With almost maximum power the surface of the core sand started melting and resulted glass-like surface, but it seemed that no material was removed from surface. An additional trial was made by changing the laser pattern hatch from 0.2mm to finer 0.1mm option, but that did not affect significantly to the result.

Altogether results with CO_2 laser were promising, but not as desired. Surface of the sand core seemed to melt and re-crystallized into glass-like form. The resulting text marking was quite sharp and clear text, but no material was removed from the surface. None of the gained results with CO_2 laser were sufficient for producing a raised text marking into casting. Table 3 illustrates used process parameters and test results.

Table 3. Process parameters and results from first test with CO_2 laser. H = hand moulded greensand sample, C= Core sand bar, A= AFS 2x2- inch specimen.

	Sample	**Laser power**	**Cutting speed**	**Focal length**	**Result**	**Comment**
Run 1	H	60 W	100 mm/s	6mm		Sand changed color from black to white, air pressure pushed hole in sand
Run 2	C	108W	100 mm/s	6mm		Glassy surface, clear text marking, no material removed from surface
Run 3	C	108W	100 mm/s	6mm		Glassy surface Pattern hatch changed 0.2 → 0.1mm, no significant difference to run 2

6.1.2 Continuous wave fiber laser

Second sand engraving test was made with 200W continuous wave fiber laser. This laser was tested to engrave hand moulded green sand sample. Several test runs were conducted step by step increasing the laser power and simultaneously slowing down the processing speed.

In the first runs green sand changed its color from black to white, but was not showing any signs of melting. Following runs with higher power and slower processing speed resulted similar white marks, but no melting was occurring. During last run with full 240W power sand started melting and re-crystallized into glassy form. Despite the melting effect, no material was removed from the surface of the sand sample. Laser system was not seen suitable for producing a sufficient recess to produce text marking in casting. Table 4 illustrates used process parameters and results from the test.

Table 4. Process parameters and results from first test with continuous wave fiber laser. H = hand moulded greensand sample, C= Core sand bar, A= AFS 2x2- inch specimen.

	Sample	**Laser power**	**Scanning speed**	**Focal length**	**Result**	**Comment**
Run 1	H	20W	1000 mm/s	255 mm		Sand changed color from black to white, no melting appeared
Run 2	H	50W	1000 mm/s	255 mm		Sand changed color from black to white, no melting appeared
Run 3	H	200W	500 mm/s	255 mm		Sand changed color from black to white, slight melting appeared
Run 4	H	240W	200 mm/s	255 mm		Sand melted resulting glassy surface, blurry text, no material removed from surface

6.1.3 Pulsed fiber laser

Third tested system was a pulsed fiber laser with 20 watts power. Despite the low nominal power value, this system was capable of producing short nano-second pulses with peak power up to 15 kW. Pulsed fiber laser was tested for engraving all three sand sample types.

Already in the beginning of tests the system showed its capabilities of melting and actually removing material from the surface of test specimens.

First test run was made for hand moulded green sand sample. Material was removed from the surface of the sample, but the result was quite blurry and unclear. Several test runs were made by increasing the power and repeating the lasers path up to three cycles. Last test runs started showing clearer result, but it was not still good enough to produce a clear text marking for casting. As the greensand sample was only hand moulded, it seemed too soft and spongy to be engraved.

Second test was made for AFS-type 2x2-inch sand compactibility test sample. AFS sample is a standard test used by green sand foundries. AFS test sample is produced by ramming a green sand sample by dropping a weight over certain volume of sand. Test runs for rammed sample showed better results than for hand moulded green sand sample, but were not perfect. With higher power, slower processing speed and shorter laser pulses again occurred melting of sand resulting glassy surface on processed areas. On last test runs with higher laser power, there was less material vanishing from the surface of samples and glassy surface appeared on processed areas.

Third test was conducted to sand core sample. This test was from the beginning a success. Immediately on the first test run a noticeable amount of sand vanished away from the surface of sample. An additional run was made with slower processing speed by repeating the process cycle twice.

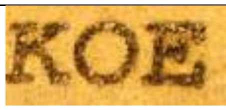
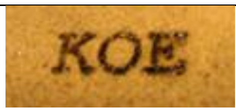
The result was a clear, about 1mm deep recessed text marking. Only some loose sand particles could be seen in the bottom of engraved text recess. The initial conclusion was that as sand in the core sample was packed into more dense form, laser beam was able to engrave material more easily away from the surface.

All in all, result from engraving of core sand were very promising and presumably good enough to produce a clear marking on cast surface if the engraved core would have been put in a mould and poured with melt. Table 5 illustrates used process parameters and results.

Table 5. Process parameters and results from first test with pulsed fiber laser. H = hand moulded greensand sample, C= Core sand bar, A= AFS 2x2- inch specimen.

	Sample	**Laser power**	**Focal length**	**Cutting speed**	**Pulse frequency and length**	**Result**	**Comment**
Run 1	H	10W	100 mm	1000 mm/s	80 KHz 30ns		Some material removed from surface Unclear marking
Run 3	H	5W	100 mm	700 mm/s	80 KHz 30ns		Repeated cycle - 3 times Some material removed from surface Unclear marking
Run 4	H	10W	100 mm	700 mm/s	80 KHz 30ns		Repeated cycle - 3 times Some material removed, Unclear marking
Run 5	A	10W	100 mm	700 mm/s	80 KHz 30ns		More material removed from surface
Run 6	A	20W	100 mm	400 mm/s	20 KHz 200ns		Bolded text Repeated cycle - 3 times Some material removed from surface, glassy finish,
Run 7	A	20W	100 mm	100 mm/s	500 KHz 4ns		Bolded text Repeated cycle - 3 times No material removed from surface, Glassy finish

Table 5 continues. Process parameters and results from first test with pulsed fiber laser. H = hand moulded greensand sample, C= Core sand bar, A= AFS 2x2- inch specimen.

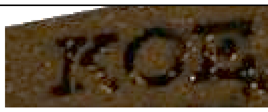
Run 8	C	20W	100 mm	400 mm/s	20 KHz 200ns		Repeated cycle - 3 times Good clear marking 1mm material removed from surface, some loose sand particles in recess
Run 9	C	20W	100 mm	600 mm/s	40KHz 100ns		Repeated cycle - 2 times Good clear marking 1mm material removed from surface, some loose sand particles in recess

6.2 Results from second sand engraving test

All laser engraving tests in the second round were carried out with 20W pulsed laser system using similar process parameters as in last runs of the first test round that gave the best results.

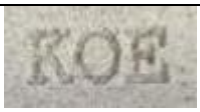
First engraving tests were done for manually compressed green sand samples. Compared to earlier tests with softer hand moulded green sand samples, laser engraving worked significantly better for denser and harder green sand samples which were manually compressed and resembled more actual foundry conditions. A substantial difference to engraving result was noticed when laser scanning pattern hatch parameter was changed to denser option. With denser scanning pattern hatch, much more material was removed away from the working area. Also, the sound during laser processing was louder than earlier. Results from last runs were really promising. Only some loose sand particles could be noticed at the bottom of recess. Otherwise laser engraved text for green sand seemed to be totally suitable for casting purposes. Table 6 illustrates used process parameters and results from second green sand engraving test.

Table 6. Process parameters and results from second engraving test with pulsed fiber laser M = manually compressed green sand specimen.

	Sample	**Laser power**	**Focal length**	**Cutting speed**	**Pulse frequency and length**	**Result**	**Comment**
Run 1	M	20W	100mm	400mm/s	20 KHz 200ns		sparser pattern hatch, 0.5mm deep recess
Run 2	M	20W	100mm	400mm/s	50 KHz 60ns		sparser pattern hatch, 0.5mm deep recess
Run 3	M	20W	100mm	400mm/s	20 KHz 200ns		denser pattern hatch, 1mm deep recess, few loose sand particles in recess
Run 4	M	20W	100mm	400mm/s	20 KHz 200ns		denser pattern hatch, 2 times repetition, 1.5mm deep recess, few loose sand particles in recess
Run 5	M	20W	100mm	400mm/s	20 KHz 200ns		denser pattern hatch, 3 times repet., 2 mm deep recess, few loose sand particles

Second round of laser engraving tests was done for two different types of sand core samples. The idea with sand cores was to engrave text markings with different depths and cast them at foundry. Similar process parameters which worked for green sand samples were used also for sand cores. Table 7 illustrates used process parameters and results.

Table 7. Process parameters and results from second engraving test for sand core samples with pulsed fiber laser. S = small core B= big core.

	Sample	**Laser Power**	**Focal length**	**Scanning speed**	**Pulse frequency and length**	**Result**	**Comment**
Run 1	S	20W	100mm	400mm/s	20 KHz 200ns		Repeated cycle - 2 times, clear marking 1mm deep recess
Run 2	S	20W	100mm	400mm/s	20 KHz 200ns		Repeated cycle - 2 times, clear marking 1mm deep recess
Run 3	B	20W	100mm	400mm/s	20 KHz 200ns		No repetition, slightly blurry marking, 0.5mm deep recess
Run 4	B	20W	100mm	400mm/s	20 KHz 200ns		Repeated cycle - 2 times clear marking 1mm deep recess
Run 5	B	20W	100mm	400mm/s	20 KHz 200ns		Repeated cycle - 3 times Good, clear marking 2mm deep recess

6.3 Results from casting test

To see how text marking produced by laser engraved moulds would stand out in actual iron castings, engraved core sand samples were delivered back to Componenta Högfors foundry for casting. Sand cores were poured with ductile iron melt taken from pouring of ladle in actual production process. After three hours solidification time, core sand moulds were broken and solidified castings were cleaned by shot blasting process to remove burnt on sand and oxide-film.

Cleaned castings showed very positive results. All engraved markings turned out to be clear text markings on cast surface. Despite some loose sand grains were noticed during laser processing of sand cores on bottom of engraved recesses, they did not show as surface defects on final cast surface.

For bigger sand core sample three different type of markings were engraved with different number of processing cycles and processing time to see how deep recess would be actually required to produce a visible text marking. Even the shallowest recess which was processed only once with shortest processing time and looked blurry in sand core turned out to be more or less clear text marking on cast surface. Sample which was processed three times stunt out very clearly and seemed almost unnecessarily high. Figure 29 illustrates sample castings with different processing times and how text markings stunt out on cast surface.

Figure 29. Sample castings with different height text marking produced by laser engraving process. Text marking height depended on the depth of laser engraved recess which increased when laser processing cycles were repeated.

With laser scanning speed of 400 mm/s which was used in test, a three-letter text marking for instance consecutive numbering for one casting cavity could be accomplished in 8 or 16 seconds within Componenta Högfors moulding line cycle time. By optimizing the laser process parameters, scanning speed and surface quality of text marking could be even increased.

All in all laser engraving process seemed to work perfectly for iron castings. Raised text markings were clear and resembled like conventionally produced static text markings. Text markings on sample castings were also durable enough as they could easily stand the relatively tough foundry shot blasting process. Figure 30 illustrates sample castings with cast text marking produced by laser engraving process.

Figure 30. Sample castings with raised text marking produced by laser engraving process.

7 DISCUSSION

Traceability

First key finding of the study was that part traceability in foundry with automatic moulding line could be improved by consecutive marking in each casting. By improved traceability the root cause in defected castings could be more easily identified and cured when recorded process parameters can be linked to solidified and cleaned casting. As an example, a defected casting with pouring temperature related issue can be traced back to incorrect process parameters. Laser marking of sand moulds would allow a fast and flexible way to identify poured moulds for instance by consecutive numbering.

Laser marking application would not substitute conventional static text marking in castings, but would be an assistive tool to improve traceability. Conclusion was that static text markings would be still be required for identification of patterns in production. It would be also good to have static marking for back-up in failure situation of laser system.

Laser selection

Three alternative lasers were studied for the purpose: CO_2 and fiber lasers with continuous and pulsed wave modes. From these three alternatives fiber laser with pulsed wave mode seemed to be most suitable for laser engraving of sand moulds.

In the experimental part, clearly best results were gained with pulsed fiber laser. Pulsed laser seemed to be most suitable for the purpose with higher peak power efficiency which seemed to be the deal breaker. The reason why tested continuous wave lasers did not seem to work very well for laser engraving of sand moulds was assumed to be lack of power density. Probably both CO_2 laser and continuous wave fiber laser with suitable power to be able to vaporize mould sand could also be suitable for the purpose. Even though two laser types with different wavelengths (1070 nm and 10600 nm) were tested, the impact of wavelength to beam absorption could not be verified.

The condition of processed material seemed to have a significant difference to the end result. Generally sand cores were most suitable for laser engraving. The assumption was that higher density and better surface quality compared to green sand specimens had clearly a positive effect to the end results. With green sand specimens, this could be clearly verified when the density and compactness of sand sample was increased by manual press during second test round. Significant difference of absorptivity of laser beam to darker green sand including coal powder compared to lighter core sand could not be clearly verified.

Even though actual green sand moulds could not be casted in the study due to their degrading feature, it was clear that laser engraving process worked also for green sand samples which were manually compressed. Laser engraved text markings in green sand samples were very similar as with sand core samples. Sand core moulds which were poured with molten iron gave good picture how laser engraved moulds result a clear text marking on casting surface. Based on the studies it can be assumed that laser engraving could be applied in similar way to green sand moulds as for the core sand samples.

Implementing laser system to foundry moulding line

It was noticed that in order to implement a laser engraving system to Componenta Högfors horizontal moulding line, a laser with large three-dimensional working area for the laser would be needed to cover all possible mould cavity geometries. This would require either a special laser scan head with very large three-dimensional working area or an auxiliary system for moving the laser scan head around the working area. The most challenging direction to cover is vertical Z-axis i.e. laser focal length direction which in most laser scan heads seem to be shortest. The proposed solution for implementing laser engraving system to horizontal moulding line would be an industrial robot or alternatively XYZ gantry table for moving the laser scan head. Requirement to move the laser head would be probably easier to realize with fiber laser where beam could be delivered in optical fiber cable vs. complicated mirror systems required by the CO_2 laser. On the other hand, XYZ gantry table would also allow the use of mirrors for laser beam delivery along straight axes.

The study did not take into consideration laser safety, and how it should be taken into consideration while implementing a laser system into foundry moulding line.
From casting marking perspective, it was concluded that at Componenta Högfors foundry laser engraving would be probably utilized to mark only consecutive numbering to each casting. This type of system could be realized as automatic system which would recognize planned production batch according to foundry enterprise resource planning (ERP) system and link correct laser path with robot program according to each part geometry. In order to realize such system, a special interface between foundry ERP system, laser scanner controller and industrial robot would be needed. Each production batch would require its own program so that engraving would be positioned to right place in each mould half.

One idea to even improve the benefits of laser marking system would be implementing a CCD camera over moulding line which would automatically take photos of each mould before assembly of moulds. With traceability provided by laser engraving process, possible pitfalls also in moulding and core setting could be traced back to pictures of defect-prone moulds and cured.

8 CONCLUSION

A novel application for laser processing to produce unique casting markings by laser engraving of moulds such as consecutive numbering within the cycle time of an automatic moulding line was presented. Unique marking in each casting provided by laser engraving of moulds would allow full traceability of individual casting to exact production parameters recorded in foundry CIM system improving, internal quality level, production yield and quality assurance.

For future research, more study would be needed about how the process parameters of laser engraving of sand moulds could be fine-tuned to even increase speed and improve quality of markings. One issue which rose in the study is the required large working area of laser beam and how it could be increased to easily cover all possible mould geometries for instance in a case where eight separate cavities in one mould half would need to be engraved within the moulding line cycle time. Also, laser safety in foundry environment was not taken into consideration in the study.

All in all, writer believes that laser processing could not be only used to solve part traceability issue in foundries with automatic moulding process, but also open many other opportunities to casting industry.

REFERENCES

American Foundry Society. Cores' Role in Casting Design [American Foundry Society web-site]. [Retrieved 4.12.2016]. Available: http://www.afsinc.org/content.cfm?ItemNumber=6926

Beeley, P. 2001. Foundry Technology. Second edition. Butterworth-Heinemann. 732 p.

Brierre, R. 2016. Diagram of a Carbon-Dioxide Laser (CO2). [Retrieved 2.1.2017]. Available: https://commons.wikimedia.org/wiki/File:Laser_CO2.png

Cambridge Technology. 2017. 3-Axis Scan Heads. [Retrieved 4.4.2017]. Available: http://www.cambridgetechnology.com/products/3-axis-scan-heads

Chen, T. C. & Darling, R. B. 2005. Parametric studies on pulsed near ultraviolet frequency tripled Nd:YAG laser micromachining of sapphire and silicon. Journal of Materials Processing Technology, 169: 2. Pp. 214–218.

Dahotre, N. B. & Harimkar, S. P. 2008. Laser Fabrication and Machining of Materials. Boston, MA: Springer Science + Business Media, LLC. 565 p.

Deprez, P. Melian, C. Breaban, F. Coutouly, J. 2012. Glass Marking with CO2 Laser: Experimental Study of the Interaction Laser – Material. Journal of Surface Engineered Materials and Advanced Technology, 2: 1.

Disa Group. 2016. Complete foundry. [Retrieved 4.11.2016]. Available: http://www.disagroup.com/en/sites/disa/content/equipment/complete_foundry.aspx

Disa Group. 2017. Core technology. [Retrieved 29.4.2017]. Available: http://www.disagroup.com/en-gb/whats-new/disa-videos-and-animations/core-technology

Industrial laser solutions for manufacturing. 2012. Laser marking with fiber lasers. [Retrieved 21.11.2016]. Available: http://www.industrial-lasers.com/articles/print/volume-27/issue-05/features/laser-marking-with-fiber-lasers.html

Ion, J. 2005. Laser processing of engineering materials: principles, procedure and industrial application, Elsevier-Butterwort- Heinemann, Oxford, UK. 570 p.

Joshi, S. N. Dixit, U. S. 2014. Lasers Based Manufacturing. 5th International and 26th All India Manufacturing Technology. Design and Research Conference. Springer India 2015.

Kaast-CNC. 2017. CO_2 SLAB Lasers. [Retrieved 3.4.2017]. Available: http://www.kaast-cnc.com/_technology_center/_cuttingsystem/_lasersources

Laser Focus World. 2016. [Retrieved 10.12.2016] Available: http://www.laserfocusworld.com/articles/print/volume-39/issue-4/features/scanners/post-objective-mirrors-allow-for-large-fields.html

Limpert, J. Schreiber, T. Tünnermann, A. 2016. Fiber based high power laser systems. Friedrich Schiller University Jena, Institute of Applied Physics, Albert-Einstein-Str.15, Jena, Germany.

Milne, I. Ritchie, R. O. Karihaloo, B. 2008. Comprehensive Structural Integrity. Castings. Jolly, M. Elsevier Science Ltd.

Moderneq, 2016. Molten metal handling solutions. [Retrieved 20.12.2016]. Available: http://www.moderneq.com/foundry/Asset/Molten-Metal-Handling-Solutions-400x300.jpg

National Aeronautics and Space Administration, 2008. Nasa Technical Handbook. NASA-HDBK-6003C. Application of Data Matrix Identification Symbols to Aerospace Parts Using Direct Part Marking Methods/Technique. [Retrieved 13.5.2016]. Available: https://standards.nasa.gov/file/487/download?token=4WkaKr4L

Physics World. 2016. Further Physics – What is laser? [Retrieved 1.2.2016]. Available: http://www.phy.cuhk.edu.hk/phyworld/articles/laser/laser_e.html

Primes. 2017. Central formulae for beam measurement. [Retrieved 5.4.2017]. Available: http://www.primes.eu/en/beam-diagnosis/formulary.html

Rao, T. V. R. 2003. Metal Casting Principles and Practice, New Age International, New Delhi, India. 255 p.

Restrepo, J. W. Fernandez-Pradas, J. M. Gomez, M. A. Serra, P. Morenza, J. L. 2006. Influence of preheating and hematite content of clay brick pavers on the characteristics of lines marked with a Nd:YAG laser. Applied Surface Science.

Spears, T. Scott, A. 2016 In-process sensing in selective laser melting (SLM) additive manufacturing. Integrating Materials and Manufacturing Innovation, Springer.

Steen, W. M. & Mazumder, J. 2010 Vol. 4. Laser Materials Processing. London: Springer-Verlang. 567 p.

Stefanescu, D. M., 1998. ASM Metals Hand Book Volume 15 - Casting. ASM International

Trumpf laser. 2016. Marking with TruMark: Marked simplicity. [Retrieved 28.12.2016]. Available: http://www.trumpf-laser.com/en/products/marking-lasers.html

VDA 5005. 2005. Traceability of Vehicle Components and Identifiability of Their Technical Design. German Association of the Automotive Industry. Berlin.

Vedel-Smith, N. K. Lenau, T. A. Casting traceability with direct part marking using reconfigurable pin-type tooling based on paraffin-graphite actuators. Department of Mechanical Engineering, Technical University of Denmark. [Retrieved 11.5.2016]. Available: http://www.sciencedirect.com/science/article/pii/S0278612511001002

Wheel Laborator Group, 2016. Overhead Rail Shot Blast Machine. [Retrieved 28.12.2016]. Available: http://www.wheelabratorgroup.fr/images/overhead%20rail%20shot%20blast%20machine_frontview%20520%20pix.jpg