THERMAL SIMULATION MODELLING FOR SUBSTRATE MATERIAL DURING LASER CLADDING PROCESS OF THIN SECTION COMPONENTS

Lappeenranta–Lahti University of Technology LUT

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Examiners: D.Sc, Ilkka Poutiainen

M.Sc (tech), Sami Westman

ABSTRACT

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Thermal simulation modelling for substrate material during laser cladding process of thin section components

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In this master's thesis work thermal simulation model creation for cladding process is being gone through. First thesis work goes through basic principles of laser technology and going more deeper into theories of different laser types, properties and benefits of use.

Thesis states out actual customer needs for thermal simulation tool to be made into their manufacturing process. Need for thermal analysis tool is to be able to estimate and prognose maximum temperature levels during customers manufacturing process with directed energy deposition process. Customer requirement was at first hand that simulation tool, model should be as accurate as possible for temperature prediction. Also, model should be adaptable to various shapes and sizes of components to be processed.

Simulation model calibration, build-up was made with constant communication with customers production unit. Tests during calibration model build-up phase were possible and were made, this to achieve as good simulation model as possible.

Validation tests were performed for finished simulation model at customers production unit. Results form validation tests were accepted by customer.

Future needs for further development are explained.

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Abbreviations

LAM-LDED	Laser Metal Manufacturing-Directed Energy Deposition
DED	Directed Energy Deposition
LMD	Laser Metal Deposition
SKF	Svenska Kullager Fabriken
NDA	Nondisclosure agreement
AM	Additive manufacturing
nd:YAG	Neodymium-doped Yttrium Aluminium Garnet
CO2	Carbon dioxide
SLS	Selective laser sintering
PBF	Powder bed fusion
LD	Laser Diode
HPDL	High power diode laser
BA-HPDL	Broad area high power diode laser
BPP	Beam Parameter Product
FWHM	Full Width at Half Maximum
LAM	Laser Additive Manufacturing
EHLA	Extreme High Speed Laser Cladding
WPS	Welding Procedure Specification
W/m2K	Thermal conductivity
FEM	Finite Element Method

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1 Introduction

This master's thesis work is about creating a thermal simulation model for Laser cladding process. Goal is to create a simulation model which illustrates the minimum- maximum and mean temperatures in appointed thin section components based on created simulation model and given laser parameters.

SKF Ab, Sweden, later referred as a "customer" ordered this study to get a working simulation model for their usage to evaluate the temperature behaviour of selected thin section components which they may use in their manufacturing process. All laser parameters, laser types, substrate material, added material information's are given to work by customer.

Thermal simulation model is vital to create, this to reduce the amount experimental tests to products for defining production parameters for LMD process. Customer especially needs to know the maximum temperature levels during LMD process in component.

This study is the first of its kind made for SKF Ab, Sweden, where a selected welding simulation software is utilized for calculation and simulation temperature behaviour in selected components to be processed with laser cladding process. Master's thesis topic was narrowed down to handle thermal imaging, simulation and behaviour only for process and components. Mechanical behaviour was excluded solely from this work. Also, based of agreement, in both, substrate and added material specification's, information is to be generalized due to no nondisclosure agreement (NDA) has not been signed between customer and University. Scope for this master's thesis was to research simulate how energy input with certain parameter is affecting the component and for its temperatures.

Results were compared into real life temperature measurements in production site with multiple pyrometers. After model approval from customer, a generalized base model for component was created and based on internal work's data a new updated simulation calculation was done. Validation tests were performed on-site to test out the accuracy of created simulation model.

2 Research problem and justifications to solutions

In this chapter background information and research problem to be solved for this master's thesis work are being explained.

2.1 Background for work and research problem description

This innovation is utilizing Laser Cladding process as a manufacturing method. Main idea is to coat two different materials, substrate and added layer together with high quality. By adding different material on top of another, cost savings can be achieved, and it is possible to combine and enhance the best qualities and properties of both materials in one final product. Main drivers for combining two materials in their products are material surface enhancements, improving corrosion resistance, improving wear resistance and sustainability in customers product portfolio. By sustainability it is meant, that by means of laser cladding one goal is to make it possible to refurbish product numerous times, and this way to decrease raw material usage.

By implementing this new manufacturing process into their manufacturing line, it has been quickly noticed, that there is a need for thermal simulation model for this manufacturing process. It is vital for customer to know how temperature distributes in components during and after cladding in components. Especially process maximum temperature is important to know, because this is directly influencing components mechanical properties and heat treatments.

The aim is to build a digital twin that is adaptable and adjustable to many different types, sizes of customers products. Main problems are that currently, component temperatures are measured on-the-go during manufacturing with temperature probes manually without controlled measuring point. Other way to see temperature behaviour with new component, is by just trial and error, test.

3 Literature review

In this chapter the fundamental of computational simulation is presented. Different possibilities, ways, methods to do analyses are described. Possible reasons for seeking out simulated output of actual welding, cladding process are opened. Laser technology and principles of laser beam is being introduced. Process description of laser metal deposition is explained.

3.1 Overview of computational simulations

During few past decades or so, simulations for different welding processes have come a necessary and powerful tool for evaluation purposes for welding procedure. With computer aided simulations it is possible to make evaluations, comparisons, validations for e.g. Welding Procedure Specification (WPS). With simulated models of welding procedure and with results from it, is possible to analyse and adjust needed parameters, specifications into process and equipment.

As it is with this master's thesis, it is the same in many other areas of industry with welding processes, live tests for welding procedure validations etc. can be time consuming with practical live test set-ups. With simulation models made with appropriate simulating software, it is possible to get analysed results of work in a fraction of time compared to real life tests. Time saving is in many cases driving force to go with simulation tools for process adjustments in welding process developments. Quality is also in crucial role with welding any sort. Made products with welds or components made completely with different welding or deposition process, e.g. laser metal deposition also requires consistent manufacturing without risks of losing product's quality.

With simulation tools it is possible to analyse, control, measure numerous different aspects and parameters of selected welding process. (Silva et al. 2022, p. 1). There are three ways to approach welding simulations with different extents, according to Silva, et al. 2022, p. 2, these are presented in figure 1.

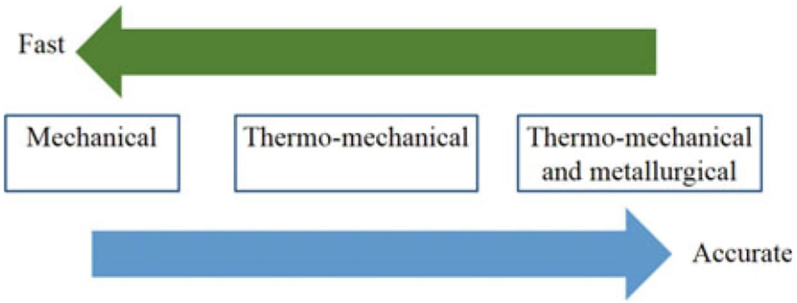


Figure 1. Approaches for welding simulations. (Silva et al. 2022, p. 2)

3.1 Analyse methods in thermal behaviour and prognosis

Prediction of thermal behavior in all kinds of welding processes is vital to knowledge to have or get from manufacturing. There are many ways to approach subject matter in scientific way. Reason to possess knowledge about welding procedures influences in heat generation, distribution inside component is important information to have. Also, how temperature levels are affecting e.g. into steel microstructure, stress levels are in a big role of importance when designing new components, order of welding's, welding parameters etc. Thermal matters also influence directly into possible material selections in substrate materials and added material selections. According to Silva, et al. 2022, p. 2-6, these three main methods analyze methods to research or investigate thermal behavior or temperature distributions in components during manufacturing are experimental methods, analytical methods and numerical methods.

As can be realized from experimental methods for temperature behavior, this method is based on experiments, tests in real environment into real components. Measurements can be done with thermocouples, infrared thermal cameras, pyrometers placed into components. This method can be accurate in quality and results, but on the other hand it is time consuming. Also, this method is not a tool for prediction for thermal measurements, it is a method to state out results after process phase.

Analytical methods on the other hand are based on intensive calculations behind predicting thermal distributions and temperature levels during process. These analytical methods came before modern computers made thermal analysis possible by numerical calculations. Analytical methods are based on the Rosenthal equation, for temperature behavior and its

distribution around heat source in component, while heat source is moving along the weld seam direction. (Silva, et al. 2022, p. 2-6)

With modern day computers, it is possible to simulate and analyse temperature distributions in component with numerical methods in accurate way with computer aided simulation software and use it as a analyse method. But even these modern numerical calculation-based simulation tools exist and as powerful and accurate they are, still experimental checks, measurements are sometimes needed for validation reasons. (Silva, et al. 2022, p. 2-6)

3.2 Thermo-Mechanical analyses

One way to simulate welding process with computational analyses is to approach it by Thermo-Mechanical way. Basically, in thermo-mechanical analyses everything from thermal analysis is of course included into simulation calculations and into model and added with features and calculation possibilities from mechanical side also. These mechanical aspects are like calculation of residual stress levels, distortions in components, welds. Also, it is possible to simulate heat expansions in components, and with help of this it is possible to estimate of need for clamping's, fixings etc. (Silva, et al. 2022, p. 55).

According to Silva, et al. 2022., p. 55-56., residual stress can be divided into four different groups, table 1.

Table 1. Residual stress groups in thermos-mechanical simulations. (Silva, et. al. 2022, p. 56)

1	Thermal, which are developed during cooling through differential deformation in the cross section, resulting from thermal expansion
2	Deformation, which result from an inhomogeneous plastic deformation field from an external loading
3	Phase transformation, caused by uneven phase transformation and a volume change
4	Precipitation, a distortion stemming from the occurrence of precipitation in the crystal structure

Main reasons for residual stresses in weld region are shrinking phenomena of component and weld, fast cooling rates in welding process and phase transformations in substrate and added material. Determination of residual stress levels in thermo-mechanical simulations

always require a thermal analysis made first. This is to determine thermal behaviour and temperature distribution in the region of weld. (Silva, et al. 2022, 53)

In this master's thesis work only thermal analysis is considered. This is to determine thermal behavior and temperature distributions in components. And these results from simulation are then used as reference data for thermos-mechanical simulation model in separate work with different simulation software.

3.3 Thermal analyses

Thermal analyses to component concentrate as name already states to heat build-up in component, substrate, weld bead, weld pool. Also, distribution of heat inside component, clamping devices or convection into surroundings might be useful insight to get out from thermal simulation calculations.

Thermal analysis simulations are applicable to almost all different welding methods in industry. These welding methods are such as arc welding, resistance welding, electron beam welding and laser welding, including cladding and DED. Important thing in calibrating, making a simulation model for thermal analysis is proper modelling of heat source. (Silva, et al. 2022, p. 19)

Ways to approach thermal modelling are, according to Silva, et al. 2022, p. 19-21., Analytical models and Numerical Simulation based on heat source modelling.

Most used calculation model in analytical modelling is based in Rosenthal Equation, with moving heat source, which calculates heat distribution to moving source. Thus, in numerical simulation with heat source modelling, goal for simulation in simple terms is to predict real life situation into simulation results. (Silva et al. 2022, p. 19-21.)

In this master's thesis work according to field studies we are practically in between these two methods of simulation for thermal analysis.

3.4 Laser heat source-based simulation models

According to Behulova, M. & Babalova, E. 2025., p. 1-4., simulating welding processes, heat sources and their behavior can be expressed by means of mathematical calculations and laser heat source simulations and modelling. Mathematical approach requires a lot of initial input before any successful calculation for simulation purposes can be done. Desired output or parameter can be e.g. temperature behavior in components, weld, fixing components or stress levels in microstructures. Required initial information for mathematical approach can be such as, all geometric information, used steel grades and their applicable properties, information form surroundings, process components and fixing relations. Alternative approach can be modelling or simulation the behaviour of laser heat source. (Behulova, M. & Babalova, E. 2025., p. 1-4)

Heat source modelling and its history can be outwritten in many ways. One opinion according to Kik, Thomas. 2020., p. 1-4., before any possible or sufficient Finite Element Method (FEM) computer software programs, simulations of different welding processes thermal behavior, simulation work required trough out analysis work to topic. With the help of modern-day powerful computer FEM based software's it is easier to do heavy calculations into components and processes. Common way to model or simulate laser heat source behavior is to use pre-modelled sub programs inside software for heat source simulation. These models are gaussian, double ellipsoid (Goldak) and conical heat source models. Heat Source Models in Numerical Simulations of Laser Welding. (Kik, Thomas. 2020., p. 1-4)

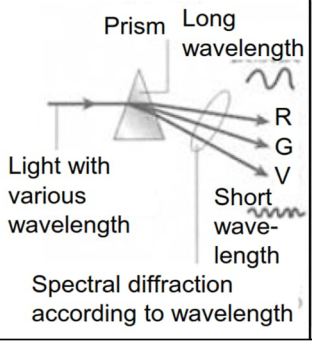
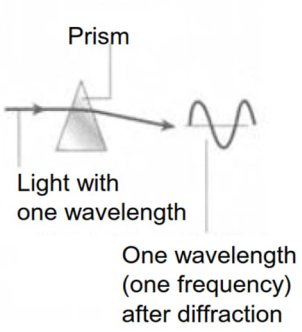
3.5 History and main characteristics of laser optics and technology

Laser technology origin goes back to early 1900's, more precisely into early 1920's. Richard Tolman wrote first time the main principles of laser technology in a theory for the process (Charles H. Townes. Laser: 50 years of Discoveries. P. 9.) It took almost 30 years more for laser technology to evolve into state that it could be really utilized in various needs in different industries and research.

Laser as a word means, Light Amplification by Stimulated Emission of Radiation. This word, Laser is opening the phenomena of what is happening in laser process, physical process description of components exposure to light ionizing radiation. Laser light as it is,

is artificially generated light, and it is not natural light. Laser light is purely monochromatic. In monochromatic light, wavelength remains the same all the time. In natural light, waves can be observed in many different wave lengths. Monochromaticity described in Table 2., (Katayma 2020, p. 1-2)

Table 2. Features of laser. (Katayma 2020 p. 2., Table 1.)

Item	Natural light	Laser
① Mono-Chro-maticity		

3.6 Stimulated Emission in Laser

One important fact in Laser, is atom, whose energy level is changing from upper to lower level in molecules. Depending on process, the laser can interact with component with absorption, fluorescence or by emission. When it comes to industrial processes, we mainly concentrate into stimulated emission of light, as the acronym Laser is stating.

In stimulated emission of light, with incoming source of light the atom in laser media is at higher level of energy. In this phenomena atom's energy is changing due to light emission into lower state of energy with correct frequency which is the same with energy potential difference. (Katayma 2020, p. 2-3)

Also, photons in molecules fuse together, with same parameters, such as phase, direction and frequency. By this way the energy concentration can be, is, amplified into desired power levels. (Katayma 2020, p. 2-3)

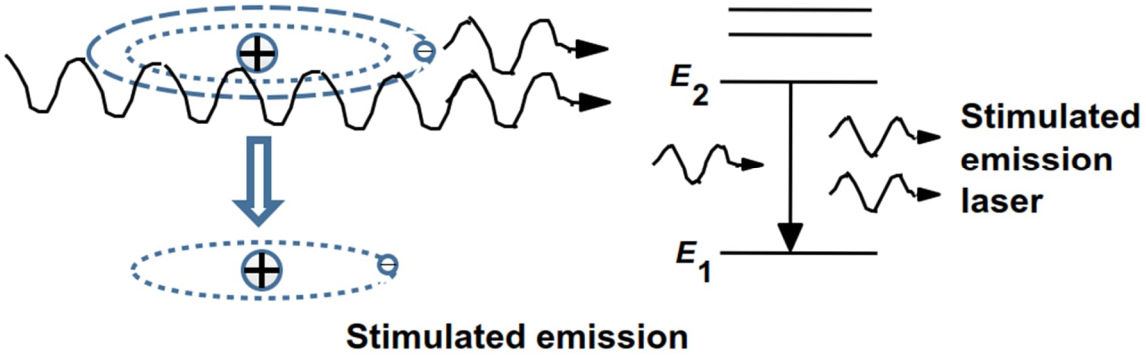


Figure 2. Stimulated emission of light. (Katayma 2020, p. 2)

3.7 Industrial lasers

Lasers can be used in various ways and to many different meanings and purposes. Commercially we use laser light in DVD players, CD players, measuring devices, such as distance meters, red- and green light laser pointers, scanners, printers etc. It can be realised, that meaning of Industrial Lasers can be such as, healthcare, commercial purposes, manufacturing purposes. In this master's thesis, we concentrate into Industrial Lasers used in manufacturing processes.

Types of lasers can be such as solid-state laser, gas or liquid, depending on the laser media used to produce laser light. Also depending on the processed material, laser used is categorized into under different meaning of use. With laser it is possible to process, or to use it as a manufacturing tool, different materials, e.g. metals, plastics, ceramics, leather, glass, different composites, alloys etc. Industrial lasers used in manufacturing purposes, such in automotive manufacturing, component treatments, component manufacturing. Industrial processes can be such as, welding, joining, surface treatments, hardening, cutting, soldering, cladding, additive manufacturing etc. In this thesis, we concentrate more into laser cladding of components in industrial manufacturing, and its computational simulation. (Ion 2005, p. 1-9)

It is known that common laser types in industrial manufacturing purposes are e.g. nd:YAG lasers and CO_2 lasers, which are widely used in industrial processes because of good beam intensity, and favourable beam wavelength. (Hitz, Breck 1991, p. 1-2). With CO_2 laser it was first to discover high energy input into processed component or process, but for beam

transportation, CO_2 was realised difficult in efficiency wise to beam handling in component. Nd:YAG operates in more favourable beam lengths for beam transportation. Later, Diode lasers are noticed to be easy for beam transportation and for producing higher energy levels for process. (Dal, Fabbro 2016, p. 2-3)

3.8 Laser media used in cladding process

Diode lasers are noticed to be relatively easy for beam transportation and for producing higher energy levels for process. (Hitz, et. Al., 1991. P. 1-2.), (Dal, et. al., 2016. P. 2-3.). From this point and forward, this thesis is concentrating into Diode lasers due to fact that this type of a laser was and is used until today by work orderer. With using diode laser, and with also earlier mentioned nd:YAG and CO_2 beam transportation is relatively easy and can reach in distance into several tenths of meters without problems. With this type of an arrangement, it is easy to build up a system set-up in needed jobsite.

In some matter, diode laser was originally developed as a high-energy output pumping source for other types of lasers, such as fiber and disk laser. (Seiji 2020, p. 5.)

As with generalized principles, Diode laser characteristics can be expressed as follows on the table 3., for diode laser.

Table 3. Diode laser characteristics. (Seiji 2020, p. 5)

Diode laser (LD)	(Wavelength: 0.8–1.0 μm; Near-infrared ray)
(Blue laser)	(Wavelength: 0.45 μm; Blue)
Laser media	: InGaAsP, Al(In)GaAs, etc. (Solid)
Average power [CW]	: 60 kW (Fiber-delivery Max.); 2 kW (Blue Max.)
Merit	: Compact, fiber-delivery and high efficiency (20–50 %)

In this thesis we talk about Diode laser technology with laser media in the group of solid-state lasers. Power levels are, if compared to table 3. up to 60kW average power maximum. For beam transportation fiber delivery is used. More detailed info of job specific laser characteristics, later in this report at job set-up chapter.

Diode lasers dates back into 1960’s when first diode lasers were introduced into markets. Advantages were and still are its compact size, simpleness of structure, power efficiency etc.

Diode laser's operating principles lies in excitation of electrical current in process. Diode lasers are also known as Laser Diodes (LD), later referred often as Diode Lasers. (Chen et al. 2025, p. 1)

Diode lasers were used first in use of scientific research purposes mainly. Later due to technology progress, the increase of laser power levels leads to increase of usage areas of diode lasers from commercial use also into industrial manufacturing applications. Later development went further, and early experiments of semiconductor lasers and use of Gallium Arsenite (GaAs) in them. Early tests were performed already in 1950's for semiconductors, but it gained more interest in the community at 1962, when at MIT Lincoln Laboratory, Robert Keys handed out experimental results of test for using Zink particles in semiconductor with GaAs. It was realised that based on this test more power could be taken out from Diode lasers, and it opened more possibilities for semiconductor lasers. Later GaAs, high power diode lasers (HPDL) established the grounds to be the best way to make optical energy out of electricity in semiconductor lasers. With this technology laser can be put directly into processed material or via acting as a pumping energy source to other lasers. (Divliansky 2020, p. 1-3)

Below a basic cross section, set-up of a semiconductor, a high-power broad area laser (BA-HPDL), figure 3.

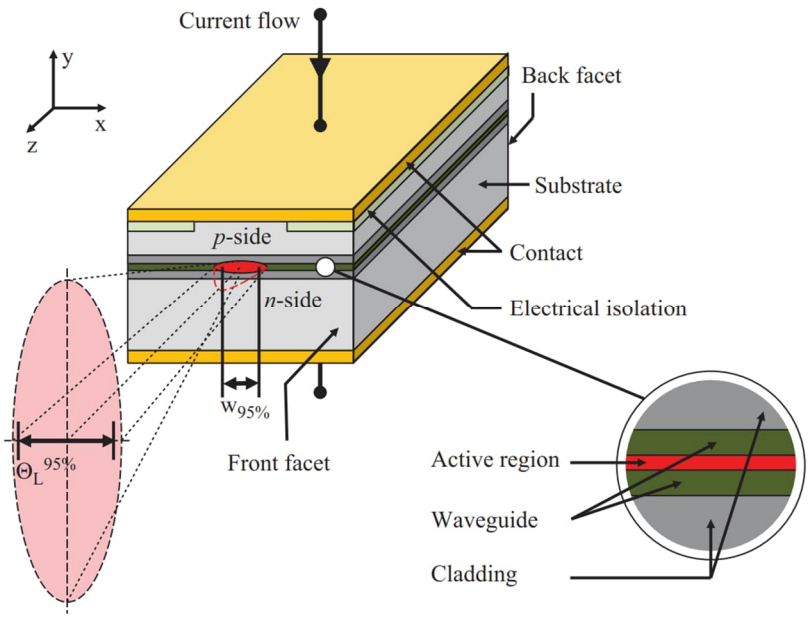


Figure 3. Schematic cross section of a BA-HPDL. (Divliansky 2020, p. 3.)

3.9 Laser beam quality

Value describing laser beam quality a parameter has been set-up. This parameter is Beam Parameter Product (BPP). Laser beam quality it is in direct relation to laser beam power intensity. Characteristic of laser beam is to produce lots of energy focused in a small area or in a small diameter for beam diameter at surface. It is possible to influence into laser spot diameter in various ways, e.g. adjusting focusing length by different set-up of optics selections or select a laser or optics with better BPP qualities. Also selecting a laser source or media with smaller wavelength is giving smaller laser spot size. Gaussian mode laser source is an ideal selection when it comes to high power density of a laser beam hence it produces high intensity laser spot with small area, equals to small spot size. (Katayma 2020, p. 27-28)

BPP as a value of beam quality is using Gaussian mode laser as a reference and beam quality is as follows in figures 4-5.

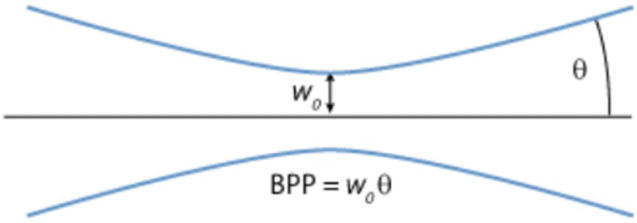


Figure 4. Illustration of BPP in laser optics. (Paschotta, Parameter Product 2025)

According to Katayma 2020, p. 28., BPP stands for half laser beam divergent multiplied with radius of laser beam.

According to Figure 6, the smaller the value for BPP is, the better the beam quality and thus the more inadequate quality when BPP value is higher.

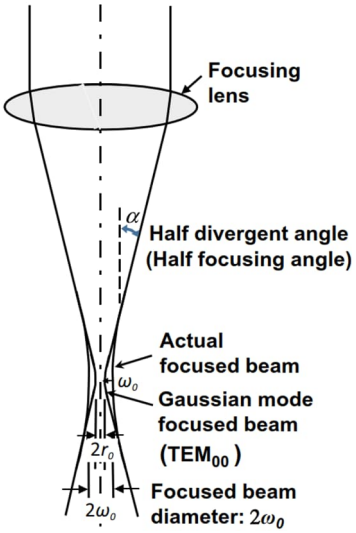


Figure 5. BPP value, α, ω0 in focusing optics. (Katayma 2020, p. 28)

Even though BPP describes laser beam quality in Gaussian mode lasers, it can be determined also to non-gaussian beams. In that case, for values beam radius and divergence, these definitions must be raised into second power in the equation. Example of Laser Beam Quality calculator in table 4. for non-circular laser beam spots, BPP is different in X, and -Y directions. (Paschotta 2025)

Table 4. Laser Beam Calculator. (Paschotta 2025)

Calculator Tool: Laser Beam Quality

Center wavelength:	1064 nm		
M^2 factor:	1	calc	(from BPP)
Beam parameter product:	0.339 mm mrad	calc	(from M^2)
Beam waist radius:	1 mm	calc	(using the BPP and divergence half-angle)
Divergence half-angle:	339 µrad	calc	(using the BPP and beam waist radius)

Enter input values with units, where appropriate. After you have modified some values, click a "calc" button to recalculate the field left of it.

Illustration of different laser beams is being presented in figure 7., where it is possible to compare beam size or diameter with different laser media sources and with different BPP.

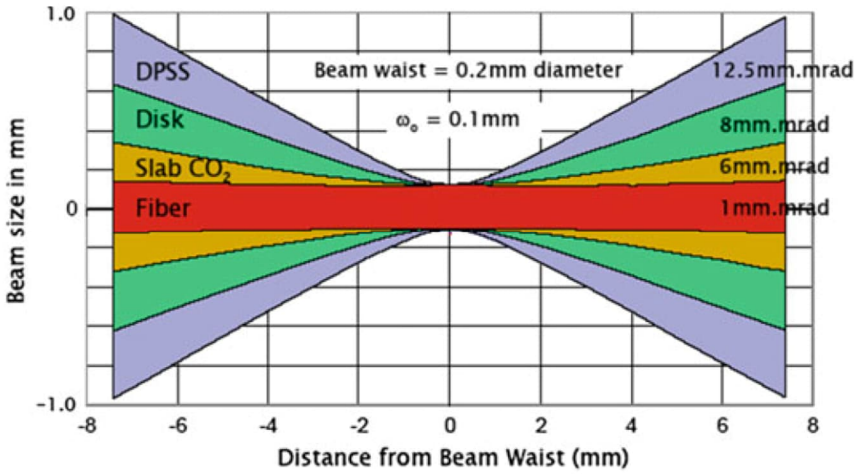


Figure 6. Laser beam size in comparison to BPP and beam waist distance. (Katayma 2020, p. 29)

3.10 Gaussian and Top-Hat laser beam modes

In industrial application Gaussian laser beam mode or profile is often used because of its high energy intensity at small area and with small spot diameter. This in the reason for e.g. laser beam with gaussian beam profile is used in laser-based welding applications. In welding purposes thing is to generate energy and heat in small area to create melt pool in substrate material. Idea is to penetrate often deep into substrate material. In gaussian laser beam profiles we talk about non-homogenous laser intensity generation in laser spot area. This means that laser intensity is higher closer to center in laser spot and being lower in the areas near edge. (Mustafa 2024, p. 1-4) For intensity profile in Gaussian laser mode, see figure 7.

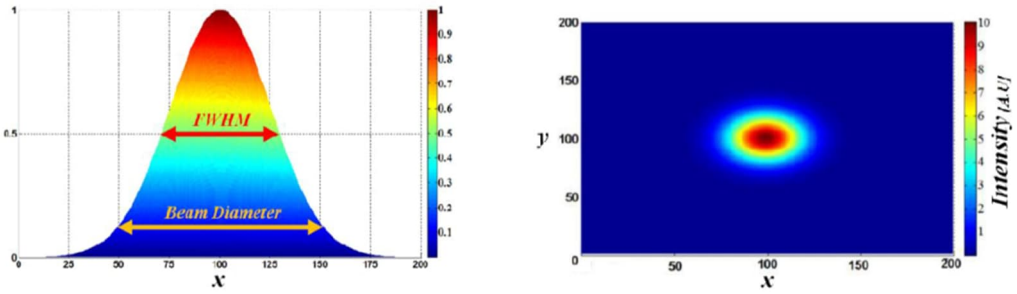


Figure 7. Intensity profile of a laser beam in Gaussian mode laser (Mustafa 2024, p. 3)

According to Mustafa 2024., theoretical beam mode TEM00 corresponds into gaussian laser beam intensity profile. Figure 9., describes TEM00 gaussian profile.

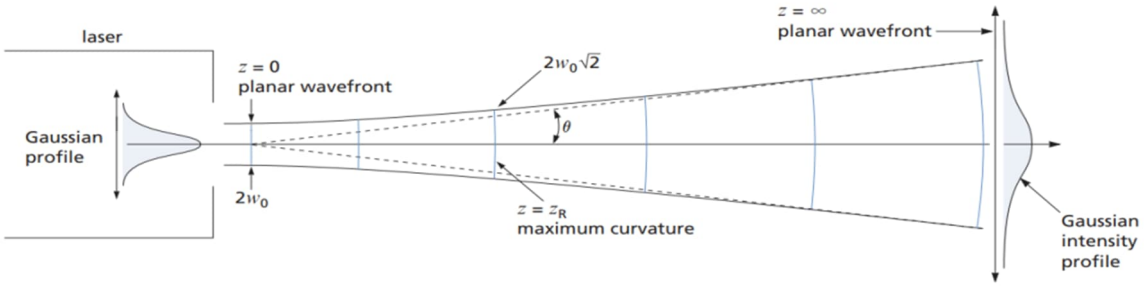


Figure 8. TEM00 Gaussian profile, fundamental transverse mode (Mustafa 2024, p. 3.)

Components added into process, see figure 9., difference in real life gaussian laser source vs. top-hat (flat-top) laser source.

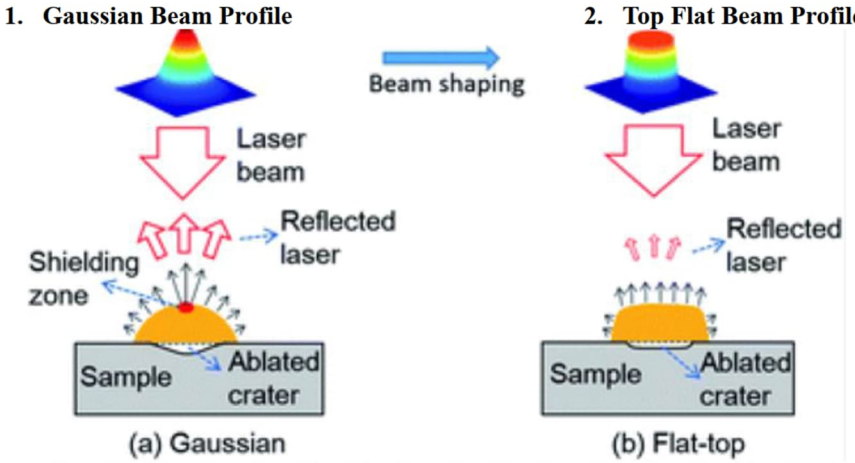


Figure 9. Gaussian profile and Top-Hat profile comparison including samples. (Mustafa 2024, p. 1)

There is a possibility to use beam shapers to turn gaussian profile into top-hat profile to get homogenous laser energy intensity in focal plane. Many times, this is done with a Fourier lens, as a beam shaper, figure 10-11. (Yizengaw et al. 2022, p. 76)

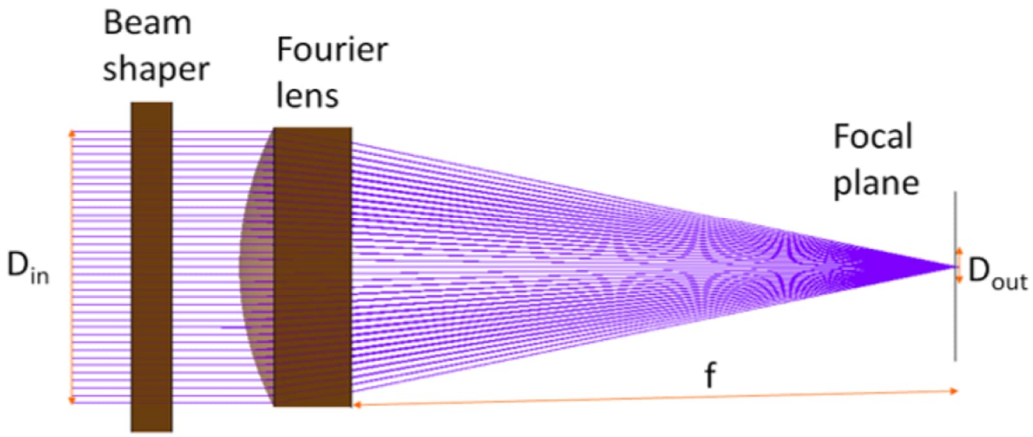


Figure 10. Beam shaper with Fourier lens. (Yizengaw, et al. 2022. , p 76)

At figure 11. With ablation it is referred to removed material (substrate, foreign particles, impurities etc.) from processed surface. With top-hat laser beam intensity profile the surface area of processed surface is greater in top-hat. With top-hat profile, the depth is smaller compared into gaussian profile and this way the power intensity levels are handled in more precise way in whole processed area, energy input is the same in area. (Hongxia, Manni, Muddiman 2023, p. 10.)

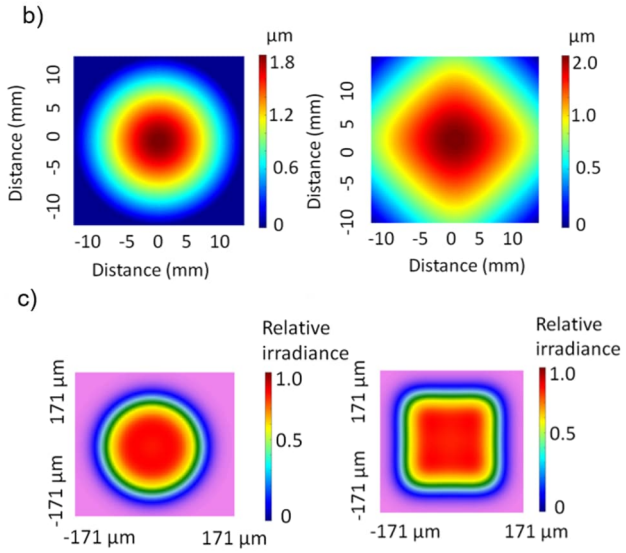


Figure. 11. (b) Beam shapers, square and circular, intensity. (c) Intensity at focal plane of a fourier lens, square and circular. (Yizengaw, et al. 2022, p. 76.)

3.11 Laser beam size

Whether you are using a gaussian laser beam mode or top-hat mode, there are ways to determine necessary or needed laser spot diameter. With selections of spot size and shape it is possible to influence into production rates of manufacturing. Bigger the spot size the bigger manipulated are per time interval or rotation.

Physics behind defining laser spot size can be evaluated. For gaussian laser beam mode, for example we discuss about first of laser beam waist. One possible way to define needed spot diameter is to evaluate where lasers intensity is in point of 13.5% or $1/e^2$ of its maximum. This also applies for its axial value.

Other way to define laser spot size is to base decision into point where laser intensity is 50% of peak value. In this case we also talk about Full Width at Half Maximum (FWHM). (Mustafa 2024, p. 3), illustrations of these can be seen in figures 12-13.

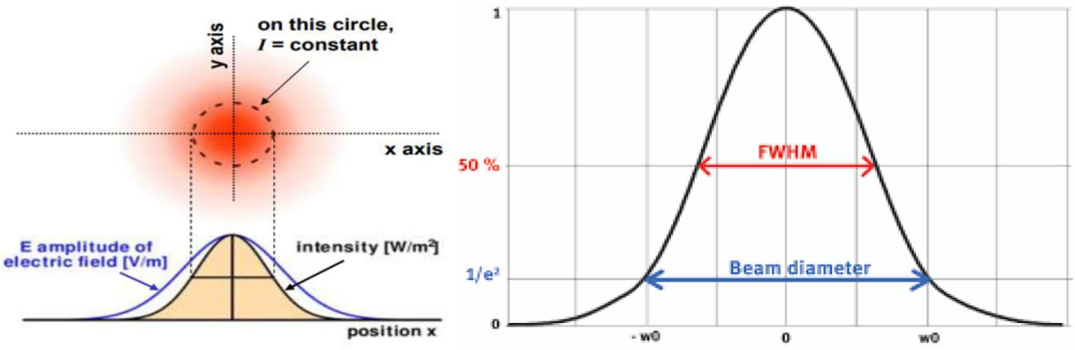


Figure 12. Gaussian laser mode spot size. (Mustafa 2024, p. 3)

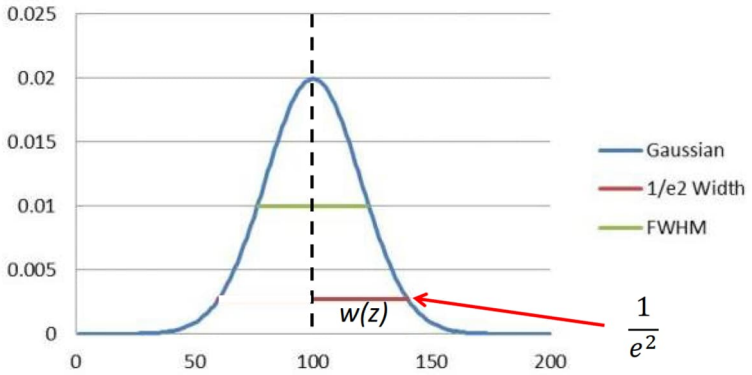


Figure 13. Gaussian laser mode spot radius at point of $1/e^2$. (Corner 2019, p. 15)

3.12 Fiber optics for laser beam transportation

Fiber optics gives a practical option for beam transportation compared into more traditional beam transportation systems. For CO_2 lasers an open beam delivery system can be said to be a traditional system.

At optical fiber cable laser light is transported through a cable, many times with lacing media made from Silica Glass and with big volume of surface area inside optical fiber. Optical fiber is easy to handle, attach and guide between laser power source and robot joints and all the laser head. Cable length can be several meters without significant power loss.

Silica Glass fiber is then pumped with electrical current. Optional ways to pump optical fiber are for example Side Pumping technology and Diode Pumping Technology. (IG Photonics, Fiber lasers 101, 2025)

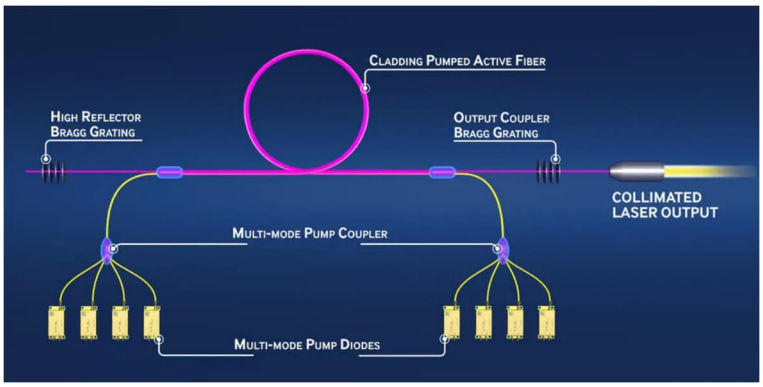


Figure 14. Diode pumping, optical fibre. (IG Photonics, Fiber lasers 2025)

According to Coherent, 2025, fiber optics use total reflection as a process to deliver bema trough cable. The cable itself consists of multiple layers, core, cladding, buffer and jacket at the surface. Core itself, when applied into high-power applications is made purely out of fused silica. (Coherent White Paper 2025). See figure 15.

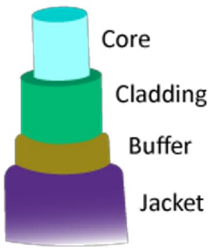


Figure 15. Optical Fiber structure. (Coherent White Paper 2025)

3.13 Co-axial and off-axial laser process heads

Process heads in laser cladding technology can be categorized to be co-axial and off-axial process heads. These names refer to how the additive material is fed into the process during for e.g. laser cladding process.

This added material can be in the form of powder or wire. At both cases feeding happens either co-axial or off-axial.

In co-axial process head, powder or wire goes through and is guided into process inside nozzle and in off-axial head, it goes into process from the side outside nozzle form separate feeding system. (Ahn 2021, p. 704-705), figures 16-17.

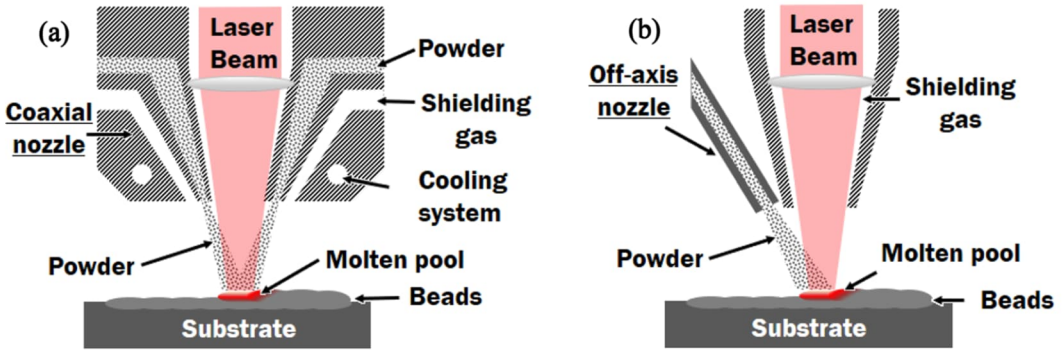


Figure 16. Powder feeding system in process head., (a) Co-axial, (b) off-axial. (Ahn 2021, p. 704)

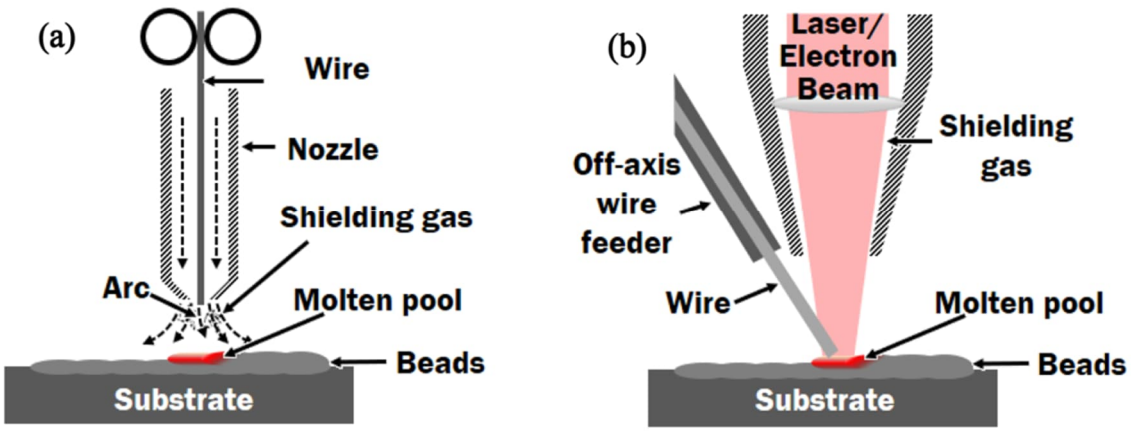


Figure 17. Wire feeding system DED., (a) Co-axial, (b) off-axial. (Ahn 2021, p. 705)

3.14 Laser metal deposition process in component manufacturing

Laser cladding process and DED process at general level are very close to each other in process parameters, equipment and in goals and needs for job. In practical way, one thing which separates these two processes is the fact that DED-process can be ran in all 5-axis with machine and component. Running the process with 5-axis basically means that it is the only manufacturing method which can be used for repairing purposes of old components which include complex 3D shapes. Moreover, in practical level, with suitable manipulator, robotics, and turning tables, it can be run as a hybrid technology to repair even complex 3D shapes. When talking about laser cladding purely, movement or cladded layer is mainly in 2D-world. (ETHzurich, Directed energy deposition 2025) In laser cladding process for example, when using powder (added material) which is fed trough nozzle or oft-set nozzle, normally powder is not melted airborne, meaning before touching substrate or entering close to molten pool. It is melted when exposed to laser radiation in process. In figure 18., an illustration of co-axial (trough nozzle) laser head nozzle.

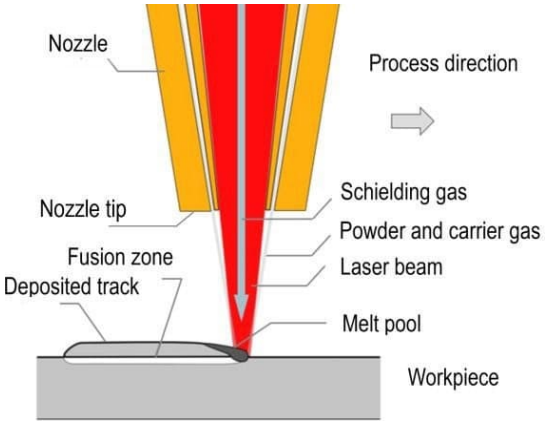


Figure 18. Co-axial nozzle, (Laser based directed energy deposition process principle with continuous coaxial nozzle 2025)

On other hand, for e.g. in Extreme High Speed Laser Cladding (EHLA), powder material is melted airborne, during material jetting or transportation from powder nozzles before it touches substrate by energy of a laser beam. (Xtreme high speed laser cladding EHLA 2025)

As a comparison, figure 19. illustrates the difference between cladding/DED and EHLA.

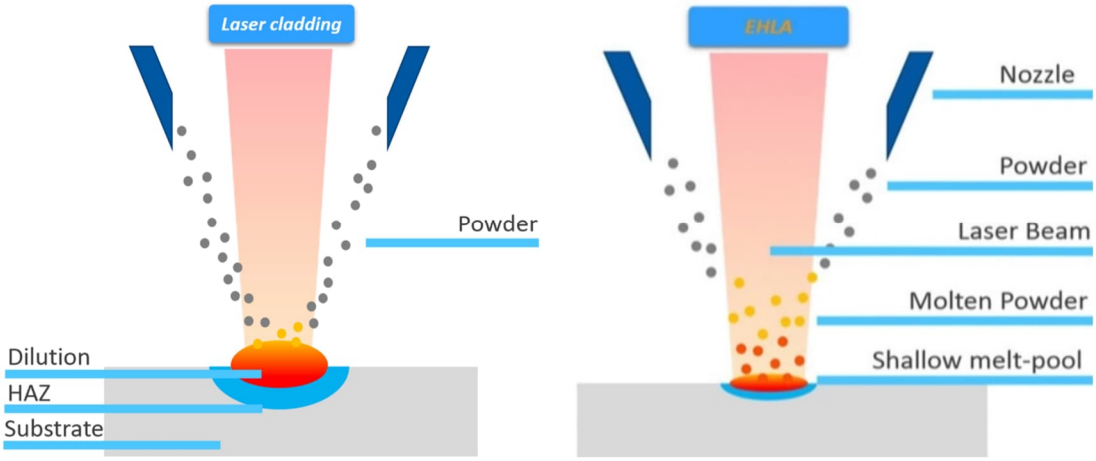


Figure 19. Process differences and principles of Laser cladding and EHLA process. (Hornet laser cladding)

EHLA, as name already states, is a high-speed cladding process and can be up to 10x faster compared to traditional laser cladding process. This is explained by powder melting already airborne and faster fusion between substrate and added material in process, and again, this allows faster speeds.

Also, heat input in EHLA is very low in substrate, which is mostly a pure benefit, but can be a limitation in certain processes. Melt pool is quite shallow in both processes. Also, dilution is less than 5% in both processes. As this master's thesis is about using traditional LMD process, more detailed information about it in following chapters.

3.15 Benefits of LMD as a manufacturing process

Using LMD process as a manufacturing process for new component manufacturing it brings many benefits when compared into many traditional, non-laser manufacturing methods.

These benefits can be such as follows,

-good quality joint between substrate and added material, with Dilution less than 1%

-practically porosity free added layer

-fast processing

-low heat input to substrate

-fast cooling rates

-post processing needs are minimized

-with post processing needs eliminated, this also excludes the need for post heat treatments

-can easily be adapted into component refurbishment purposes

(What is laser cladding 2025)

One big advantage with laser metal deposition or laser cladding process is to make changes into substrate material surface properties. With the help of LMD process it is possible to enhance and improve surface properties, such as wear resistance, corrosion resistance, surface roughness and reduce post processing needs for component.

When we talk about manufacturing in general, expenses in production and components act a big role in it. With utilizing LMD process it is possible to influence in the overall expenses of manufactured components, for example use of cheaper base material and add surface material on top with desired surface material properties. With these actions total costs can be reduced and no surface properties are missed.

Mechanical behaviour can also be altered with combining two different materials together. It can be that substrate it is desired to be more with ductility properties and from surface e.g. wear- or corrosion resistance is needed. Many different materials, such as steel grades can be joint together.

If there is a non-compatibility issues with base- and added material layer, it is possible to use so called buffer material in between these two. Buffer material acts like an extra layer between completely different materials, goal is to make substrate and added material compatible to join with laser metal deposition process.

3.16 Cladding process categorization and process parameters

According to Hofman, Johannes Tjaard, Development of an Observation and Control System for Industrial Laser Cladding., 2009., laser cladding process can be characterized to be a method for surface treatment purposes. There are many ways to treat surface properties, and cladding is one of those possible methods.

Laser process-based modifications into component surface properties are divided between Thermal and Thermochemical methods. Laser metal deposition (LMD) belonging into thermochemical methods.

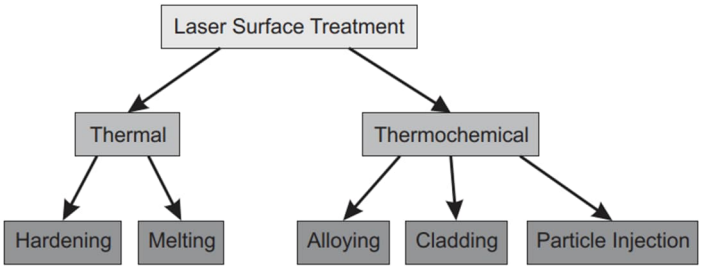


Figure 20. Different surface treatment processes. (Hofman 2009, p. 7)

Laser metal deposition includes and requires multiple different aspects, parameters, material choices, component selections in process equipment's which directly influences in end results in manufactured or refurbished component. (Hofman 2009, p. 7), see figure 21.

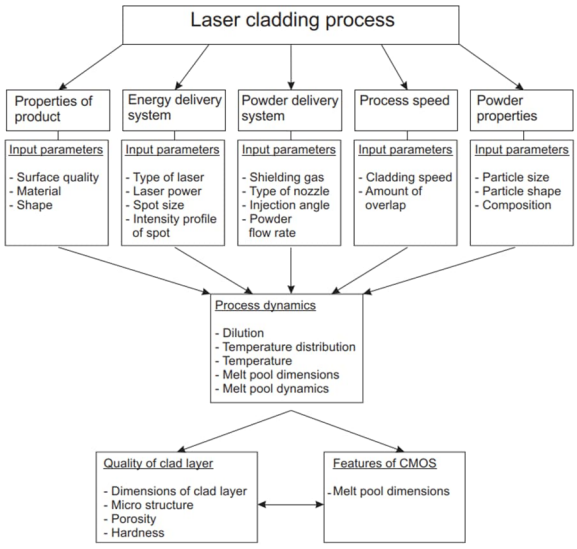


Figure 21. Correlations in cladding process parameters, selections, quality. (Hofman 2009, p. 12.)

In LMD, process parameters such as components to be handled, dimensions, material grades, heat source parameters, added material selections, gas selections, cladding speed, and weld bead generations are directly influencing the behavior of process. According to Hofman, 2009., P. 12., behavior of the process is referred to as Process Dynamics. Process dynamics can be divided as follows, see table 5.

Table 5. Process dynamics of a laser cladding process. (Hofman 2009, p. 12)

Process dynamics parameters
Dilution
Temperature distribution
Temperature
Melt pool dimensions
Melt pool dynamics

From process dynamics table 5., it is seen clearly how and for what early-stage process selections in laser cladding are influencing in process. Although melt pool and its dynamics are important factors of course, in next two chapters more detailed information is gone through, such as Dilution and temperature behavior in laser metal deposition process.

3.17 Dilution rate

Dilution or dilution rate expressed as percentages in laser cladding process is describing the mixture of base material (substrate) and added material. During cladding process laser energy is melting added layer or weld bead into the substrate material in the area and in between layers in laser metal deposition process. Amount of mixing between these two materials is expressed in percentages. Greater the dilution rate is the greater the change in metallurgical structure in both added material and substrate. Vice versa, smaller dilution is, the more homogenous these two materials remain. Thus, if the dilution rate is too low there might be bad or insufficient bond between substrate and added layer. When dilution rate is too high, mixing, mixture of both materials with each other is too big. This can decrease both material performance and properties. Dilution rate is a matter of finding balanced situation and rate for dilution. This often requires cross section microscopic investigations to

determine correct dilution and using reverse engineering, to adjust necessary parameters, materials, laser types, power etc. to achieve set goals. (Dongsheng et al. 2021, p. 2-3.)

Illustration of a dilution zone in laser cladding process is presented in figure 22.,

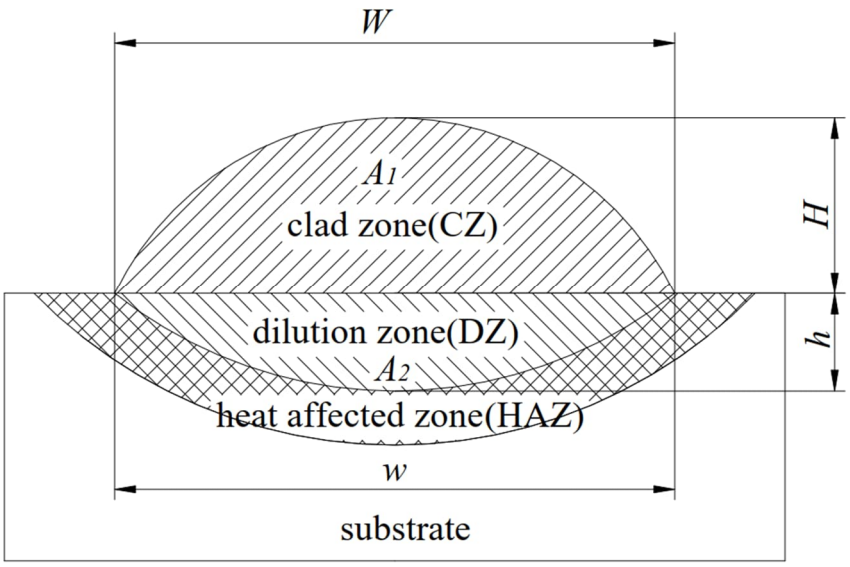


Figure 22. Cross sectional cut from laser cladded substrate. (Dongsheng et al. 2021, p. 6)

Dilution rate is a meter for qualitative measurement of cladding process. Idea is to map out changes in metallurgic structure and different elements during melting. Dilution rate can be calculated when needed. One way is using geometric approach to calculate dilution rate. Next sentence illustrates geometric approach calculation. (Dilution degree in laser cladding, 2025)

Dilution rate in cross sectional area of coating = matrix melting area / (coating area + matrix melting area) x 100%

If weld bead thickness stays constant together with laser source power, dilution rate increases at same time with the increase of laser spot power density. Dilution rates decrease in process when laser head speed increases. Dilution rate should be as low as possible, at least not greater than 10%, but preferable closer to 5%. (Dilution degree in laser cladding, 2025)

3.18 Temperature behaviour

Temperature behaviour and temperature distribution in manufactured component, grippers and other surrounding components plays an important role in customers LMD manufacturing

process. It is vital to know how temperature levels are propagating and how temperature distributes in component to be worked on. In this master's thesis work both factors, temperature distribution and especially maximum process temperature levels during and right after process play a vital role. Referring into this work and research problem, R&D and manufacturing personnel must know or would be required to know the component maximum temperatures during and after manufacturing process.

Heat convection rate can be expressed in various way with different units. In table 6., different ways to express heat convection rates. In this master's thesis work (W/m^2K) is used. More of these in chapter for practical research equipment set-up.

Table 6. Heat convection rate units. (Convective heat transfer 2025)

1 $W/(m^2K)$
1 $Btu/(ft^2\ h\ ^\circ F)$
1 $kcal/(h\ m^2\ ^\circ C)$

4 Materials and methods

This chapter illustrates the system set-up used both in calibration phase and in validation phase of the master's thesis work. Also, principles of building up simulation model and physical tests arrangements are being explained. Equipment's remained the same, only parameters such as laser power, cladding speed and carrier gas flow were changed to the model validation tests.

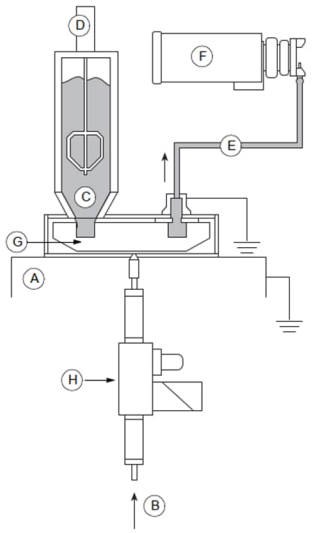
Laser cladded component was changed into simplified cylinder shape for validation tests to be performed in August 2025. This not to expose actual component geometry from model calibration and internal phase. Thermal simulation model was created first to internal component and based on findings into validation model.

4.1 Process set-up

In this thesis, used laser power source remained the same in calibration phase and trough to validation phase. Laser power source is Laserline LDF 5000-100 (VG64) Diode laser, output power of 5kW, optical fiber beam delivery system, 10m/1000µm. Beam Quality 110mm*rad.

Figure 23. Laser power source, Laserline LDF 5000-100, VG64

Powder feeding system used in simulation model calibration phase and validation phase were same. Powder feeder used was Sulzer Metco, Twin 10-C powder feeder. Powder feeder unit itself was Oerlikon metco 5.0 APS powder insert. There was two of these inserts in equipment, but only one insert was in use of calibration phase and validation phase cladding. Illustrations in figures 26-27.



A Powder feeder
B Carrier gas
C Powder container with powder and stirrer
D Stirrer drive with power supply
E Powder hose
F Spray gun
G Metering disk
H Mass flow controller

Figure 24. Powder feeder insert Oerlikon Metco 5.0 APS. (Product manual 5.0 APS Powder insert, Oerlikon Metco 3/2021.)

Figure 25. Sulzer Metco, Twin 10-C powder feeder.

Flow rates in in model calibration phase were for carrier gas, 6,5l/min, and for shielding gas, 20l/min. For model validation phase flow rates were, carrier gas, 6,0l/min and for shielding gas, 20l/min.

Laser head and optics equipment remained same trough out whole master's thesis work. Laser head used was Laserline OTZ-5-VC. For illustration, see figures 28-29. Table 7. For basic laser optics specifications.

Table 7. Laser optics specifications.

Parameter	Value, type
Spot diameter	6mm
Collimation	72mm
Focus	300mm
Fiber	1000µm
Beam quality [BPP]	110mm*rad
Powder delivery	Trough the head, co-axial, 6-way-GTV-PN6625

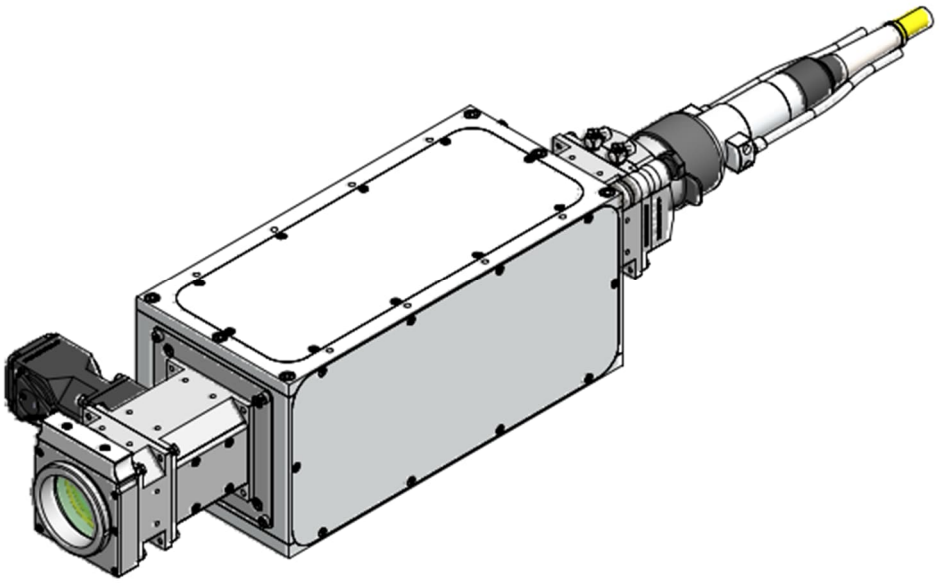


Figure 26. Laserline OTZ-5-VC laser head. (Laserline drawing no. Z-34296).

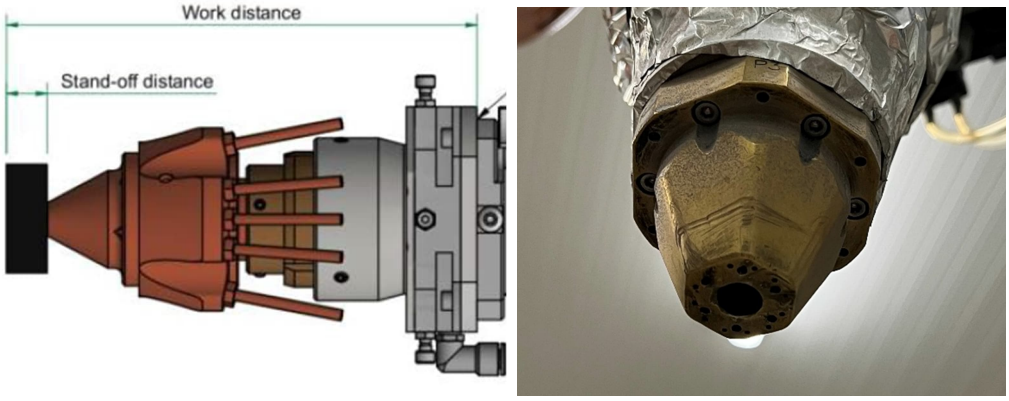


Figure 27. Nozzle general lay-out, Co-axial, 6-way-GTV-PN6625. (Instructions for use for adjusting the correct position of the cladding nozzle, SKF LCV).

Robot used during master's thesis work was Kuka KRC 250, 6-axis robot, see figure 28.

Figure 28. Kuka KRC 250, 6-axis robot.

For turning and fixing the component there was Kuka DKP400 V2 turning table with special clamping plate fabricated into it. Also, various additional different fixing, clamping devices were optional to use. Turning table technical information, figure 31.

Figure 29. Kuka DKP400 V2 turning table technical specifications.

Figure 30. Kuka DKP400 V2 turning table equipped with validation tests component and grippers.

4.2 Test equipment arrangements for validation

Laser optics, power source, feeder, optical cables where same equipment as were used already in calibration phase. Hardware remained the same, only the component physical dimensions, laser power- and speed changed.

In figure 31. a system set-up from fixing the component into rotating table with fixed, with thread bars, M3. No securing plates at side faces of component. Set-up the same with simulation model. Pyrometers can be seen as a red dot inside cylindrical component.

At calibration- and validation model weld trajectories are modelled in outer surface and temperature measurement plots are placed into inner surface as they are in physical test. Pyrometers were placed roughly on the centerline of the inner surface in physical test and in simulation model.

Figure 31. Validation model component placed in rotation table with two pyrometers.

There was total 4pcs of sample rings to be tested. First two were processed with full fixing plates mounted front- and back of the component. This was ordered from customer. That set-up was not an exact image of simulation set-up. Biggest difference is heat-convection into steel plates, acting like heat sinks and again lower temperatures in component.

Test ring no. 3 was done with exactly same specifications as simulation model, figure 43. illustrates the set-up for test ring no. 3.

Fourth test ring was processed with completely different speeds and power levels for different future needs from customer to see deviating results.

4.3 Simufact Welding simulation software

Simufact Welding software was selected to be used in this thesis. Software is a product of Hexagon. Software packages are sold as Tokens with year license. With provided academic licence there was 50 tokens available for master thesis work installation.

Tokens included Welding, Material, Monitor and Mesh modules. Software version was 2024.3.

4.4 Simulation components selections

First thing when opening new simulation is to define and select components into project. As a minimum, an actual component, fixing geometries(s) [grippers] and a robot must be selected to able to run simulation. Fixing geometries(s) are acting like physical connection between component and robot, and without those, simulation cannot be run or executed correctly.

4.5 Model building principles

Model creation is very similar when compared into other common simulation software's. Model creation is done mainly in two windows, Process tree and Object catalogue. Between these two windows it is possible to toggle between and add, transport, move, edit information as you like.

4.6 Selection of simulation process type

With use of Simufact Welding software, there is several possibilities for process type selections.

For readers attention it must be noted that with this software set-up there is no Laser welding- or cladding selected as a process type, since there are only traditional types of laser welding processes to be selected, such as butt, v-joints etc. welding.

After discussions with Hexagon technical support about needs for this master's thesis work and its nature, advice for process selection was DED-process. DED process describes and suits better for this works nature.

4.7 Simulation configuration and analysis mode

Next it is to select simulation configuration for project. Taking to account for the nature of this master's thesis work, selection for this is Thermal solution only, not Thermomechanical. For analysis mode, Normal mode was selected to keep calculation not too heavy. Analysis mode, normal and precision are referring into quality output of a thermal simulation calculation.

4.8 Component import into project

Before importing component into project, correct file type, mesh type must be verified. This is to make sure that it is suitable for Simulation purposes in Simufact Welding.

Correct file type is in format of Nastran, Hexa8. It is imported as one solid mesh file. Component can be imported or created in object catalogue inside software and imported in process tree. Alternatively, component can be modelled outside, with external software to be then imported to Simufact process tree inside project.

4.9 Creation of fixing and boundary conditions

Creation of fixing (grippers, fixing table) and boundary conditions in practice means in model the creation of bounding's for the component with the robot. This is done because it creates a physical connection between component and robot.

This phase of model creation is very important, because with this connection, heat source parameters and weld trajectories are being calculated and handled in program. Basically, this phase is for defining the specifications of a robot and its process phases.

It is possible to create these fixing, or as they are called fixed geometries in software by hand inside program or to import them from external program as like component itself.

After creation or importing externally of fixed geometries, it is mandatory to define attachment parameters to them. This means the physical connection type between component and fixed geometry. This is done in Contact Tables, found from process tree.

For calibration model, fixed geometries (fixing) are acting as a mechanical grip to fix component in customers equipment. These grippers can be magnetic, fixed with threads etc.

4.10 Selection of materials for substrate and added material

Selections of materials used in modelling is done in object catalogue and imported in to process tree. Selections must be made to both, substrate and added material. It is possible to search and import materials form software database or make suitable material by user definitions.

For calibration model and for validation model two common type of steel grades were used in simulations. This is due to customers desire to keep internal information about used materials away from public papers.

For substrate material a general carbon steel with good weldability properties and heat treatability properties was selected.

Steel grade for substrate is DIN 1.7131, 16MnCr5 steel.

For added material selected steel grade is common stainless steel with proven good weldability properties and suitability properties for laser cladding.

Steel grade for added material is DIN 1.4406, AISI 316L.

4.11 Calibration model initial temperatures for components and heat source settings

It is mandatory to set initial temperatures for substrate (imported component) and robot. With robot it means the initial temperature of added material, such as powder. It was decided at early stage that both are to be set into +20C Degrees Celsius. This mimics general room temperature. In this stage of model creation, it is possible to define preheating procedures for component if necessary. Temperatures are defined in object catalogue and placed into the process tree.

Heat coefficient values should be put for both, substrate and added material. According to Data Sheet, Steel 1.7131/16MnCr5, Materiadatacenter.com, heat conductivity is 41W/m^2K for selected DIN 1.7131 steel grade. According to Thyssenkrupp heat convection is 15W/m^2K for stainless steel 316L.

Values for heat convection rates in model calibration work and validation work were tried with several different values to see the possible difference. In this work, only heat input energy from laser source and its effects to component are only considered in analytics, and because of that most important heat convection rate is convection rate for substrate.

Simulation results are identical with convection rates 35W/m2K to substrate and added material compared to results with 35W/m2K for substrate and 15W/m2K for added material. This comparison was tested and simulated many times during model calibration phase.

Heat source definitions are in important role in simulation model creation. As it is said earlier about differences between Top-Hat laser and Gaussian laser, there is difference between these two laser types. And because of that, heat source definitions were challenging to find suitable adjustments. Power intensity or BPP is different on both, and in internal and validation phase, with testing workshop they are using solely Top-Hat lasers in work.

Heat source must be added in every weld trajectory separately. Heat source can be made in object tree and imported into every weld trajectory in process tree.

Figure 33. is presenting the most suitable parameter set-up for this thesis work to get accurate output from simulation vs. real life results. With these parameters and adjustments, heat source is behaving as close to wanted and as close to Top-Hat as possible.

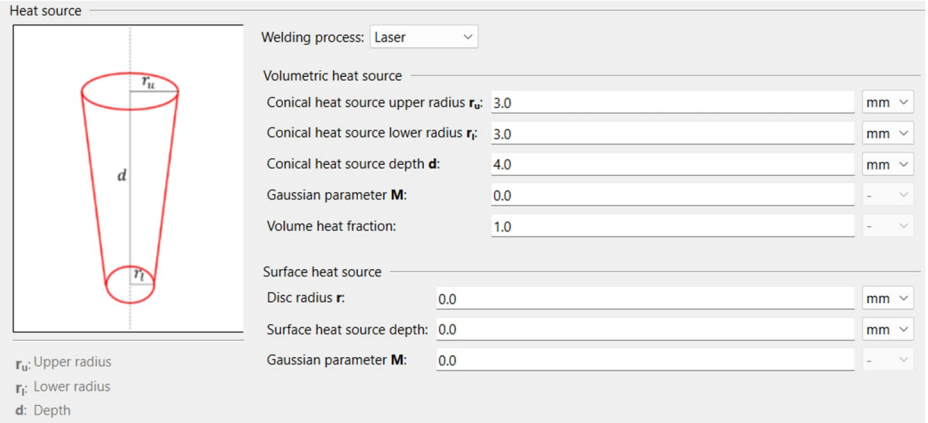


Figure 32. Heat source parameters for Laser.

One thing what is missing from these adjustments is to select also Top-Hat laser parameter, now there is parameter adjustment only for Gaussian laser.

Conical heat source radius parameters define the laser beam diameter. Conical heat source dept is defining the actual depth (penetration) of laser beam inside substrate material. It is in straight correlation in laser beam power density in relation to volume of laser beam.

In real life the beam itself does not penetrate inside component, but to get correct results from simulation, conical depth of 4,0mm is the optimal value and the beam spot starts from the surface plane.

For e.g. if this conical depth parameter is set up into the surface and 4,0mm upwards conical volume, it increases the surface temperatures and lowers internal temperatures.

Volume heat fraction is defining the portions of laser source energy distribution between heat input at conical volume and surface heat input,

Volume heat fraction

1.0: 100% heat input at conical volume, no heat input at surface (Recommendation: 0.7 - 0.9), (Simufact, Heat Source settings, instructions, 2025)

Volume heat fraction based on multiple tests is in optimal value when set to 1.0. This value is used both in calibration model results and in validation work.

Gaussian parameter M defines the laser beam parameter type. In Simufact, Gaussian is the only option for beam parameter type, although in our DED process laser beam type is Top hat. By setting this into 0 (zero), laser beam is as close as it gets compared to Top-hat. (Hexagon, Simufact specialist comments from technical support emails, 2024-2025.). Value 0 is used trough out both works.

Surface heat source parameters can be set up if there is another heat source present. In this work all parameters were put to zero.

Figure 33. is presenting lay-out table for setting the welding parameters for heat source, e.g. movement and power levels and idea for this figure is to illustrate how and what is influencing into process,

-velocity of laser beam or component

-selection of mode, direct power or indirect power

-power level for e.g. in watts

-energy input per length, efficiency is set to constant, 1.0.

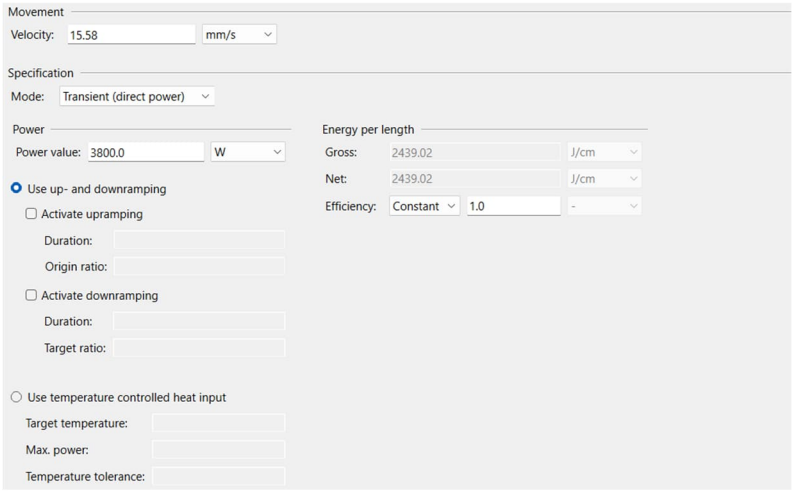


Figure 33. Heat source setting, welding parameters.

4.12 Creation of weld trajectories

Trajectory creation tool for robot in Simufact Welding software, based on experience e.g. a spiral trajectory cannot be created inside Simufact Welding trajectory module. Module supports simple trajectories like simple straight trajectory swept around cylinder.

Basically, it means that based on imported geometry and its dimensions, you must create certain number of trajectories to fully cover desired surface. Creation of trajectories comes in heavy manual work when component is something else than for example a plain and simple cylinder.

It must be noted that with Simufact Welding the base component cannot be rotated during cladding process. Instead, laser heat source is moving around components axis. At this thesis work and in real physical robot cell in manufacturing unit, component is rotating with rotating table, not the heat source. Laser, heat source is static during cladding process.

Trajectories are created in trajectory creation module, with help of surface point/node selection tool. This selection is fully manual selection work. Basically, it is manual G-code selection/creation process. With components complex geometrical shapes this comes in heavy workload to do.

With help of Query dialog tool, it is possible to select multiple points, as many you like for selected surface. For comparison, to complete cylindrical component first trajectory is made manually and rest of trajectories are copy paste or copy and move functions for trajectories.

Weld bead creator can also be used, but according to tests during calibration model work, the file mesh size for weld beads comes to proportional large size and causes very long calculation times with computers.

It was agreed internally that weld beads (geometries) are excluded from thermal model simulation and only heat source (laser) and its heat input, energy in component is simulated in calculations.

Under robot, during set-up of weld trajectories, system is constantly updated with added information, for. e.g. in calculations of welding time, welding sequences, start and ending times of weld beads, weld lengths and order.

As welding sequence is to be defined, also the trajectory management is to be determined under robot settings. In this, the orientation, possible offset, rotation angle of each trajectory is set. Figure 34. with modelled trajectories and orientations, image is from validation model.

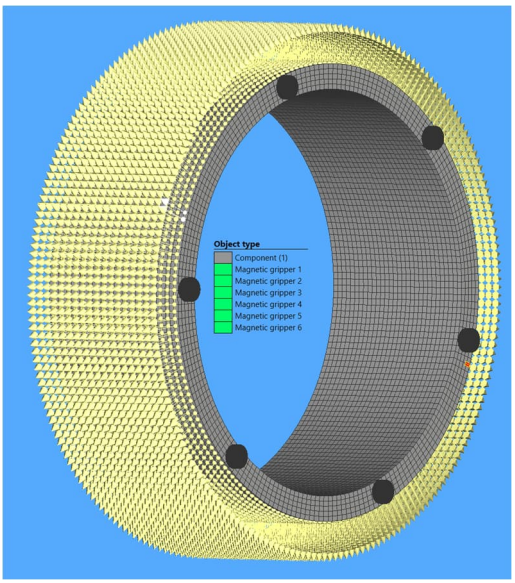


Figure 34. Component with modelled trajectories.

4.13 Model quality and consistency check prior to simulation calculation

Prior any simulation calculation done to model, it is wise to update all parameters in contact table with all its connections, times and input data. Finally run a model quality check to check for possible errors in input data and/or model.

4.14 Setting up calculation output data

When all steps for making a simulation analysis is done, then actual simulation can be run without problems, with pressing the Start Analysis icon. Calculation duration is fully dependable about project file data, such as component(s) file sizes, possible weld beads size and amount, computer performance level etc. Normal calculation time without weld bead generation, only heat source input and component, normal thermal calculation time is approximately 2 hours.

4.15 Results window

After calculation is finished, it is possible to evaluate the results form Results icon in process tree. Alternatively results, temperature behaviour can be evaluated in tools bar below the model view.

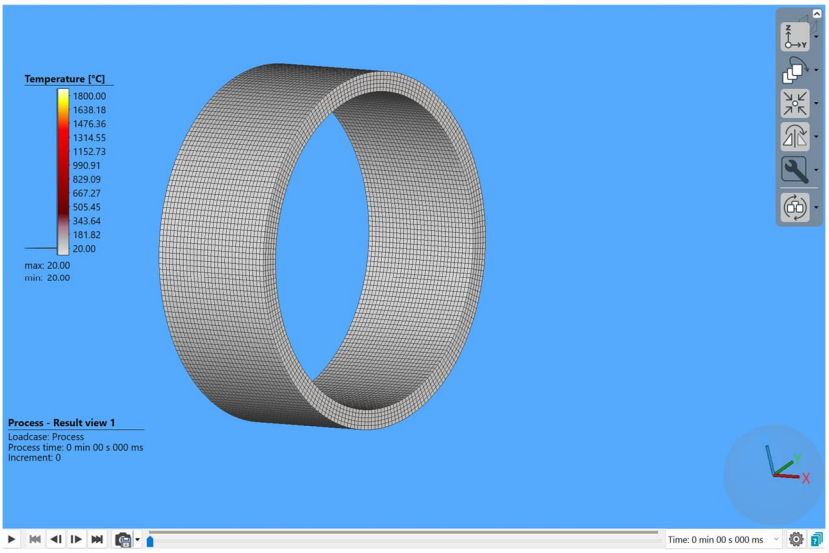


Figure 35. Results in model view.

It is possible to make selections that what you want to measure, temperature, contact, heat flux etc. from integrated plot in model view, figure 36. Also, it is possible to adjust temperature levels, type of illustrations, ways of calculation methods etc. Also, very useful properties is a possibility to use node selection tool to point out monitored points in component to get out results.

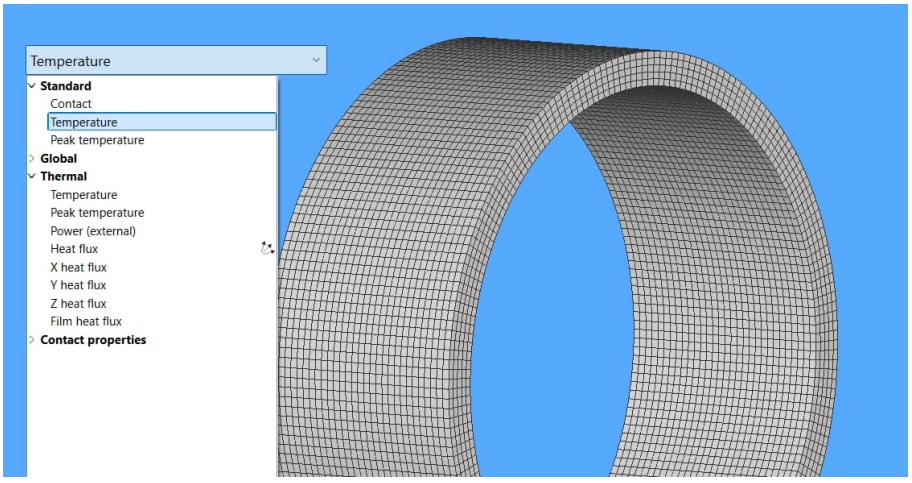


Figure 36. Possible output of measured data from simulation.

4.16 Validation tests simulation model file import

Model for external component was made with external software, Ansys 2024 R2 and was imported into simulation software. File type was Nastran, Hexa8 and was imported as one solid mesh component. Main dimensions for imported component were,

Internal diameter, 240mm

Outer diameter, 270mm

Width, 104mm

4.17 Validation tests parameters and specifications for cladding process

Parameters and specifications in validation tests were as they were calibrated and adjusted during calibration phase in simulation work. Information gained and learned from calibration model were implemented directly into validation model as they were. Laser speed and power levels were altered for validation tests, otherwise parameter adjustments were according to calibration model.

Parameters used for cladding process for validation tests, table 8.

Parameter	Value, type
Conical Heat Source Depth	4,0mm
Laser beam spot size	6,00mm
Laser speed	15,58mm/s (935m/min)
Laser power	3800W
Laser beam type	Gaussian, parameter [M], 0
Laser spot focal point	Spot on surface [0,0mm]
Convective heat transfer rate	35W/m2K rate in substrate, added material
Conical heat source radius	3.0mm [upper, lower]
Initial temperature	+20,0˚C Degrees Celsius, substrate, added material
Substrate	16MnCr5, Case hardening steel
Added material	316L, Stainless Steel

5 Results

5.1 Calibration model simulation analysis results

In this chapter, temperature graph extracted from customers pyrometers in calibration model tests are presented. These results and calibration model were synchronized during calibration model build up phase.

Figure 37. shows temperature graph from internal model pyrometer temperature curve. Temperature curve and internal extracted measurement data (excel extract) from pyrometers shows maximum temperature during cladding process reaching up to +398,06C Degrees Celsius at the end of cladding process.

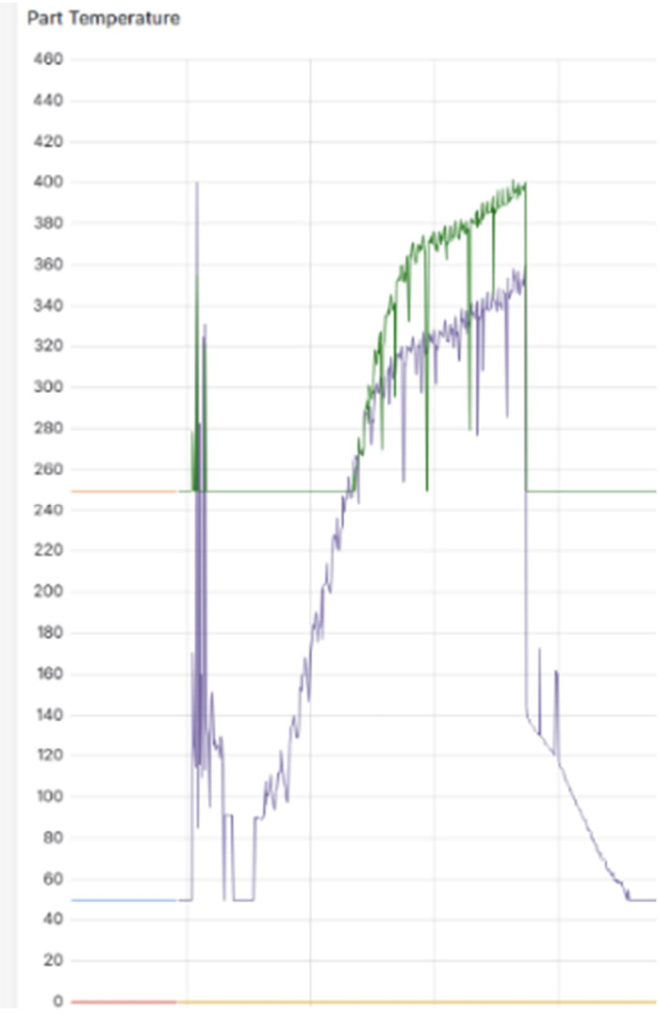


Figure 37. Temperature graph from internal model.

Calibration work for internal model, its results showed promising levels and accuracy for temperature measurement points. Result from Simufact simulation calculation for maximum temperatures in component, digital probes on the same location as they were in physical test, see figure 40.

Temperature results were like physical tests performed and it could be decided that calibration of simulation model is in level of accepted accuracy. Additionally, from the results, values such as live maximum temperatures in weld pool, minimum temperature point(s) can be seen. Histogram can be defined for visual purposes for temperature behaviour, see figure 38.

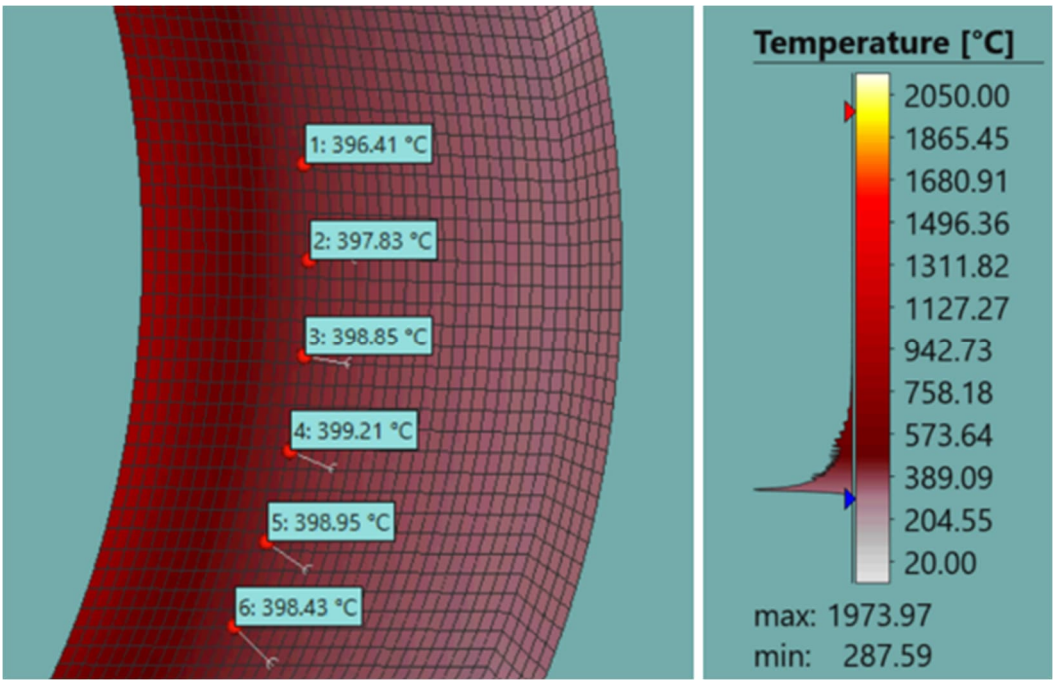


Figure 38. Temperature plot from simulation work for calibration model

It was discussed after getting out results from model calibration that can this set-up brought into use with different shapes of components. Internal model was not cylindrical in all shapes and surfaces, which naturally brings slightly different temperature distribution into the component.

Validation of internal calibration model with cylindrical tube (validation model) is tested with live physical tests at manufacturing unit. Results from internal model were promising in accuracy and were approved by customer and these parameters and principles were transferred directly as they were into external validation model.

5.2 Validation model simulation analysis results

Prior actual live tests at customers factory, simulation results from Simufact validation model were sent to customer. Test results for heat generation and maximum temperature levels shown in figure 39. Mean value for maximum temperature was agreed into +315C Degrees Celsius together with customer.

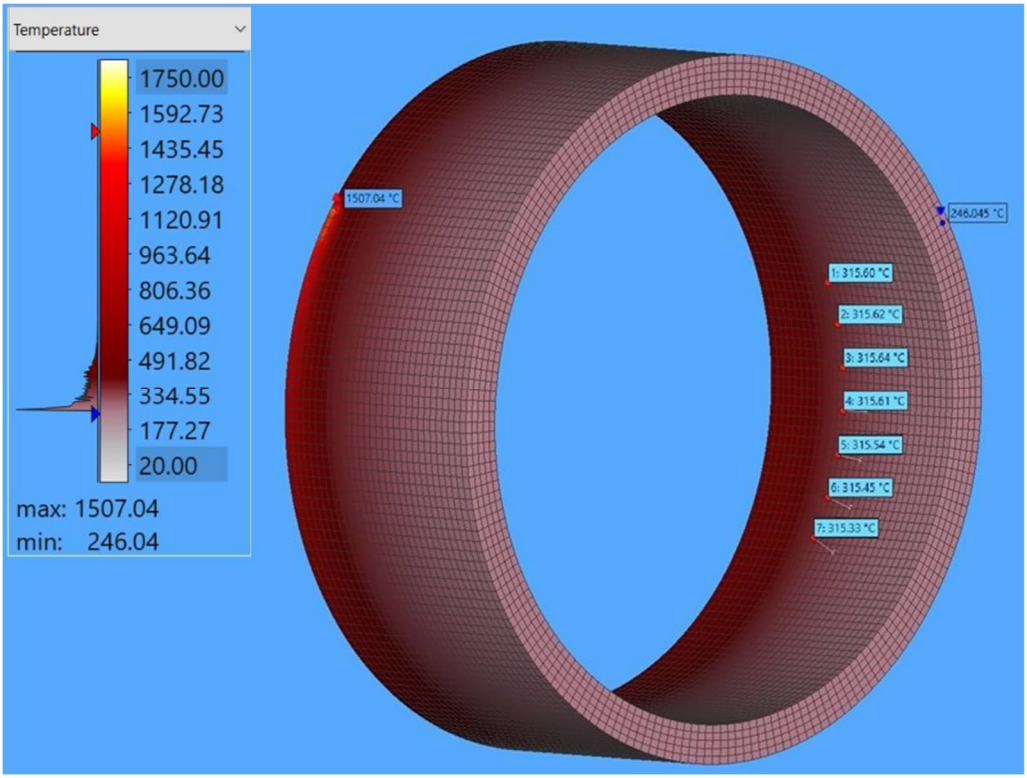


Figure 39. Validation model simulation results in model view.

Temperature graph from simulation calculation for validation evaluation purposes, see figure 40. graph starting from room temperature.

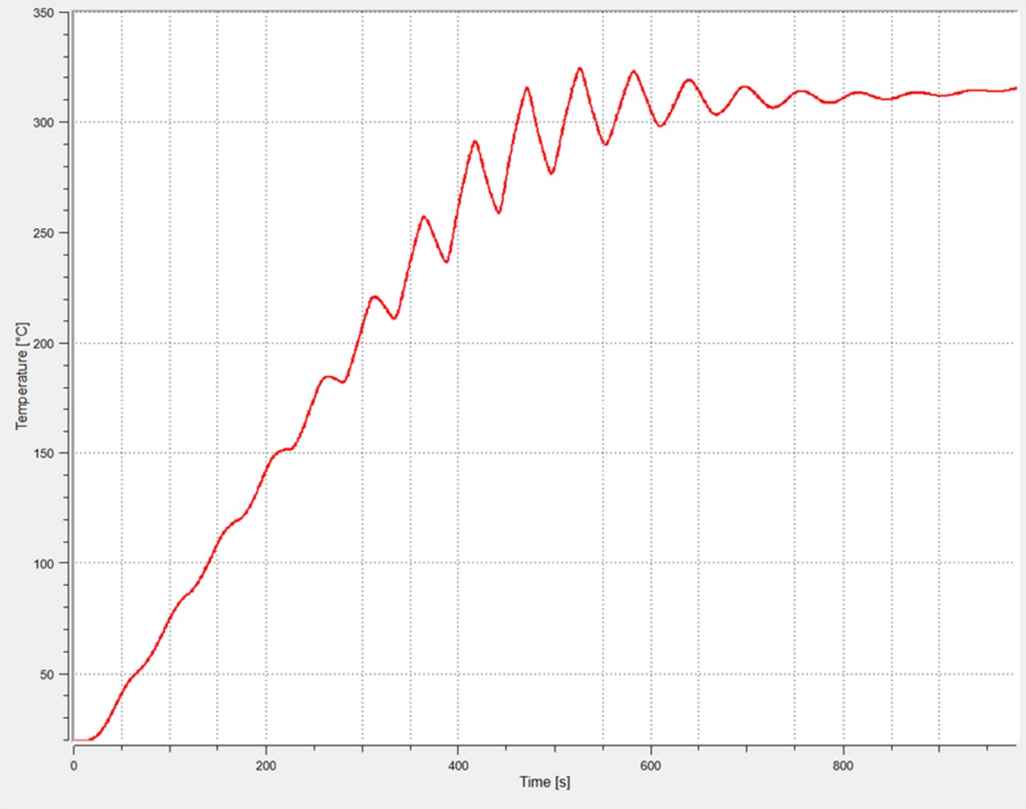


Figure 40. Temperature chart, simulation results for validation.

5.3 Physical validation tests results

Validation tests with laser cladding process into component were done in customers manufacturing unit's robot cell. In tests, there was total of three layers welded on top of cylinder. Pyrometers data extracted from customers data management system shows temperature behaviour starting from pre-heating all the way to the end of weld trajectory (one layer).

With customers machine weld trajectory is spiral and not consisting of multiple trajectories as they are in simulation model. Spiral is easily and naturally done, since component is rotating and laser head is moving axially and generating a spiral.

Even though customer uses pre-heating for components, results are in a good accuracy level considering that in simulation modelling starting temperatures were at room temperature.

It can be seen from figure 41., that starting temperature levels are increasing between layers and maximum peaked temperatures are also altering a bit. Mean value for maximum temperature is roughly +320C Degrees Celsius.

At simulation modelling only one layer was added into component. If weld bead geometries are used in simulation work, there is possibility to add 3 layers as it was done on validation tests.

Results for temperature levels and temperature behaviour in graphs are close to each other in validation simulation model and actual live tests performed. Customer accepted the accuracy of validation simulation model accuracy based on performed tests on-site at customers manufacturing unit.

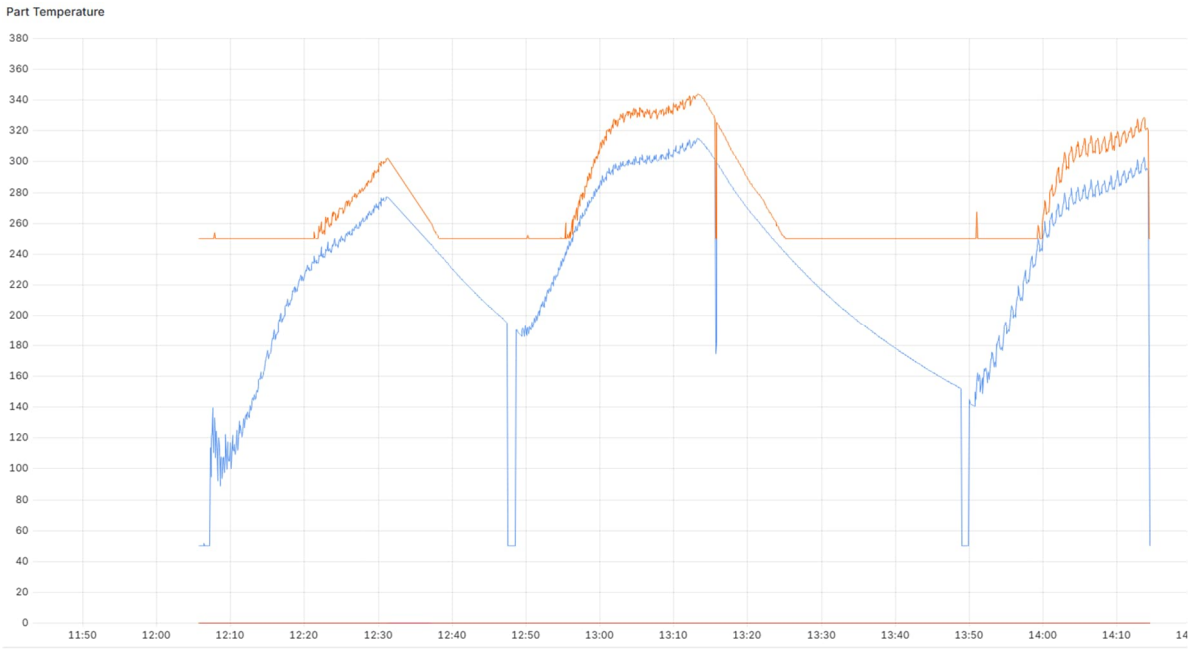


Figure 41. Validation test temperature chart in three layers.

As a comparison, the first two tests on cylindrical components showed visibly that there are differences in temperature behavior and reached temperature levels in pyrometers when solid fixing plates were used between component and robot turning table. These differences are a result of different heat convection rates and different sizes of heat sinks.

For first two tests, temperature levels were 13% lower in test samples no. 1. & 2. When compared into test sample no. 4, which is an accurate image of simulation calculation in Simufact. Average temperature levels were approximately +280C Degrees Celcius.

In validation model and accurate image in tests set-up, there are small inserts acting as grippers, and the surface area for heat convection is rather small, when as it is big in test samples no 1. & 2. Heat convection in simulation model, most of it goes into surrounding air and not into fixing plate and towards robot. Temperature graphs, figure 42., from test samples no. 1. & 2. with same parameters as in test no. 3., with solid fixing plate.

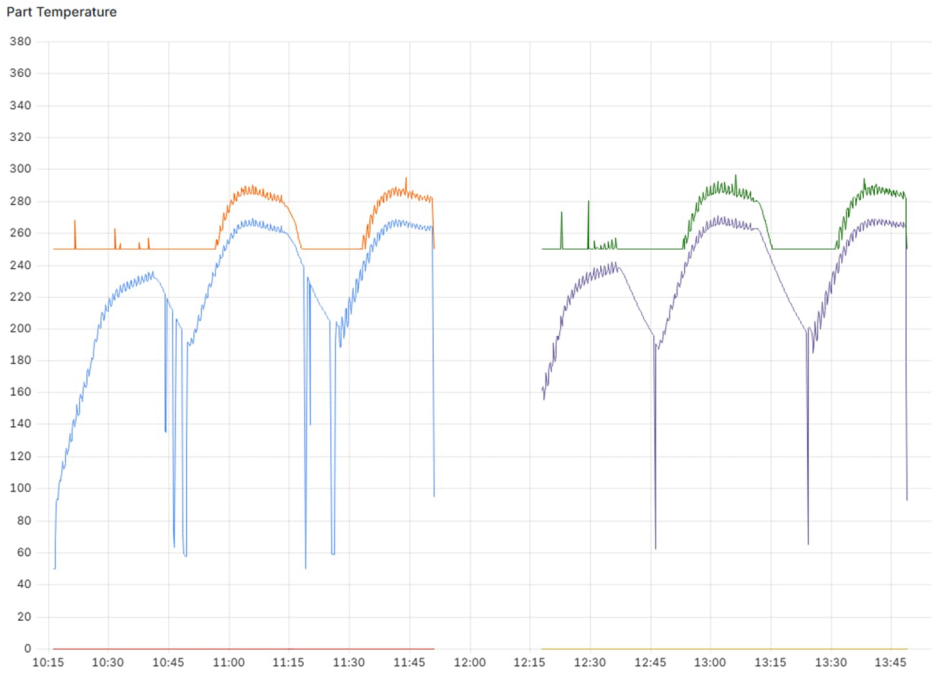


Figure 42. Temperature graphs from test samples 1. & 2., with solid fixing plate

6 Discussion

In this chapter findings for this thesis work simulation calibration phase and validation phase are to be concluded. Major differences between simulation work and real-life arrangements and specifications are being clarified. Results analyse, result accuracy, results quality is being justified, and deviations are explained.

6.1 Calibration model results vs. physical test results

It can be said in this point that specifications and parameter justifications learned and adapted from calibration model can be transferred into different shape of component with different power levels and speeds with good quality and accuracy.

Accurate prognosis results for predicting maximum end temperature levels are possible to execute with this software and can be done in expectable and expected quality levels. This, even there are some critical parameter adjustment possibilities missing from used software, simulation model was possible to generate with certain parameter adjustments.

It was clear based on live tests in validation phase that big influence in reached temperature levels during manufacturing process are used laser power, heat source speed, used fixing plates or smaller grippers and their geometry. Also, pre-heating is influencing in end results but not in that scale what was expected.

There is a big difference in thermal behaviour in component between used grippers in manufacturing process when they are solid or smaller ones, for fixing component into robot. These reached temperature levels difference is due to different heat convection rates within component and out from it. Reality and simulation model results combined in this sense well against each other.

6.2 Deviations between simulation model and real-life execution

There are several things that makes impacts and differences in results between simulation model and real-life production execution set-up. In real life, component is rotating while processing, and in in simulation model laser source is rotating around static component. In practise it a matter of difference which of components is rotating to put in simple words. In real effects, there are matters like airflow, powder behaviour proximity to weld pool due to differences in flows of material (powder, gas). From these no exact (measured) differences are known based on thesis work. 2

Cladding trajectory in real life set-up is spiral, because of system set-up, component is rotating on its's axis, while staying static in all other directions. At same time, laser head is moving along it's programmed direction and creating a spiral shape weld trajectory. In simulation model weld trajectories are created with multiple separate trajectories with moving laser source. Differences are not exactly in temperature levels, but more into programming side during designing phase.

Laser mode in real life execution is Top-hat laser mode and in simulation model with Simufact it is Gaussian mode laser only. This deviation makes a big impact on simulation phase. Reason is that it is demanding to get accurate results out of simulation because energy concentration is different between gaussian laser and top-hat laser. And when there is no option to select top-hat mode in simulation software, programmers must find a way to bypass the problem by altering all other parameters to get gaussian mode to behave like top-hat.

Added material, stainless steel 316L was in Simufact database as wire only but does not influence in results or heat generation in calculations. In real life powder is used.

Pre-heating is used in real production and was not used in Simulation with agreement with customer. End temperature results were still at an accurate level. Also, accuracy for repeating reached temperature levels between pre-heating's in production unit is unclear. Pre-heating's were done by hand with gas torch and measured with contacting temperature probe. This way of doing and measuring preheating temperatures is not a valid and repeatable way of doing it.

7 Conclusion

Task to research and investigate a possibility to make a thermal simulation model to Laser Cladding process, or LMD as customer calls it came from customer needs. It was clear from first discussions onwards that customer really needs a practical everyday tool to evaluate their LMD process with reliable way, preferable with some computer aided simulation software. Main task was to create a simulation tool which can predict temperature levels in customers components during and after production process.

Currently customers way to gain information about maximum reached temperature levels are done with physical trials. Physical trials are time consuming, with no prediction available of reached maximum temperature levels and there are also physical risks for component handling and fixing if temperatures go above max. allowed temperature levels.

There were no requirements stated how accurate possible simulation tool or calculation must be, only to get it as close as possible, and possibly model should be adaptable into various sizes, shapes of components. With this tool customer can predict and adjust their process, equipment's and gain shorter lead times in manufacturing process.

It was clear at very early stage of this master's thesis work that this is not going to be easy task to make. Based on literature research, lots of different studies has been made in field of Laser Cladding, LMD, Additive Manufacturing, especially in steel microstructures and mechanic's side. Numerous scientific research has been made for combining different materials, focus many times on enhancements of materials with e.g. cladding, DED or surface treatments, not solely into thermal analyses.

Also, no totally exact and detailed information was found for reference material to this master's thesis work, using LMD nor DED-process for cladding purposes with top-hat diode laser with combining case hardened steel and stainless steel together. Neither to make a simulation based thermal behaviour prediction tool or model to mentioned process. After a trough out and consistent work with simulation software tool, model was possible to be correctly calibrated and adjusted correctly, even though in some cases with quite unorthodox ways, but still performing the task. Validation tests showed that calibration model adjustments were in good quality level and fulfilling customer requirements well.

8 Needs for future research work

It remains to be seen that is this simulation tool made with Hexagon Simufact Welding going into use in production. To make it easier to use and more adaptable for everyday use in production software needs certain improvements to get full potential out of it.

Laser mode selections need additional check box for changing the mode of laser, only Gaussian mode is not sufficient to perform needed tasks in this customer and probably same issue can be the same with other customers.

Weld trajectory creation needs to be simplified somehow to make possible different trajectories with for e.g. with different commands in trajectory creation tool. With improvements into these it reduces the need for time consuming coding for trajectories. Also to make it more accurate to simulate live process software also needs a possibility to make component to rotate, not only the laser source. With component rotation, the spiral trajectory creation could be easily handled just by moving along the laser source.

In short, Simufact Welding is a good and precise tool for temperature predictions, at least based on this master's thesis work for process simulation. To make it more efficient, software needs re-coding of some new parameters and adjusting some current parameters.

Customer is actively investigating alternative software's to perform same simulation as this simulation software in this thesis parallel. Final selections are not made completely in which software customer is going to invest in future.

Customer is also investigating a possible software which could handle also mechanical side, for example FEM calculations and thermal analysis in same software.

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