

**MODELING OF TEMPERATURE FIELD, RESIDUAL STRESSES AND
DISTORTIONS IN DIRECT LASER METAL SINTERING**

**DİREKT METAL SİNTERLEME YÖNTEMLERİNDEKİ SICAKLIK
ALANLARININ, ARTIK GERİLMELERİN VE ÇARPILMALARIN
MODELLENMESİ**

by

Erdem Kundakcıoğlu

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This is to certify that I have examined this copy of a doctoral thesis by

Erdem Kundakcioğlu

and have found that it is complete and satisfactory in all respects,
and that any and all revisions required by the final
examining committee have been made.

Committee Members:

Ismail Lazoğlu, Ph. D. (Advisor)

Alphan Sennaroğlu, Ph.D

Erdem Alaca, Ph. D.

Evren Yasa, Ph.D.

Emrecan Söylemez, Ph.D.

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TO MY FAMILY



ABSTRACT

Additive manufacturing provides new opportunities for weight reduction in the aerospace industry where high fly-o-buy ratio is desired. Selective laser sintering of advanced engineering materials like Nickel super-alloys are also expanding to reduce the cost and time of the manufacturing in the aerospace industry. Elevated temperature and temperature gradients are critical factors in selective laser sintering of metals and they significantly affect the quality and integrity factors of produced parts such as microstructures, porosity, residual stresses and distortions. Therefore, an advanced simulation tool is needed to predict the temperatures, temperature gradients and molten pool geometries for a better understanding of the physics of the selective laser melting process as well as process optimizations. Moreover, it is essential to predict residual stresses and distortions so that preventive actions such as support design or changing build direction can be taken. Although researchers have been studying for more than a decade to understand and model the complex physical phenomena involved in the Direct Laser Metal Sintering (DMLS) process, the solutions provided in the literature are not fully applicable in industrial cases due to long computation time.

This thesis, introduces an adjustable finite element based multi-physics and multi-software platform thermal model for direct metal laser sintering (powder bed systems) to predict the transient temperature and the molten pool geometry. The developed model is able to simulate 3D transient temperature and molten pool shape in the laser additive manufacturing process by including the features of melting and solidification, porous media and temperature-dependent thermal material properties for different materials. A set of experiments of Inconel 625 is carried out in order to measure the size of the molten pool and to validate the developed thermal model. An experimental study on temperature distribution carried out with Titanium and an experimental study on molten pool sizes carried out with

Inconel 625 in the literature are also compared with the developed thermal model. The prediction errors of the developed model are in the range of 11 – 18 %.

Moreover, an analytical approach and a multi-physics based finite element modeling approach are introduced in this thesis for quick estimation of the residual stresses and distortions of the parts in the direct metal laser sintering. The modeling approach incorporates the features of plasticity and hardening mechanism into the FEM environment. FEM simulation results on residual stress and distortions are validated by experimental measurements on Inconel 625. The simulation results agree with the experimental measurements within a range of 0.2 – 9%.

Finally, the developed thermo-mechanical model is tested for complex freeform and thin-walled structures. Four freeform and seven thin-wall structures are additively manufactured and simulated. Experiments on thin wall hollow and complex freeform structures are performed in order to validate the developed model for the residual stresses and distortions in direct metal laser sintering process in industrial parts. The simulation results agree well with the experimental measurements.

It should be noted that for the first time in the literature, additive manufacturing of industrial parts can be successfully simulated in much shorter computation time using the developed model. The unique model developed in this thesis is used in the aerospace industry in the thermal, residual stress and distortion simulations of additive manufactured engine parts of the unmanned air vehicles.

ÖZET

Bu çalışmada, lazerli eklemeli imalat süreci parametrelerinin parça üzerindeki termal ve mekanik etkileri araştırılmıştır. Eklemeli imalat üzerine detaylı bir literatür araştırması yapılmıştır. Süreç parametrelerinin parça üzerindeki etkilerini (mekanik özellikler, artık gerilme, çarpılma vb.) belirlemede ilk adım olarak termal modelleme çalışması yapılmıştır. Termal modelde, hareketli lazer matematik modeli, toz yatağı malzeme modeli, erime mekanizması ve indeksleme yöntemi geliştirilmiştir. Termal model sonuçları literatürdeki örnek deneysel çalışmalarla karşılaştırılmış ve yakın sonuçlar alınmıştır.

İkinci aşama olarak hem analitik hem sonlu elemanlar metodu kullanılarak, termomekanik ve termal-mekanik model çalışması yapılmıştır. Geliştirilen termal model ile beraber ya da ayrı çalışan, zamana bağlı ya da bağımsız dört farklı sonlu eleman tabanlı mekanik model geliştirilmiştir. Geliştirilen bu sonlu eleman tabanlı modellerden hem çözüm süresi hem de tahmin doğruluğu açısından en hızlı ve doğru çözüm yapanı seçilmiştir. Deney doğrulamasında, geliştirilen analitik ve sonlu eleman tabanlı modelleri kullanılmıştır. Deneyler sonucunda, basit geometriler için analitik modelin kullanılabildiği ancak daha karmaşık geometrilerde kullanılamadığı görülmüştür. Öte yandan, sonlu eleman tabanlı model gerek basit gerekse karışık geometriler için deneylere yakın sonuçlar vermiştir.

Son olarak, geliştirilmiş termomekanik model serbest yüzeyli geometriler ve ince cidarlı geometriler üzerinde denenmiştir. Dört adet serbest yüzeyli ve yedi adet ince cidarlı parça için eklemeli imalat modeli koşturulmuş ve üretilmiştir. Endüstriyel parçalar üzerinde yapılan bu deneyler, geliştirilen artık gerilme ve çarpılma modelini doğrulamak için yapılmıştır. Geliştirilen modelden alınan sonuçların, deneysel ölçümlere yakın olduğu görülmüştür.

Şu nokta belirtilmelidir ki, geliştirilmiş olan bu model sayesinde, çok kısa çözümleme süresiyle endüstriyel parçaların eklemeli imalat modellemesi literatürde ilk defa

başarılmıştır. Bu tez kapsamında geliştirilen özgün model, bu açıdan bir ilki gerçekleştirmiş ve insansız hava araçlarının motor parçalarının eklemeli imalat yönteminde ortaya çıkan sıcaklık, artık gerilme ve çarpılma modellemesinde kullanılmıştır.



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NOMENCLATURE

ρ	Density
C_p	Heat Capacity
k	Thermal Conductivity
h	Heat Convection Coefficient
q	Input Heat Flux
$\hat{n}$	Unit Normal Vector
Q	Laser Heat Generation
P	Total Laser Power
η	Laser Absorption Coefficient
d	Diameter of the Laser Beam
x_0	Pulse center x - coordinate
y_0	Pulse center y - coordinate
z_0	Pulse center z - coordinate
h_p	The penetration depth of the laser
σ	Stefan-Boltzmann Constant
k_{powder}	Thermal Conductivity (Powder)
k_{eq}	Effective Thermal Conductivity of Powder Bed
k_g	Thermal Conductivity of Gas (Between Particles)
k_s	Thermal Conductivity of the Skeletal Solid
B	Deformation Parameter of the Particle ($B=1$ when the particle surface is that of a sphere)
φ	Porosity
k_R	Conductivity by Radiation
ϕ	Flattened Surface Fraction of Particle in Contact with Another Particle

$k_{contact}$	Contact Conductivity between two particles according to the value of ϕ
T_{ext}	Gas Medium Temperature
T_{amb}	Room Temperature
q_{rad}	Heat Loss due to Radiation
ε	Emissivity
b	The distance to the neutral axis
ρ	The radius of the curvature
$\varepsilon_{non-thermal}$	Non-thermal strain
ε_{total}	Total strain
α	Thermal expansion coefficient
ΔT	Temperature difference
A	Relaxation factor
$w(z)$	Deformation equation
σ_{ys0}	Initial yield stress
$\sigma_h(\varepsilon_p)$	Hardening stress
s	Overall stress tensor
s_0	Initial stresses
ε_0	Initial strains
f	Form coefficient
δ	Deflection
$\delta_{adjusted}$	Adjusted deflection

Chapter 1

INTRODUCTION

1.1 Overview

The usage of the additive manufacturing process is gradually increasing over two decades in the manufacturing world. It is a manufacturing technique where the part is manufactured layer by layer. Due to its methodology, which allows manufacturing any geometry from a 3D solid model, it is referred to as “Engine of Industrial Revival”. On the special report published by Euractiv in 2017 [1], it was said that the European community invested €95 million in additive manufacturing related projects. It was also mentioned a similar investment move was planned by the US government for the first five years and \$100 million were gathered for the research and development of the additive manufacturing so far. It should be mentioned that there are several trade names for metal additive manufacturing such as Laser engineered net shaping® (LENS), Direct metal laser sintering (DMLS), direct metal laser melting (DMLM) etc. The technical name of the metal additive manufacturing is selective laser melting (SLM) but in this study, direct metal laser sintering (DMLS) will be used for referring purposes.

Researchers mainly focused on the improvements in the geometrical constraints of the additive manufacturing machines. Several slicing algorithms as well as several scanning strategies were introduced to obtain end shape parts, especially on metal additive manufacturing, it is seen that considering only the geometrical constraints are not enough to manufacture end shape parts. Therefore, the physics of metal additive manufacturing needs to be examined thoroughly. Although researchers are working on the modeling of the additive manufacturing, the research status shows that detailed research can be done on the thermomechanical modeling of the additive manufacturing. By achieving an advanced

thermomechanical model, the transient temperature distribution, the residual stresses and the distortions can be predicted. Moreover, using such a virtual additive manufacturing tool, the users will be able to see the effects of the parameter of the additive manufacturing on the part and will be able to adjust the parameters according to the thermo-mechanical model.

1.2 The advantages of thermo-mechanical modeling

For additive manufacturing of a part, a slicer software is used to obtain the scanning strategy according to the 3D geometrical data of the corresponding part. As mentioned before, the slicer is generating the scanning strategy regarding only the geometrical constraints. Hence, the thermo-mechanical effects are not taken into consideration, which results in distortions in the final part.

A thermo-mechanical tool for additive manufacturing can give the following information:

- The effects of the scanning parameters on the temperature distribution, the dimension of the molten pool and the overall melted zone,
- The effects of the scanning parameters on the residual stresses and the distortions,
- The thermomechanical behavior of different materials.

Although there has been a lot of research on the subject of thermo-mechanical modeling of the additive manufacturing process (detailed in Chapter 2), the developed models are not suited for industrial applications. The analytical models are not applicable on 3D complex geometries and the finite element method (FEM) based models require high computation time and they become impractical to solve (i.e. 10 years of computation time) when used on industrial applications (Figure 1-1/2). Therefore, there is a need to have a fast prediction tool for temperature distribution, the dimensions of the molten pool, residual stresses and overall distortions for the additive manufacturing process. In this thesis, the thermal problem will be examined firstly, then it will be combined with the mechanical problem.



Figure 1-1 – A 3D-printed nozzle of GE LEAP Engine [2]

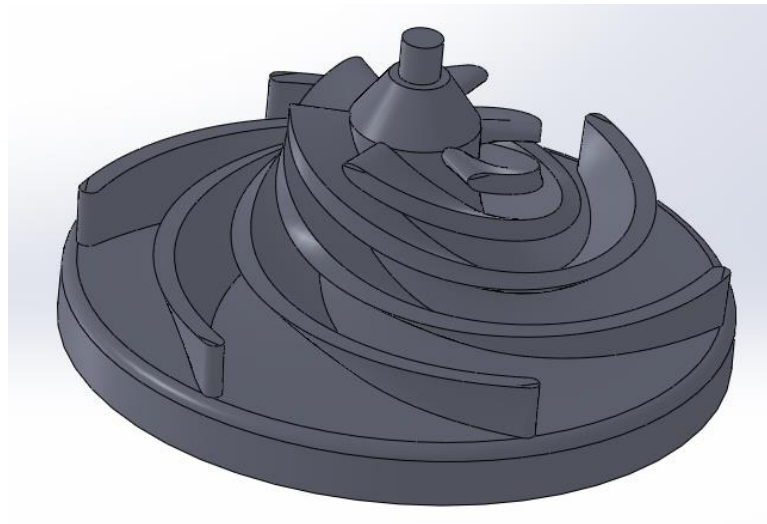


Figure 1-2 – A biomedical heart pump impeller

1.3 Research Objectives

In order to understand the physics of the additive manufacturing (AM) process, thermal and mechanical mechanisms should be explored in detail. In this thesis, direct metal laser sintering (powder bed system) will be investigated. In this process, the heat source (the laser beam) melts the powder according to the 3D CAD data and the sequence is repeated in each layer until the process is finished. The difficulty of the modeling of AM results from the nature of the process. During the process, the powder material is melted in small zones (microscale) and after the laser beam is moved, melted zones are solidified. Thus, the thermal model should cover the melting of the powder and the solidification of the molten zone. Introducing the thermal expansion in the mechanical analysis, the thermo-mechanical modeling of the AM process becomes a cumbersome work. For that reason, the following subjects are investigated to segment the thermo-mechanical problem:

- Thermal Model
 - Powder Bed Model
 - Heat Source Model
 - Phase Change Model
 - Heat losses
- Mechanical Model
 - Thermal Expansion
 - Plastic Deformation
 - Hardening Mechanism (if it is available for the corresponding material)

The main aim of this thesis is to introduce a FEM based thermo-mechanical model for direct metal laser sintering (powder bed system), from which the effects the material properties and scanning parameters on the temperature distribution and molten pool geometry during the metal additive manufacturing can be predicted. Including the powder-liquid-solid transformation and a 3D heat source model, the developed model can predict the

temperature evolution and the dynamic molten pool geometry. In addition, a technique is developed to allow the application of the thermal models on 3D freeform parts. With the thermal information acquired from the thermal model and introducing this information to the mechanical model where the thermal expansion & contraction, the plastic deformation, and the effects of the hardening mechanism are calculated in order to predict the residual stresses and resulting distortions. Moreover, to meet the industrial need in terms of fast computation, the thermomechanical model is decoupled to thermal-mechanical model, which decreases the computation time drastically. An overall schematic of the developed model is shown in Figure 1-3.

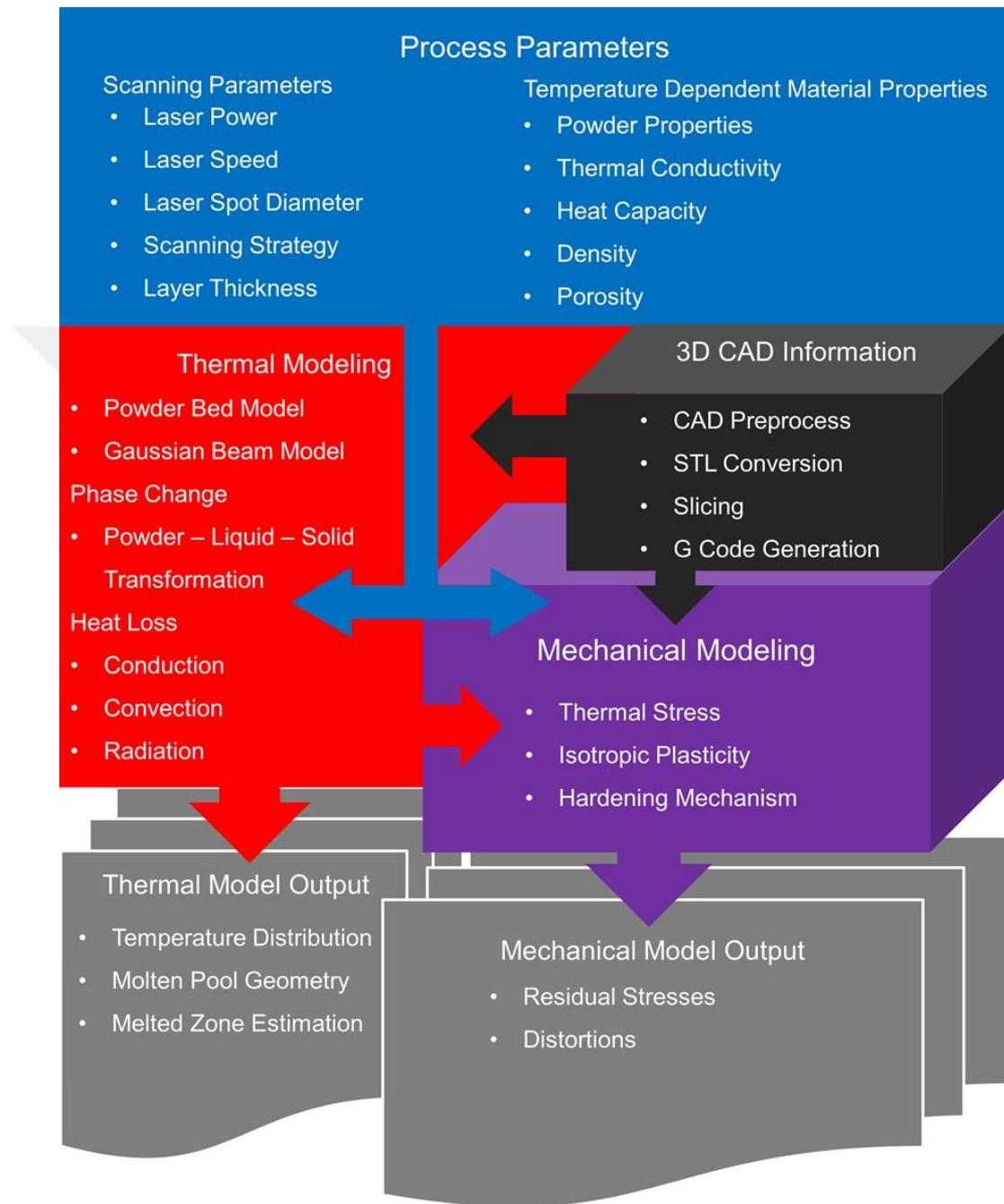


Figure 1-3 – The representation of the developed thermal – mechanical model

As shown above, the developed thermo mechanical model should be as much detailed as possible and should accomplish:

- The prediction of temperature field, dimensions of molten pool with an error below 25%,
- The prediction of residual stresses and distortions (orientation as well) during and after the DMLS process with an error below 25%,
- The compensability of the prediction error in both thermal and mechanical model using experimental results,
- The application on complex and freeform geometries,
- A computation duration that is below three hours for the mechanical model in order to use it for optimization purposes

with the following assumptions:

- Isotropic material properties,
- Constant laser absorption coefficient,
- Constant thermal expansion coefficient (in mechanical model),
- Neglecting the effects of phase transformation on residual stresses,

Chapter 2

LITERATURE REVIEW

2.1 Overview

Manufacturing techniques have been developed since the industrial revolution in the late 19th century, to satisfy the needs of society. “Design & Designers” concept has been brought into the business to obtain the best mechanical properties with the required geometrical constraints. In most applications, there is a geometrical limit, so the designer has to take the manufacturing process into consideration.

In the year of 1970, a milestone in the field of manufacturing, a new technique called “Layer Manufacturing” was mentioned. The main idea of this technique was to manufacture a part layer by layer like the construction of a building, which meant to have complete freedom in terms of geometrical complexity. In 1984, lithography was invented and other types of layer manufacturing followed this invention. At first, polymer-based materials were used for this process, then with the laser technology included in layer manufacturing, metal-based materials were used. Over 25 years, researchers studied layer manufacturing under the name of Rapid Prototyping, to understand the nature of this manufacturing technique and how to improve the process quality. The mechanical properties and the surface quality of the additively manufactured parts are explored. There have also been works on finite element modeling of the several layer manufacturing techniques.

In the following section, an extensive literature survey about additive layer manufacturing (ALM) will be presented. For this matter, the historical background for ALM has been investigated. Next, the historical background of direct metal laser sintering (DMLS) process has been explored. A detailed survey has been done about DMLS in between 2010 until today. Then, the studies related to the thermal or/and thermo-mechanical modeling have been explored.

2.2 Historical Background of Layer Manufacturing

It is mentioned that ALM technologies begin with the invention (Chuck Hull) of Stereolithography in 1984 [3]. Table 1 shows the brief history of ALM process development.

Table 2-1- ALM development years [4]

Name of the Process	Acronym	Development Years
Stereolithography	SLA	1986-1988
Solid Ground Curing	SGC	1986-1988 (Disappeared in 1999)
Laminated Object Manufacturing	LOM	1985-1991
Fused Deposition Modelling	FDM	1988-1991
Selective Laser Sintering	SLS	1987-1992
3D Printing	3DP	1985-1997

With the invention of SLA, many new processes are developed in this area. ALM is also mentioned as Rapid prototyping (RP) [4]. The figure below shows the patent timeline for Rapid Prototyping. It is noted that at the very beginning, plastic is used mainly as material, which is followed by metal. [3]

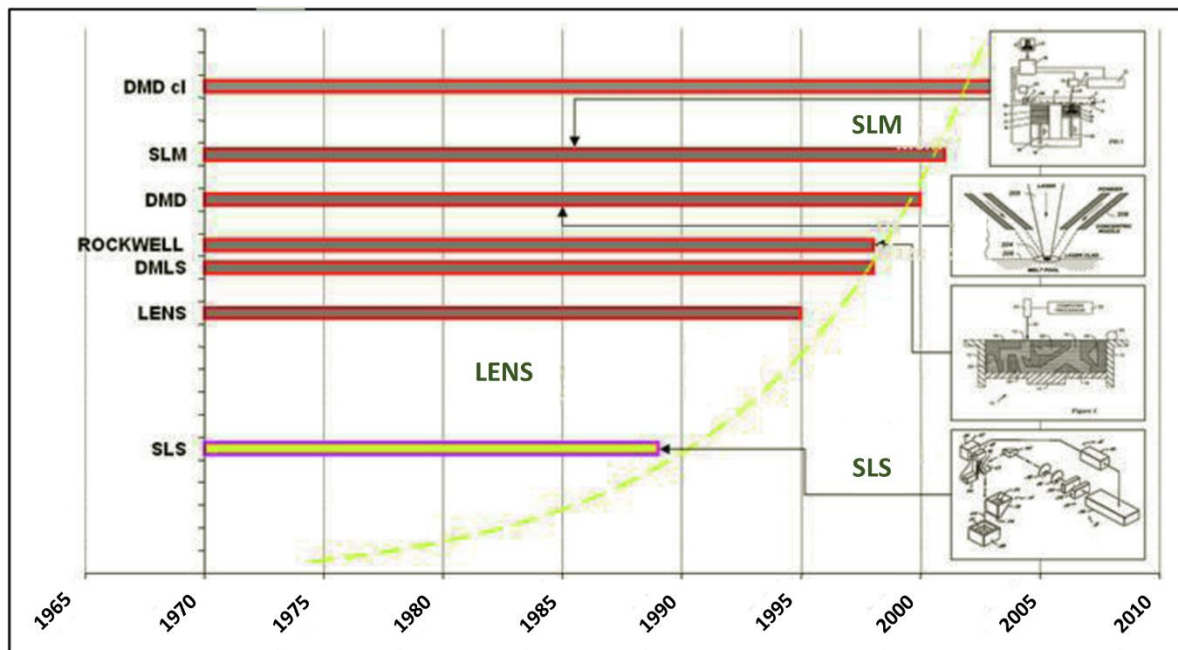


Figure 2-1- Patent timeline for rapid prototyping [3]

The Rapid Prototyping process for metals is rooted back to 1971 (patent of Ciraud) [3] and 1977 (patent of Housholder) [6] which led to the idea of Selective Laser Sintering (SLS) and Selective Laser Melting (SLM). [7] The Rapid Prototyping patent timeline for metal is shown in Figure 2-2.

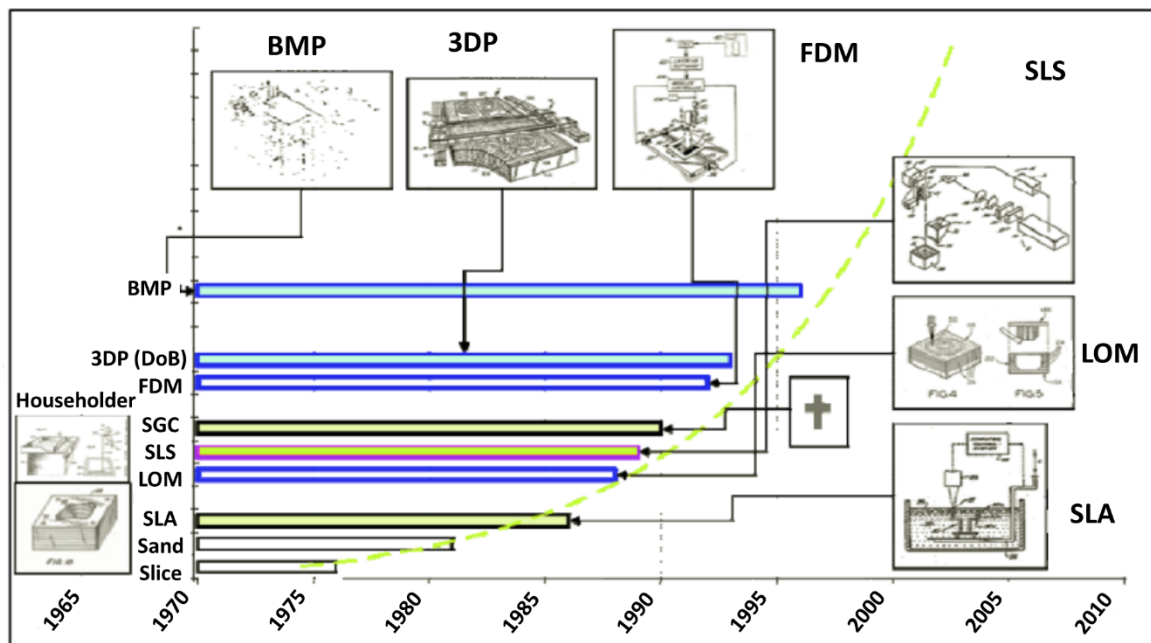


Figure 2-2-Patent timeline for rapid prototyping of metals [3]

In 1995, Laser Engineered Net Shaping (LENS), which is a metal melting technology, was initiated at Sandia National Laboratories [3]. After a couple of years, the powder beds (SLM) were invented [9].

Table 2-2-Additive layer manufacturing techniques and development periods [3]

Name of the Additive Manufacturing Process	Acronym	Energy Type	Material	Development
Stereolithography	SLA	Laser	Polymer	1986-1988
Selective Laser Sintering	SLS	Laser	Polymer / Metal	1987-1994
Fused Deposition Modeling	FDM	Extrusion	Polymer	1988-1991

3D Printing	3DP	Binder/UV Light	Polymer/ Metal	1985-1997
Selective Mask Sintering	SMS	IR	Polymer	1998-2007
Solid Plastic Sheet Lamination	LOM (PSL)	Cutter	Polymer	2005
Selective Laser Melting	SLM	Laser	Metal	2001-2004
Laser Engineered Near Net	LENS®	Laser	Metal	2000-2002
Electron Beam Melting	EBM®	Electron Beam	Metal	1977-2002

2.3 Historical Background of Direct Metal Laser Sintering

With the development of the laser technology, Rapid Prototyping (or Additive Layer Manufacturing) has taken a step towards the mass production concept and, lots of studies are being conducted on this area to improve the manufacturing procedure.

Layer manufacturing techniques and the development period for these techniques are given in Table 2-2. From this table it can be seen that, there are lots of techniques using different types of energy source and material.

It is said that additive direct manufacturing techniques for metals can be categorized as Melting and Non – Melting processes [4] shown in below figure.

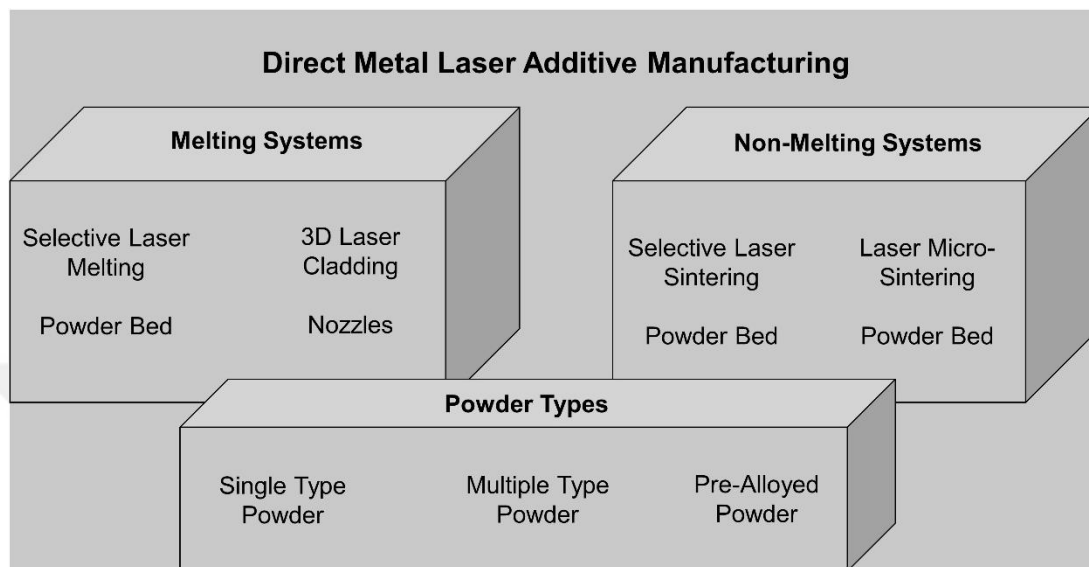


Figure 2-3- Direct metal laser additive manufacturing categorization [7]

2.3.1 Non-Melting ALM Techniques

2.3.1.1 Selective Laser Sintering

As mentioned before, the SLS process was invented by Householder [6] and developed by Deckard [25]. Although SLS provides a geometrical complexity, it is noted that the material of the process is a major constraint [8].

SLS process is divided into two groups; one stage SLS and two-stage SLS. One stage SLS is performed in a liquid (partially melted) phase [26-29].

There is a delivery system which contains the material powder. Before scanning, a roller ensures that the layer is properly laid down. Laser scanners start to scan according to the CAD model loaded to the machine. After scanning the selected powder section with the laser, the delivery piston lowered by one step and the second layer is dropped on the first (sintered) layer. The process continues until all layers of the part are completed.

The important issue in SLS is that, there is no complete melting so that the final part density and mechanical properties will be different from the original powder material

properties. Hence, powder mixtures are brought into the SLS process to have better mechanical properties. To give an example, in a two powder type mixture, the powder which has a low melting point is used as a binder in the SLS operation [10-13]. This manufacturing type is called as One Stage SLS [4] or Direct Metal Laser Sintering (DMLS) [14].

The laser source type and porosity of the powders are critical due to their effects on the manufactured parts. In one stage SLS (and also SLM), for metals, Nd:YAG Laser is preferred because metals have better absorption for shorter wavelengths [15-21]. It is noted that, although the productivity is lowered very much, the introduction of 20-micron sized powders improves the porosity (decreased) and mechanical properties. [22, 23]

In two-stage SLS; Gatto A. and Luliano L. introduced a micro-joining mechanism between the particles. A binding polymer has to be unbound; then thermal sintering is applied to those particles [30]. It is also mentioned in two-stage SLS, a green part appears and after sintering an infiltration process is made by using copper or bronze. A dense solid part is obtained at the end of the process. [24, 31]

In conventional designs, the manufacturing process and the part material are nearly unrelated factors and the designer has wide freedom while selecting these factors. But in SLS, the material selection and manufacturing process are bound to each other, meaning selecting the process type will define the mechanical properties. [32]

2.3.2 Melting ALM Techniques

2.3.2.1 Selective Laser Melting

SLM is explained in US Patent 6,215,093 where metallic powders are melted using a heat source (laser or electron beam) and without any help of binders or agents, a fully molten pool zone is obtained in order to accomplish the additive manufacturing process. [33, 34]

Selective Laser Melting (SLM) and Selective Laser Sintering (SLS) are almost the same but in SLM, there is a complete melting which results in the mechanical properties of the part being nearly the same as that of the original powder material. Hence, it provides freedom

in material selection. It is also noted that Nd:YAG laser is used commonly in SLM systems. [35-37]

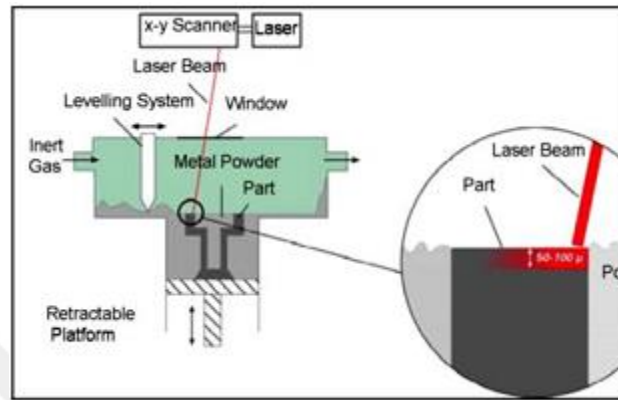


Figure 2-4- Selective laser melting process schematic [4]

Figure 2-4 is an example of the SLM technique (Similar to the SLS technique). During the manufacturing process, the ductility decreases in a significant way; thermal treatments can fix this phenomenon [38-41]. Materials available for SLM technique are listed in Table 2-3 with material properties.

Table 2-3- Mechanical properties of some of the materials available in SLM [38-41]

Material	Stainless Steel	Tool Steel	TiAl6V4
Tensile strength	440-520	780-840	1200-1400
Elongation	10-15%	2-3%	1-2%
Surface Finish	Rz 30-60 μ m	Rz 30-60 μ m	Rz 30-60 μ m

In the patent of Herzog, the Concept Laser GmbH mentioned, the accuracy of SLM process below values of 0.04 mm. The laser is coupled with an X-Y linear motor system for scanning [42-44].

2.3.2.2 3D Laser Cladding

This technique is similar to Selective Laser Melting technique. Complete material melting is obtained during the process, but the material powder is delivered by a nozzle onto the manufacturing platform. The powder flows through the nozzle and with laser heating, it melts down. Figure 2-5 is an example of 3-D Laser Cladding.

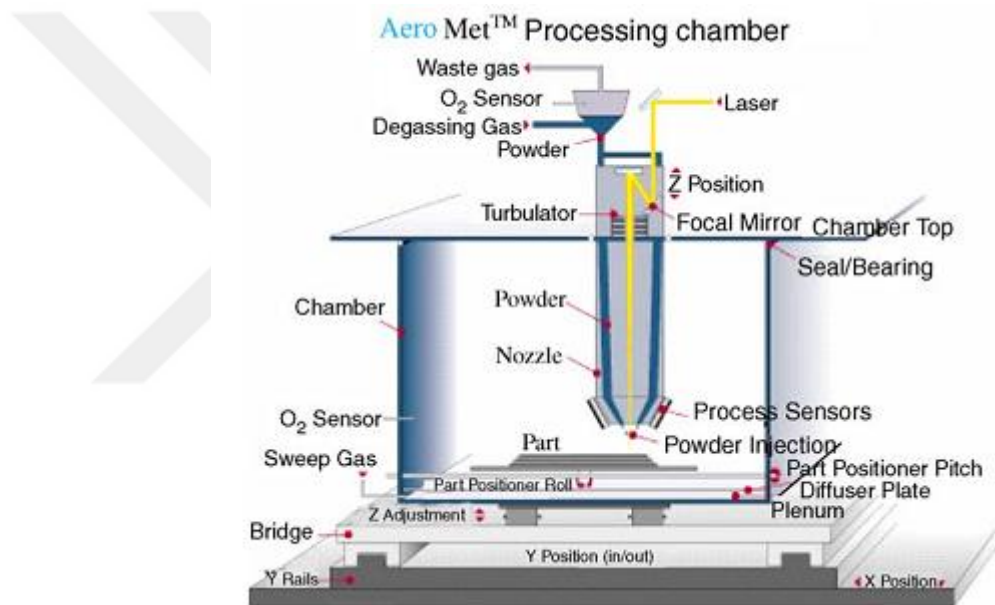


Figure 2-5- 3D laser cladding process schematic [45]

It is noted that 3D cladding technique is used with a closed loop control in the study [46]. The process allows the manufacturing of fully dense parts with mechanical properties similar to the mechanical properties of the part manufactured by conventional methods [47-50]. For example, to manufacture hip implants, Hedges used an Nd:YAG laser in Lens machine and the material properties of the manufactured part was similar to the material properties of a part manufactured by conventional techniques in terms of fatigue and tensile properties [49].

The 3d cladding is also mentioned as Laser Engineered Net Shaping® (Lens). A freeform part (i.e. parts with protruding structure) can't be manufactured due to the lack of support of the powder bed in 3 axis manufacturing. But the technique can be improved by using 5 axis machines to overcome this issue. The main materials are aluminum alloys, titanium alloys, cobalt alloys, nickel alloys and steel alloys for 3D cladding process [4, 51].

2.4 Current Status of Direct Metal Laser Sintering

In this section, brief information will be given about studies made on DMLS. These studies have been conducted from 2010 until now.

Jian Xing and Weimin Sun studied the transient temperature effects on the performance of SLS. They developed a model to obtain a 3D transient temperature field. The model includes Al_2O_3 coated ceramic powder, solid-liquid two interface and temperature dependent material properties. For the experiment, a high-speed charge-coupled device was used to get the temperature image. It is noted that model results and experimental results match approximately and the model can calculate the temperature field if the thermal properties and phase changing mechanism are correctly given [52].

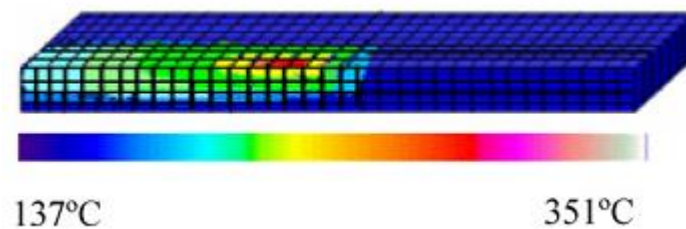


Figure 2-6- 3D transient temperature simulation [52]

A 3D dynamic analysis of thermal behavior during single-pass multi-layer for rapid prototyping was studied by Huihui Zhao and Guangjun Zhang. It is stated that during the process there is a thermal cycle of heating and cooling. Experiments are done on a specimen

of single pass ten-layer deposition and thermal behavior of the specimen is investigated. The study includes a 3D numerical transient model with temperature dependent material properties to observe the temperature gradient and thermal cycling and the effects of deposition direction on the thermal behavior. Experimental results validate calculated results and show that increasing the deposition height causes decreasing heat diffusion of the molten pool. It is mentioned that this phenomenon can be countered by optimizing the deposition path. It is also noted reverse depositing is worse than the same depositing directions [53].

A study was made on the manufacturing technique of 3D molded interconnect devices (MID) by Amend P., Pscherer C. The work is focused on the experimental results of MID-prototypes manufactured by selective laser sintering (SLS). Materials used in the study, are “PA12” SLS powder and SLS additives (ADDIMID particles 5 wt. %SiO₂ encapsulated aluminum). The effects of the additives on the melting temperature are investigated. Then, SLS is accomplished. The parts manufactured by this process are eligible in terms of mechanical properties, surface quality and density. Surface finishing techniques are also mentioned; glass bead blasting and corundum blasting were applied to increase the surface quality by ablation. This study showed a possible way to manufacture MID-prototypes by SLS even though there are some issues to handle the additives used in the SLS process [54].

Olivier Kerbrat, Pascal Mongol and Jean-Yves Hascoet did a study about a new DFM (Design for Manufacturing) approach to combine machining and additive manufacturing. This new approach allows checking the manufacturability of the part in the design stage. The system is analyzing the CAD model and checking which module will be the best choice for the manufacturing process. For the purpose of analysis, geometrical indices are used in this paper. Automotive parts are used for experimental tests. It is noted that they did not take into consideration the parameters which need a complete manufacturing preparation analysis like cutting toolpath strategy. It is mentioned that the indices may include other parameters as

specifications or material information. This will offer a more detailed view of complex manufacturability [55].

An adaptive process planning approach of RP and manufacturing study was made by G.Q. Jin, W.D. Li and L. Gao. They demonstrate an approach to increase the efficiency of the RP process by using an adaptive process planning for manufacturing complex models like biomedical models. To keep the geometrical accuracy of the models, Non-Uniform Rational B-Spline based curves are used. To increase productivity and reduce the computing time, a mixed tool-path generation algorithm is used. Then, the speed of the RP print head or nozzle is adaptively generated to find the best path to obtain minimum build time. Performance of this approach is validated by five biomedical case studies [56].

A study, called “Laser cladding of Inconel 690 on Inconel 600 superalloy for corrosion protection in nuclear applications”, was made by T. Baldrige et al. In the nuclear industry, there is a known issue of repair of the heat exchanger tubes. High-temperature corrosion-resistant Inconel metal is used as a material for these tubes. The laser is used as a heat source for the repair; Inconel 690 3 mm thick powder cladding layer is melted on top of Inconel 600 alloy 10 mm thick plate. In the cladding technique, there is a feed control to control the feed rate. They also investigate the effects of the process parameters to decrease the cracks which are occurring during cooling. The parameters are powder feed rate, laser power, preheating, beam overlap and scanning speed. After the process, a strong bond was seen in SEM images. There were no impurities between two Inconel layers. It is noted that a small amount of Cr_2O_3 film on the surface of large pieces, which increases the corrosion resistance. It is stated that surface defects and porosity were at minimum levels when the high power Yb Fiber laser is used during the cladding process [57].

A biomedical manufacturing issue was investigated by A. Cerardi et al. Here they mentioned that additive manufacturing provides a way to manufacture new parts with good mechanical properties. In a biomedical aspect, AM provides the manufacturer to produce

parts with porosity or lattice structure like parts for the purpose of replacing human bone to obtain the necessary stiffness. Since there is structural design freedom, the study focuses on the relation between the porosity and the strength of the part. In another of their study, they developed a linear model for this relationship. The model is developed from the data sets obtained from tensile tests made on parts with different porosities. The effects of porosity on mechanical properties are investigated using finite element analysis. They claimed that using this method, in AM process, the lattice structure can be optimized [58].

A study on customized implants manufactured by SLS was done by Fangxia Xie et al. from University of Science and Technology Beijing. The material used for this work, is AISI 316L stainless steel (316L SS) powder. A porous structure of 316L SS was manufactured with a coat of ethylene-vinyl acetate copolymer. It is stated that the green part is affected greatly by the laser energy density meanwhile mechanical properties and the porosity depend on sintering temperature. Given an example, sintering the 316L SS powder at 1100 °C results in 160 µm sized pores and 58% porosity with an elastic modulus of 1.58 GPa and a compressive yield strength 6.64 MPa. Sintering the 316L SS powder at 1300 °C results in 35 µm and 26% porosity with an elastic modulus of 6.64 GPa and compressive yield strength 52.8 MPa. They revealed that the porosity and mechanical properties could be adjusted by sintering temperature and SLS parameters. Hence, the requirement for cancellous bone can be obtained in terms of porosity and mechanical properties [59].

Giovanni Strano et al. investigated parts made of AISI 316L stainless steel alloy manufactured by the Selective Laser Melting. It is mentioned that the Selective Laser Melting process is progressed in terms of mechanical properties and design-material flexibility yet the surface roughness is still an issue for manufacturers. The study focuses on the morphology and surface roughness of parts of AISI 316L stainless steel alloy manufactured by SLM. Experiments are made on truncheon samples to see the actual a surface roughness. Scanning electron microscope (SEM) and surface profilometer are used for the analysis. The

results show that increasing the surface sloping angle leads to the density of the spare particles will increase along the step edges. It is mentioned that surface roughness is affected by the particles filling the gaps between successive layers. They come up with a new mathematical model including the experimental data, which leads to model the effects of the presence of particles on top of the surface. An accurate roughness model is obtained and the prediction values and experimental data are matching. In this study, the parameters, which are related to surface roughness, are found in order to minimize the needs of surface finishing after the selective laser melting process [60].

David E. Cooper et al. investigated DMLS process for the part improvements in Formula 1 racing. It is known that part efficiency and low weight component are the main issues in the racing industry. The study shows the benefits of the AM for manufacturing of hydraulic components. Direct metal laser sintering is used in this work. EOS Titanium Ti64 is used as a material for experimental samples. There are no significant losses or failure during the hydraulic soak test at 25 MPa. Particle image velocimetry (PIV) is used to measure the efficiency of hydraulic flow. Comparison between DMLS technique and conventional manufacturing techniques are made; and it is stated that the channels and bores built by DMLS are 250% better in terms of flow characteristics [61].

A study about direct laser fabrication was made by Hussam El Cheikh et al. This technique comes from 3D laser cladding. 316L stainless steel powder is used as material in this work. It is claimed that the final part is greatly affected by the layer geometry. This study focuses on the analytical relationships between the characteristics of the laser tracks (penetration depth, width, area, height) and process parameters (powder mass flow, scanning speed, laser power). 27 different experiments are made and validated by studying the correlation coefficient R. They investigated two types of models to predict the geometrical characteristics and the form of the single laser tracks cross sections. In the first model, the laser clad geometry is governed by the distribution of the powder in the feed jet. Uniform,

polynomial and Gaussian distributions are proposed. A disk shape is considered to present the general form of the clad cross section in the second model because of the surface tension forces. It is stated that in all the area experimentally explored, the laser track geometry can be regenerated by using the relationships between the process parameters and the radius & the center of the disk mentioned in the second model [62].

Table 2-4-Parameters and experimental results of each single track
for 0.025 gram/sec powder flow rate [62]

Power [Watt]	Speed [mm/min]	W [mm]	H [mm]
180	300	0.56	0.47
180	600	0.50	0.19
180	900	0.43	0.15
280	300	0.66	0.32
280	600	0.60	0.14
280	900	0.53	0.09
360	300	0.83	0.49
360	600	0.72	0.27
360	900	0.68	0.20

Another study was made on selective laser sintering by Andreas Wegner and Gerd Witt, where it is mentioned that laser sintering process has process interruptions, poor repeatability of part quality. It is noted that to avoid this kind of problems, the relationship between part properties and process parameters should be investigated. It is proposed to use response surface methodology to understand this relationship. The study focuses on prediction and improvement of part properties using this relationship. A tensile test is chosen to check the material properties of the parts manufactured after laser sintering process. Test specimens

are taken as mentioned in DIN EN ISO 3167. It is also noted that parts are manufactured in four different orientations. They claimed that the relationship is established with five main parameters with the density and mechanical properties of the part. It is noted that, there is a non-linear relationship with multiple parameter interactions. It is stated that interaction of scan spacing, scan speed, scan spacing and layer thickness have the major effect on mechanical properties of a part. They claimed that using the results of this study, part properties are optimized [63].

Shishkovsky I. et al. did a study about selective laser melting of Nitinol powder. It is noted that Nitinol is a biocompatible material with damping, superelasticity and shape memory effect. In this study, fully dense 3D parts are manufactured by selective laser melting. A preheating (up to 500°C) was applied. They investigated the effects of SLM process parameters on the parts. Experimental specimens are analyzed by the methods of optical metallography, SEM, X-ray, EDX analysis, microhardness measurement. They discuss the optimum conditions for the fabrication of Ni-Ti parts. It is noted that non-porous samples obtained from this study, can be used in maxillofacial surgery, orthopedics and trauma recovery [64].

As it was mentioned before, the selective laser melting has issues in terms of surface quality. E. Yasa and J-P. Kruth investigated the microstructural of AISI 316L stainless steel parts which were under the effects of laser re-melting. Here they explained “laser re-melting” where after scanning a layer, the same zone is rescanned before depositing a new layer of powder. This method is used to avoid the residual porosity which might cause problems in some cases where high fatigue resistance and strength are required. As expected, they state that this leads to an increase the production time. They suggest that surface quality and surface properties can be improved by laser re-melting of the last layer or outer skin of the part. They use a continuous wave laser during the SLM process and focused on the effects of the different process parameters on the microstructural of 316L stainless steel.

Experimental results showed that “Laser re-melting” improved the surface quality of 316L stainless steel. The average surface roughness decreased from 12 μm down to 1.5 μm and the porosity decreased from 0.77% down to 0.036%. It is noted that “laser re-melting” improves surface roughness by 90% and density almost by 100% at the cost of productivity. Better mechanical properties are achieved by high density. It is stated that the re-melting process refines the microstructure [65].

V. Seyda, N. Kaufmann and C. Emmelmann studied the aging of Ti-6Al-4V powder after the laser melting process. They believe that the desired mechanical properties of melted components largely depend on powder material quality. It is noted repeated recycling causes changes in the powder material. Here, Ti-6Al-4V powder aging processes are investigated. Here they end up with coarsened powder particles and an increased flowability. Experiment parameters are 200W fiber lasers with standard exposure parameters and a layer thickness of 30 μm . In contrast with bulk material properties, significant effects of aged powder on laser melted components are observed. It can be said that there are non-negligible effects of aged powder on density, hardness, porosity, surface roughness and mechanical strength of the bulk material. It is claimed that after 12 cycles the porosity decreases by 0.06%. Authors believe that further studies on the basic material are needed for the complete understanding of Ti-6Al-4V powder behavior during the laser melting process [66].

Leuders et al. made a study on the fatigue resistance and crack growth performance of Ti-6Al-4V used in selective laser melting. The process induces imperfections and residual stresses are factors to be considered. It is noted that fatigue loading should be investigated as well. The study aims to define a relationship between microstructure and defects under cycling loading. According to experiments (mechanical tests, electron microscopy and computer tomography) they come up with the conclusion that the micron-sized pores mainly affects fatigue strength and fatigue crack growth are largely influenced by residual stresses. They present the following findings: the material behavior is directly related to its

microstructure and using heat treatment it can be adjusted. Pores heavily influence the fatigue behavior in the high cycle fatigue regime. Internal stresses come into the picture during crack growth. According to the test results, even heat treatments at a low temperature to relieve stresses, can cause a fatigue crack growth behavior [67].

2.5 Thermal, thermo-mechanical modeling of Direct Metal Laser Sintering

2.5.1 Thermal modeling of Direct Metal Laser Sintering

The metal additive manufacturing process, additive layer manufacturing (ALM), was introduced in the mid-'90s via the application of high energy density lasers [4]. This new technique allows manufacturing a part layer by layer by using 3D CAD information. As a result of this progress, manufacturing of 3D complex freeform geometries has become relatively easier, whereas with other conventional methods this has been costly and time-consuming [68].

Although design flexibility is provided by additive manufacturing [69], an extensive research and development stage is required beforehand in order to achieve end shape parts with the required mechanical properties. In metal additive manufacturing, high-temperature gradients appear on the manufactured structure due to the employment of high energy density laser. These gradients affect the microstructure and physical properties of the part such as mechanical strength, surface and overall quality of the parts.

The first step of controlling the mechanical properties of the additively manufactured parts is the prediction of the temperature distribution and molten pool geometry. Such a prediction tool is crucial for both industrial and scientific perspectives in order to optimize the manufacturing process.

The effects of the heat transfer mechanisms in the porous media undergoing phase changes are investigated in the literature by several mathematical and finite element techniques [70–80] in metal additive manufacturing. A mathematical model of a moving heat

source on a medium was studied by Jeager [70]. In order to predict the final geometry, Huang et al. developed an analytical model for laser powder-fed systems [71]. Matsumoto et al. proposed a 2D finite element model to examine temperature development during a single layer process in powder beds for metallic powder [72]. Tolochko et al. investigated Nd: YAG laser sintering mechanism including powder melting [73]. Li et al [74] did a parametric study of laser speed and laser power to investigate the thermal behavior during selective laser melting process. They carried out a series of experiments by using different laser powers and speeds in order to see the effects of these parameters on single-track scanning. A microstructure study was carried out by Farshidianfar et al. to control the microstructure in real time during laser additive manufacturing [75]. Kolossov et al. demonstrated the effect of the temperature-dependent thermal conductivity on the temperature gradients in a laser sintering using the 3D finite element model [76]. Another 3D transient finite element analysis was carried out by Nisar et al. to investigate phase change and moving heat source problem [77]. Roberts et al. carried out a study for powder beds to understand multilayer sintering mechanism with porosity and temperature-dependent material properties. The model specifically provided the remelted zones and temperature history for each layer [78]. Ganci et al. carried out a similar study for the selective laser sintering of thermoplastics to predict the temperature distribution and part distortion including phase transformations and cooling process [79]. Somashekara et al. investigated the effects of the deposition pattern on the residual stress evolution in metal additive manufacturing [80].

2.5.2 Thermal-mechanical and thermo-mechanical modeling of Direct Metal Laser Sintering

Even though the direct metal laser sintering allows great design flexibility, it can be said that it is still crawling in terms of physics-based process modeling and simulations. In metal additive manufacturing, as mentioned before, high energy density leads to high-temperature gradients in manufactured structures. These gradients cause thermal expansion and

contraction of the parts, which is one of the main reasons for the residual stresses and distortions. In order to investigate this relationship, a rapid prediction tool is crucial for the direct metal laser sintering from both industrial and scientific perspectives.

In literature, analytical and finite element approaches [4–15] are introduced in order to understand the effects of the heat transfer mechanisms on residual stresses and distortions in direct metal laser sintering. An analytical approach was used by Mercelis et al. to predict the residual stresses after metal additive manufacturing process and to investigate the effects of the layer thickness of the base plate and the part [81]. The modeling of the welding process for Inconel 625 was presented by Siwek et al. in order to predict the molten pool geometry [82]. Li et al. [83] did a parametric study of laser power and laser speed to investigate the temperature distribution during selective laser melting process. Alimardini et al. developed a 3D numerical thermal stress model for laser solid freeform fabrication to predict the thermal behavior and resultant thermal stresses and the geometry of the wall dynamically [84]. Szost et al. [85] compared the microstructure and residual stress generation of laser cladding process and wire + arc additive manufacturing. An analytical stress field model was developed by Safronov et al. [86] for the additive manufacturing in order to predict residual stresses and distortions at layer by layer. Cooper et al. [87] investigated the design and additive manufacturing of the high-performance valves in order to improve the performance of the valves. Ye et al. [88] presented work about numerical modeling for metal-based additive manufacturing. The velocity field, temperature field and phase changes were investigated using level set method coupling heat transfer and fluid dynamics. Irwin et al. [89] carried out a study to demonstrate the effects of thermal cycling on microstructure during additive manufacturing of Ti6Al4V. An fem approach was used by Vastola et al. to control the residual stress generation in direct metal laser sintering [90]. Denlinger et al. presented a study about residual stress and distortion prediction [91] and showed the relaxation effect on modeling [92].

According to the literature review given, it can be said that there is a need of a thermomechanical model for the accurate prediction of temperature field, residual stresses and distortions occurring during the direct laser metal sintering, which is quickly computable, applicable on freeform geometries, and suitable for the optimization of process parameters.



Chapter 3

THERMAL MODELING OF DIRECT METAL LASER SINTERING

3.1 Overview

In the literature review, it is seen that the process parameters, such as laser power, laser speed, laser spot size etc., affect the mechanical properties and overall quality of the parts. Therefore, the relation between the process parameters and the temperature distribution and the dimensions of the molten pool should be investigated. This relationship is essential to improve overall part quality. Moreover, the prediction of the residual stresses and the distortions will be possible using the thermal information.

The purpose of this study is to introduce a FEM model for the powder bed system, from which the effects the material properties and scanning parameters on the temperature distribution and molten pool geometry during the direct metal laser sintering can be predicted. Including the powder-liquid-solid transformation and a 3D heat source model, the developed model can predict the temperature evolution and the dynamic molten pool geometry.

In order to achieve the mentioned model, the following steps were accomplished:

- Heat transfer equations
- Phase change modeling
- Heat source modeling
- Powder bed modeling

In this chapter, these steps will be explained in detail. A new technique, which allows the thermal simulation of the 3D freeform parts, will also be explained. Titanium, Ti-6Al-4V and Inconel 625 were used as materials in this study. The developed thermal model is validated by the experiments. In addition, to test the model in different materials,

comparisons of the temperature distribution are made between the model results and the experimental studies found in the literature.

3.2 Heat transfer equations

In the metal additive manufacturing process, a laser heats up and melts the powder material, forming a small molten pool (Figure 3-1). After the laser moves from the molten zone, solidification starts and the generated heat dissipates in three ways; conduction, convection, and radiation.

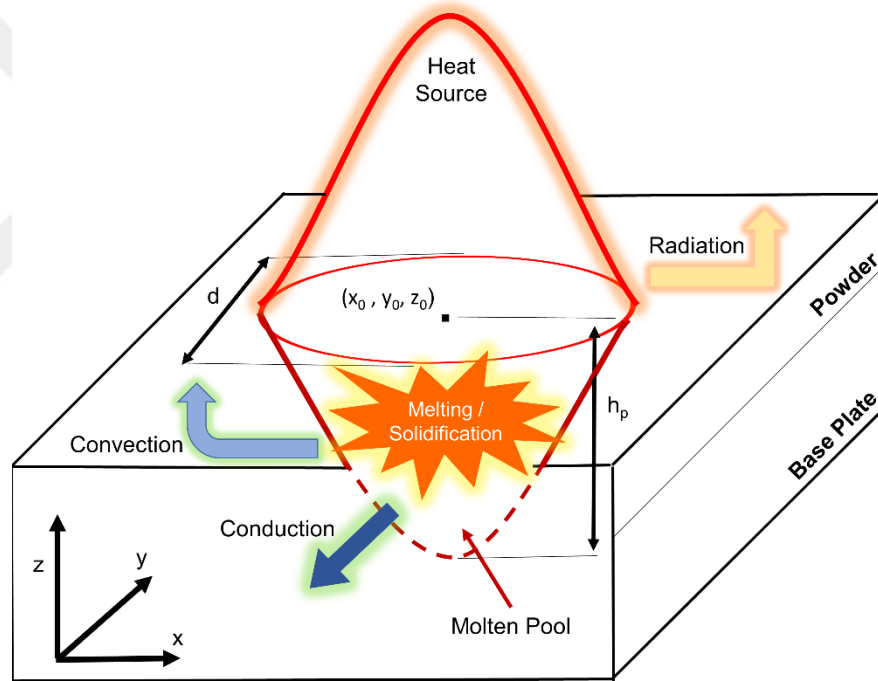


Figure 3-1- Illustration of the heat zone in the DMLS powder bed system [93]

In the DMLS (powder bed system) with moving laser source, the heat transport equation can be defined as

$$\rho C_p \frac{\partial T}{\partial t} = \nabla \cdot (k \nabla T) + q \quad (3-1)$$

Convection and radiation losses in the DMLS process are expressed in equations 3 and 4, respectively, as follows:

$$h(T_{ext} - T) = -\hat{n} \cdot -(k\nabla T) \quad (3-2)$$

$$q_{rad} = \varepsilon\sigma(T_{amb}^4 - T^4) \quad (3-3)$$

3.3 Phase change modeling

The phase transformation between solid and liquid phases of a material can be introduced into the equation (1) with the following relations

$$\rho = \theta\rho_{solid} + (1 - \theta)\rho_{liquid} \quad (3-4)$$

$$C_p = \frac{1}{\rho}(\theta\rho_{solid}C_{p,solid} + (1 - \theta)\rho_{liquid}C_{p,liquid}) + L\frac{da}{dT} \quad (3-5)$$

$$k = \theta k_{solid} + (1 - \theta)k_{phase2} \quad (3-6)$$

$$a = \frac{(1 - \theta)\rho_{liquid} - \theta\rho_{solid}}{\theta\rho_{solid} + (1 - \theta)\rho_{liquid}} \quad (3-7)$$

where θ is the phase fraction (solid=0, liquid=1), L is the latent heat of phase change from solid to liquid and a is the mass fraction.

An FEM package is used for the heat transfer modeling. In the module the heat equation (3-1) and the phase change equations (3-4-3-7) are utilized as a platform for the integration of the heat source model and the powder bed material model. Furthermore, a script is written in order to simulate the melting and solidification during the additive manufacturing process (powder to liquid, solid to liquid and liquid to solid). The script introduces a phase transformation coefficient as a variable dependent on the temperature distribution. The role of this phase transformation coefficient is to hold the information of whether the powder is melted or not. In other words, the FEM model uses the temperature history and the melted

zone history in order to decide which phase transformation will occur according to the temperature and the phase transformation coefficient in that zone.

3.4 Heat source modeling

For the heat source modeling, two different analytical models were used: a 2D and a 3D approach. The 2D heat source is defined as a heat flux on the surface of the powder bed. The 3D heat source is defined as a volume heat source in the powder bed. For both approaches the fundamental mode of the Gaussian beam (TEM00) is selected. The irradiance of the laser can be written as

$$I(r) = I_0 \exp\left(-\frac{2r^2}{w_0^2}\right) \quad (3-8)$$

and heat generated by the laser can be shown as

$$Q(r) = \frac{2P}{\pi w_0^2} \exp\left(-\frac{2r^2}{w_0^2}\right) \quad (3-9)$$

and assuming the diameter, d , of the laser beam is constant, the laser heat generation for any given x, y in the Cartesian coordinate point is formulated and the 2D heat source model is

$$Q(x, y) = \frac{8\eta P}{\pi d^2} \exp\left(-\frac{8[(x - x_0)^2 + (y - y_0)^2]}{d^2}\right) \quad (3-10)$$

For the 3D heat source modeling, a penetration term is defined in order to simulate the laser in the z orientation. Using the same Gaussian beam mode, the 3D heat source model is

$$Q(x, y, z) = \frac{8\eta P}{\pi d^2} \exp\left(-\frac{8[(x - x_0)^2 + (y - y_0)^2]}{d^2}\right) \frac{1}{h_p} \exp\left(\frac{-abs(z - z_0)}{h_p}\right) \quad (3-11)$$

The absorption coefficient is dependent on powder material, surface roughness, the interaction between the powder material and wavelength of the laser. A wave length of

1.06 μm solid state laser: Neodymium-Doped Yttrium Aluminum Garnet (Nd:YAG) is used for the process. For Ti-6Al-4V, the absorption coefficient η value in the simulations is taken as 0.4 [94]. The penetration depth of the laser h_p and the absorption coefficient η between the powder material and the wavelength of the laser, for Inconel 625, are taken 110 μm and 0.37 [95], respectively and for Titanium, are taken 63 μm [76] and 0.42 [96], respectively. It should be noted that the absorption coefficient η may depend on laser speed, laser power or other process parameters. For simplicity sake, the absorption coefficient η is considered as constant in this study.

3.5 Powder bed model

The powder bed model is a must because the thermal conductivity is significantly affected by porosity. In the literature, there have been several approaches, which calculate the equivalent thermal conductivity by just using the porosity of the powder bed. Although, the thermal conductivity of bulk materials is dependent on temperature, the thermal conductivity of the powder bed is also dependent on powder geometry and the thermal conductivity of the protective gas. Therefore a much more sophisticated model was chosen under the assumption that the powder is uniformly distributed. Sih et al. [97] proposed a detailed thermal conductivity model for powder beds, which includes the effects of porosity, emissivity, powder size, and protective gas conductivity. Equivalent thermal conductivity can be expressed as,

$$k_{eq} = k_g(1 - \sqrt{1 - \phi}) \left(1 + \frac{\phi k_R}{k_g} \right) + k_g \sqrt{1 - \phi} \left\{ (1 - \phi) \left[\frac{2}{1 - \frac{B k_g}{k_s}} \left(\frac{B}{\left(1 - \frac{B k_g}{k_s} \right)^2} \left(1 - \frac{k_g}{k_s} \right) \ln \left(\frac{k_s}{B k_g} \right) - \left(\frac{B + 1}{2} \right) - \left(\frac{B - 1}{1 - \frac{B k_g}{k_s}} \right) \right) + \frac{k_R}{k_g} \right] + \phi \frac{k_{contact}}{k_g} \right\} \quad (3-12)$$

3.6 Material properties

The inclusion of temperature dependent material properties in the model is one of the key points to predict the temperature in the DMLS process. As mentioned before, three different materials were used in this study. The thermal conductivity, the density and the heat capacity of titanium were taken from the reference [96]. Figure 3-2 shows the plots of temperature-dependent physical properties [13, 15] such as density, thermal conductivity, heat capacity and emissivity of Ti-6Al-4V. Table 3-1 shows the temperature-dependent thermal conductivity and heat capacity of Inconel 625 used in the model.

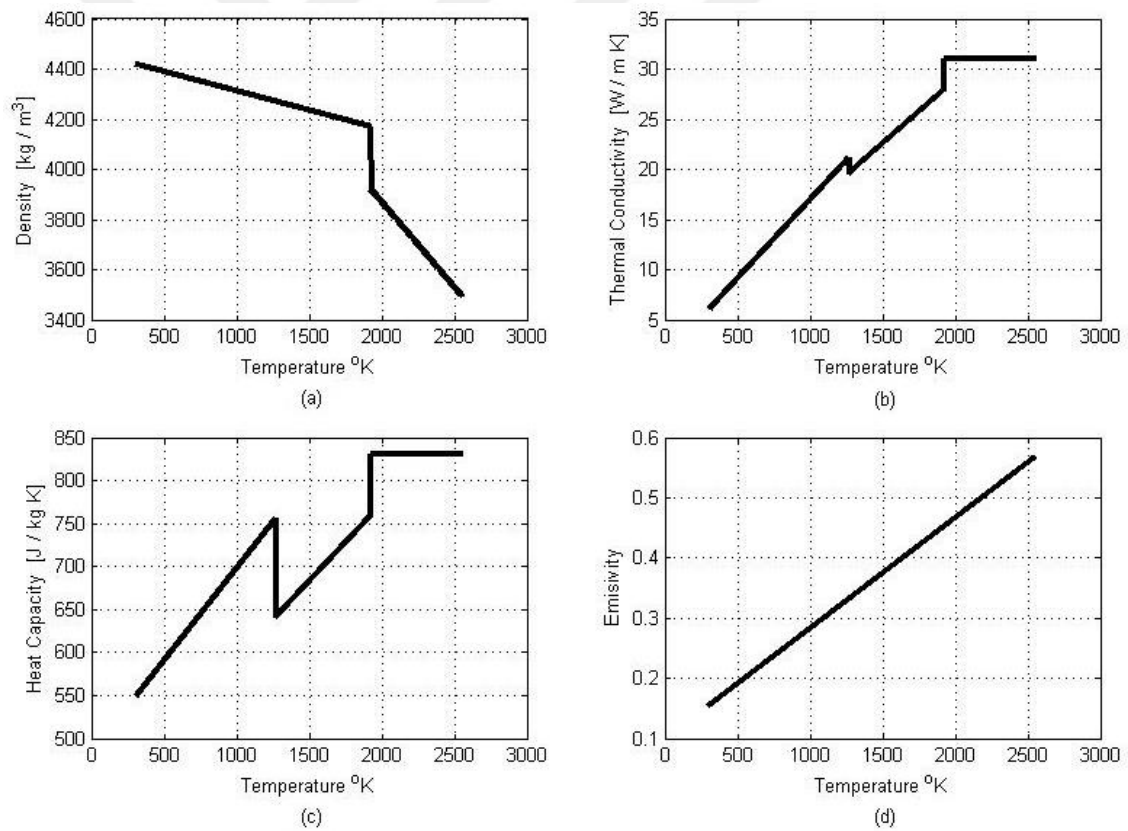


Figure 3-2- Temperature Dependent Material Properties of Ti-6Al-4V

a) Density b) Thermal Conductivity c) Heat Capacity d) Emissivity [96, 97]

Table 3-1- Material Properties of Inconel 625 [95]

Temperature, T ($^{\circ}\text{C}$)	Thermal Conductivity, k (W/m.K)	Heat Capacity, C_p (J/kg)
20	9.9	410
93	10.8	427
205	12.5	456
315	14.1	481
425	15.7	511
540	17.5	536
650	19.0	565
760	20.8	590
870	22.8	620

In the Material Module, the temperature dependent functions of bulk material properties and gas material properties are fed to the mathematical modeling module, where the bulk material properties and gas material properties are assembled by the equation (12) to form a file containing the powder material properties and then, it is fed to the FEM software. By feeding the necessary files such as powder material properties file and time-coordinate file (will be explained in next section) and the mathematical modeling module and its two submodules (3D CAD module and material module), together with the DMLS process parameters, are embedded in the finite element analysis. Here, the effects of phase change and heat loss are simulated. A general illustration of the developed thermal model is given in Figure 3-3.

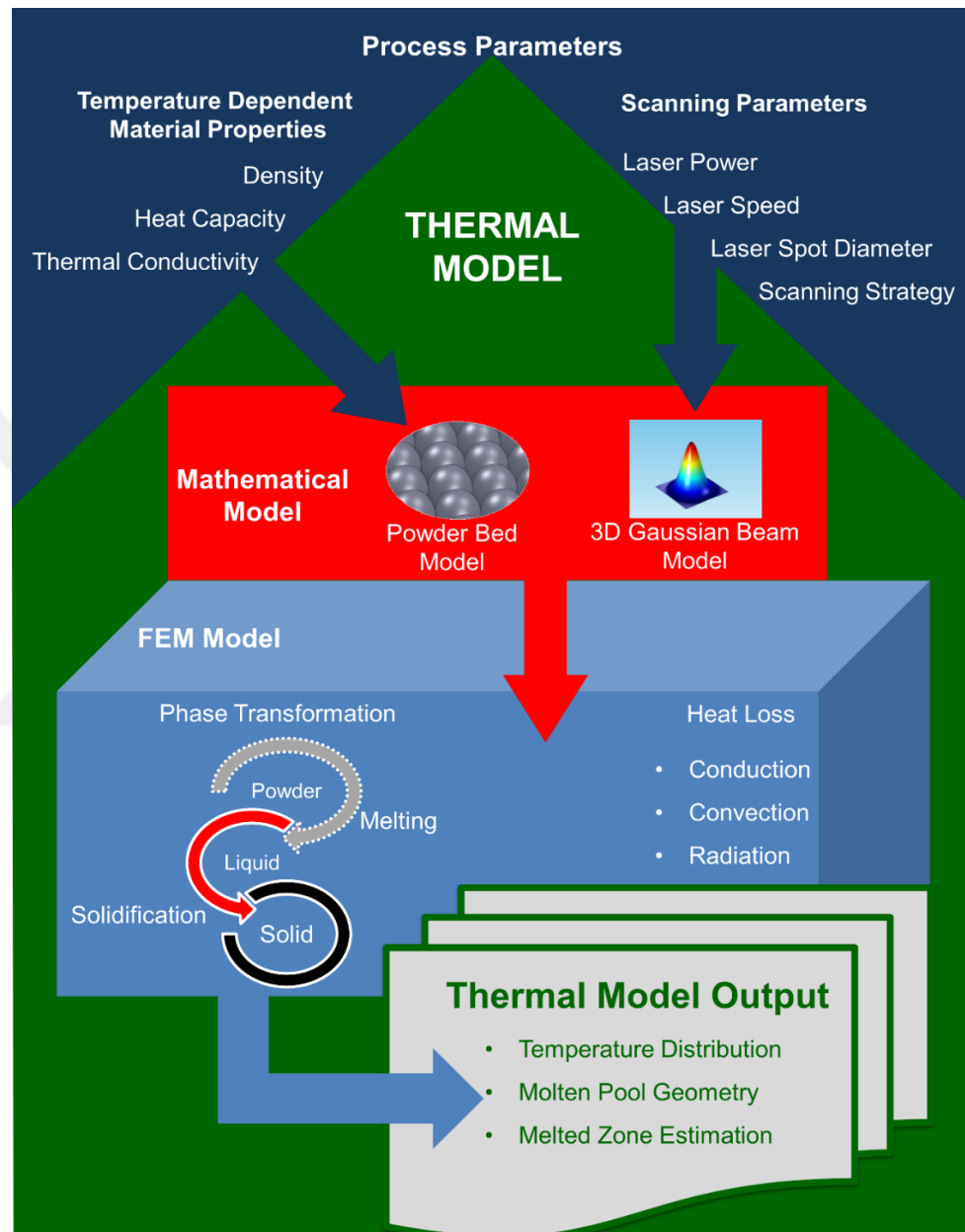


Figure 3-3- Schematic of the multi-physics based thermal model [93]

3.7 Implementation of the thermal model on 3D freeform structures

A biomedical impeller was selected for the implementation illustration of the developed technique. Technical drawing of the impeller is shown in Figure 3-4. For the freeform implementation procedure, the 3D part data from any solid model based CAD package is taken and converted to the STL format. An off-the-shelf slicer program (ReplicatorG) is used to slice the geometry and to generate the laser path (Figure 3-5). In the Mathematical Modeling Module, scanning lines are broken into laser position points according to the laser beam diameter. Then, the laser interaction time at each position point is calculated. Therefore, the individual coordinates and DMLS process parameters are assembled to form a file containing 4D data (time and 3 position coordinates), which is then transferred to the Gaussian Laser Beam Model. The coordinates of the laser points are put into the equation (3-10) or (3-11) (depending on which heat source model is going to be used); hence the laser beam is moved according to the laser position points.

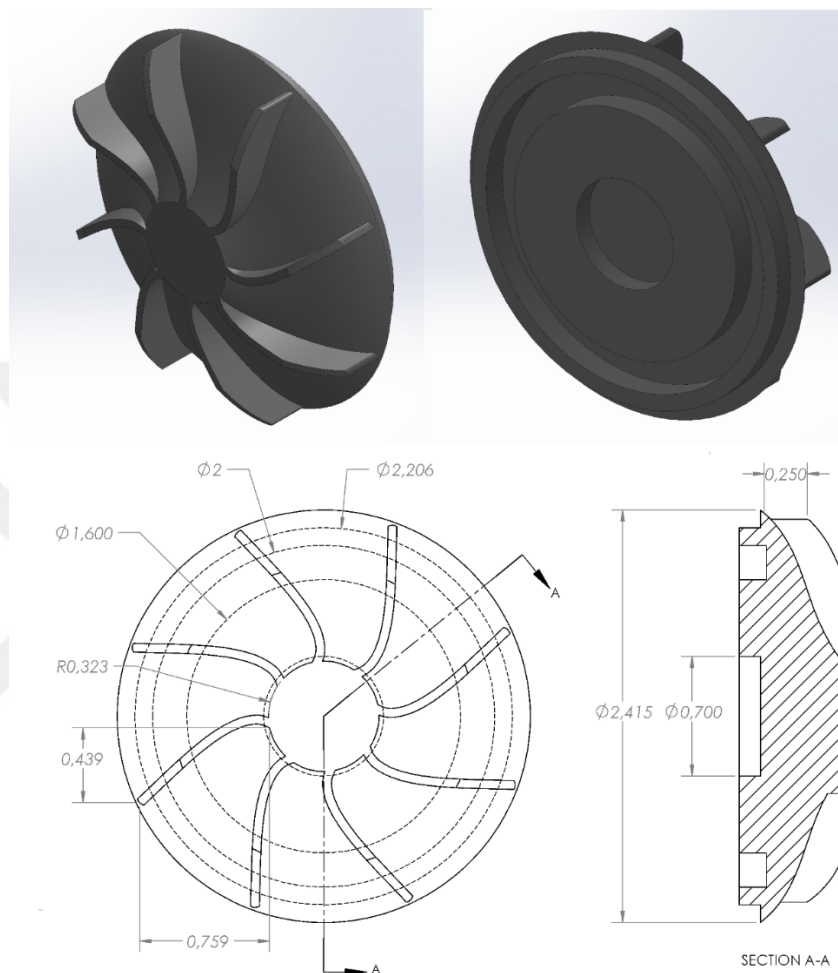


Figure 3-4- A biomedical Impeller geometry [94]

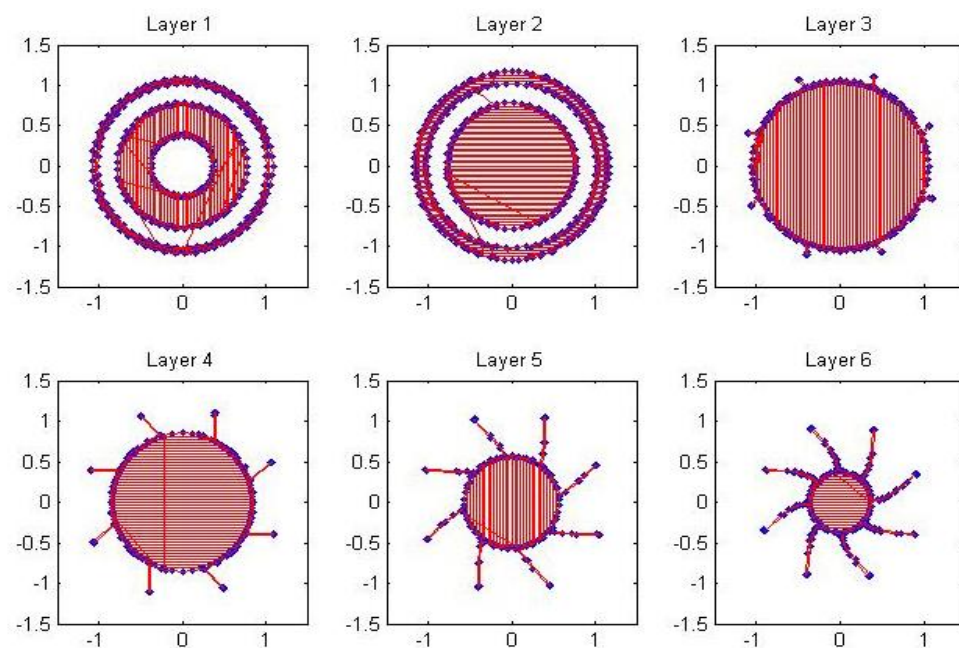


Figure 3-5- Layer-by-layer scanning patterns of the mini impeller [94]

3.8 Experimental Setup

In order to validate the developed thermal model, the dimensions of the molten pool were compared. For the experiment, EOS M290 additive manufacture machine was used. (Figure 3-6)



Figure 3-6- EOS M290 [99]

The machine has a fiber YAG laser with a wavelength of 1064 nm. Prismatic parts with the length of 50 mm, the width of 10 mm and the height of 7 mm from EOS Nickel Alloy IN625 powder. The additively manufactured specimens were cut with wire electric discharge machining in order to obtain smaller pieces for metallurgical evaluation. The cut specimens were then mounted onto a bakelite puck, which had been polished with a grinder and chemically etched. Finally, the microscopic investigation was conducted using NIKON / ECLIPSE MA200 optical microscope. (Figure 3-7)



Figure 3-7- Nikon eclipse MA200 [100]

3.9 Thermal model validation

The developed model is first compared to a work carried out by Kolossov et al. [76] on a 5 mm x 5 mm x 2 mm Titanium powder block. The developed model can perform with different materials by using equation (12). With the process parameters of laser power, beam diameter, scanning speed and powder size as 2W, 0.025mm, 1mm/s and 30 μ m, the thermal model was simulated with the same conditions of the experiment. The 3D temperature distribution obtained from the developed model is shown in Figure 3-8 and the comparison between the experimental and simulation results is shown in Figure 3-9.

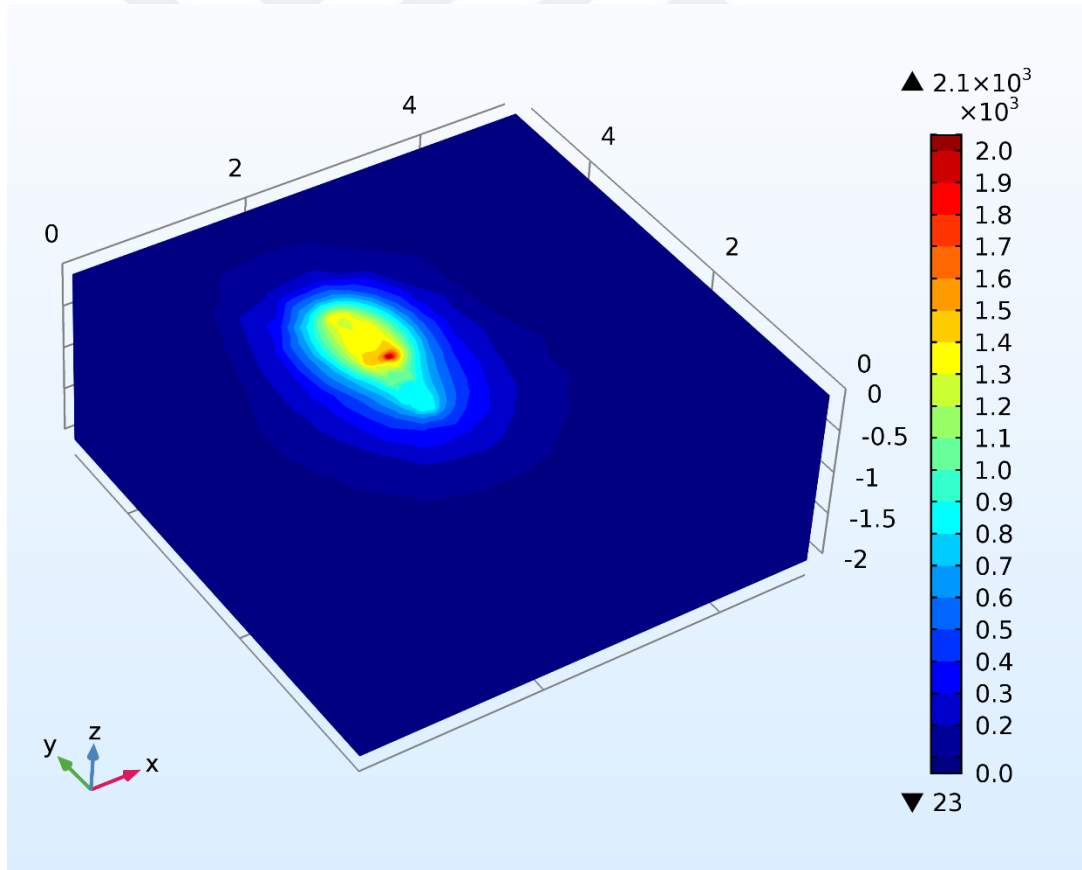


Figure 3-8- The 3D temperature [$^{\circ}$ C] distribution of the 5 mm x 5 mm x 2 mm sample [93]

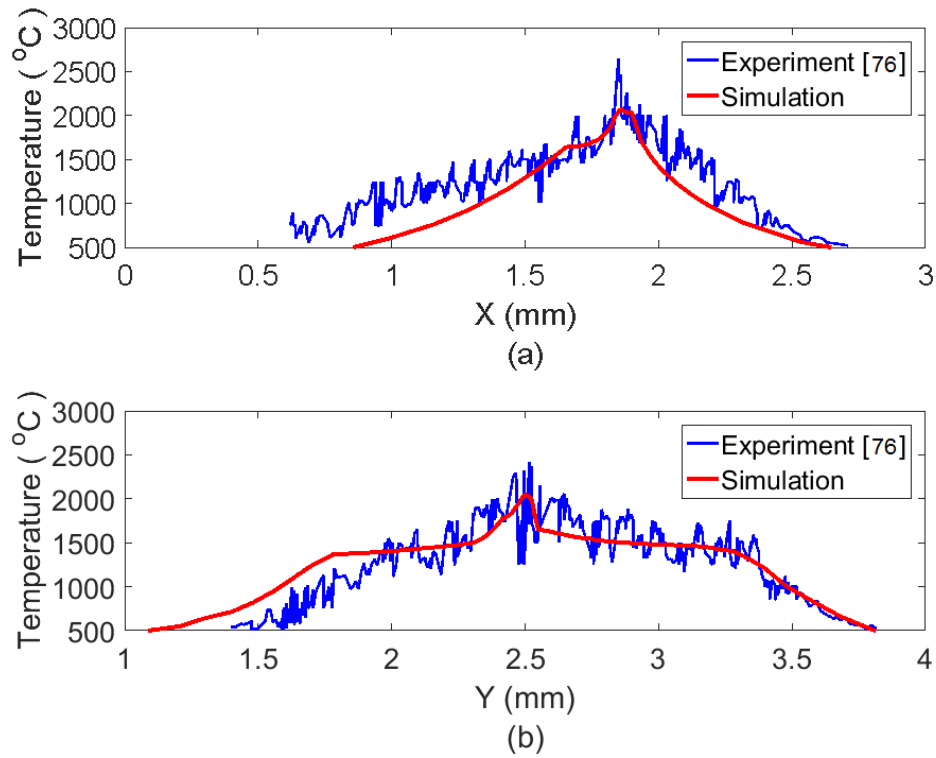


Figure 3-9- The comparison between experimental and simulation results [93]:

(a) The temperature distribution of x-profile at y=2.5 mm and z=2 mm

(b) The temperature distribution of y-profile at x=1.85 mm and z=2 mm

Figure 3-10 shows the microscopic photos of the manufactured specimen (IN625 parts using EOS290M) which were taken using 200X magnification. The thermal model was simulated with the same parameters and the simulation results are shown in Figure 3-11 and Figure 3-12. The width and depth of the molten pool are calculated respectively, 155 μm and 129 μm .

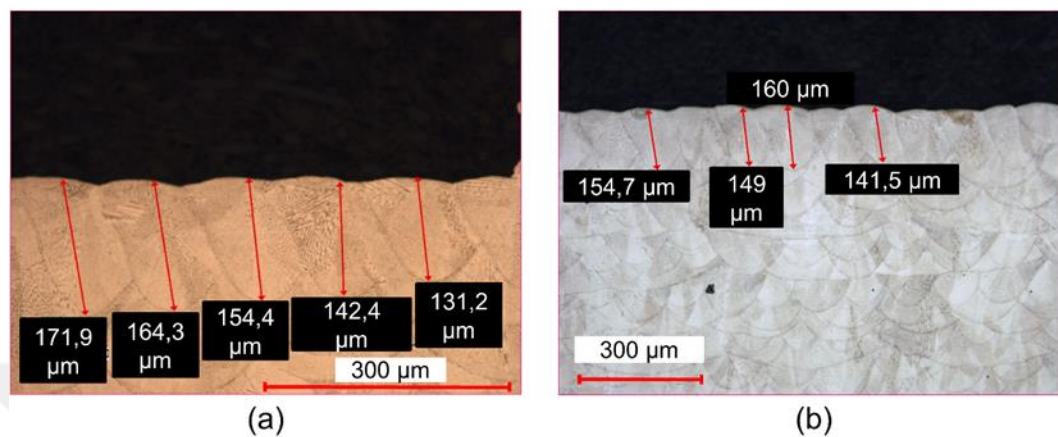


Figure 3-10- Cross-sectional views of (a) First measurement and (b) Second measurement [93]

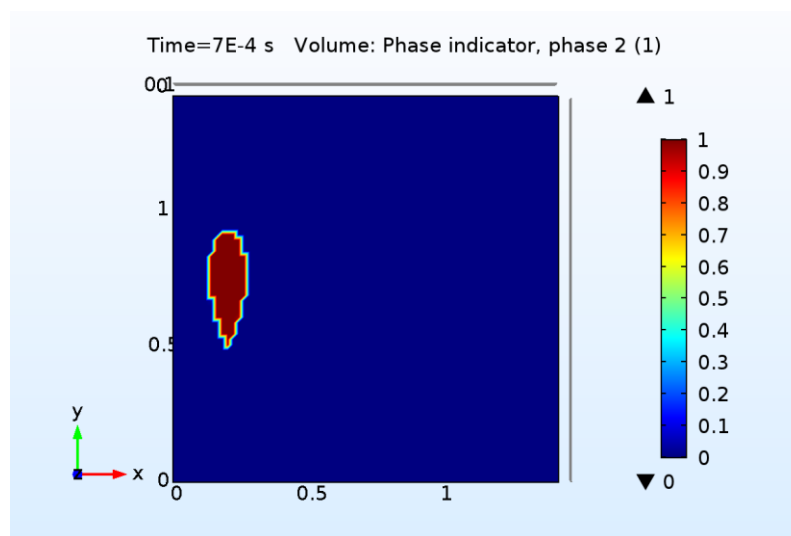


Figure 3-11- Molten pool geometry in x and y-direction [93]

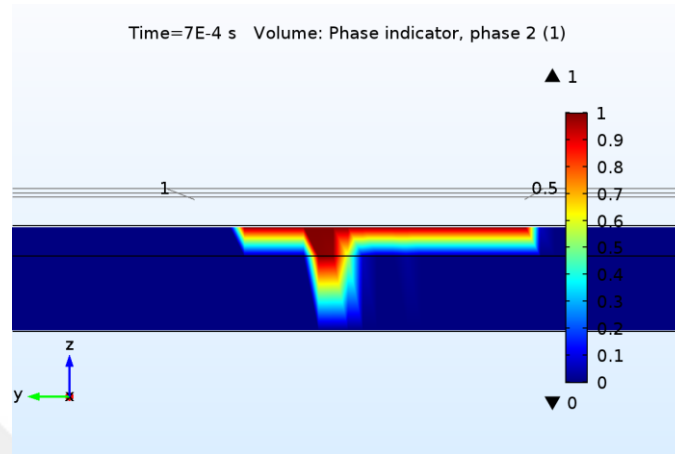


Figure 3-12- Molten pool geometry in y and z-direction [93]

Another experimental work on Inconel 625 was performed by Li et al [74]. Four different types of laser track characteristics were obtained: discontinuous, semi-continuous, continuous and smooth zone. To compare the experimental work and the developed model, the simulation is run with the scanning parameters for continuous zone characteristic (laser power and laser speed are taken as 65 W and 1500 mm/min respectively). The experimental and simulation results of the laser track are shown in Figure 3-13. The track width and penetration depth reported in the study are compared to the simulation results in Table 3-5. The process parameters for the experiments and the studies found in the literature are listed in Table 3-2. The prediction errors for the experiments carried out in this study are listed in Table 3-3. The prediction errors for the studies found in the literature are listed in Table 3-4 and Table 3-5.

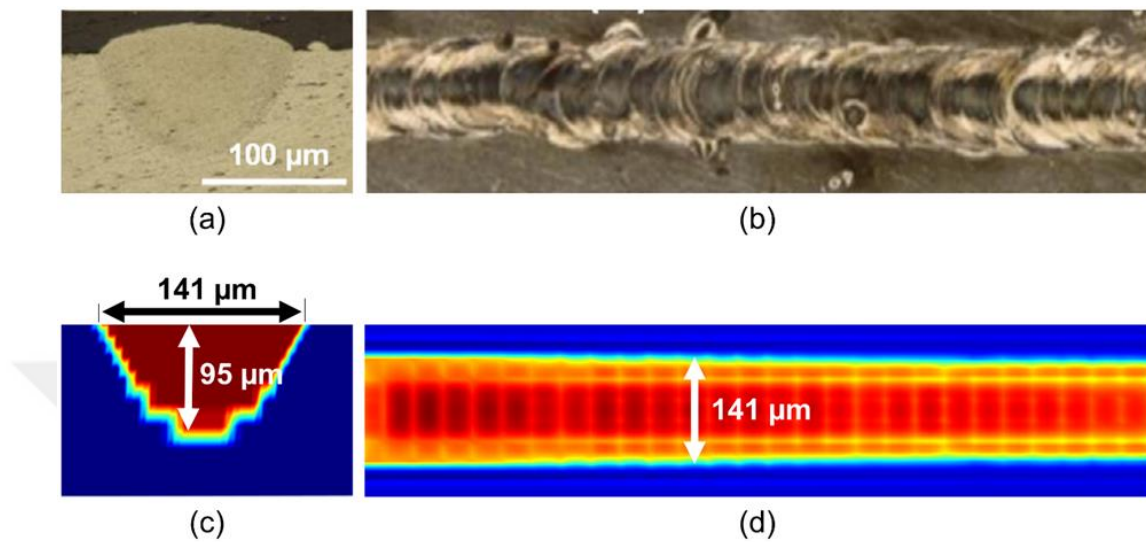


Figure 3-13- Laser track results: (a) the cross-section (Experimental) (b) the top view (Experimental) (c) the cross-section (Simulation) (d) the top view (Simulation) [93]

Table 3-2- Process parameters of the experiments and the studies found in the literature

Process parameters	Laser Power [W]	Laser Speed [mm/s]	Laser Spot Size [μm]	Material
Experiment	200 – 300	900 – 1000	50 – 100	Inconel 625
Study from literature [76]	2	1	25	Titanium
Study from literature [74]	65	960	72	Inconel 625

Table 3-3- Comparison of the simulation and experimental results

	Penetration Depth	Prediction Error
Simulation	129 μm	15.1 %
Experimental	152.1 μm	

Table 3-4- Comparison of the simulation and experimental results extracted from the literature [76]

	Maximum Temperature	Prediction Error
Simulation	2073 $^{\circ}\text{C}$	13.6 %
Experimental	2400 $^{\circ}\text{C}$	

Table 3-5- Comparison of the simulation and experimental results extracted from the literature [74]

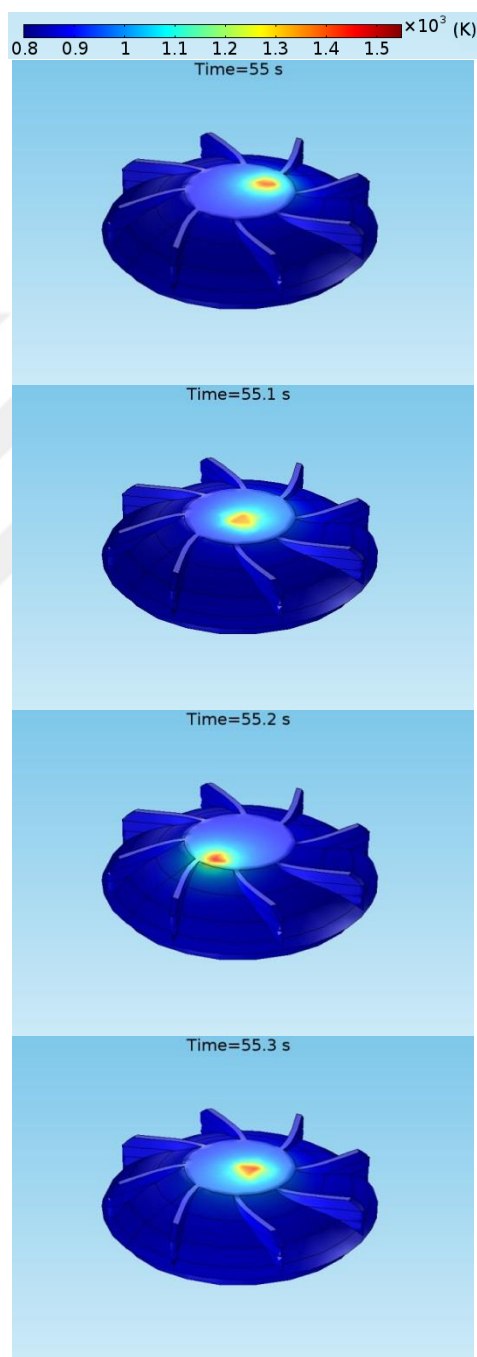
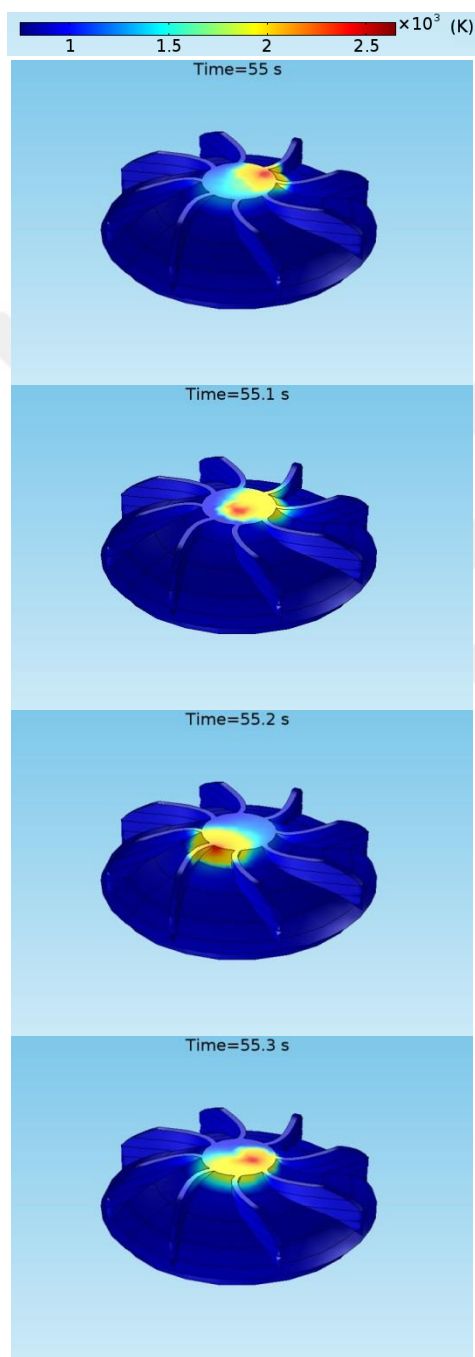
	Penetration Depth / Track Width	Prediction Error
Simulation	95 μm / 141 μm	11.7 % / 18 %
Experimental	85 μm / 121 μm	

3.10 Discussion

For the first comparison, the same scanning parameters and material reported in [76] are used in the developed model. The maximum temperature is predicted with 13.6% error. Moreover, as it can be observed from Figure 3-9, the temperature distribution in x and y-direction agree well with each other. For the second comparison, the scanning parameters are shown in Table 3-2, are used for the manufacturing of the sample part. The sample part is cut from two different places; the cross-sectional images were taken and the penetration depth is measured. The results of the penetration depth of the developed model and the results of the experiments carried out in TEI are compared and the model satisfies the experimental results with 15% error. In addition, with the same material in use, the scanning parameters of the work of Li et al [74] are tested in the developed thermal model. The track width prediction agrees with the reported results by 18% error and the penetration depth (reported as the sum of melted depth and track height) prediction agrees with the reported results by 11.7 % error. As it can be seen from the experimental validations and the comparisons made from literature, the developed thermal model can predict approximately the temperature and the molten pool region.

3.11 Application of freeform geometry

Figure 3-14 demonstrates that, with the new approach in this study, now it is possible to simulate 3D transient thermal analysis for additive manufacturing of 3D complex part geometries with freeform features in powder bed systems using a laser heat source. Ti6Al4V is used for the freeform application. In Figure 3-14, the time frames between 55 sec and 55.4 sec were given. This shows that the developed thermal model can simulate the temperature distribution in three dimensions, meaning the temperature history can be obtained for a whole part for any time. This attribute of the thermal model will be used in the mechanical model in order to predict the residual stresses and distortions in a fast way.



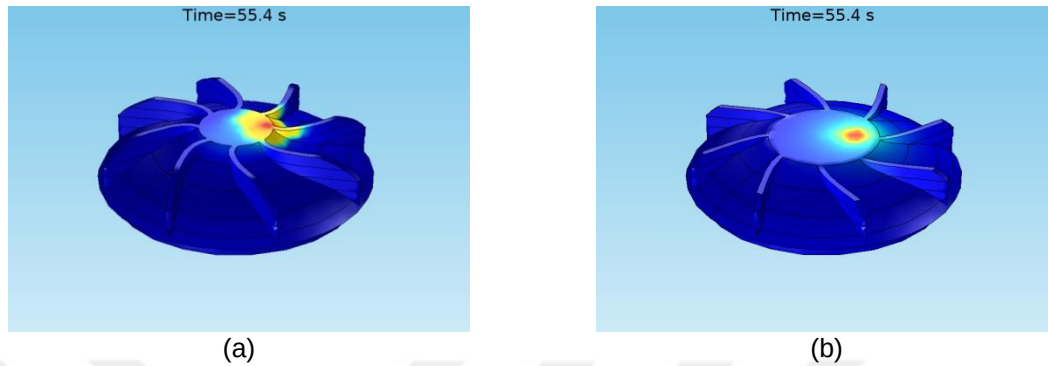


Figure 3-14- Illustration of the evolution of 3D transient temperature fields in Additive Layer Manufacturing of 3D complex part with freeform (the impeller example)

(a) 3D temperature field at the layer six and below,

(b) 3D temperature field at the layer five and below between 55 and 55.4 seconds

3.12 Issues encountered while FEM modeling

During this study, it is observed that the meshing and time stepping is one of the key elements. Due to the nature of the powder bed system discussed in powder bed modeling, the mesh size should be selected according to the thermal conductivity. In other words, if the mesh size is not selected as small as it should be, the model will not capture the temperature distribution, negative temperature values will appear. On the other hand, selecting the time steps larger helps to remove the negative temperature. The other constraint is the computation time. As expected, the smaller mesh size results in longer computation time. Therefore, mesh size should be selected regarding these two points. In order to see the relationship between the mesh sizes, time step, the appearance of negative temperature and computation time, a sample FEM study was performed.

The sample geometry is shown in Figure 3-15. The mesh of the sample geometry is given in Figure 3-16. The scanning points are listed in Table 3-6. The temperature distributions were given in Figure 3-17, Figure 3-18, Figure 3-19 and Figure 3-20.

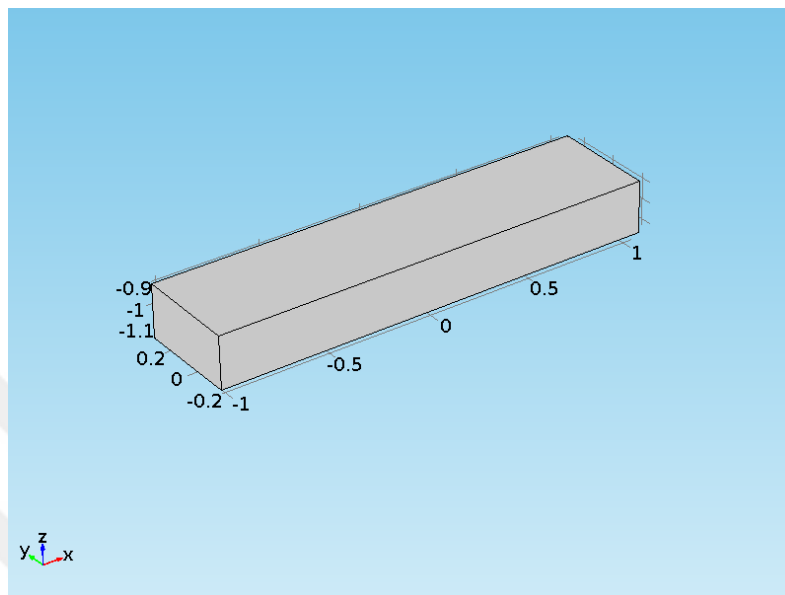


Figure 3-15- Sample geometry (0.5 mm x 2.1 mm x 0.25 mm)

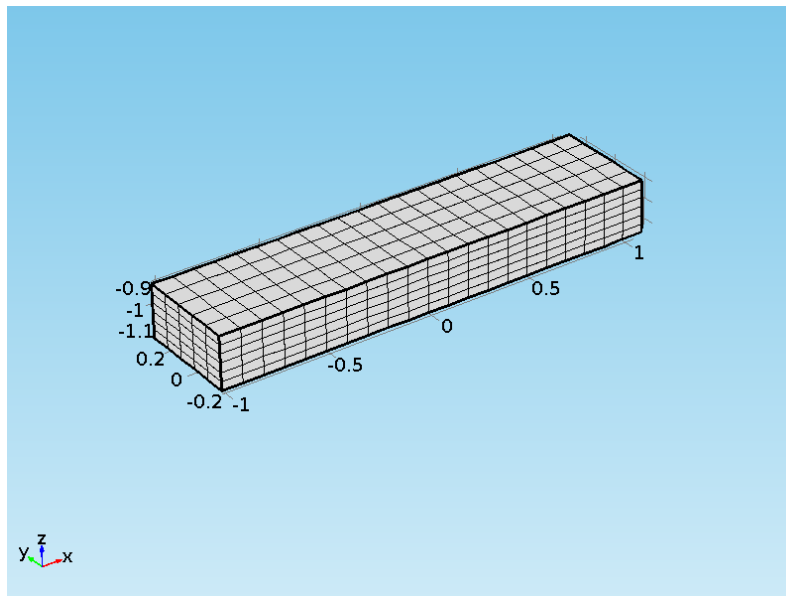


Figure 3-16- Meshing of the sample geometry

Table 3-6- Laser Scan Points

X [mm]	Y[mm]
-0.9	0
-0.8	0
-0.7	0
-0.6	0
-0.5	0
-0.4	0
-0.3	0
-0.2	0
-0.1	0
0	0
-0.1	0
0.2	0
0.3	0
0.4	0
0.5	0
0.6	0
0.7	0
0.8	0
0.9	0

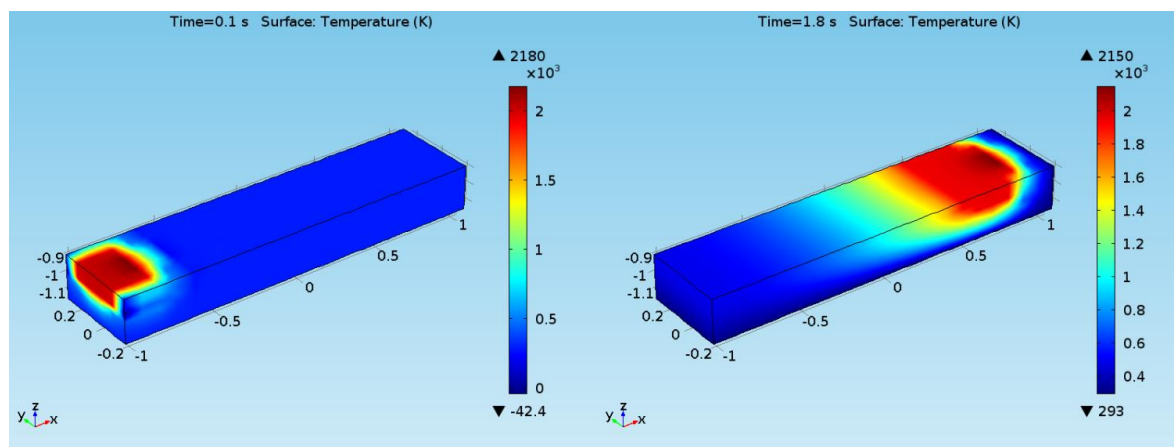


Figure 3-17- Temperature distribution for the mesh size: 0.1mm, the time step: 0.1 sec

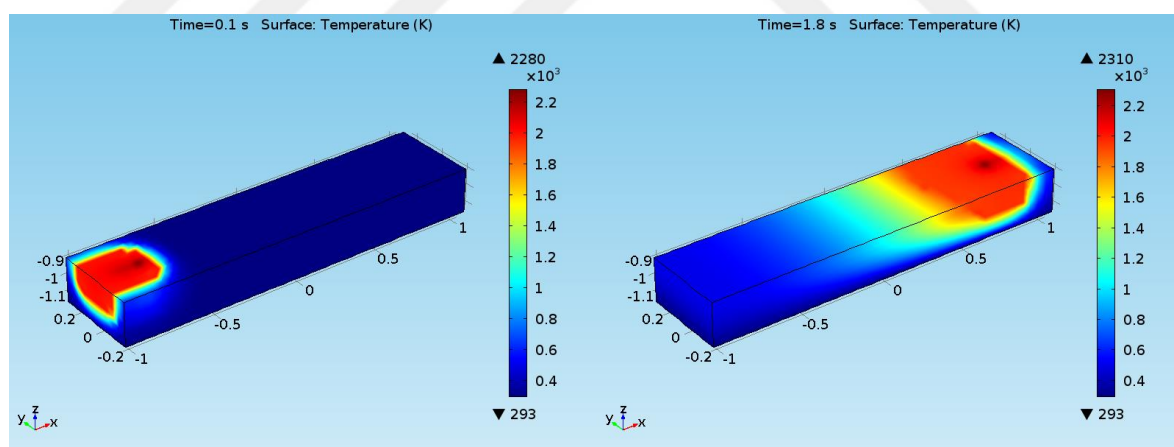


Figure 3-18- Temperature distribution for the mesh size: 0.05mm, the time step: 0.1 sec

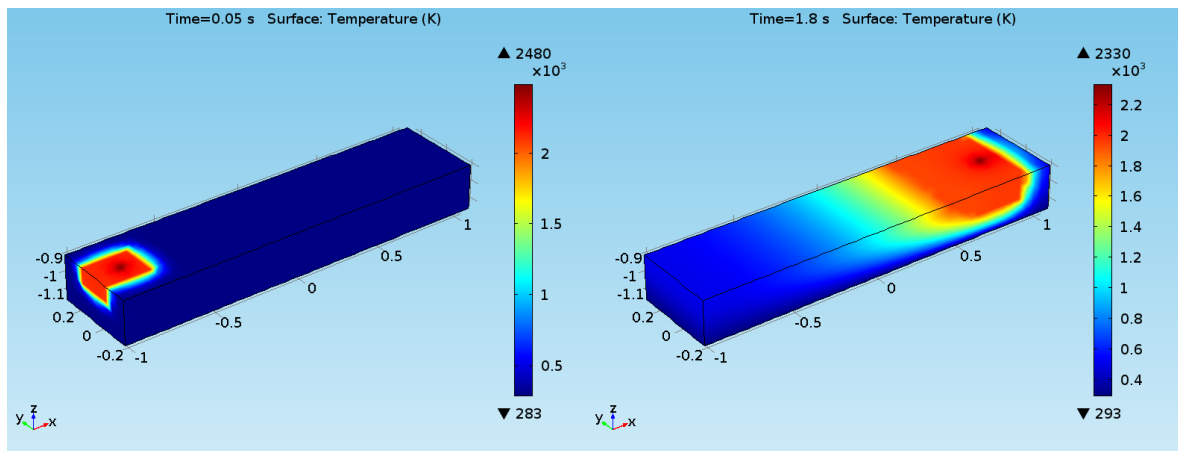


Figure 3-19- Temperature distribution for the mesh size: 0.05mm, the time step: 0.05 sec

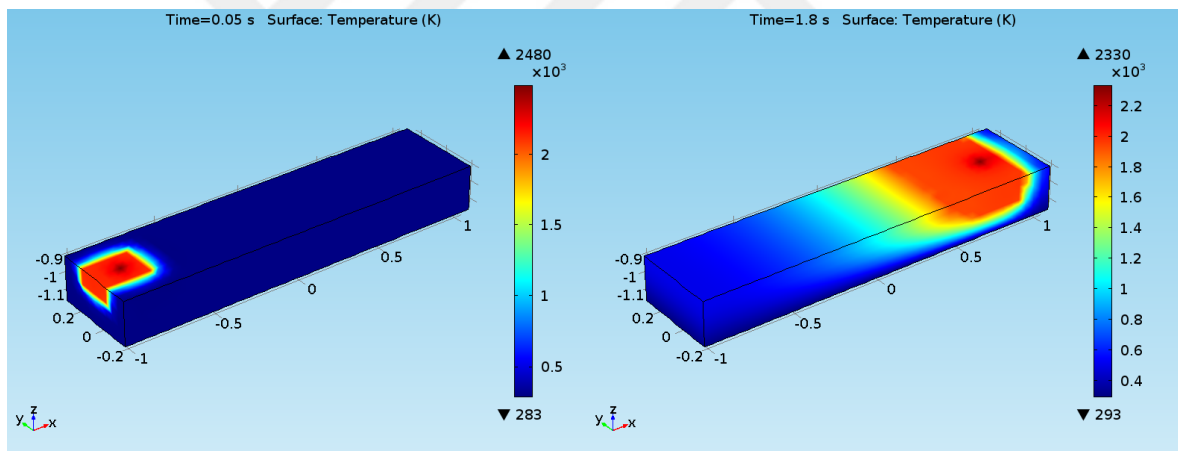


Figure 3-20- Temperature distribution for the mesh size: 0.025mm, the time step: 0.05 sec

Table 3-7- The temperature distribution according to the mesh size and time step

Laser power	Mesh size [mm]	Time step [s]	Negative temperature	Max. temperature in the last time step [$^{\circ}$ K]	Computation time
1 [W]	0.1	0.1	Starts at 0.1s Ends at 1.8s	2160	20 minutes
1 [W]	0.05	0.1	Not seen	2530	1 hour 21 minutes
1 [W]	0.05	0.05	Starts at 0.05s Ends at 0.1s	2530	1 hour 34 minutes
1 [W]	0.025	0.05	Not seen	2470	26 hours 22 minutes

It is seen that in order to avoid the appearance of the negative temperature, the mesh size should be selected as small enough. There is a relation between the mesh size and time step. In order to simulate a smaller time step, a smaller mesh size should be selected. The smaller mesh sizes increase the computation time exponentially.

3.13 Summary

In this study, the direct metal laser sintering (powder bed system) was investigated thoroughly. Heat transfer equations, phase change modeling, heat source modeling and powder bed modeling were accomplished. Three different material were studied in order to see the performance of the developed thermal model. In addition, a new technique was introduced to allow the temperature simulation of the 3D freeform geometries.

To sum up, via 3D heat source modeling and phase transformation modeling, a 3D thermal model has been developed for the powder bed system. The developed model both contains mathematical and FEM modeling in order to achieve appropriate predictions. The

developed model is validated by a new set of experiments with Inconel 625 powder and also compared with the studies found in the literature. The prediction errors of the developed model are found to be lower than 20%. The developed thermal model can be used to investigate the temperature distribution and the molten pool geometry for the additive manufacturing of 3D freeform complex geometries.



Chapter 4

THERMO-MECHANICAL MODELING OF DIRECT METAL LASER SINTERING

4.1 Overview

From the previous chapter and literature review, it is seen that during the additive manufacturing of metals, due to the temperature gradients, the manufactured parts are under the effects of a heating and a cooling cycle. Moreover, while scanning a layer, the previous layers heat up and it results in thermal expansion meanwhile the scanned layer cools down and results in thermal contraction. Due to this effect, residual stresses appear in part during the additive manufacturing process. After the additive manufacturing process, the part and the base plate will be separated and the residual stresses often cause distortions in part. In order to investigate this relationship, a rapid prediction tool is crucial for the direct metal laser sintering from both industrial and scientific perspectives.

Due to the computation limitations, residual stress and distortion prediction models are not enough to satisfy the needs of the industry, where a prediction tool for large-scale parts are required. In order to achieve such a prediction tool to understand the effects of the thermal contraction and expansion on residual stresses and distortions, mathematical and finite element techniques were studied. The purpose of this study is, by using the thermal history from the developed thermal model (Chapter 3), to introduce an analytical and FEM model to enhance the prediction accuracy of distortions with decreasing the computation time drastically.

In this study, firstly, an analytic approach was used to understand the mechanism of additive manufacturing in terms of residual stress and distortion. Then, four different FEM approaches were studied. Finally, analytic and best FEM approach were compared with the distortions experiments.

4.2 Analytical modeling

In terms of macro thermal-mechanical modeling for direct laser sintering, the main reason of the residual stresses is the plastic deformation due to the heating (thermal expansion) or / and cooling (thermal contraction) [101] between the part and the base plate. A demonstration of the part and the base plate is given in Figure 2.

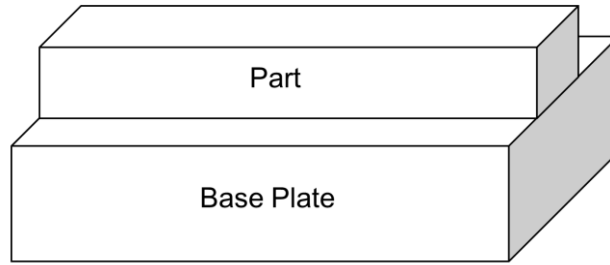


Figure 4-1- Schematic of the part and the base plate

The part and the base plate are bound together in the additive manufacturing process. After the process, the part and the base plate are separated. To derive the necessary equations for the prediction of the residual stresses and the distortions, the part is considered as just separated from the base plate. It is also assumed that only the bending stresses act on the part.

For this approach (Figure 4-2), the non-thermal strain can be written as follows,

$$\varepsilon_{non-thermal} = \frac{(y - b)}{\rho} \quad (4-1)$$

where b and ρ are respectively the distance to the neutral axis and the radius of the curvature. Moreover, the total strain is as follows,

$$\varepsilon_{total} = \alpha \Delta T + \frac{(y - b)}{\rho} \quad (4-2)$$

where $\alpha, \Delta T$ are respectively the thermal expansion coefficient and the temperature difference.

It is observed that the last molten zone (red colored zone in Figure 4-2 and Figure 4-3) has a higher stress distribution compared to the previously manufactured layers. In other words, previous layers experience an annealing effect due to the laser heating during the additive manufacturing process. Hence, this relaxation effect relieves the stresses on the previous layers (to some extent).

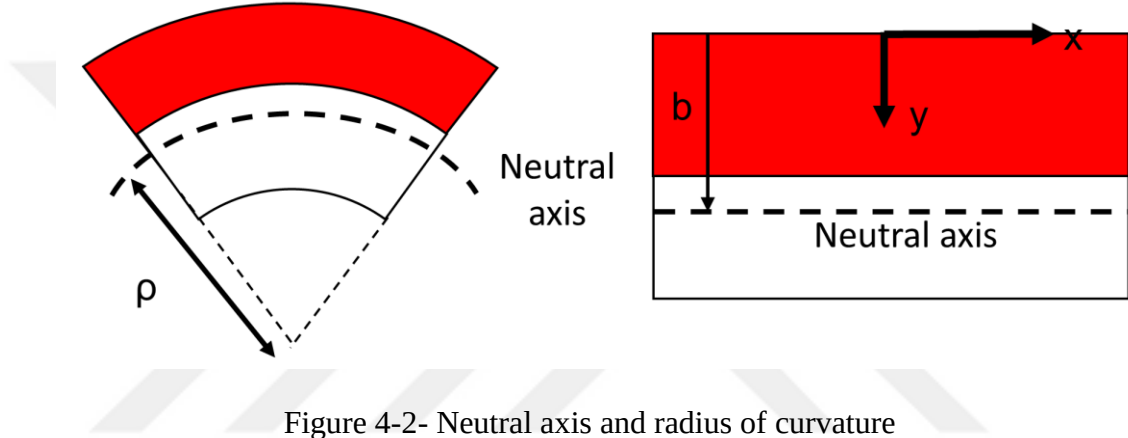


Figure 4-2- Neutral axis and radius of curvature

The stress equations can be written as below:

$$(\sigma_{zz})_1 = E \cdot \left(\frac{(y - b)}{\rho} - \alpha \Delta T \right) \quad (4-3)$$

$$(\sigma_{zz})_2 = E \cdot \left(\frac{(y - b)}{\rho} - A \alpha \Delta T \right) \quad (4-4)$$

where A and E are respectively the relaxation factor and the Young's modulus of the part. It should be noted that the behaviors of the material in the elastic and the plastic region are considered the same. The force equilibrium equation can be written as below:

$$\sum F_z = 0 \quad (4-5)$$

$$\int_0^{h_1} (\sigma_{zz})_1 \cdot dy + \int_{h_1}^{h_2} (\sigma_{zz})_2 \cdot dy = 0 \quad (4-6)$$

$$\int_0^{h_1} \left(\frac{E_1 \cdot (y - b)}{\rho} - \alpha \Delta T E \right) \cdot dy + \int_{h_1}^{h_2} \left(\frac{E_1 \cdot (y - b)}{\rho} - A \alpha \Delta T E \right) \cdot dy = 0 \quad (4-7)$$

The moment equilibrium equation can be written as below:

$$\sum M = 0 \quad (4-8)$$

$$\int (\sigma_{zz})_1 \cdot y \cdot dy + \int (\sigma_{zz})_2 \cdot y \cdot dy = 0 \quad (4-9)$$

$$\int_0^{h_1} \left(\frac{E_1 \cdot (y - b)}{\rho} - \alpha \Delta T E \right) \cdot y \cdot dy + \int_{h_1}^{h_2} \left(\frac{E_1 \cdot (y - b)}{\rho} - A \alpha \Delta T E \right) \cdot y \cdot dy = 0 \quad (4-10)$$

b and ρ are derived by solving equations (4-7) and (4-10) together, and the following relations are obtained as below,

$$b = - \frac{3h_1^2 h_2 - 3Ah_1^2 h_2 - 4h_1 h_2^2 + 4Ah_1 h_2^2 - Ah_2^3}{6(-1 + A)h_1(h_1 - h_2)} \quad (4-11)$$

$$\rho = \frac{h_2^3}{6(-1 + A)\alpha_1 \Delta T h_1 (-h_1 + h_2)} \quad (4-12)$$

where h_1 is the height of the last molten zone, which is calculated from the developed thermal model, and h_2 is the height of the part. (Figure 4-3)

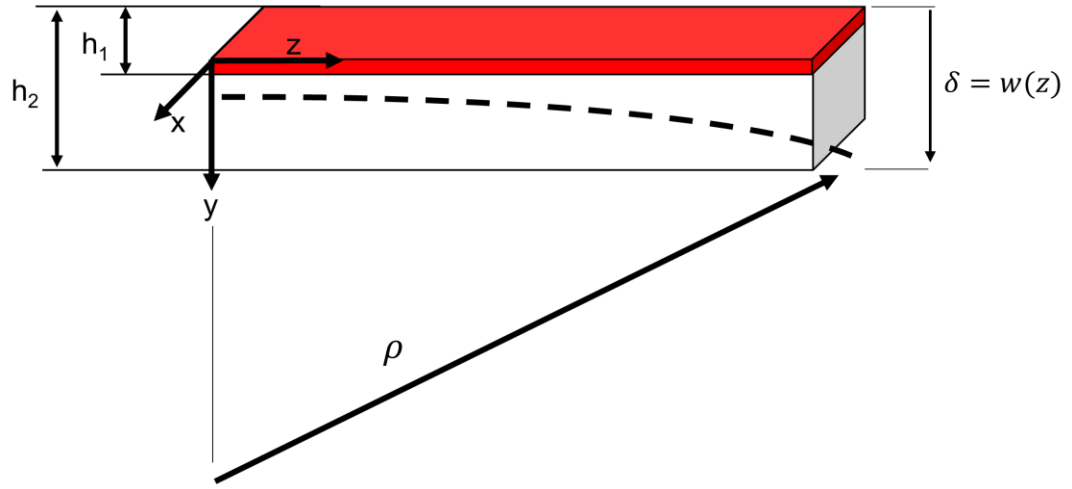


Figure 4-3- The deformation of the part

The deformation function $w(z)$ can be obtained as follows:

$$\frac{\partial^2 w}{\partial z^2} \approx \frac{1}{\rho} \quad (4-13)$$

There is no deflection at $z=0$, hence $w(0) = 0$. The slope of the curve is horizontal at $z=0$, hence $w'(0) = 0$.

The deformation equation is obtained as follows:

$$\delta = w(z) = \frac{1}{2} \frac{z^2}{\rho} \quad (4-14)$$

4.3 FEM modeling

Although the analytical approach provides an edge over the behavior of the residual stresses and distortions occurring after the DMLS process, for 3D geometries, a FEM model is required for an accurate prediction.

The governing stress σ equilibrium equation is given as:

$$\nabla \cdot \sigma = 0 \quad (4-15)$$

The constitutive law is:

$$\sigma_{ij} = C_{ijkl} \varepsilon_{kl} \quad (4-16)$$

where constitutive tensor C is a 4th order tensor, the stress tensor σ and the strain tensor ε are 2nd order tensors. The material model has been chosen to be isotropic and temperature dependent. Considering small deformation, total strain ε can be written as:

$$\varepsilon = \frac{1}{2} (\nabla u + \nabla u^T) \quad (4-17)$$

The Von Misses yield criterion is used to calculate plastic deformation. In addition, an isotropic hardening model is considered where a hardening function and a yield stress function (dependent on temperature) for Inconel 625 is used to calculate plastic deformation that may occur during the additive manufacturing process.

$$\sigma_{ys} = \sigma_{ys0} + \sigma_h(\varepsilon_p) \quad (4-18)$$

where σ_{ys} is the stress, σ_{ys0} is the initial yield stress (obtained from the yield stress function) and $\sigma_h(\varepsilon_p)$ is the hardening stress term.

The temperature prediction model is run for a sample geometry to determine the history of the temperature distribution and the melted region. The temperature history, the elastic and plastic strain tensors can be related to the overall stress tensor by the equation;

$$s = s_0 + C : (\varepsilon - \varepsilon_0 - \varepsilon_p - \alpha \Delta T) \quad (4-19)$$

where s_0 , ε_0 , α , ΔT are initial stresses, initial strains, the thermal expansion tensor and temperature difference which is obtained from the temperature prediction model,

respectively. This information is then fed to the mechanical model in order to simulate the residual stress and distortions.

4.4 Developed FEM models

As mentioned before, in this study, four different FEM models were developed. It should be noted that the developed model should not just predict the residual stresses and the distortion accurately, but also it should be solved fast. Moreover, the required computation time of a part should not exceed the required additive manufacturing time of the same part. In Section 4.4.1, 4.4.2, 4.4.3 and 4.4.4, a brief information is given about the methodology and the computation time of the developed thermal-mechanical models.

4.4.1 Thermo-mechanical FEM model (First FEM model)

In this FEM model, the developed thermal model (Chapter 3) and the mechanical model are coupled. In other words, a transient thermo-mechanical model computes the melting, the solidification, the thermal expansion and the thermal contraction in the powder bed at same time. Including the plastic deformation with a hardness function, the computation time of the first FEM model became impractical. To give an example, on a workstation with the specification of 32 GB memory RAM and 8 processor with 3.33 GHz, the first layer of the additive manufacturing simulation of a sample part (1.4mm x 1.4mm x 0.6mm) was solved in approximately 117 hours.

4.4.2 Thermal-mechanical FEM model (Second FEM model)

Due to the high computation time, the thermal model and mechanical model were decoupled. After the thermal model is solved, the temperature history and molten zone history of each time step can be fed to the mechanical model. This means that the thermal model is still solved as time-dependent, but the mechanical model is solved as stationary for each time step. Although, the first layer of the thermal-mechanical model was solved (on the

same workstation mentioned in Section 4.4.1) in 28 hours for the sample part (1.4mm x 1.4mm x 0.6mm), which is faster than the first FEM model, it is still not meeting the computation time requirements.

4.4.3 Thermal-mechanical FEM model (Third FEM model)

A different methodology was followed in third FEM model in terms of defining the loading conditions. In the first two models, the information of the temperature distribution and the melted region were fed to the mechanical model in order to calculate the stresses. In this model, 3D CAD information of the part will be used in order to directly extrapolate the melted region information into the powder bed. In other words, the part geometry will be marked as melted in the powder bed and the mechanical model will be simulated. It should be noted that the marked regions are the thermal load conditions. The marking operation is based on the thermal model using the additive manufacturing process parameters. To compare the computation time of the third FEM model, the simulation of the sample part (1.4mm x 1.4mm x 0.6mm) were carried out (on the same workstation mentioned in Section 4.4.1) and the model was solved in 20 seconds. The computation time of the third FEM model is enough for the industrial applications.

4.4.4 Thermal-mechanical FEM model (Fourth FEM model)

Even though, the third FEM model meets the computation time requirement, it is seen that the application of the model on freeform geometries is impractical due to the marking operation. Therefore, a different methodology was followed in terms of the initial geometry of the FEM model. In three FEM models, the powder bed geometry was positioned on the base plate geometry. In the fourth FEM model, the 3D CAD geometry is directly brought in the FEM environment. In terms of loading, the thermal model was run for a sample geometry in order to see the material behavior, the molten pool and temperature distribution on

multilayers. Then, this information is fed to the mechanical model to calculate the residual stresses and distortions. The fourth FEM model was run (on the same workstation mentioned in Section 4.4.1), like previous FEM models, for the sample geometry (1.4mm x 1.4mm x 0.6mm). The model was solved in 9 seconds.

4.4.5 Third and fourth FEM model comparison and FEM model selection

The third and fourth FEM models are fast enough in terms of computation for the industrial applications. In order to compare the accuracy of these two models, an experiment was carried out. It should be noted that the experiments will be given in detail in further sections. The geometry of the part is given in Figure 4-4. The dimensions of the part is listed in Table 4-1.

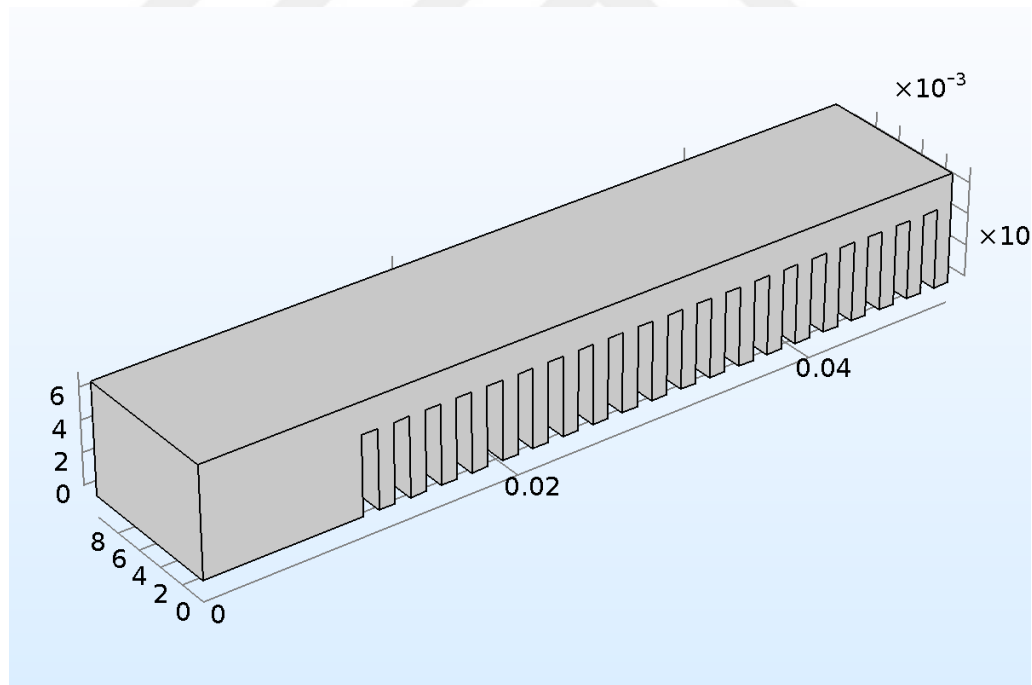


Figure 4-4- The geometry of the part

Table 4-1- The dimensions of the part

Width	10 mm
Length	50 mm
Height	7 mm
Tooth Width	1 mm
Tooth Height	5 mm

The distortion result of the third and fourth model are given respectively in Figure 4-5 and in Figure 4-6.

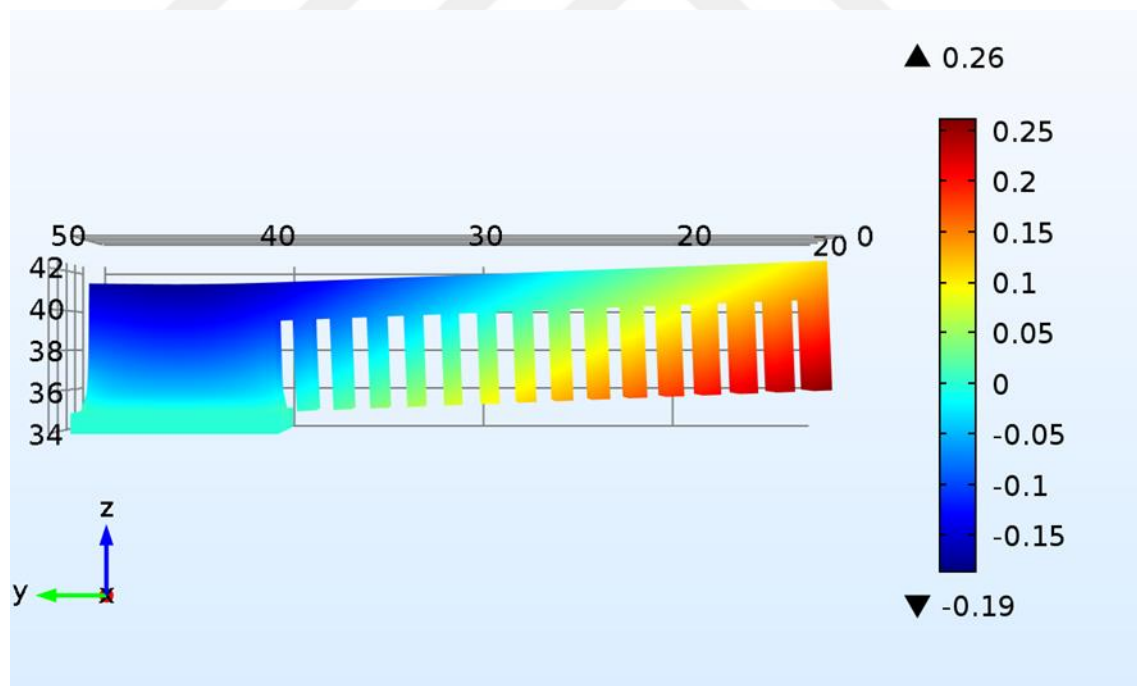


Figure 4-5- Distortion simulation result of part (third FEM model)

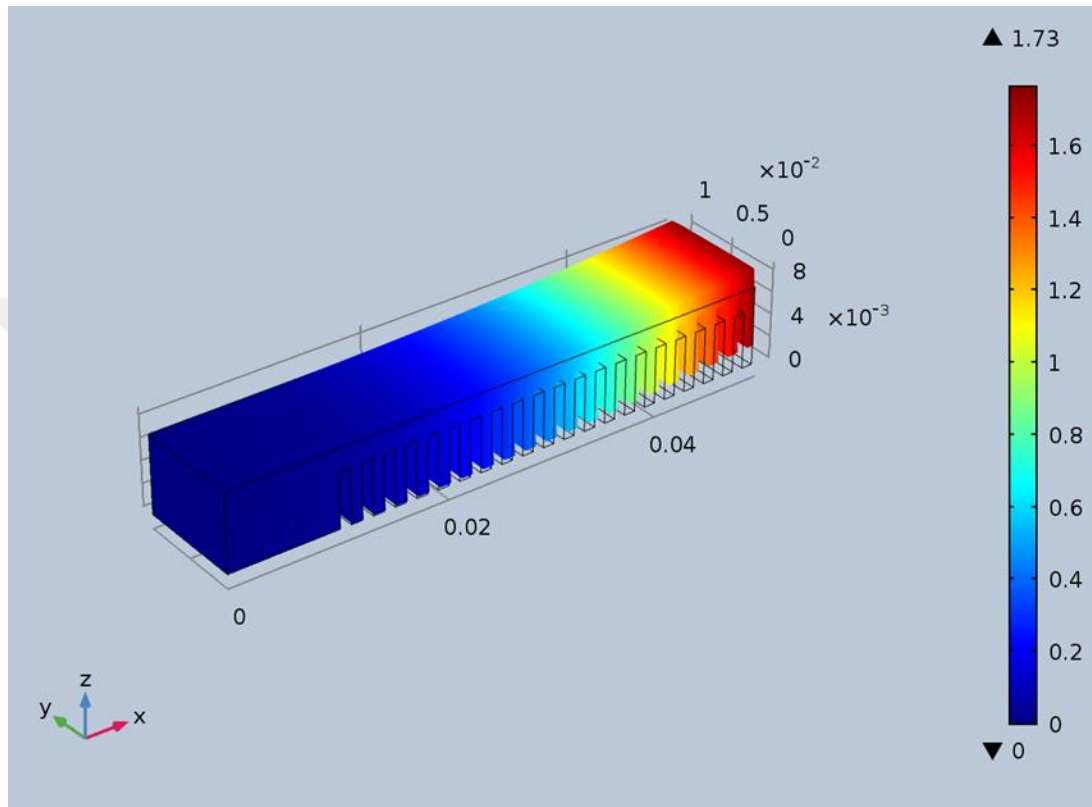


Figure 4-6- Distortion simulation result of part (fourth FEM model)

The tip distortion measured in the experiment (which will be given in detail in further sections) is 1.87mm. As it can be seen from the results, even though the third FEM model can be solved fast, the prediction error is not in the acceptable range. Hence, for the model validation, the fourth FEM model is selected as the thermal-mechanical model.

4.5 Thermal information and relaxation factor

In order to simulate the mechanical part of the fourth FEM model, the thermal model should be run for a sample geometry in order to see the temperature distribution between the layers. For this purpose, the chosen geometry is given in Figure 4-7. The thermal model was

simulated for three-layer deposition on a base plate. The dimensions of the geometry and the process parameters are given in Table 4-2.

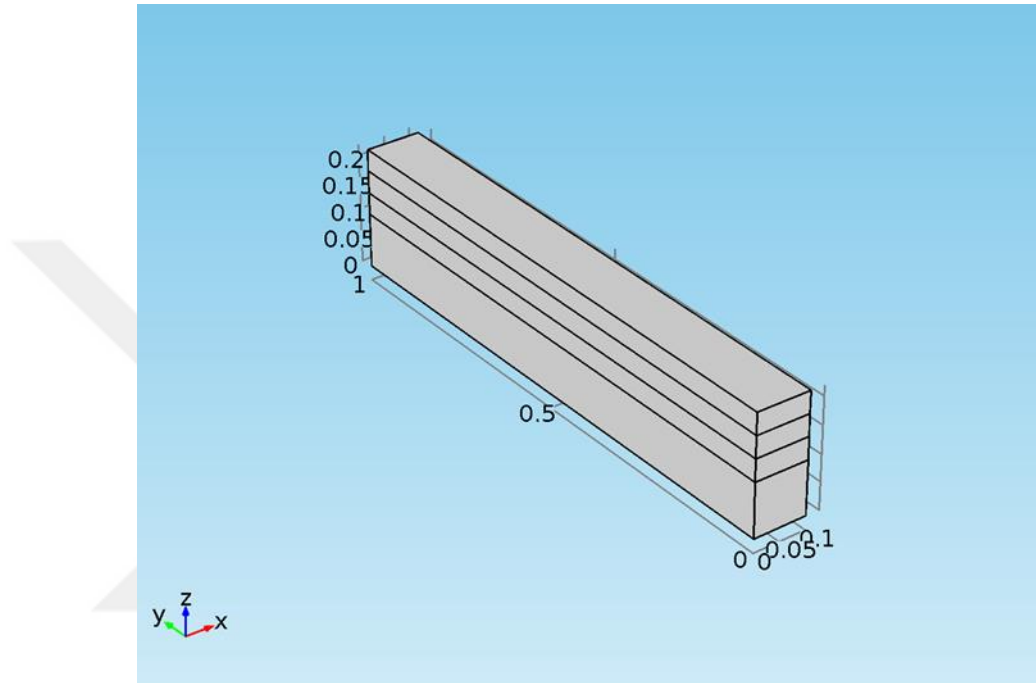


Figure 4-7- The powder layers and the base plate

Table 4-2- Geometrical data and process parameters

Dimensions of the powder Layer		The dimensions of the base plate		Process parameters	
Length	1 mm	Length	1 mm	Laser power	285 W
Width	0.1 mm	Width	0.1 mm	Laser spot size	80 μ m
Height	40 μ m	Height	0.1 mm	Laser speed	960 mm/s
The number of layers	3			Material	Inconel 625

Four points were selected in the geometry. The location of the points is shown in Figure 4-8. The temperature distributions of each layer had been obtained via thermal model and are given in Figure 4-9, Figure 4-10 and Figure 4-11.

In the literature, there have been a couple of studies about the residual stresses in the additive manufacturing process. In these studies, it was noted that while scanning a layer, the previous layers might go under an annealing effect due to the temperature rise [91,102-104]. It was also pointed out that if the temperature of a scanned layer rises up to the annealing temperature of the material, the residual stresses and plastic strain can be ignored [91].

Considering the relaxation effect, the loading input for the mechanical part of the thermal-mechanical FEM model was prepared. The relaxation factor is calculated by dividing the maximum yield stress at the temperature of solidification to the maximum yield stress at room temperature. This means that for each material, a new relaxation factor should be calculated.

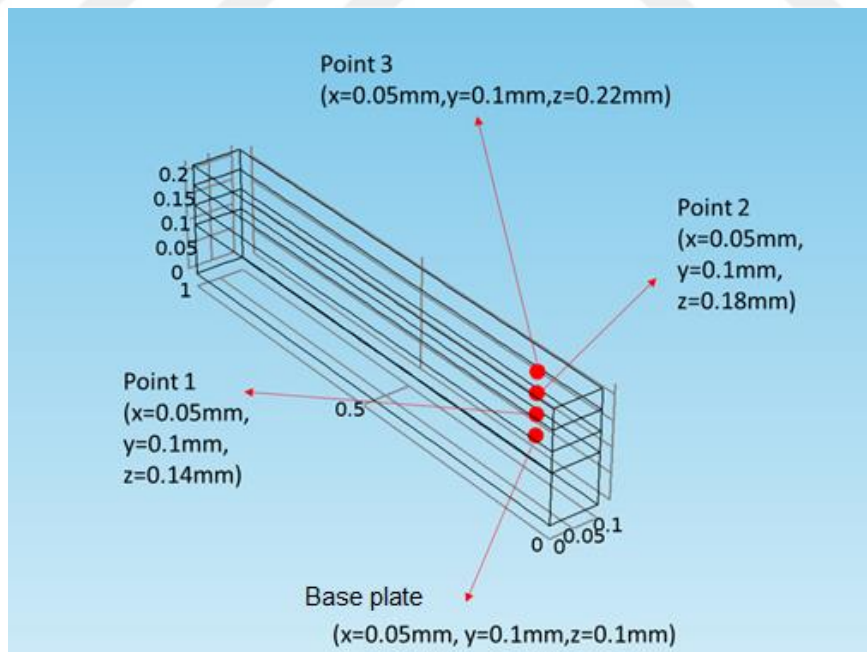


Figure 4-8- The coordinates of the selected points

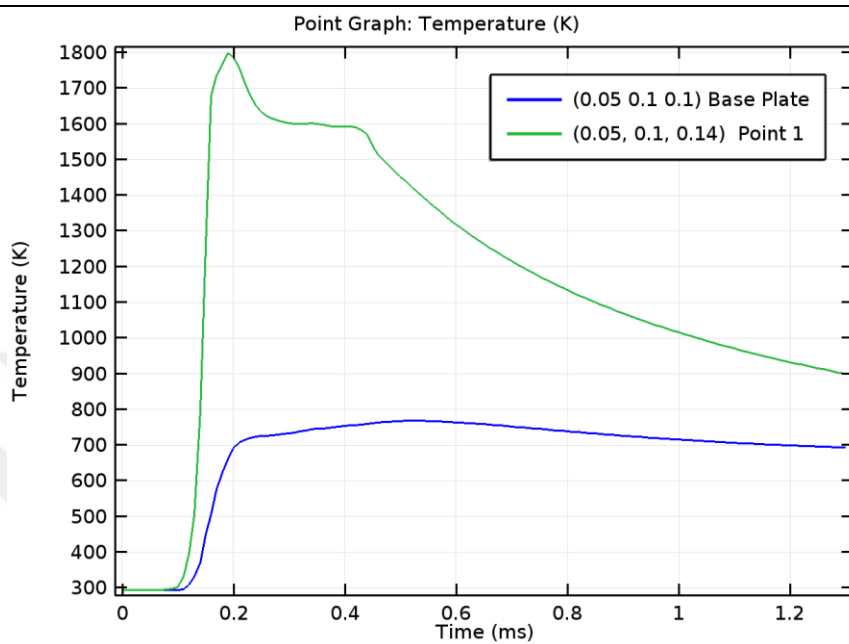


Figure 4-9- Temperature distribution during the first layer scanning

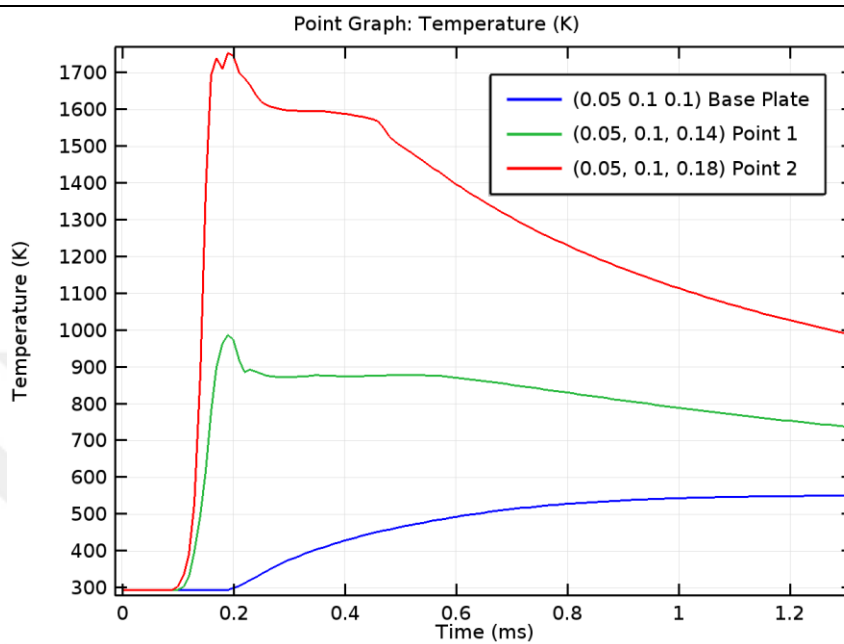


Figure 4-10- Temperature distribution during the second layer scanning

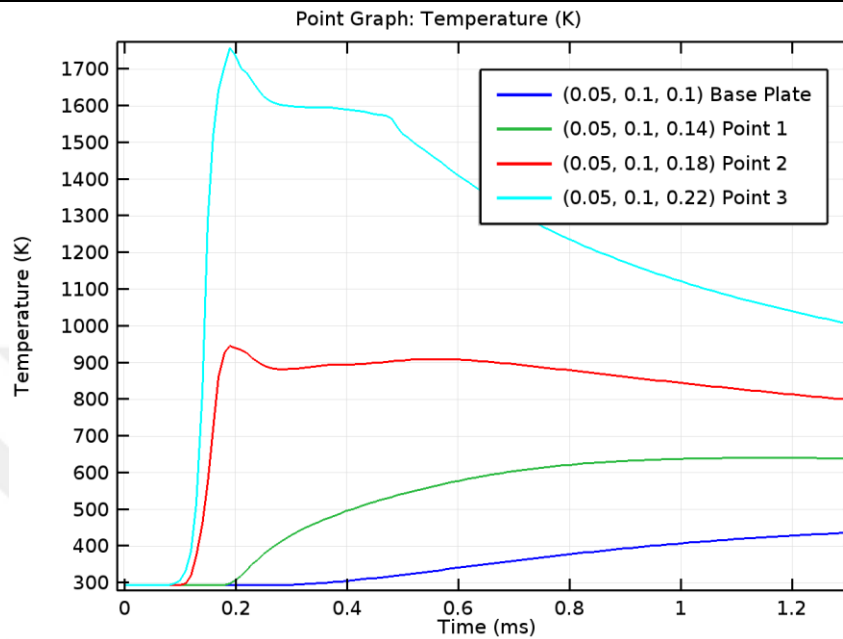


Figure 4-11- Temperature distribution during the third layer scanning

As it can be seen from the temperature history, the maximum temperature of the scanned region rose up to 920-940 $^{\circ}\text{K}$ (647-667 $^{\circ}\text{C}$). Therefore, a relaxation effect is happening, rather than annealing effect.

It should be noted that the dimensions of the molten pool are important because the loading input (needed for the mechanical part of the thermal-mechanical FEM model) is tailored according to this information.

4.6 Experimental setup

For the validation of the thermal-mechanical FEM model, distortion results were used. In order to measure the distortions of the experimental parts, EOS M290 additive manufacturing machine (Figure 4-12) were used to manufacture the parts. Then, the parts and the base plate were separated by using wire EDM (Electro discharge machining). Finally, the cut parts were measured by Nikon Altera CMM (Coordinate measuring machine).



Figure 4-12- EOS M290 additive manufacturing machine

The top surfaces of the parts were scanned and saved as a Parasolid file in order to compare the distortion results of the thermal-mechanical model.

4.7 Analytic and thermal-mechanical FEM model validation

4.7.1 Material properties

In this study, an analytical model and a FEM model had been developed. Experimental validation is done with Inconel 625 powder, then compared with the corresponding simulation for this material. Some of the material properties of Inconel 625 [95,105] are given in Table 4-3.

Table 4-3- Material properties of Inconel 625 [95,105]

Density	8440 [kg/m ³]
Young Modulus	207 [GPa]
Poisson Ratio	0.295
Thermal Expansion Coefficient	16.6 [1/ ⁰ C]
Melting Range	1290 – 1350 [⁰ C]

4.7.2 Model Results, experimental results and model validation

For all experiments, the process parameters are the same and listed in Table 4-4.

Table 4-4- Process parameters

Laser Power	200 - 300 W
Laser Spot Diameter	50 - 100 μ m
Laser Speed	900 - 1000 mm/s
Layer Thickness	20 - 60 μ m
Material	Inconel 625

A simple geometry is selected for the first validation of the analytical and FEM model. (Figure 4-13). The dimension of the geometry is given in Table 4-5.

Table 4-5- The dimensions of part 0

Width	10 mm
Length	50 mm
Height	7 mm

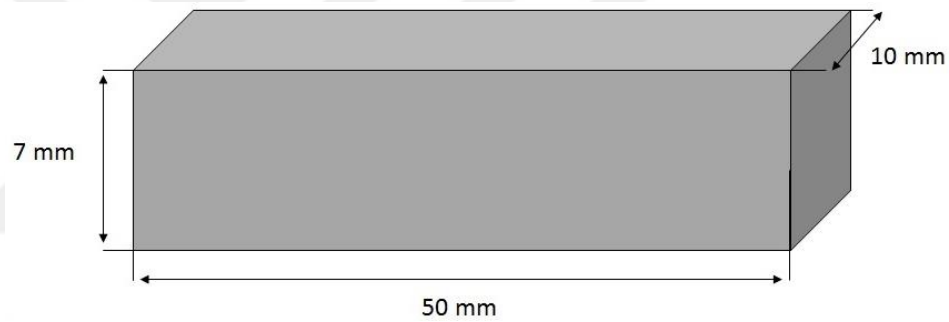


Figure 4-13- The geometry of part 0

Table 4-6- The results of the analytical approach

b	10.8 mm
ρ	3.485 m
δ	359 [um]

The FEM model was run to simulate the distortion occurring in part 0. The simulation result is shown in Figure 4-14.

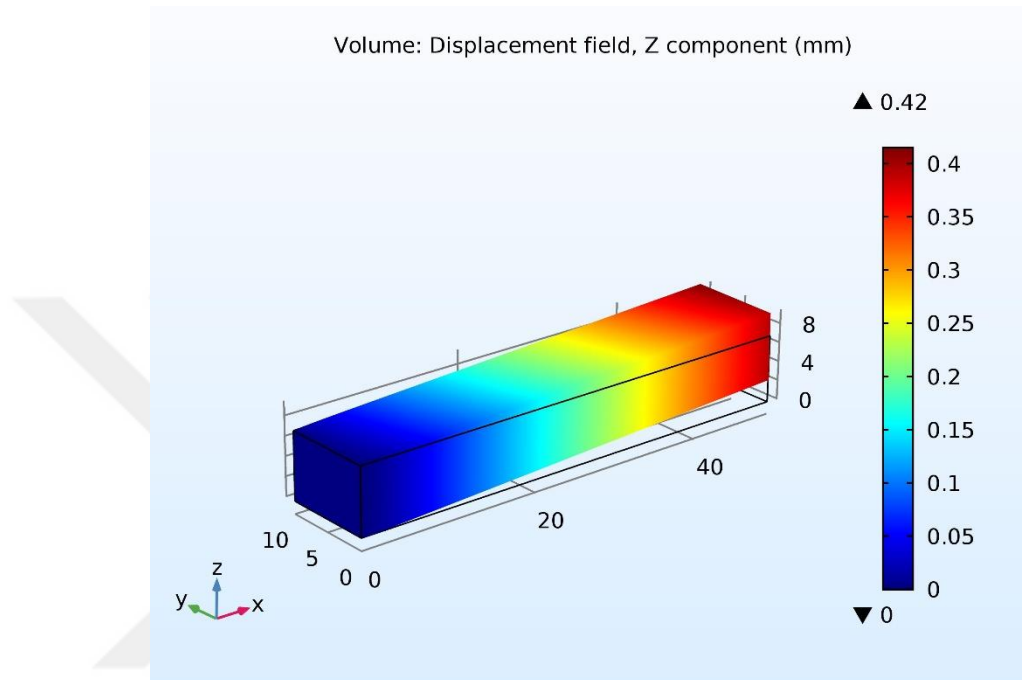


Figure 4-14- Distortion simulation result of part 0

As mentioned before, EOS M290 metal additive manufacturing machine is used for the experiments. The model geometry is manufactured twice times in order to check the repeatability. After detaching the manufactured parts from the base plate, the 2D curvatures of the parts are captured via CMM. The tip deflections for each sample are given in Table 4-7.

Table 4-7- The results of the experiments (tip deflections)

Exp1	0.432 mm
Exp2	0.438 mm

To test the performance of the developed analytical and FEM models, a much complex geometry shown in Figure 4-15, is selected for the second model validation. The process parameters and the dimension of the geometry are given in Table 4-4 and Table 4-8, respectively.

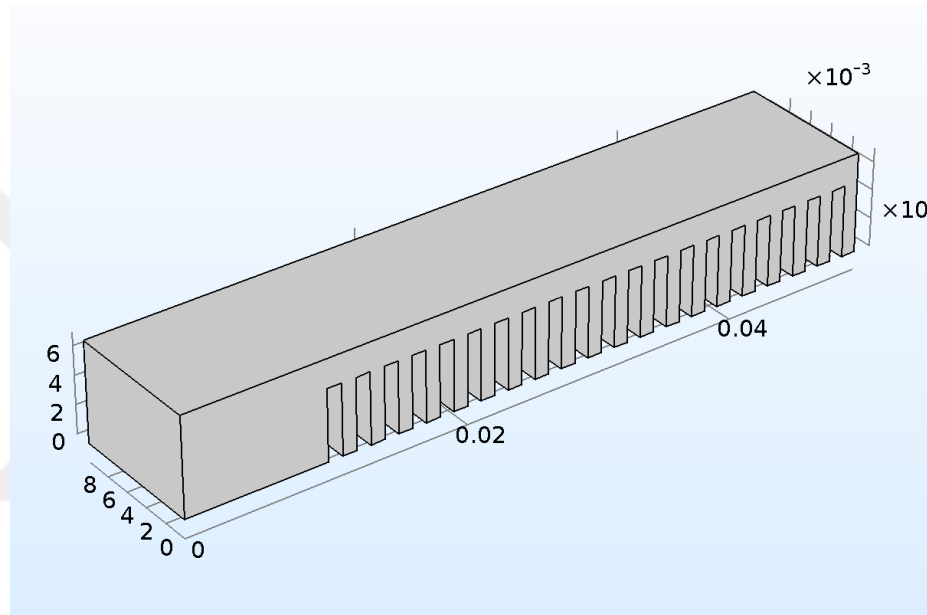


Figure 4-15- The geometry of part I

Table 4-8- The dimensions of part I

Width	10 mm
Length	50 mm
Height	7 mm
Tooth Width	1 mm
Tooth Height	5 mm

It should be noted that the analytical approach cannot simulate the geometrical details. In order to do that for part I, a form coefficient can be calculated for the same loading and boundary conditions using FEM. The equation (4-14) can be adjusted as follows,

$$\delta_{adjusted} = f \cdot \delta \quad (4-20)$$

where f is the form coefficient and is calculated as "4,12". The adjusted tip distortion is calculated as "1.479 mm". The residual stresses results of the analytical approach are shown in Figure 4-16.

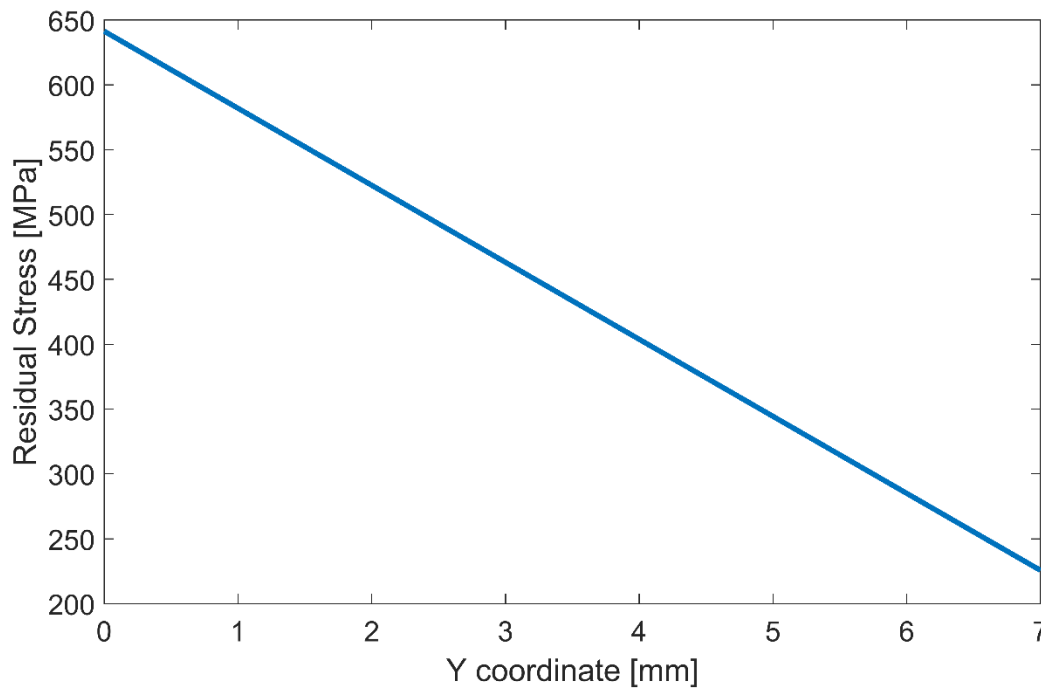


Figure 4-16- Simulated residual stress distribution of part I (Analytical approach)

The residual stress distribution using the developed FEM model, for the case that the part is still attached to the base plate, is shown in Figure 4-17.

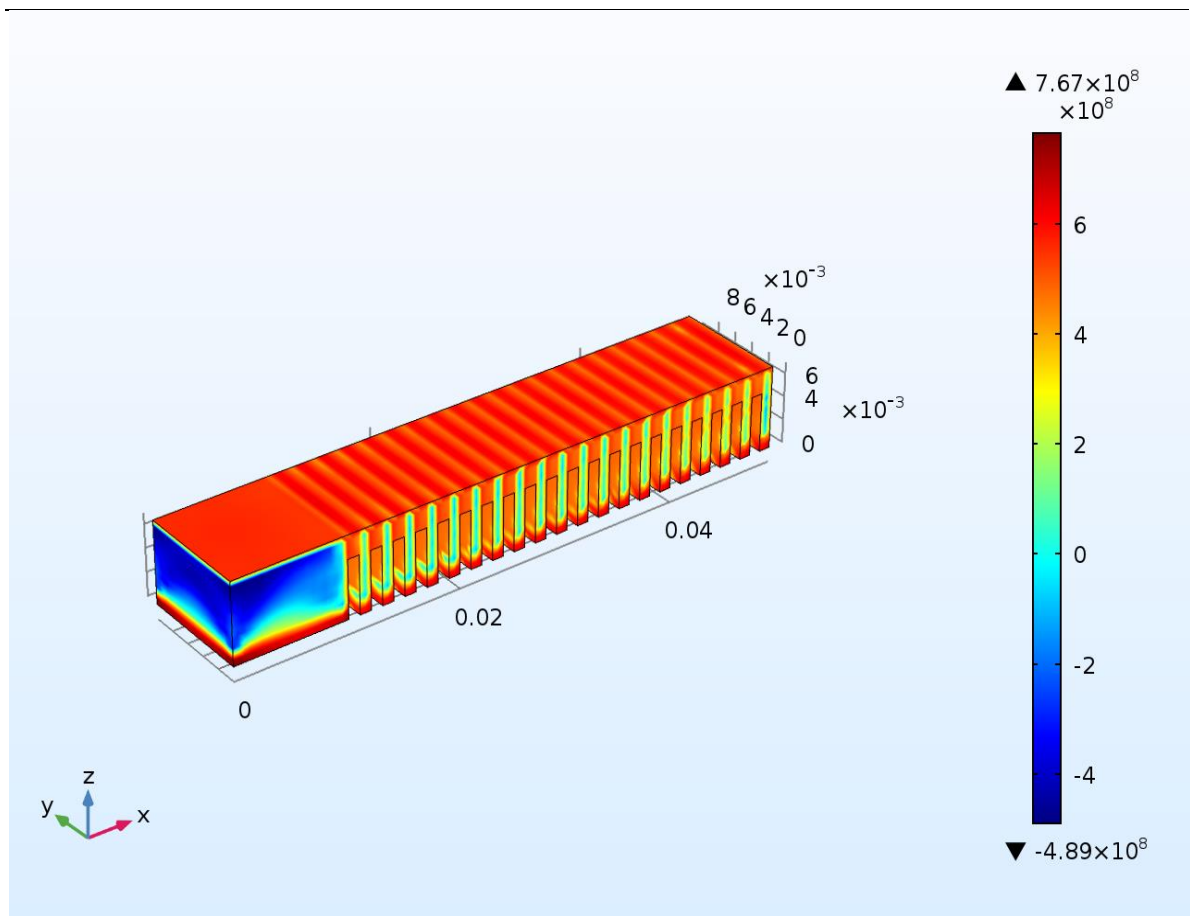


Figure 4-17- Simulated residual stress distribution of part I in [Pa] (FEM model)

It should be noted that the distortions occur after detaching the part from the base plate. Hence, for the case of detaching, the developed model calculates the distortions which may occur on the manufactured part due to the residual stresses. The simulated distortion results are given in Figure 4-18.

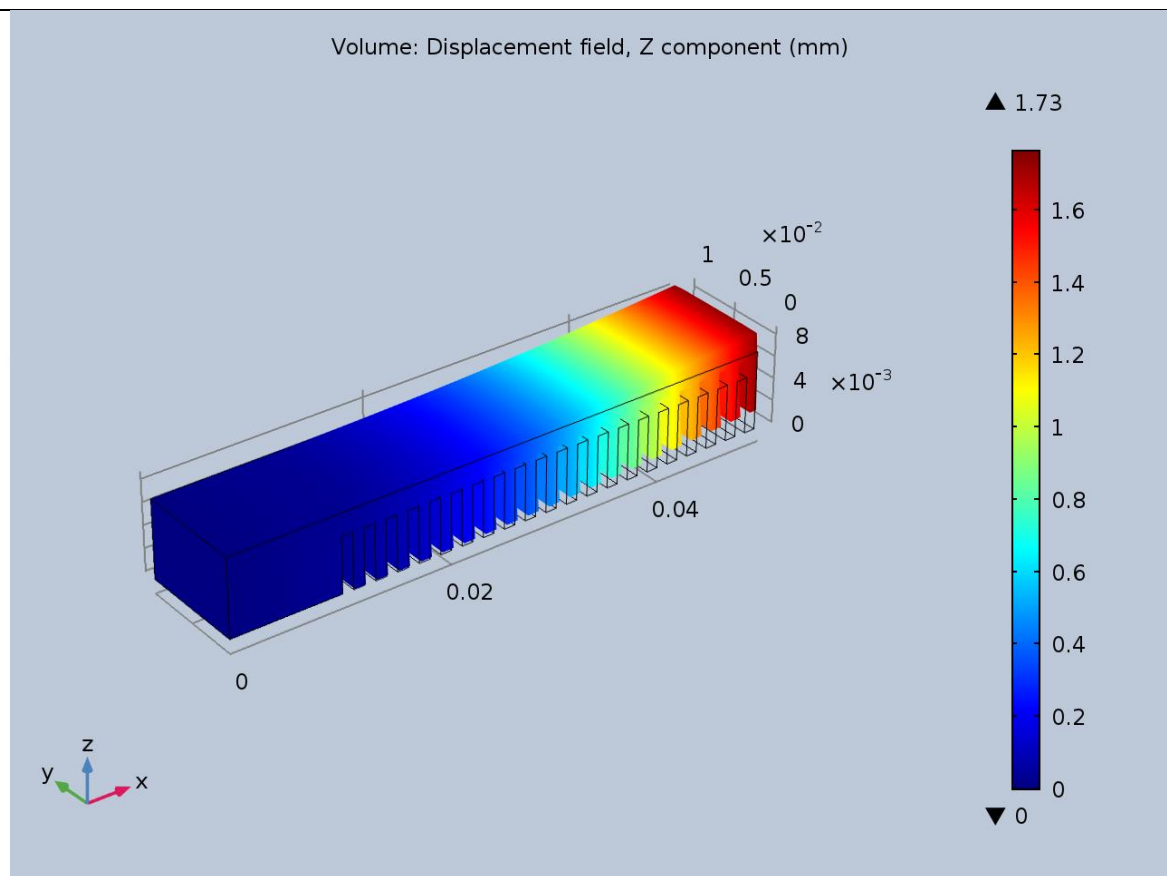


Figure 4-18- Distortion simulation result of part I (FEM model)

The model geometry is again manufactured twice in order to check the repeatability. After detaching the manufactured parts from the base plate, the 2D curvatures of the parts are again captured via CMM. In order to compare the models and the experimental results, they were transformed via a CAD software into 2D data points and plotted in MATLAB. Figure 4-19 and Figure 4-20 demonstrate the comparison between the FEM simulation and the experimental results.

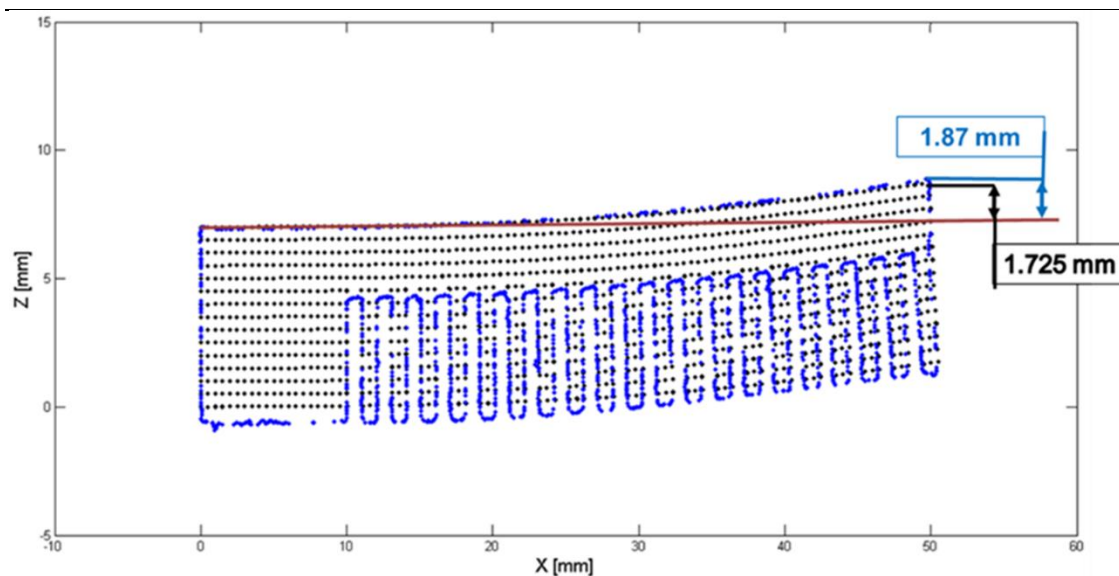


Figure 4-19- Displacement simulations (black points) and experimental measurements (blue points)

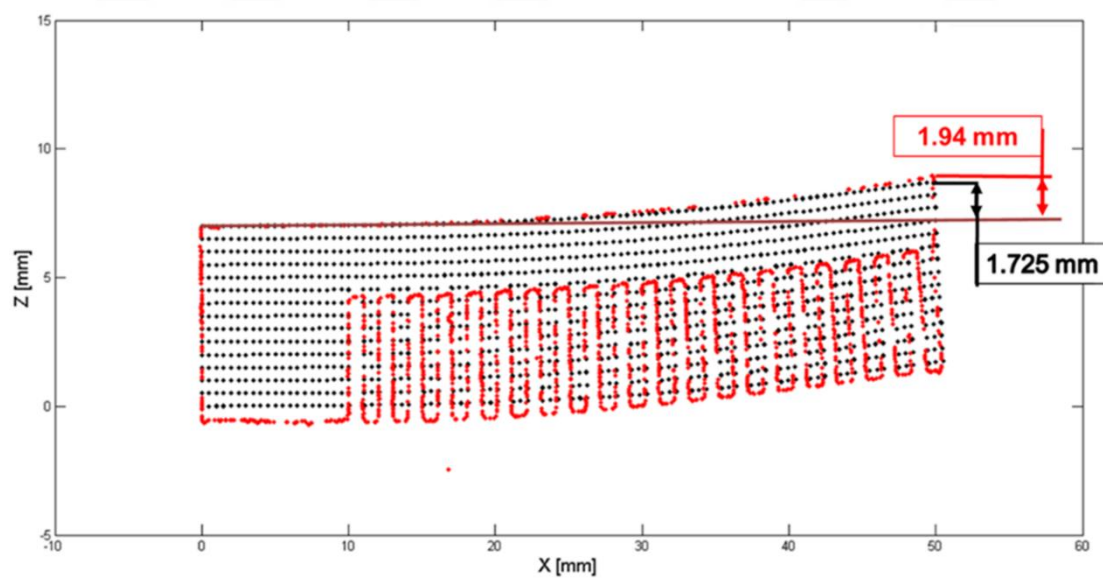


Figure 4-20- Displacement simulations (black points) and experimental measurements (red points)

In Table 4-9, the analytical approach, the developed FEM model and the experimental results are compared.

Table 4-9- The comparison of the analytical approach, FEM model and experimental results

Maximum Distortion Error (%)		Analytical Approach	FEM Model
Part 0	Experiment 1	16%	3%
	Experiment 2	18%	4%
Part I	Experiment 1	21%	6%
	Experiment 2	24%	9%

In order to check the performance of the developed FEM model, four different geometries (with the same process parameters given in Table 4-4) shown in Figure 4-21–Figure 4-22, were manufactured. It should be noted that a form coefficient cannot be calculated for such complex geometries. Thus, the analytical approach cannot be used. The dimensions of the geometries are given in Table 4-10. Simulation and experimental results are compared in Figure 4-23, Figure 4-24, Figure 4-25 and Figure 4-26.

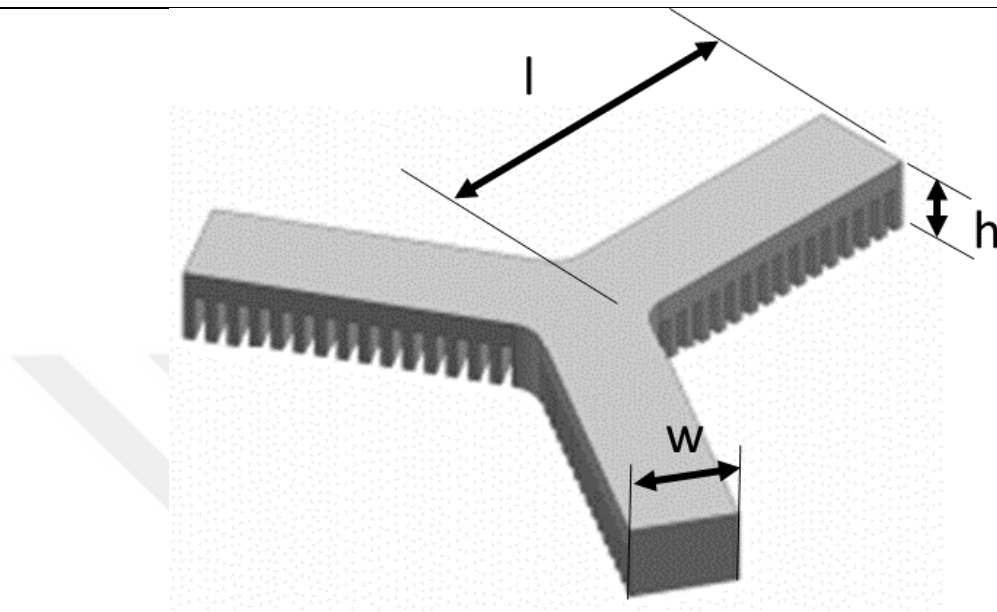


Figure 4-21- The geometry of Part II

Table 4-10- The dimensions of part II

h	7 mm
w	10 mm
l	30 mm
Tooth Height	5 mm
Tooth Length	1 mm

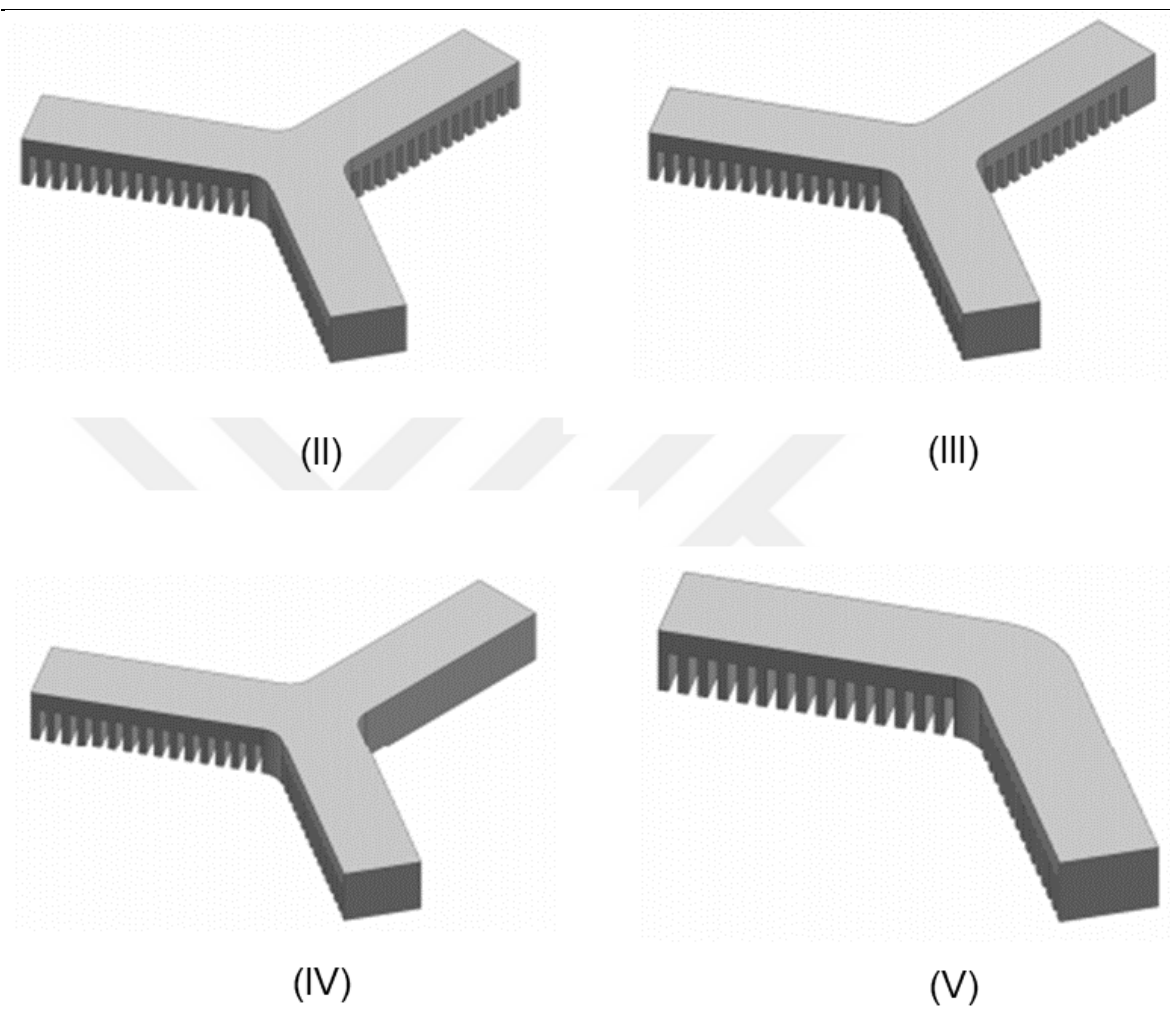


Figure 4-22- New sample geometries: Part II, part III, part IV and part V

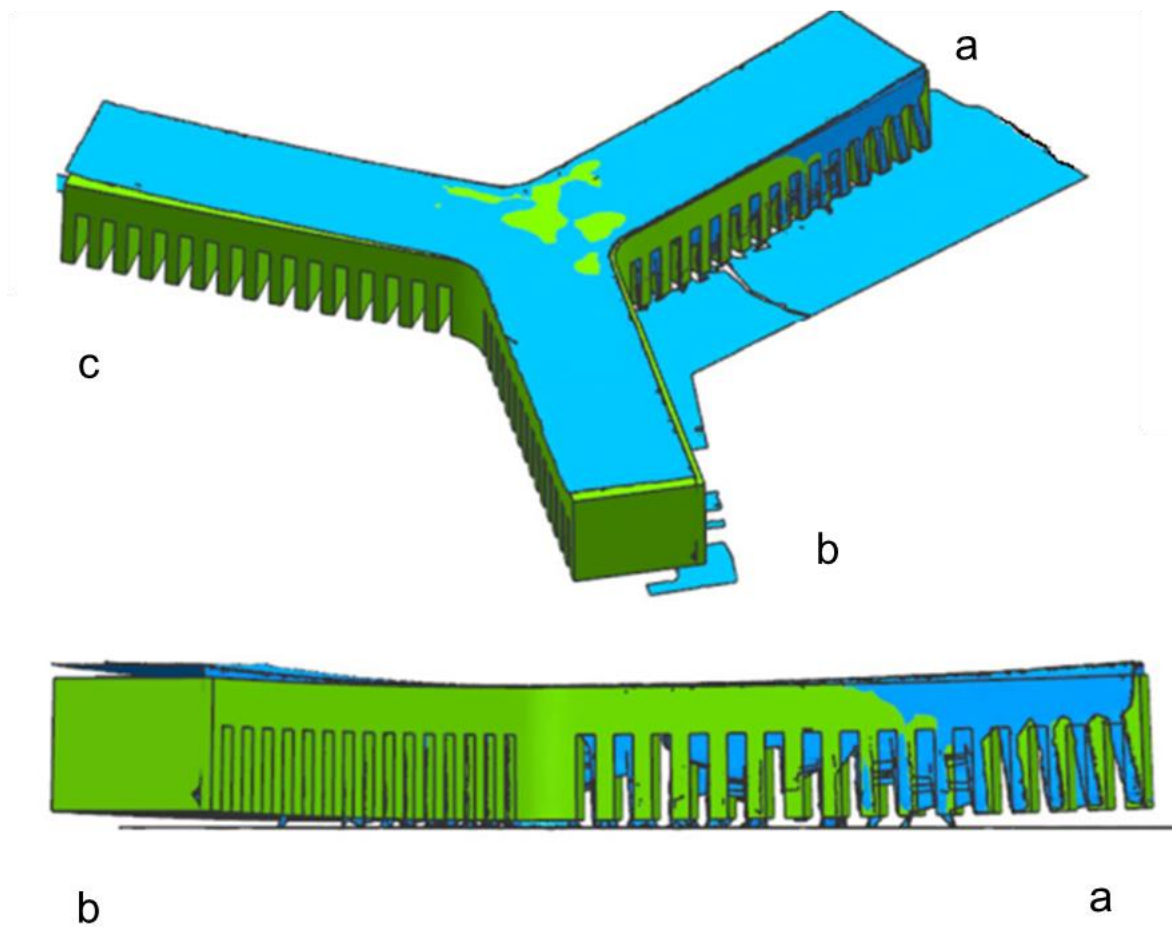


Figure 4-23- Isometric view (top) and front view (bottom) of part II
(Green: simulation, blue: experiment)

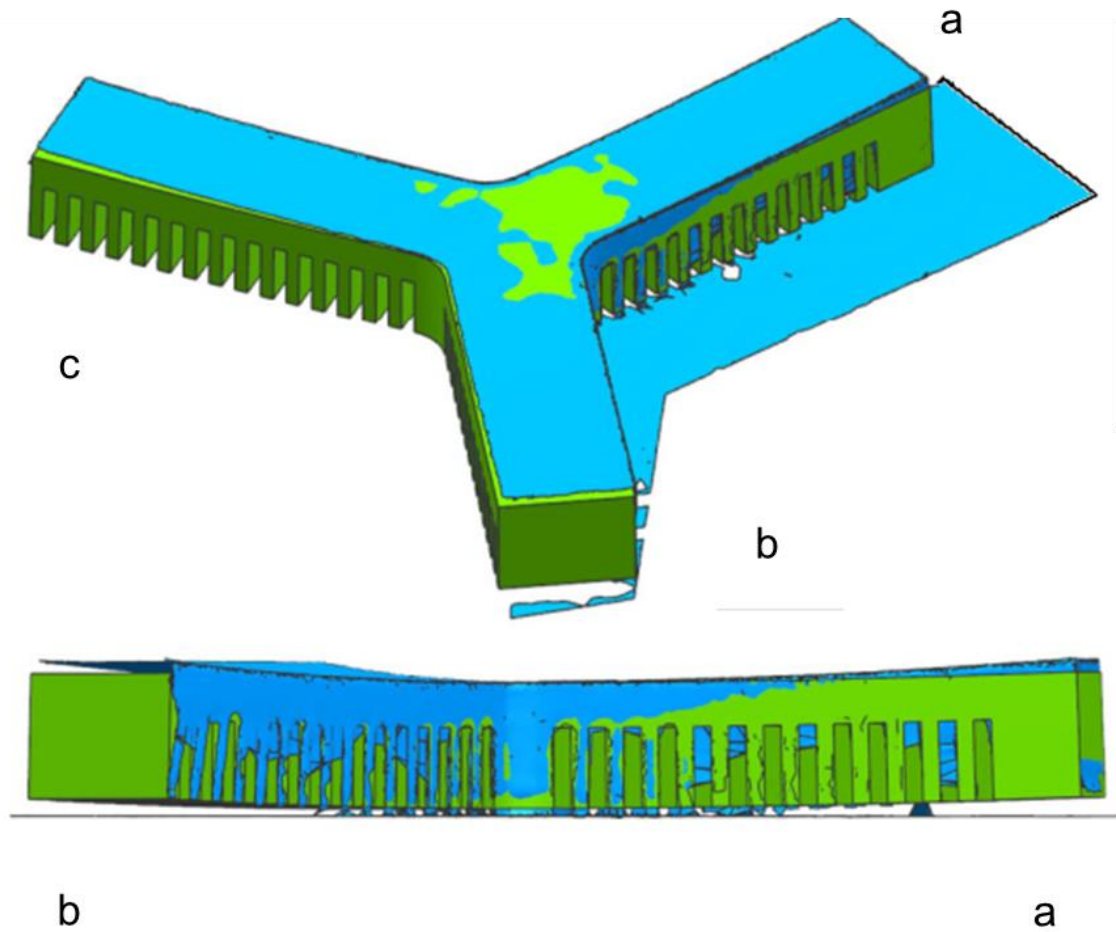


Figure 4-24- Isometric view (top) and front view (bottom) of part III

(Green: simulation, blue: experiment)

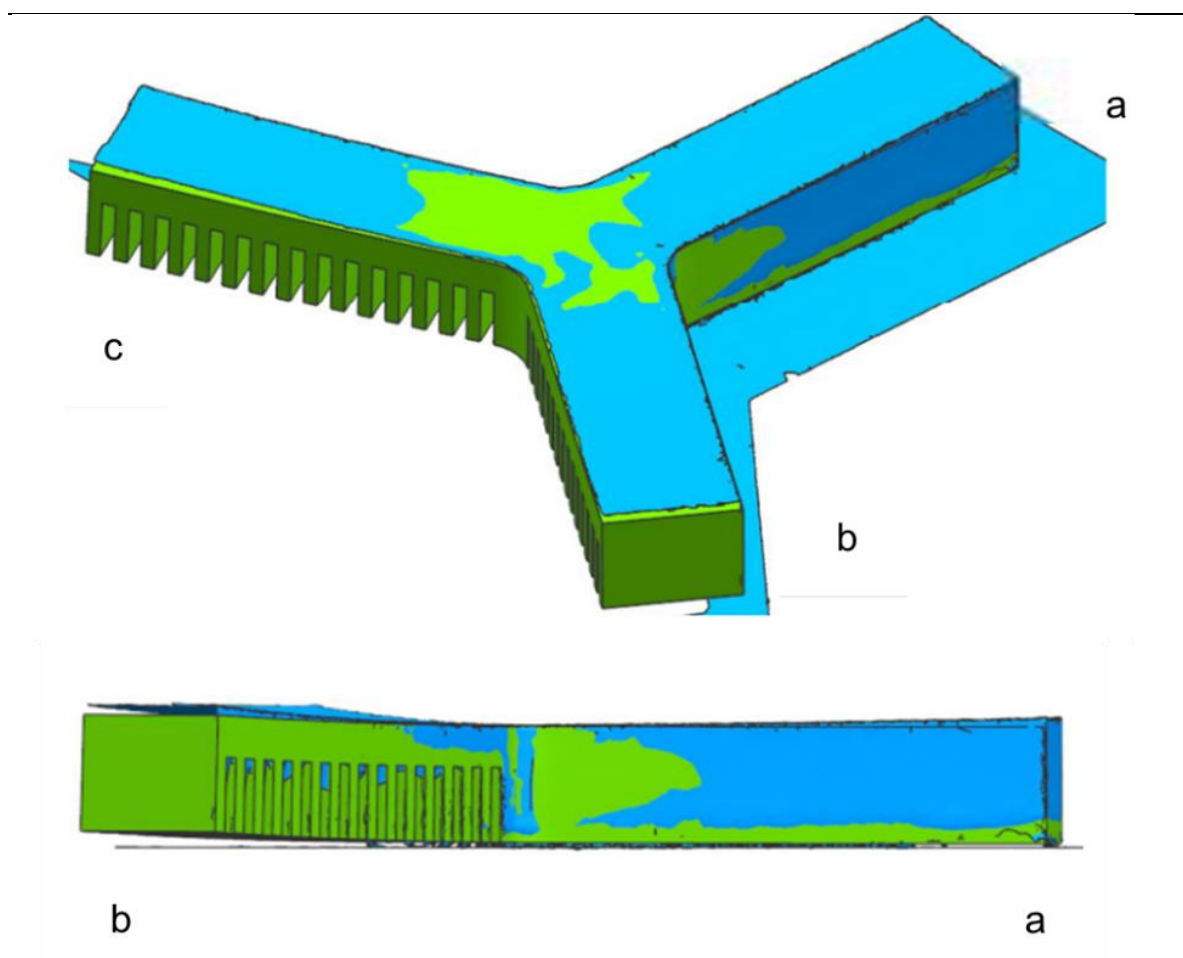


Figure 4-25- Isometric view (top) and front view (bottom) of part IV
(Green: simulation, blue: experiment)

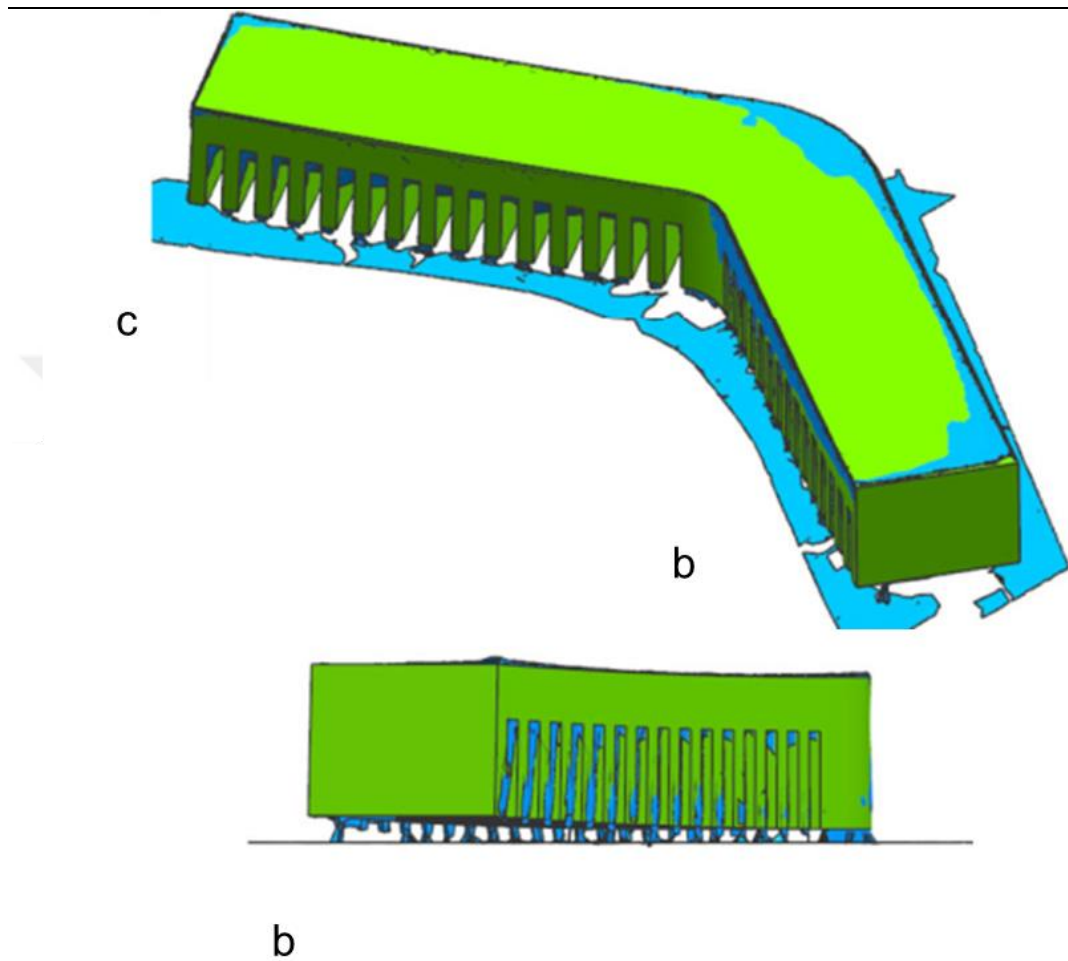


Figure 4-26- Isometric view (top) and front view (bottom) of part V

(Green: simulation, blue: experiment)

In Figure 4-23, Figure 4-24, Figure 4-25 and Figure 4-26, there are marked points on the geometries depicted as a, b and c. In Table 4-11, for each marked point, both simulation and experimental maximum height values are listed and compared. (The point II-a means the point “a” on part II.)

Table 4-11- Comparison of maximum height for selected points:

Simulation results and experimental measurements

Measurement Point	% of the difference between simulation and experiment
II-a	5.2
II-b	5.8
II-c	4.9
III-a	6.4
III-b	6.3
III-c	6.7
IV-a	5.4
IV-b	5.3
IV-c	5.2
V-b	0.2
V-c	1.8

4.8 Discussion

For part 0 (Figure 4-13), the analytical and FEM models are solved. Both models predicted the distortions in the acceptable range. For part I (Figure 4-15), a much more complex geometry than part 0, a form coefficient was used in the analytical approach in order to simulate the geometrical difference between part 0 and part I. Even though, the distortion results of both models are in the acceptable range, the developed FEM model is better at predicting the distortions compared to the analytical model. For the third comparison, four different geometries were used to test the developed FEM model. From Figure 4-23, Figure 4-24, Figure 4-25 and Figure 4-26, it is seen that the simulation and experimental distortions agree with each other with an overall error of 5%.

Table 4-11, it should be noted that for the part II, III and IV, the support structure increased the actual height of geometry about an average of 0.5 mm and that is the reason for the difference in maximum height between the simulation and experimental results. The results of part V, are similar to each other. The reason for this is the symmetry of the part and residual stresses occurring in both arms are canceling each other out. In addition to this, there is not a third arm to unbalance the stress distribution in the part.

In order to make a comparison in terms of computation time, the thermal model [93] and the developed FEM model were used to solve the geometry of part I in a coupled way. On a workstation with the specification of 32 GB memory RAM and 8 processor with 3.33 GHz, the first layer of the coupled model was solved in approximately 117 hours. With a 40 μm layer thickness, the simulation of the entire part will take an impractical amount of time. However, using the uncoupled solution method, the FEM model for the given geometries and their corresponding simulations shared in this article, were solved for the entirety of the parts in between 30 minutes and 2.5 hours. Hence, it can be said that by uncoupling the thermal and the mechanical solution, a great deal of computation time can be saved and this will make this type of prediction tool suitable for industrial practices.

4.9 Summary

In this chapter, mechanical modeling of the direct laser metal sintering has been explored by investigating the thermal expansion, plasticity and hardening effects on the additive manufacturing process. An analytical approach and a FEM-based mechanical model have been introduced to predict the residual stresses and distortions. In order to increase the prediction speed, thermal and mechanical models were detached from each other and solved separately. For the model validation, two different sets of experiments were carried out. In the first set, both models predicted the distortion accurately. In the second set, using a form coefficient in the analytical approach, both approaches predicted the distortion in the acceptable range. However, the prediction error of the analytical approach (21-24%) was more than the prediction error of the FEM model (6-9%). In the third set of experiments, (where four different geometries were used), the simulation distortions were compared with the experimental measurements. The trend of the distortions obtained from the developed model was agreed with the experimental results (5% error). In addition to the model validation, a comparison was made in terms of computation time between coupled and uncoupled version of the mechanical model. It is seen that the uncoupled version of the developed model saves a great deal of computation time. This work introduces an analytical approach for simple geometries and a fast FEM based residual stress and distortion prediction tool that allows modeling of the large-scale complex parts in direct laser metal sintering.

Chapter 5

APPLICATION OF THE THERMO-MECHANICAL MODEL ON FREEFORM AND HOLLOW STRUCTURES

5.1 Overview

A review of the literature concludes that there is a need for a thermo-mechanical model for the prediction of the residual stresses and distortions of the freeform and/or hollow structures. In this study, a set of new experiments are carried out in order to test the performance of the developed model for freeform and hollow geometries.

5.2 Experimental Setup

The experiments carried out for this study contain two stages of measurement. First, distortions of the parts were measured before the separation from the base plate. Then, the parts and the base plate were separated by using wire EDM (Electro discharge machining). Then, distortions of the parts were measured again. For both measurements, COMET 6 – high end 3D sensor was used with FOV80 microlenses. The resolution of the device (with the lenses) is 8-10 μm . For the additive manufacturing, the same machine, EOS M290, mentioned in Chapter 4, was used with the same material powder (Table 4-3) and the process parameters are given in Table 4-4. The dimension of the base plate is 252 mm X 252 mm X 36 mm.

The CAD data, used in the experiment, is shown in Figure 5-1. The chosen scanning strategy is parallel tracking to the X-axis (See the coordinate frame in Figure 5-1).

During the additive manufacturing process of the parts, an issue was encountered in the rectangle parts R1-R4 (See Figure 5-2). The coater blade was hitting the walls (along with the Y-axis) of the rectangles causing bending on the wall. The developed thermo-mechanical

model cannot simulate this effect. Therefore, the measurement of the rectangle parts will not be compared with the simulation results.

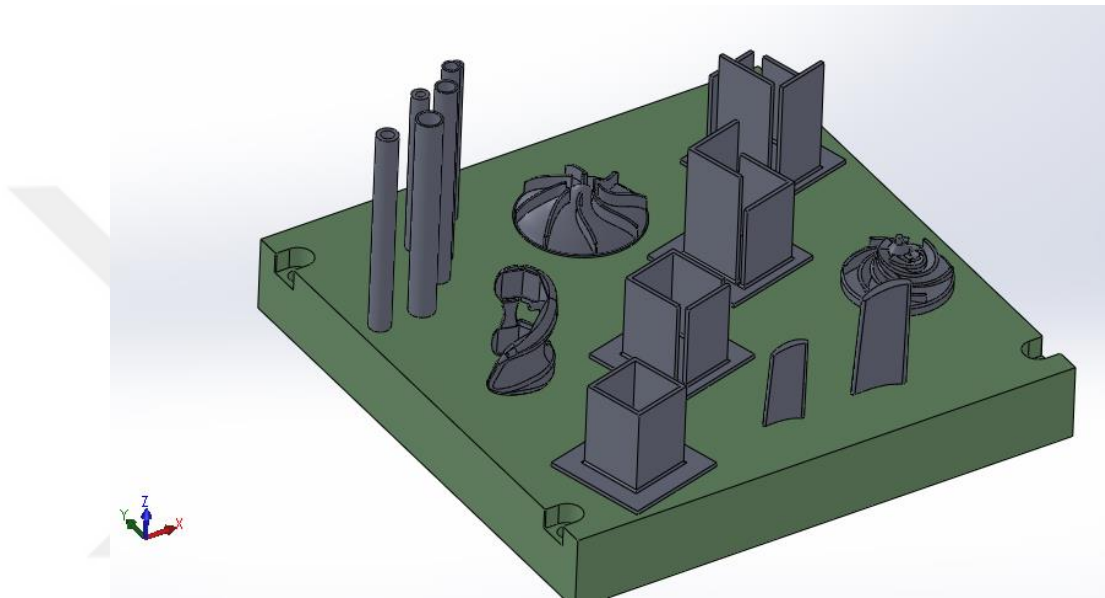


Figure 5-1- Part geometries and the base plate

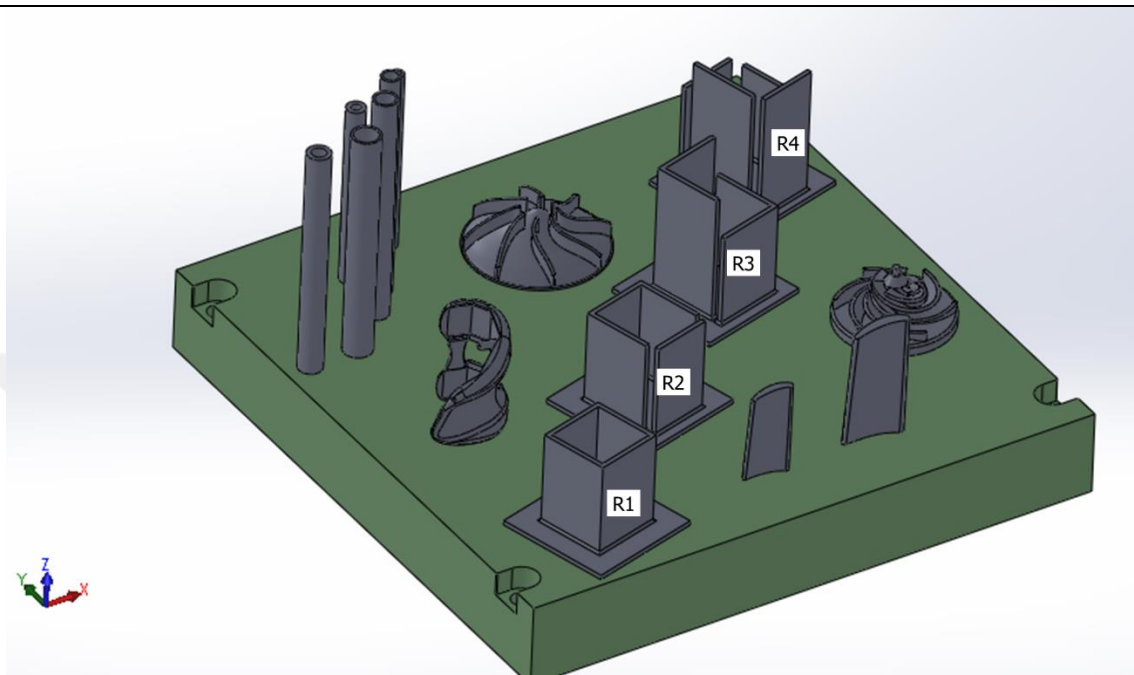


Figure 5-2 – Rectangle parts labeling

5.3 Simulation – Experimental – CAD Comparison: Stage I

As explained in Chapter 4, the developed model was prepared according to the material properties, process parameters and scanning strategy defined for the experiment. The model was used for each part and the distortion results were obtained. For further references, a list of the parts and their corresponding labels are given in Table 5-1. It should be noted that the names of the pipes are given in format “Pipe-X-Y-Z” where X, Y and Z means respectively the diameter of the pipe, the thickness of the pipe and the length of the pipe.

Table 5-1- List of the parts and part labels

Part Name	Part Label
Impeller	F1
Impeller_5Axis	F2
Fan Blade	F3
Knee Implant	F4
Pipe-6-2-60	P1
Pipe-8-2-80	P2
Pipe-6-1-80	P3
Pipe-8-1-100	P4
Pipe-10-1-100	P5
Pipe-10-2-100	P6
Pipe-12-1-100	P7

5.3.1 Simulation Results: Stage I

The simulation results for Stage I are given in the list order given in Table 5-1. It should be noted that Stage I is the case before the separation of the parts from the base plate. The distortion results of the developed model are shown in Figure 5-3 to Figure 5-13.

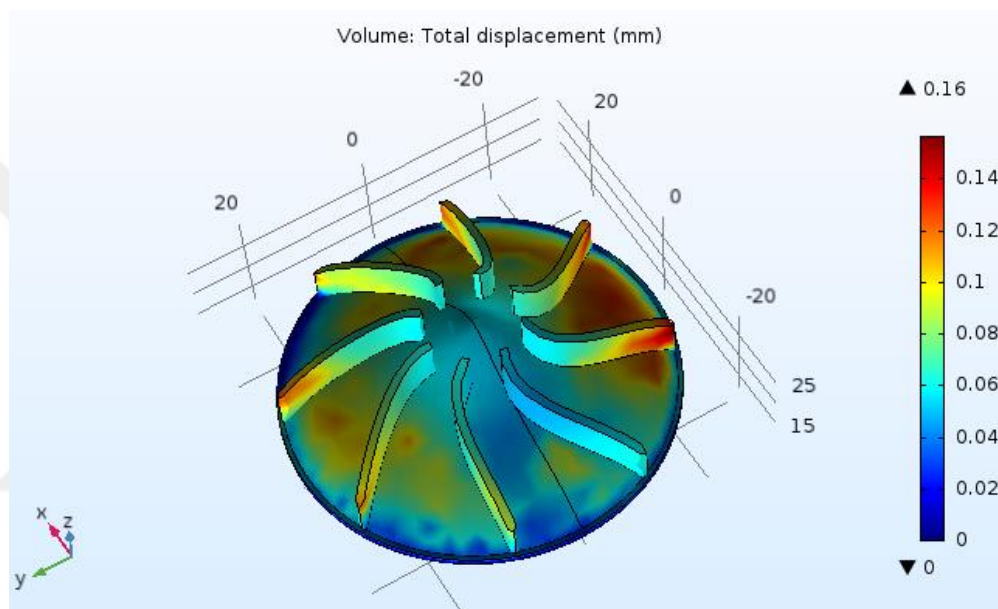


Figure 5-3- F1, Simulation Results (Stage I)

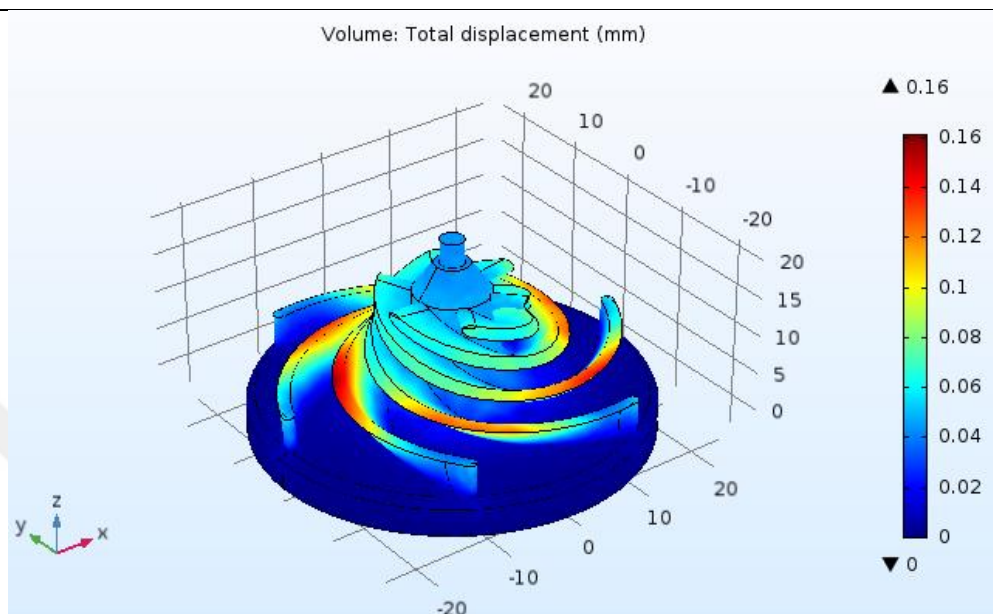


Figure 5-4- F2, Simulation Results (Stage I)

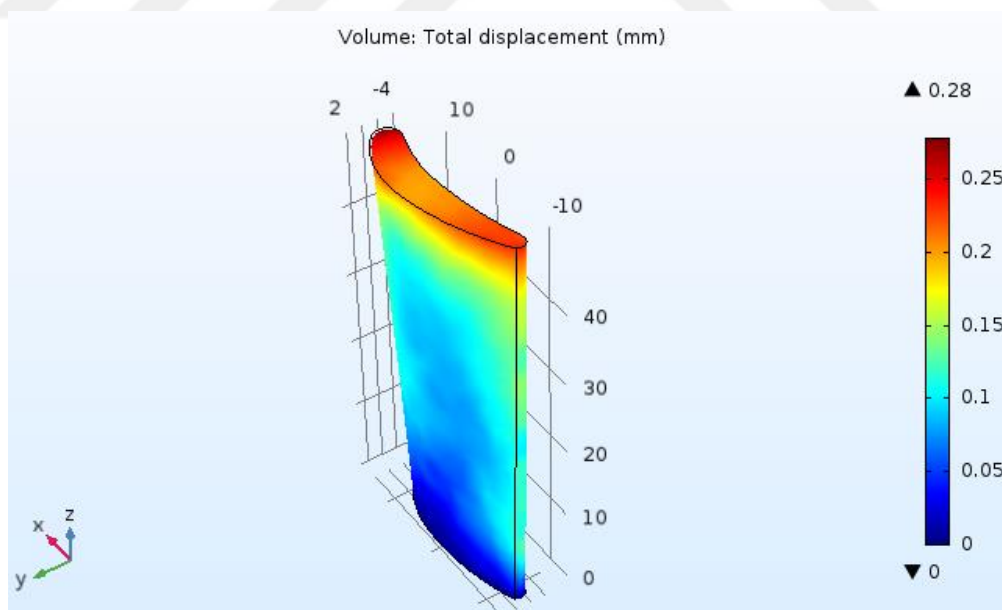


Figure 5-5- F3, Simulation Results (Stage I)

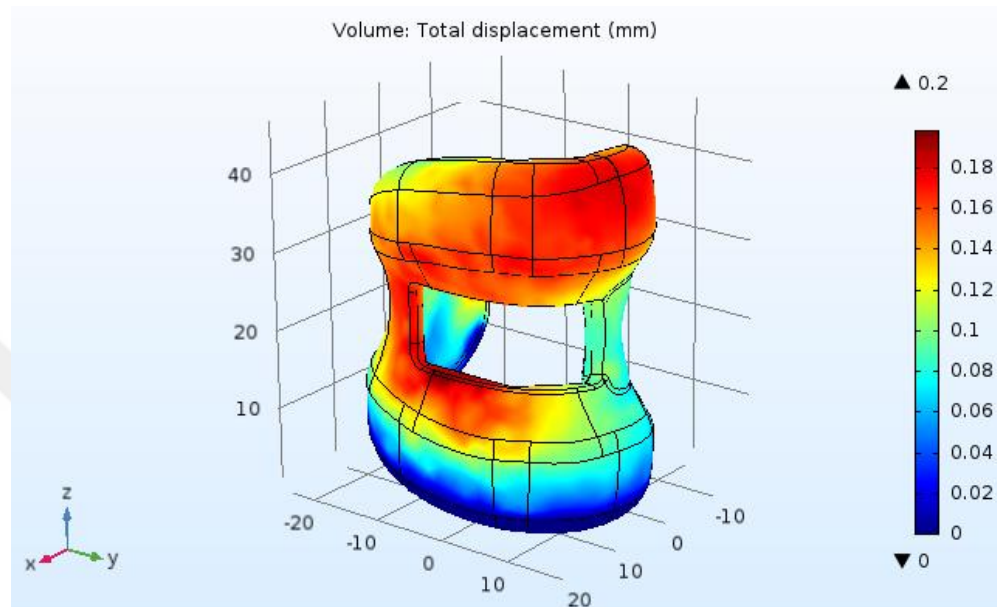


Figure 5-6- F4, Simulation Results (Stage I)

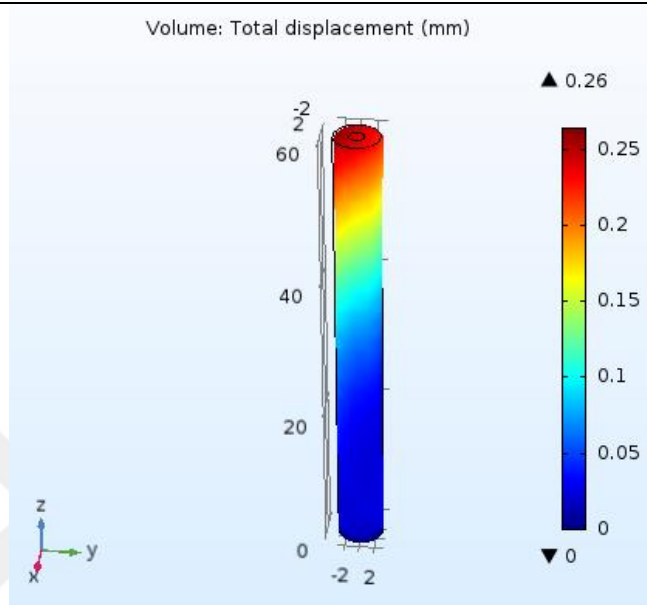


Figure 5-7- P1, Simulation Results (Stage I)

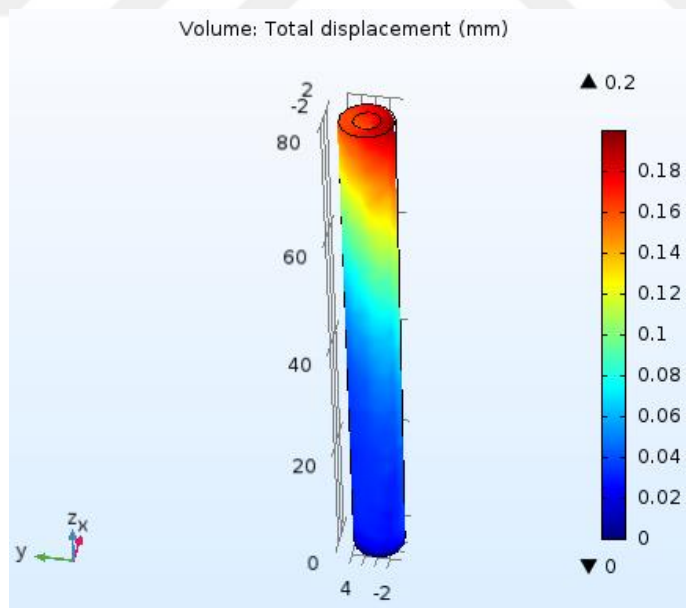


Figure 5-8- P2, Simulation Results (Stage I)

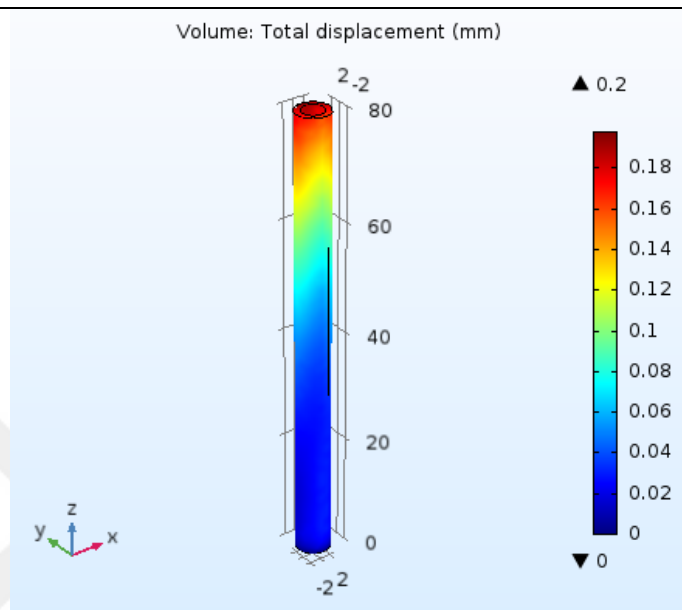


Figure 5-9- P3, Simulation Results (Stage I)

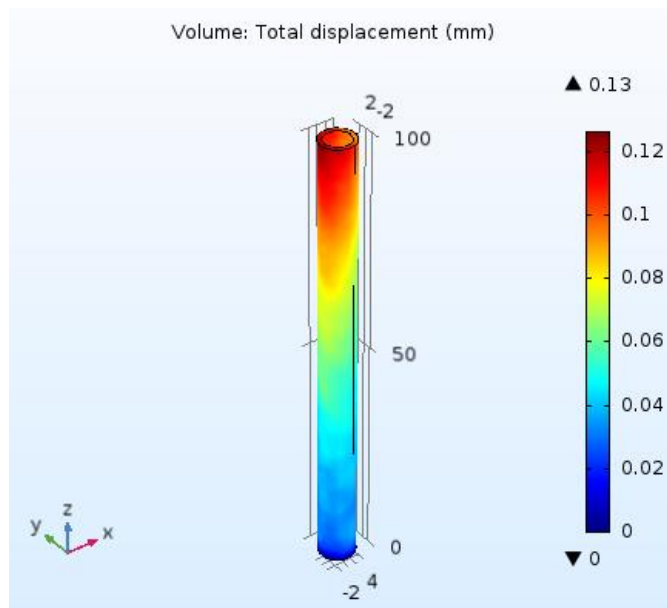


Figure 5-10- P4, Simulation Results (Stage I)

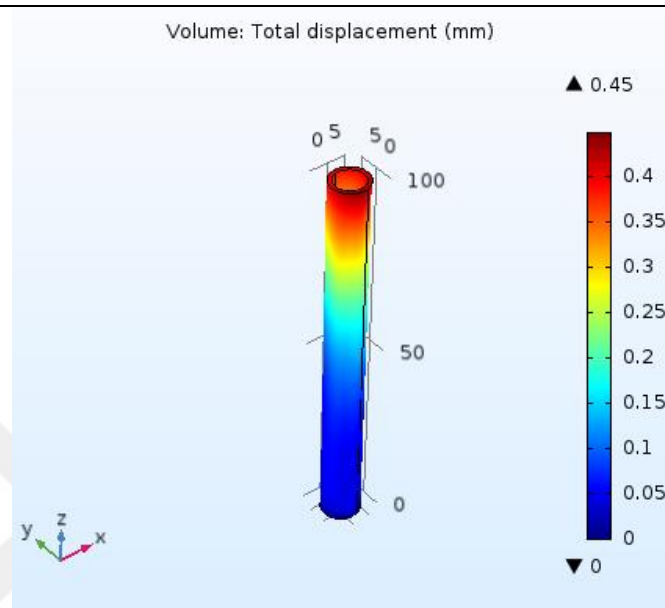


Figure 5-11- P5, Simulation Results (Stage I)

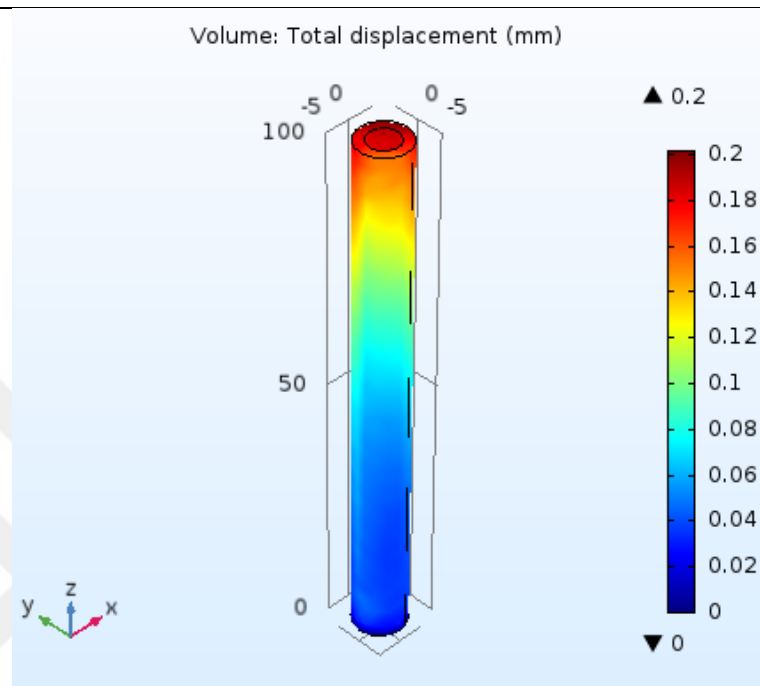


Figure 5-12- P6, Simulation Results (Stage I)

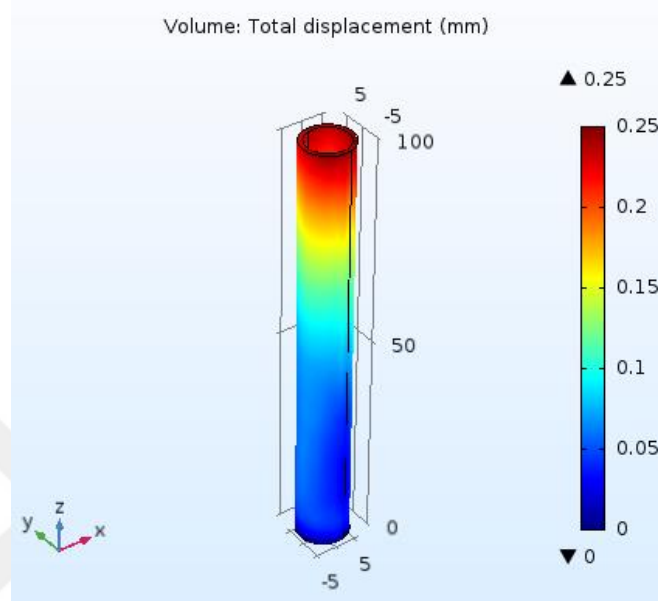


Figure 5-13- P7, Simulation Results (Stage I)

5.3.2 Experimental Results: Stage I

Optical scanning was performed using Comet 6 -16MP. Figure 5-14 shows the manufactured parts. The scan results of the parts are given in Figure 5-15.



Figure 5-14- Parts manufactured via EOS M290 additive manufacturing machine

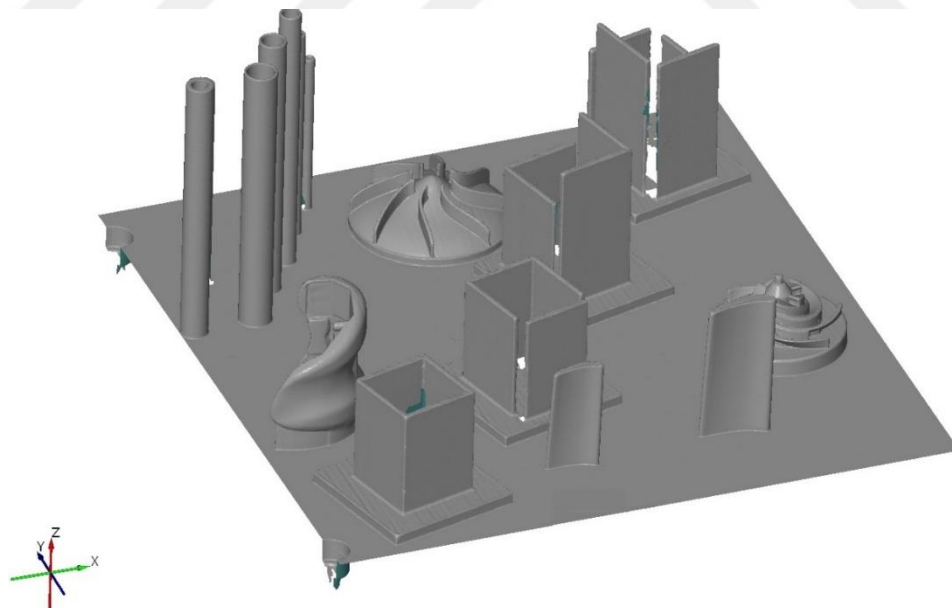


Figure 5-15- Measurements of the parts (Stage I)

5.3.3 Comparison: Stage I

In order to compare the simulation and experimental results, experimental, simulation and CAD data were brought to the Siemens NX. The point of this technique is to align experimental, simulation and CAD data before comparison. After aligning them, they were brought to Matlab environment to enhance the comparison. This was needed due to the fact that, the distortions in Stage I are smaller compared to those obtained from Stage II.

XY, XZ and YZ cut – planes are taken from the simulation, measurement and CAD data. These cross sections are used to accomplish the simulation, experiment and CAD comparison. The comparisons results are shown in Figure 5-16 to Figure 5-37. It should be noted that sets of surface points for each results (CAD, experiment and simulation) were compared. The simulation and experimental results for each point and part are given in Table 5-2 to Table 5-12. The average prediction errors are also given in Table 5-13.

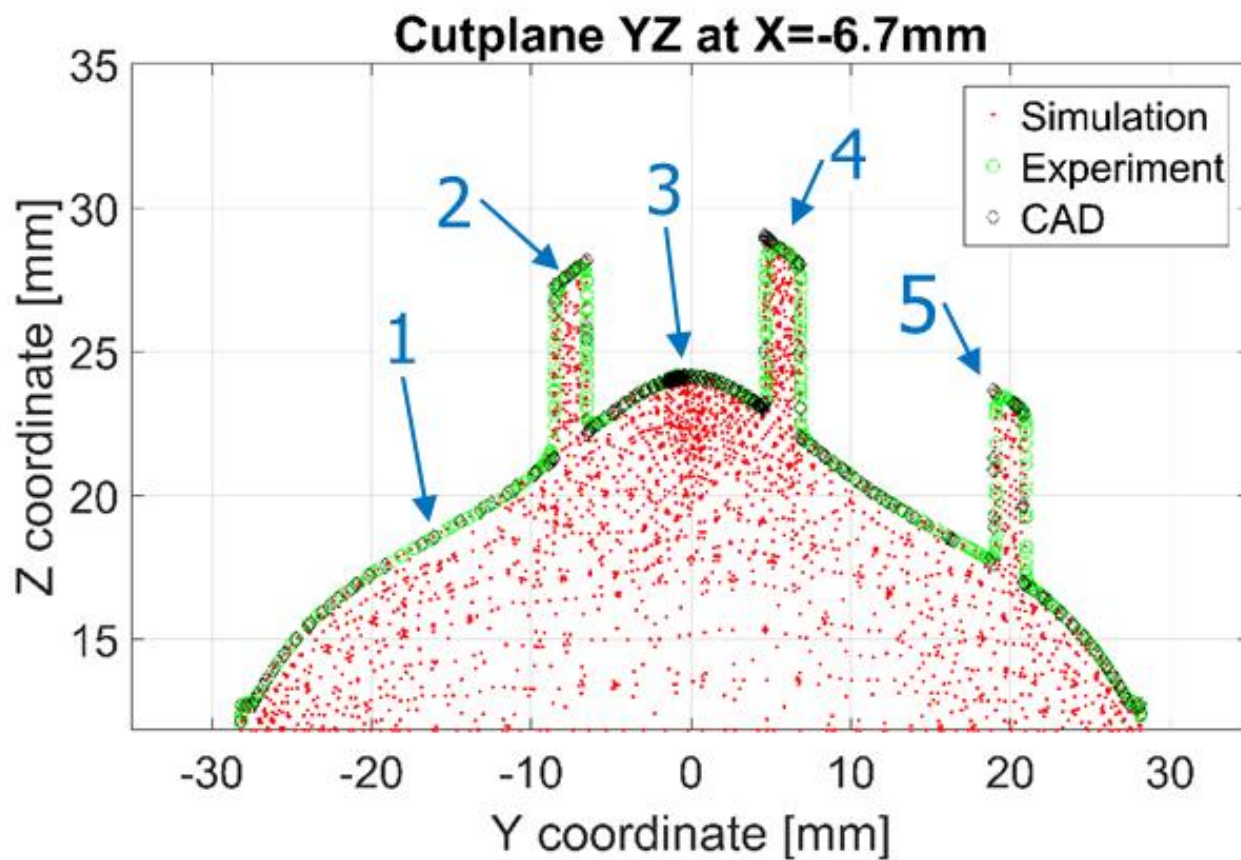


Figure 5-16- F1, Comparison of CAD, simulation and experimental results

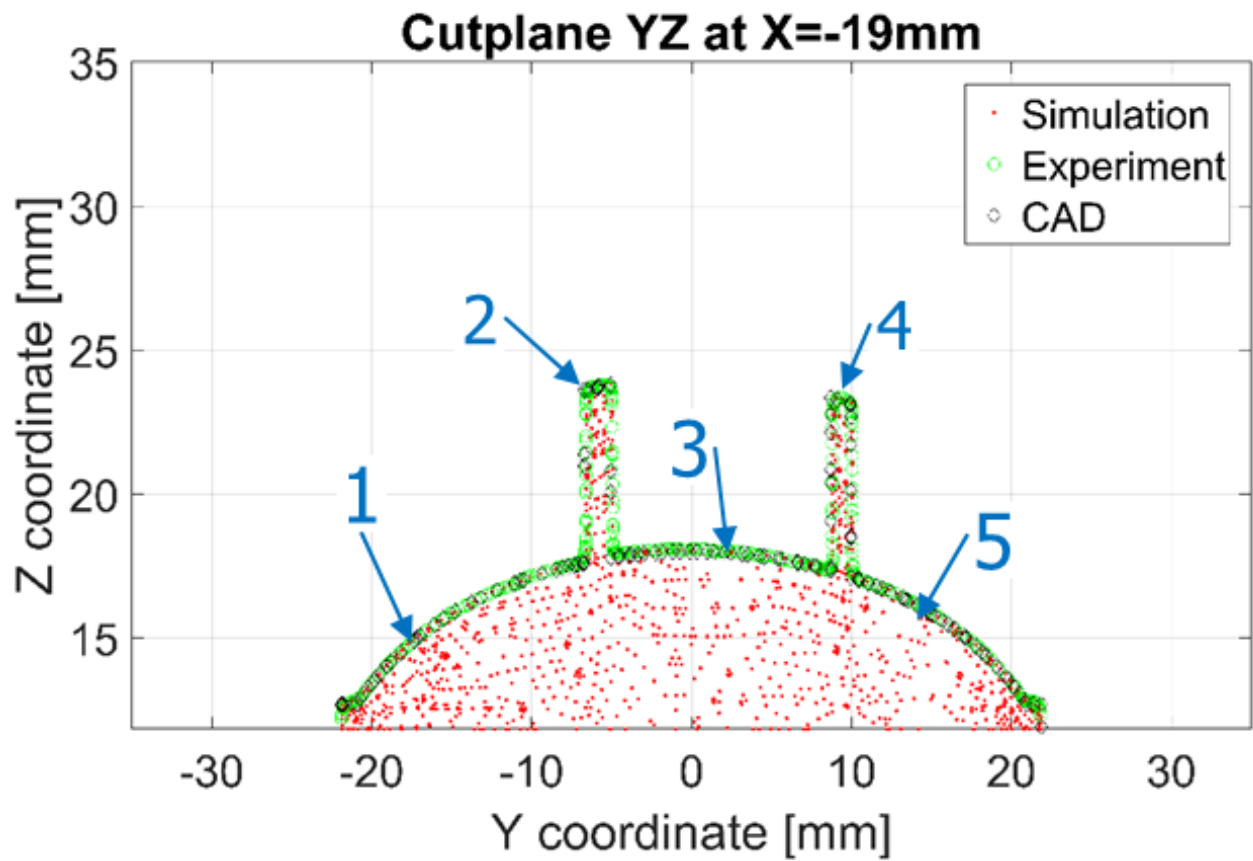


Figure 5-17- F1, Comparison of CAD, simulation and experimental results

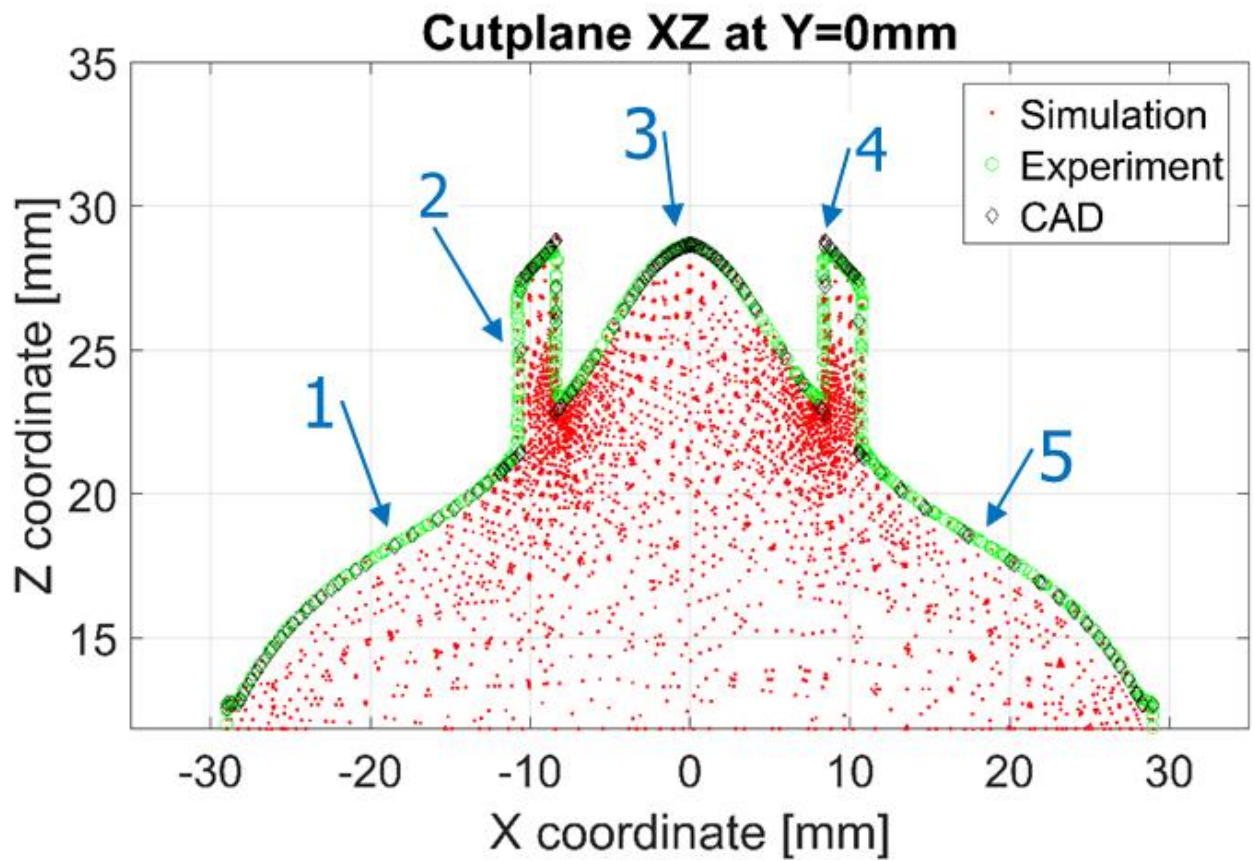


Figure 5-18- F1, Comparison of CAD, simulation and experimental results

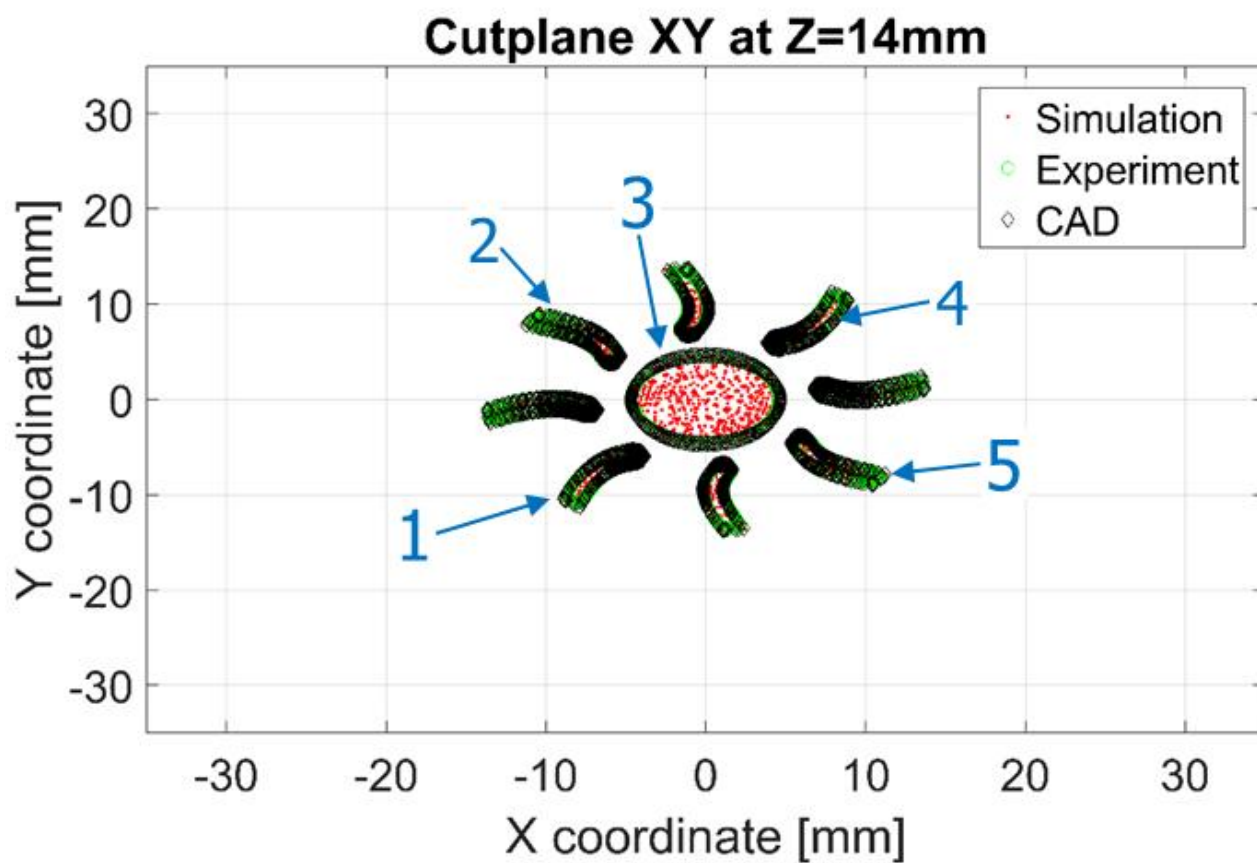


Figure 5-19- F1, Comparison of CAD, simulation and experimental results

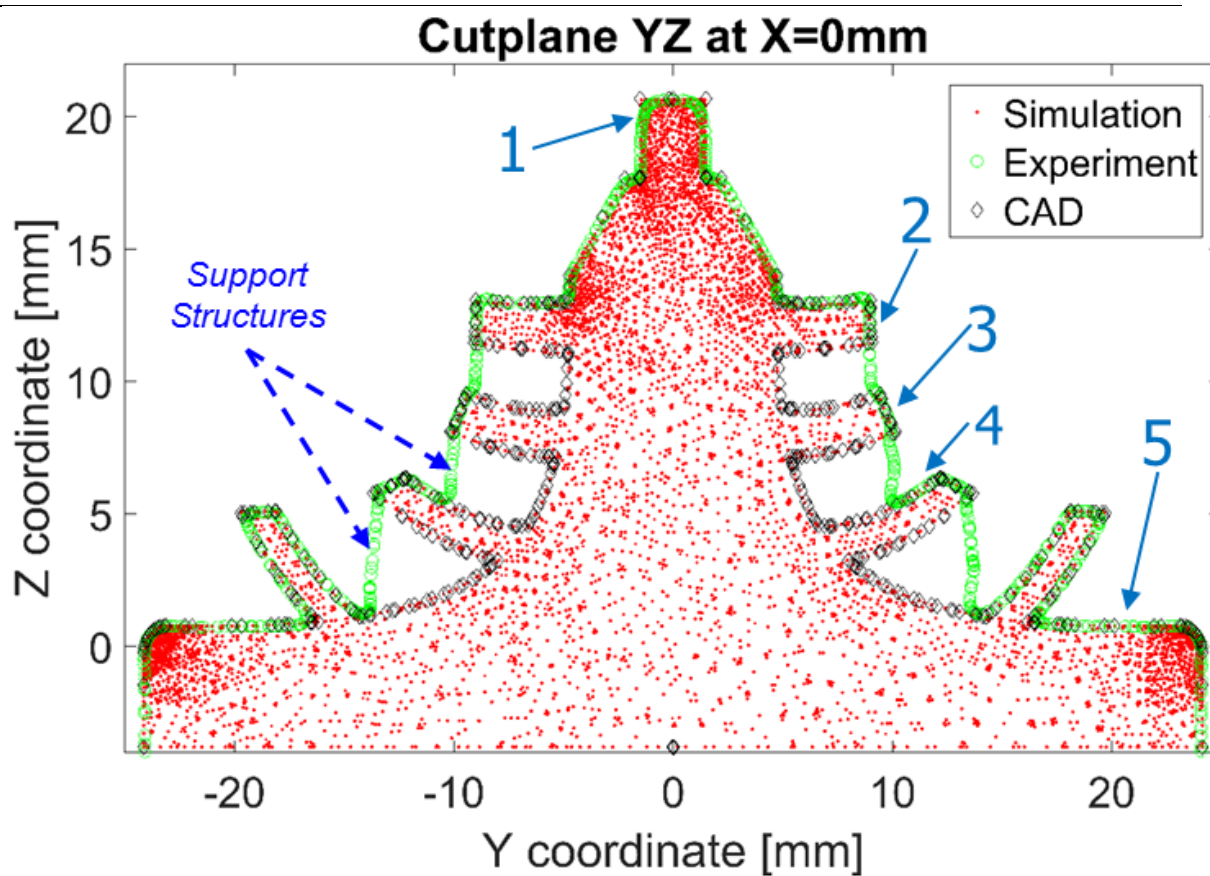


Figure 5-20- F2, Comparison of CAD, simulation and experimental results

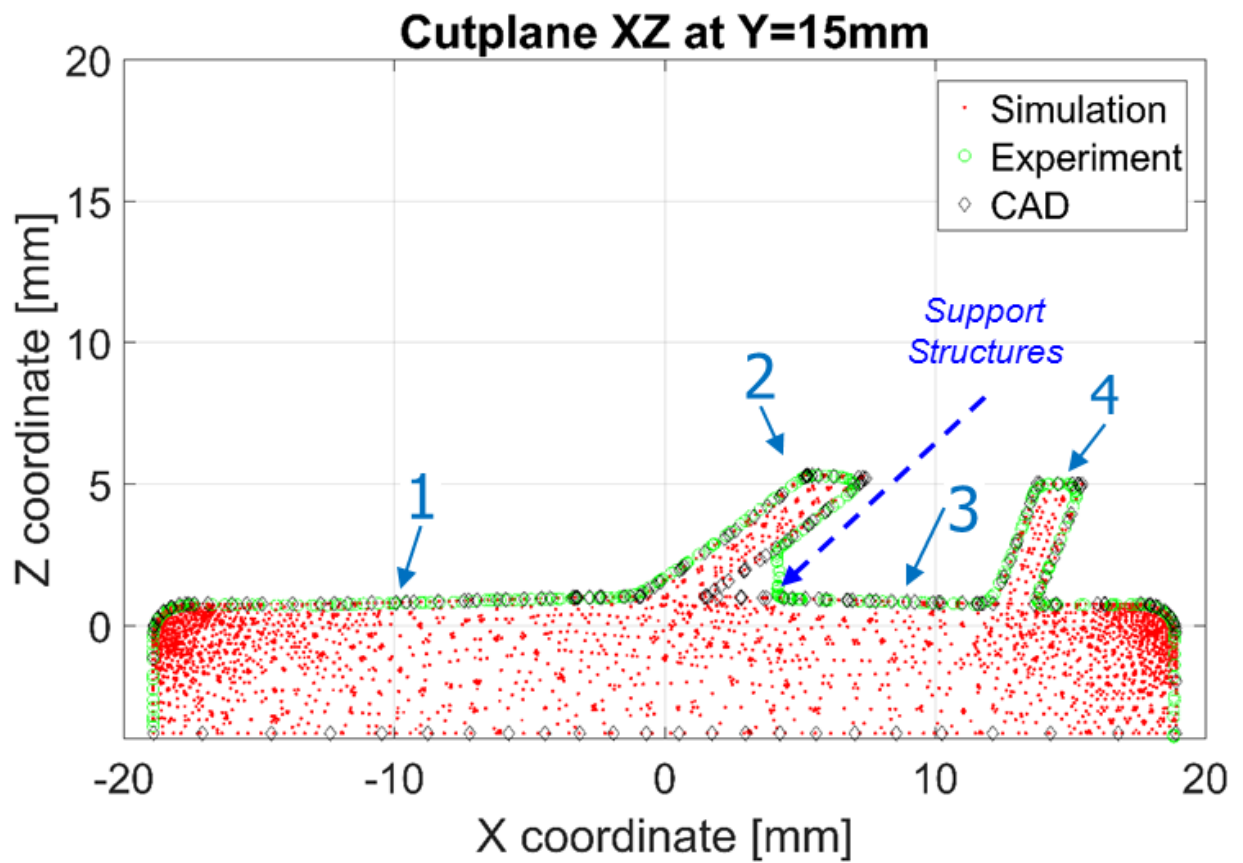


Figure 5-21- F2, Comparison of CAD, simulation and experimental results

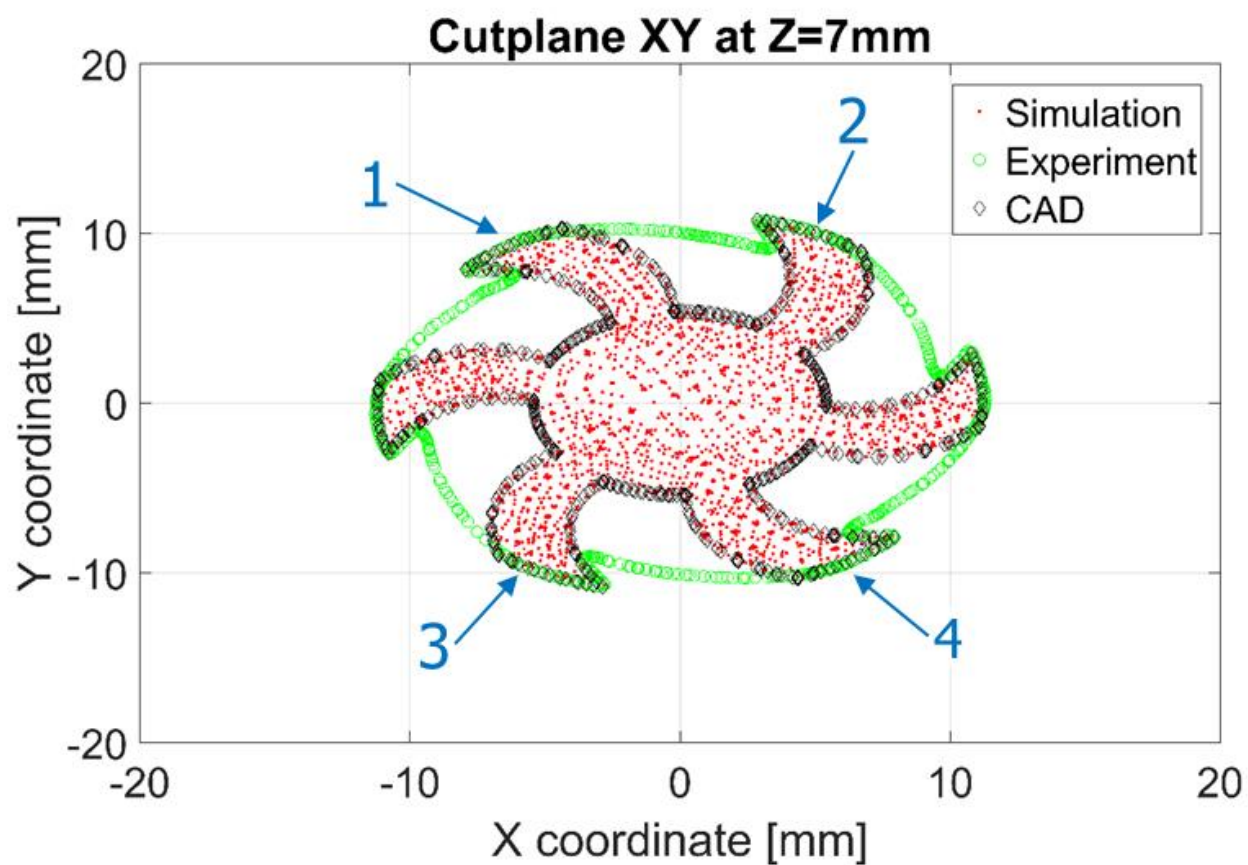


Figure 5-22- F2, Comparison of CAD, simulation and experimental results

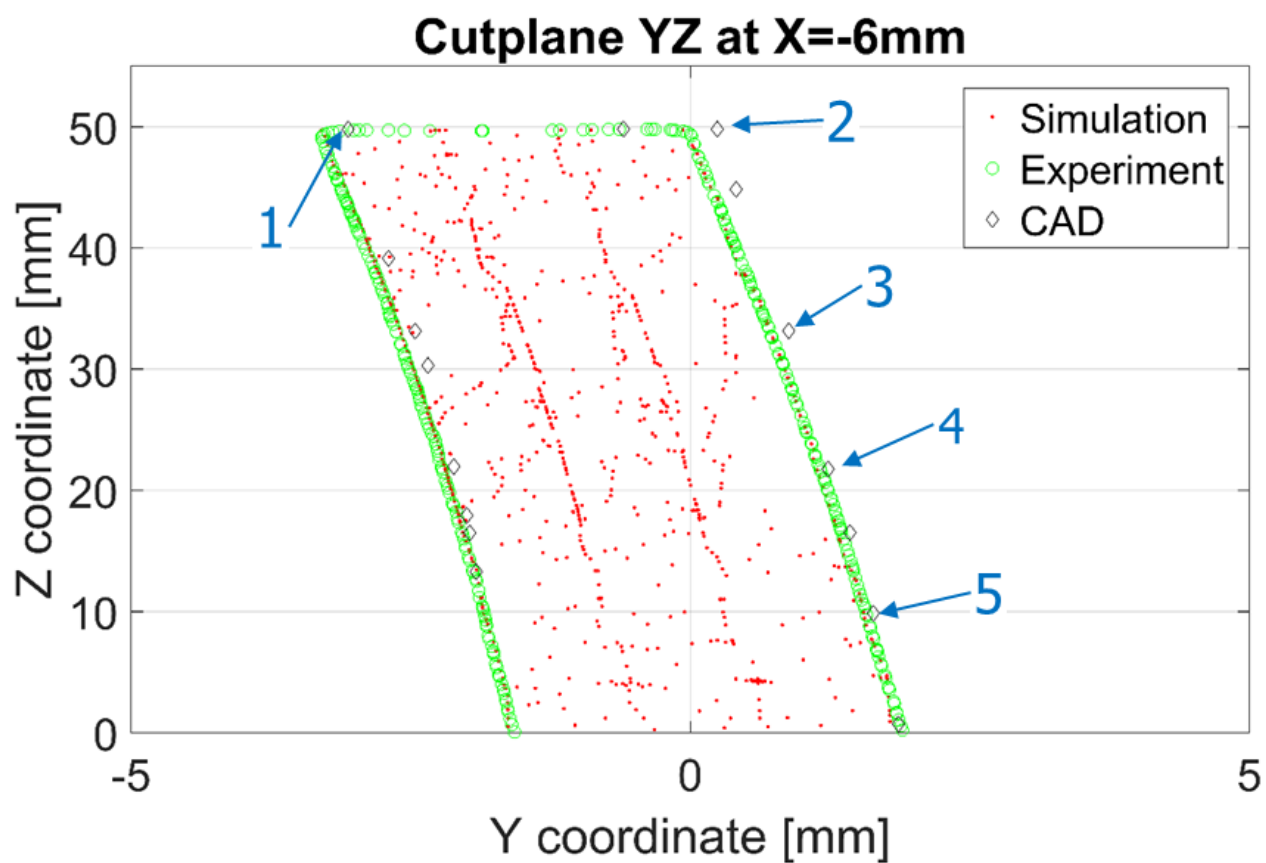


Figure 5-23- F3, Comparison of CAD, simulation and experimental results

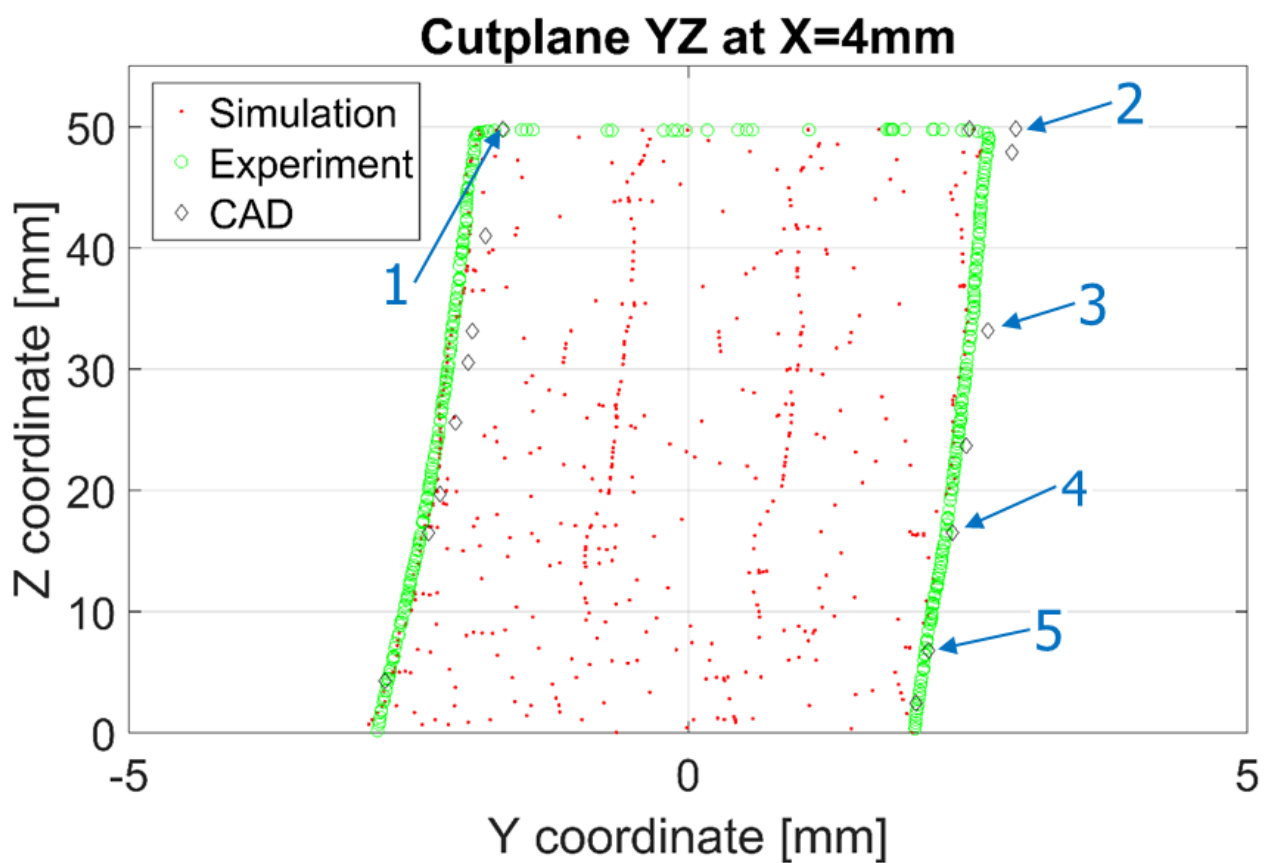


Figure 5-24- F3, Comparison of CAD, simulation and experimental results

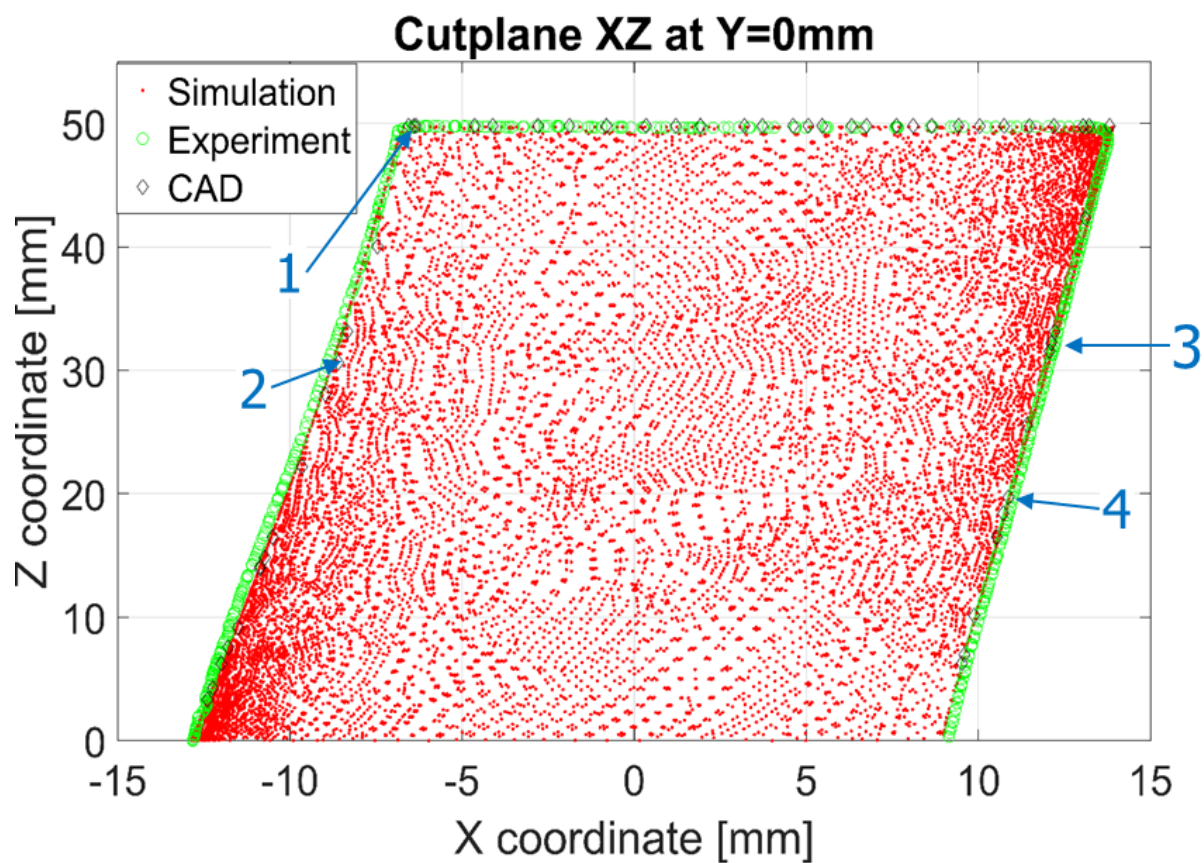


Figure 5-25- F3, Comparison of CAD, simulation and experimental results

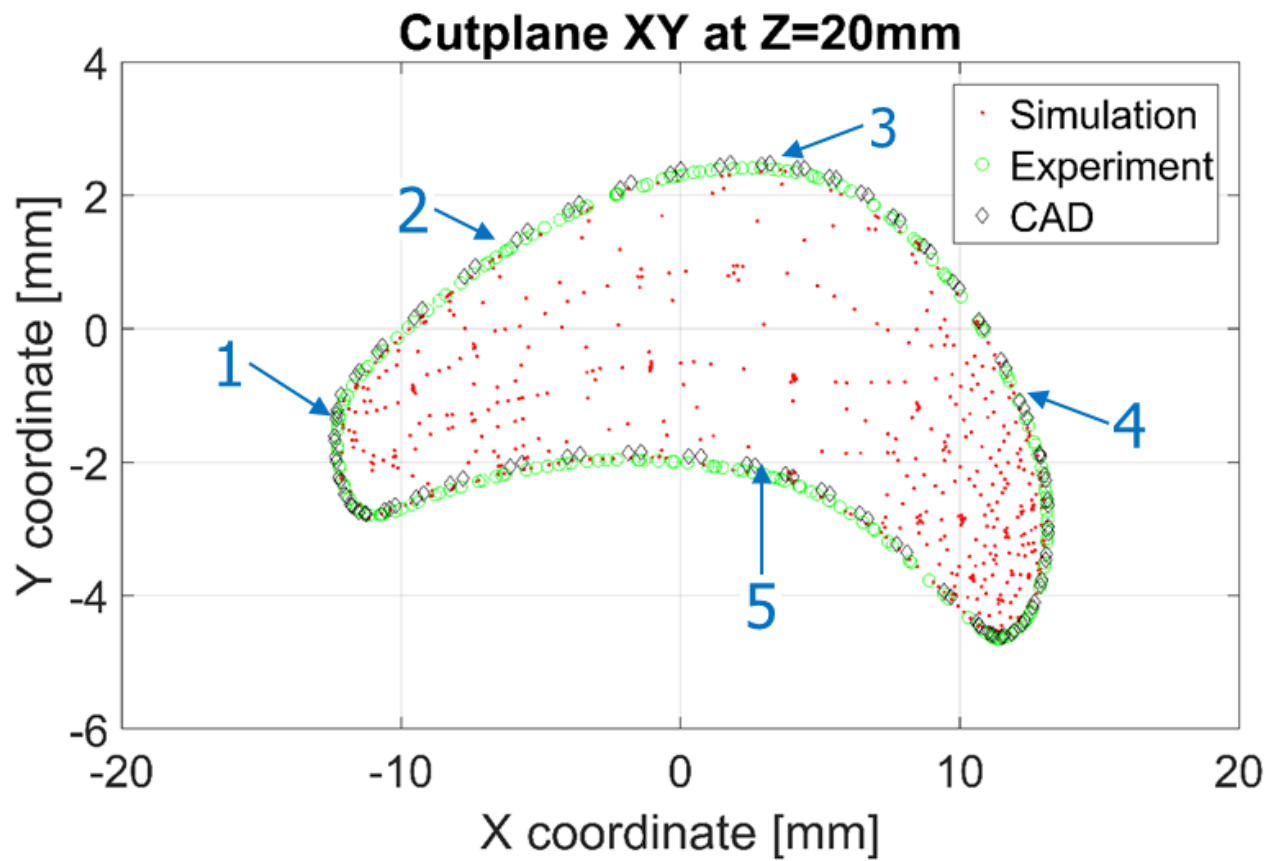


Figure 5-26-F3, Comparison of CAD, simulation and experimental results

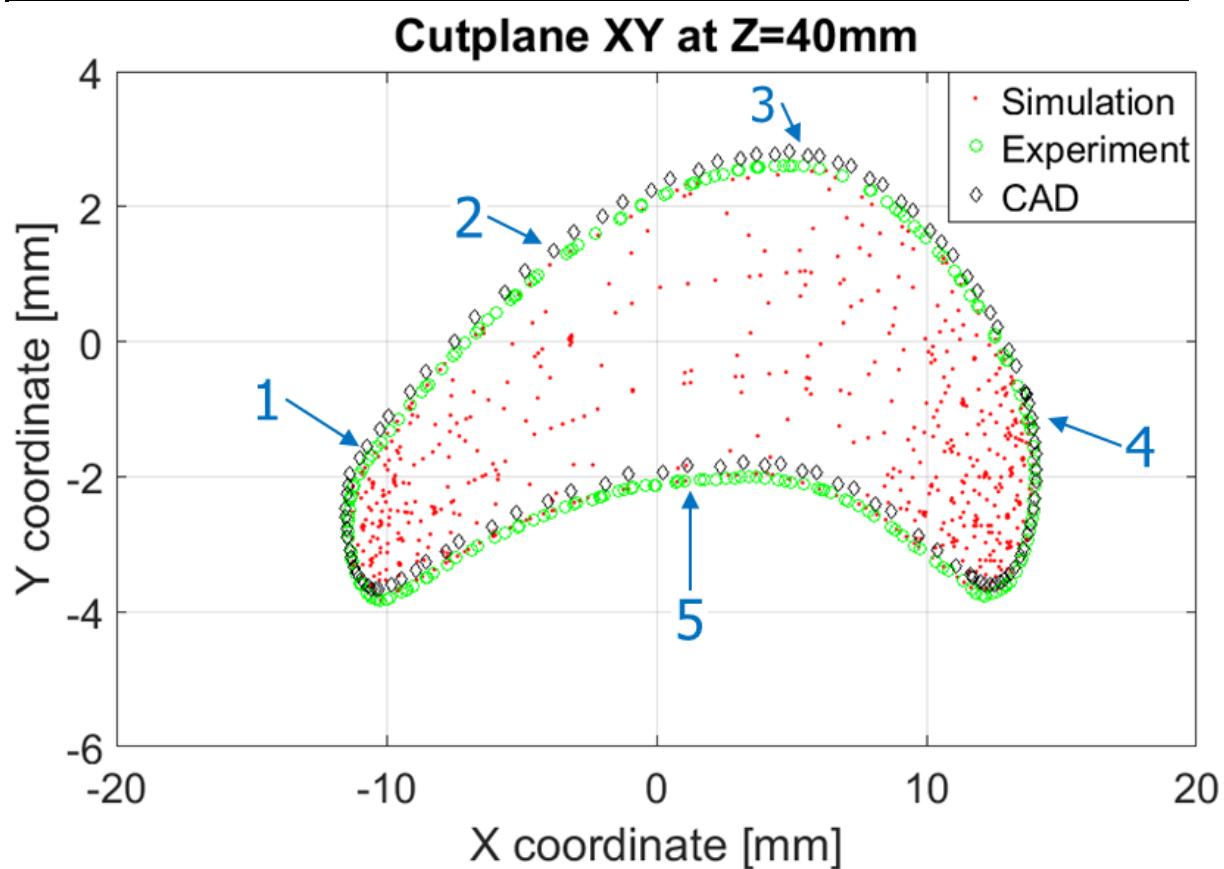


Figure 5-27- F3, Comparison of CAD, simulation and experimental results

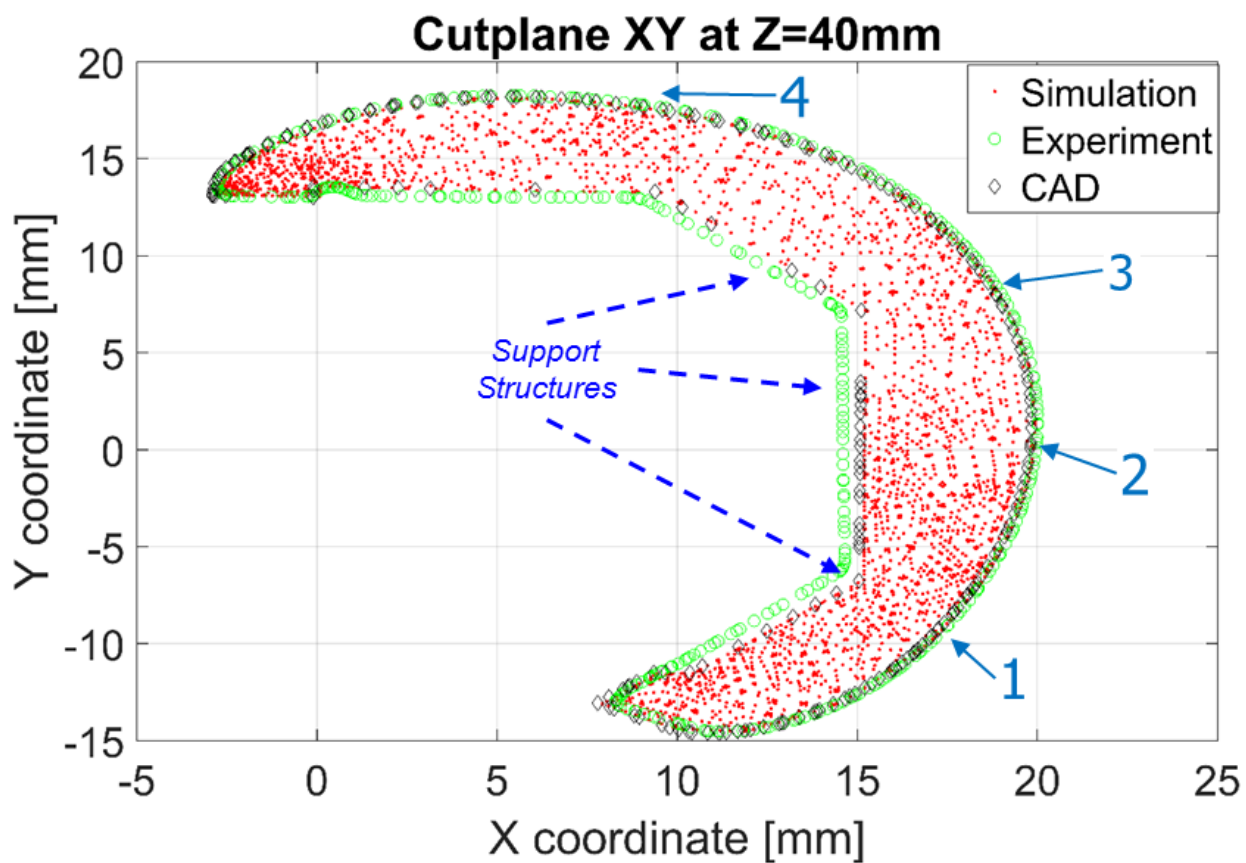


Figure 5-28- F4, Comparison of CAD, simulation and experimental results

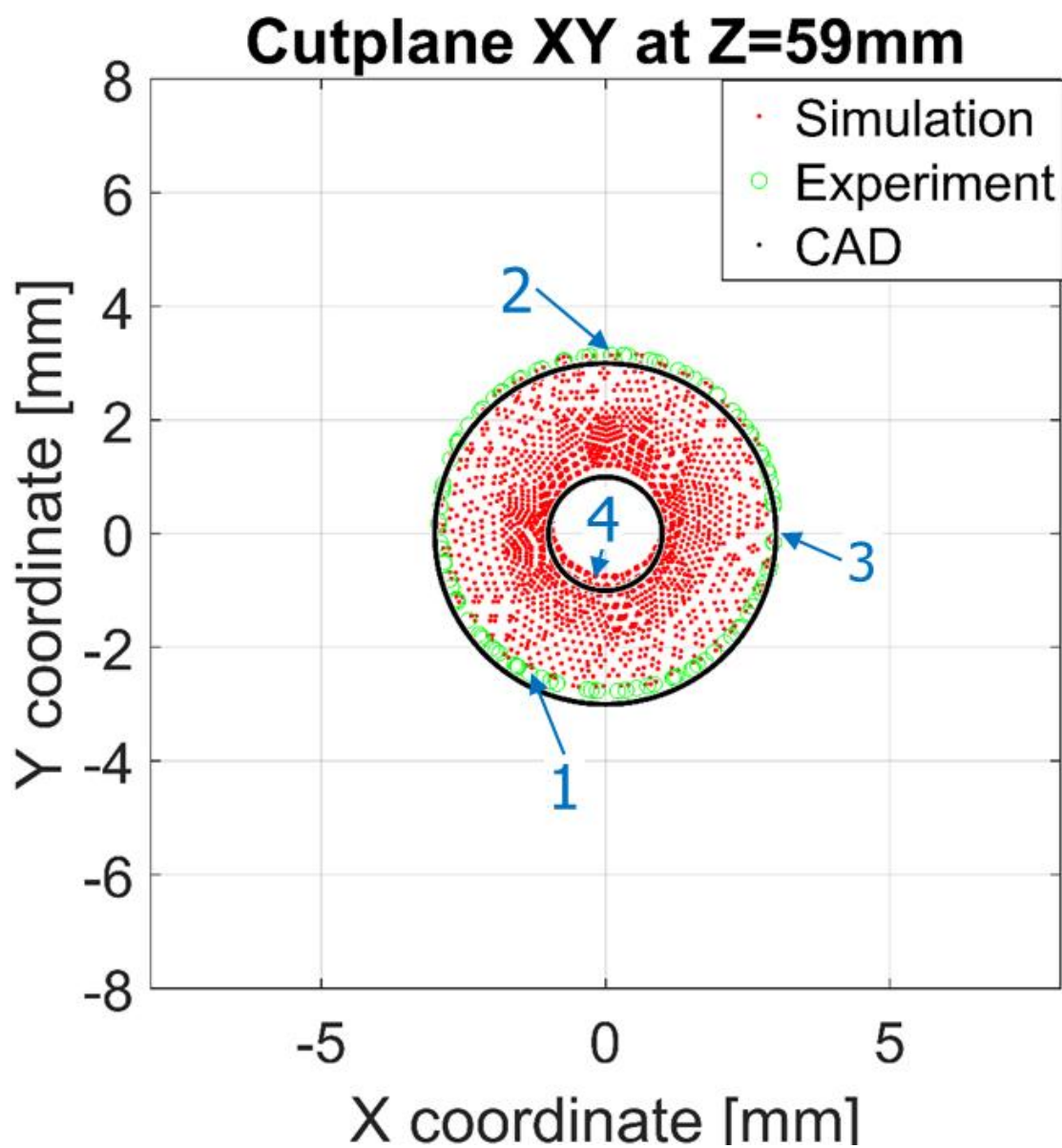


Figure 5-29- P1, Comparison of CAD, simulation and experimental results

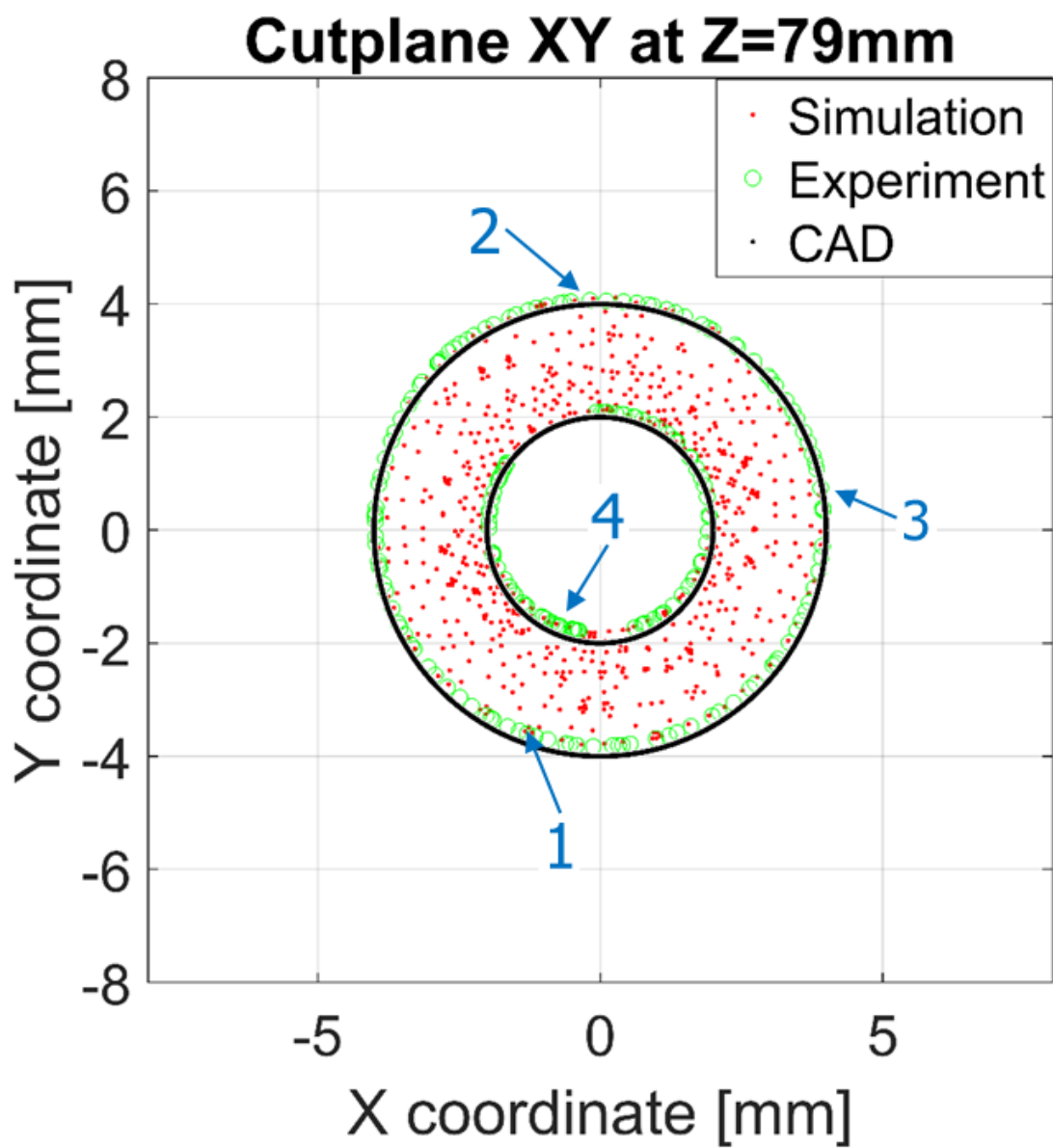


Figure 5-30- P2, Comparison of CAD, simulation and experimental results

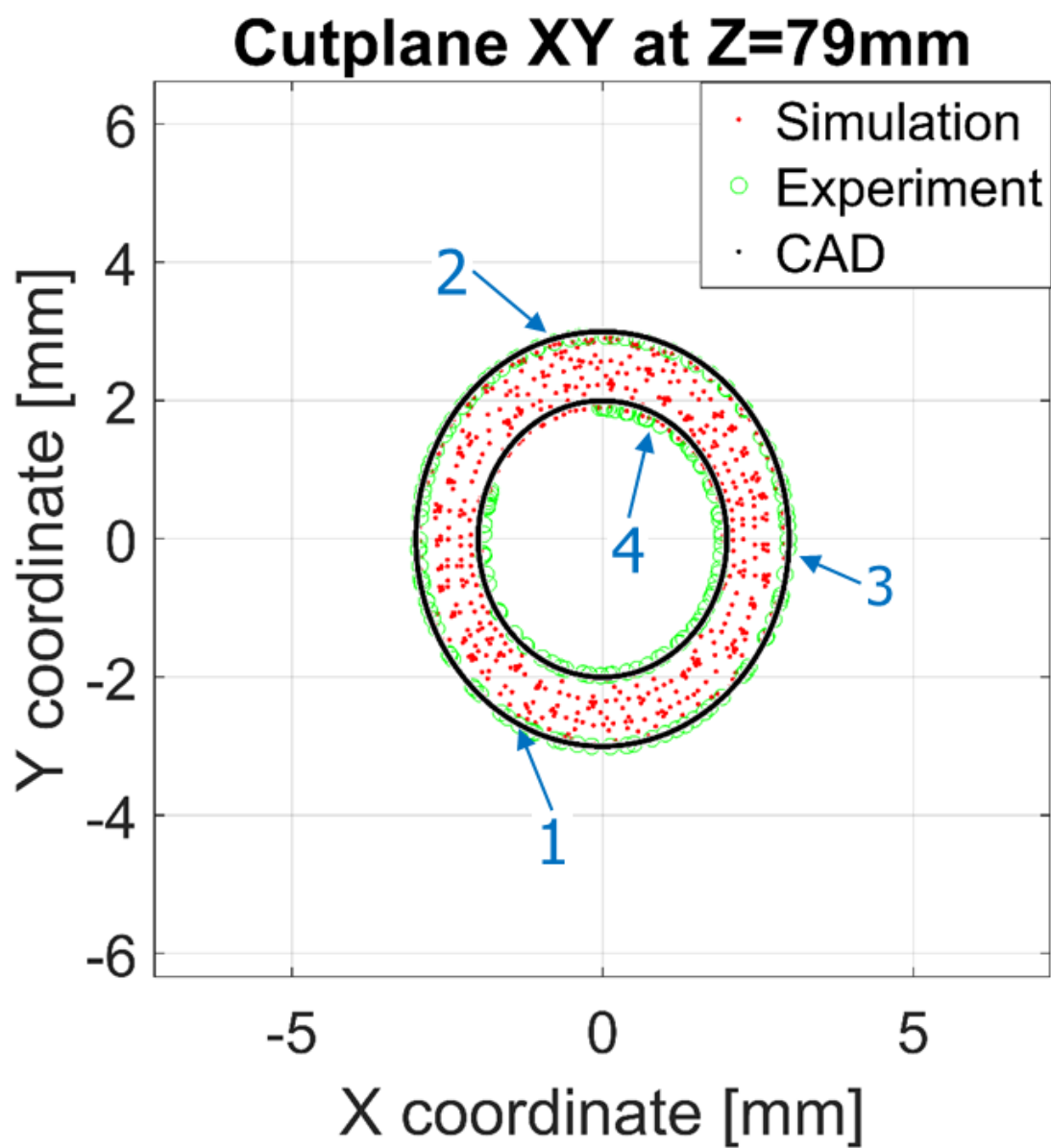


Figure 5-31- P3, Comparison of CAD, simulation and experimental results

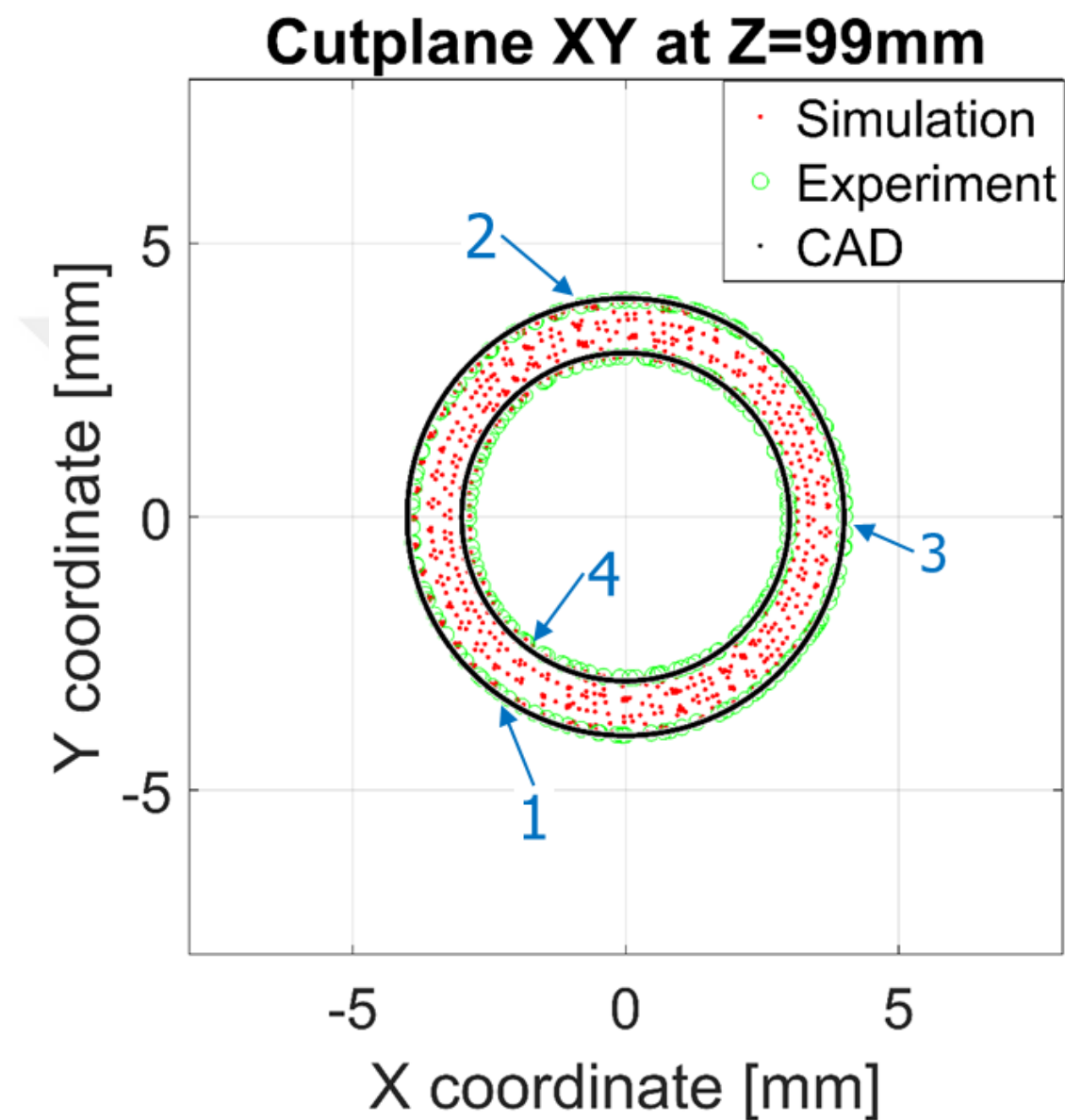


Figure 5-32- P4, Comparison of CAD, simulation and experimental results

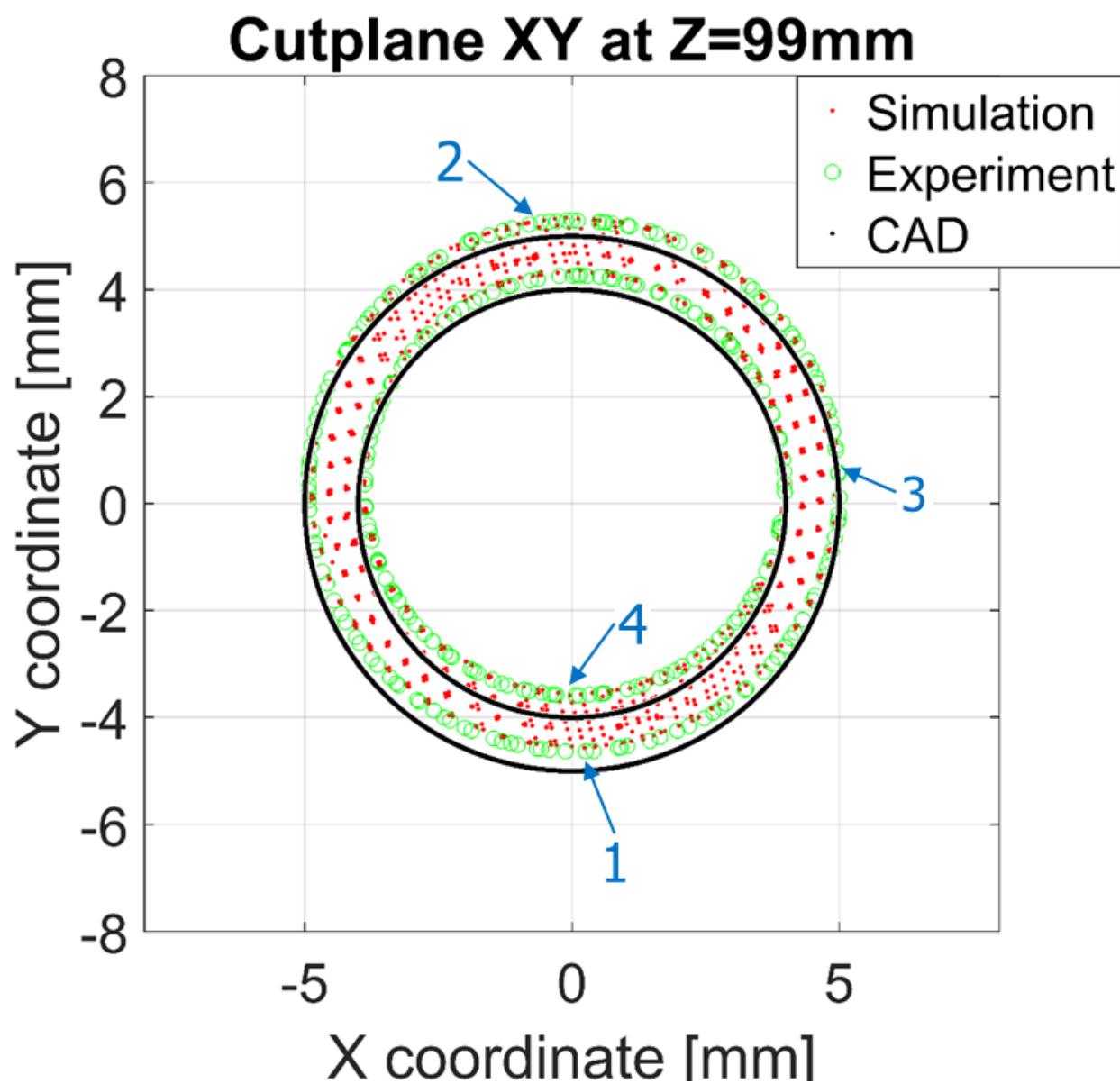


Figure 5-33- P5, Comparison of CAD, simulation and experimental results

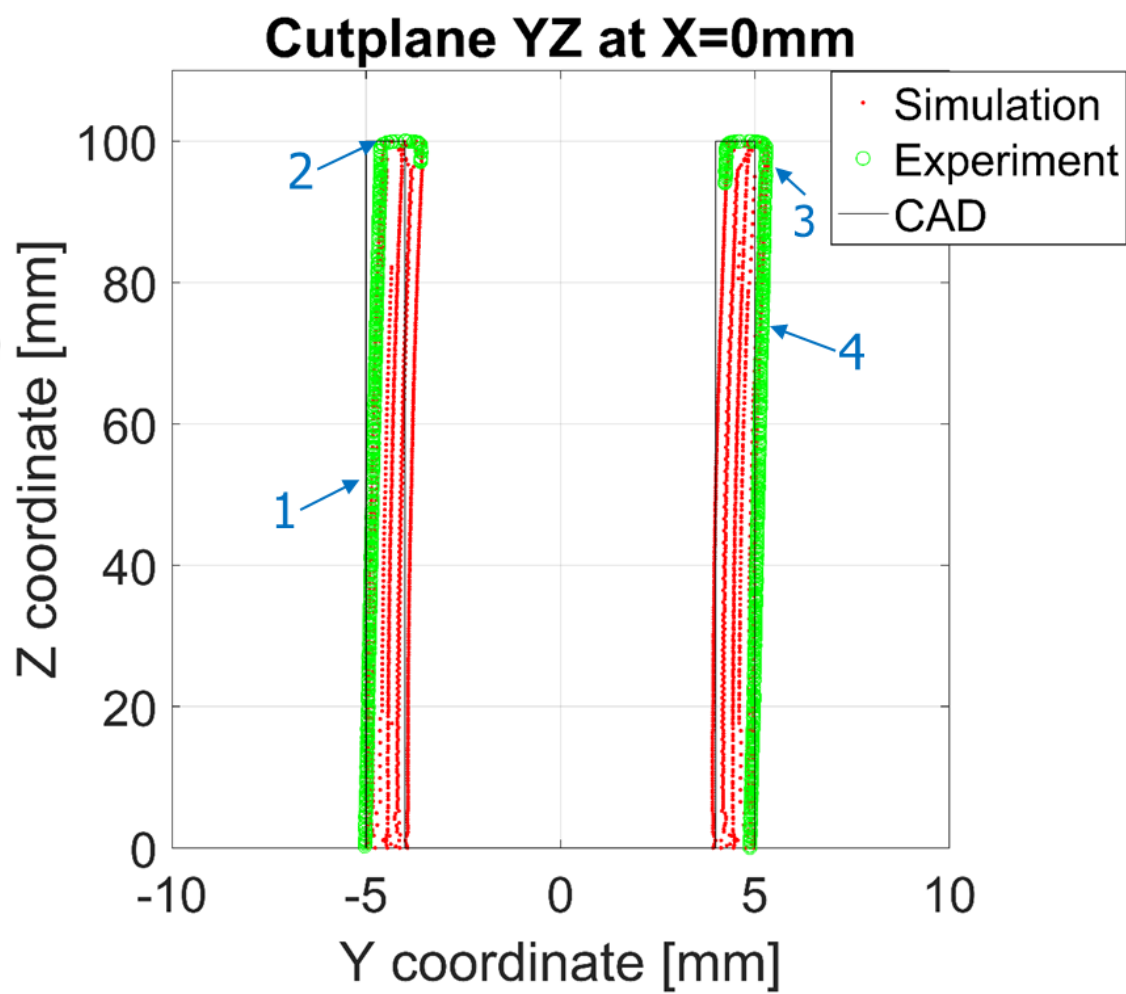


Figure 5-34- P5, Comparison of CAD, simulation and experimental results

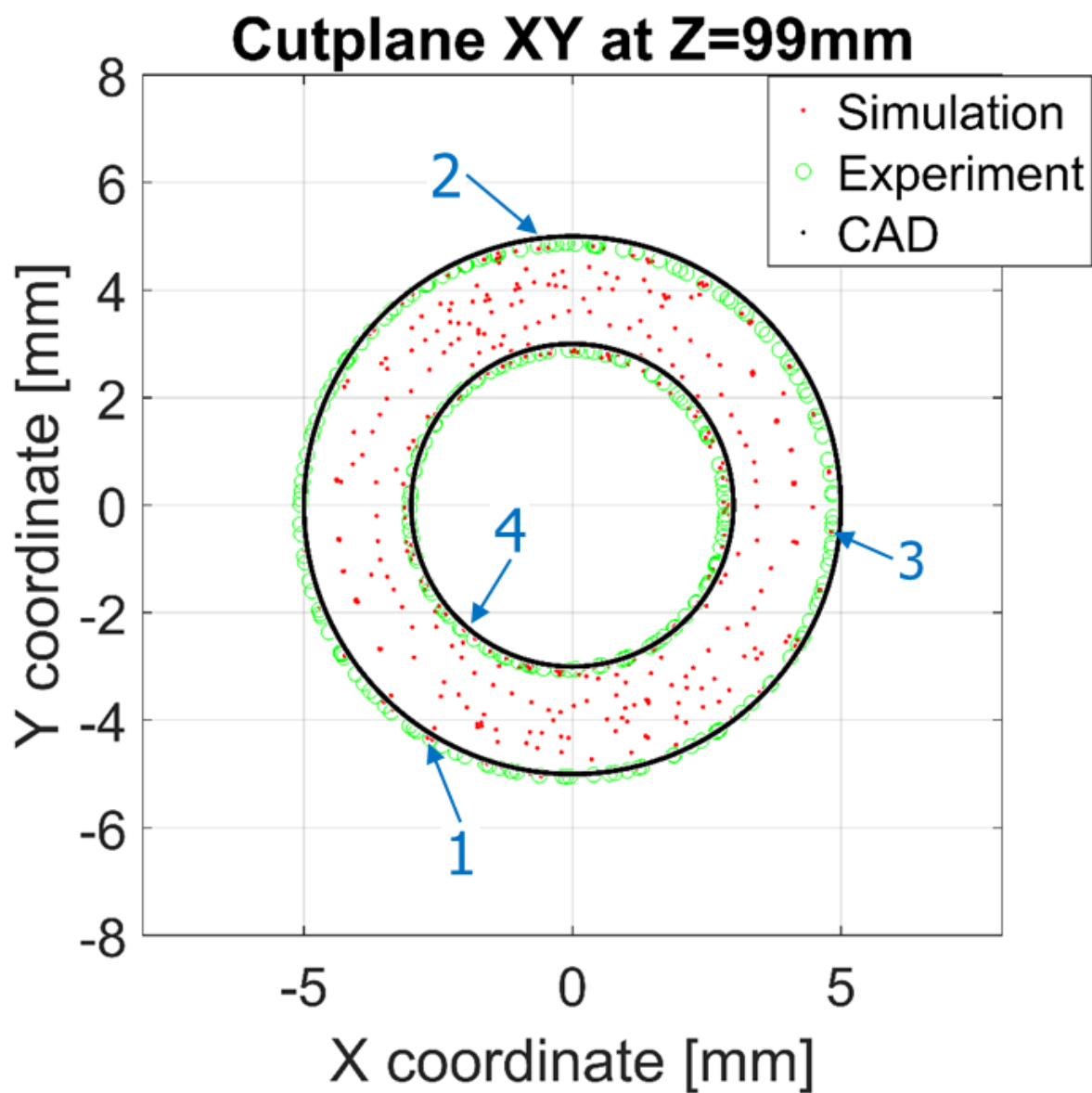


Figure 5-35- P6, Comparison of CAD, simulation and experimental results

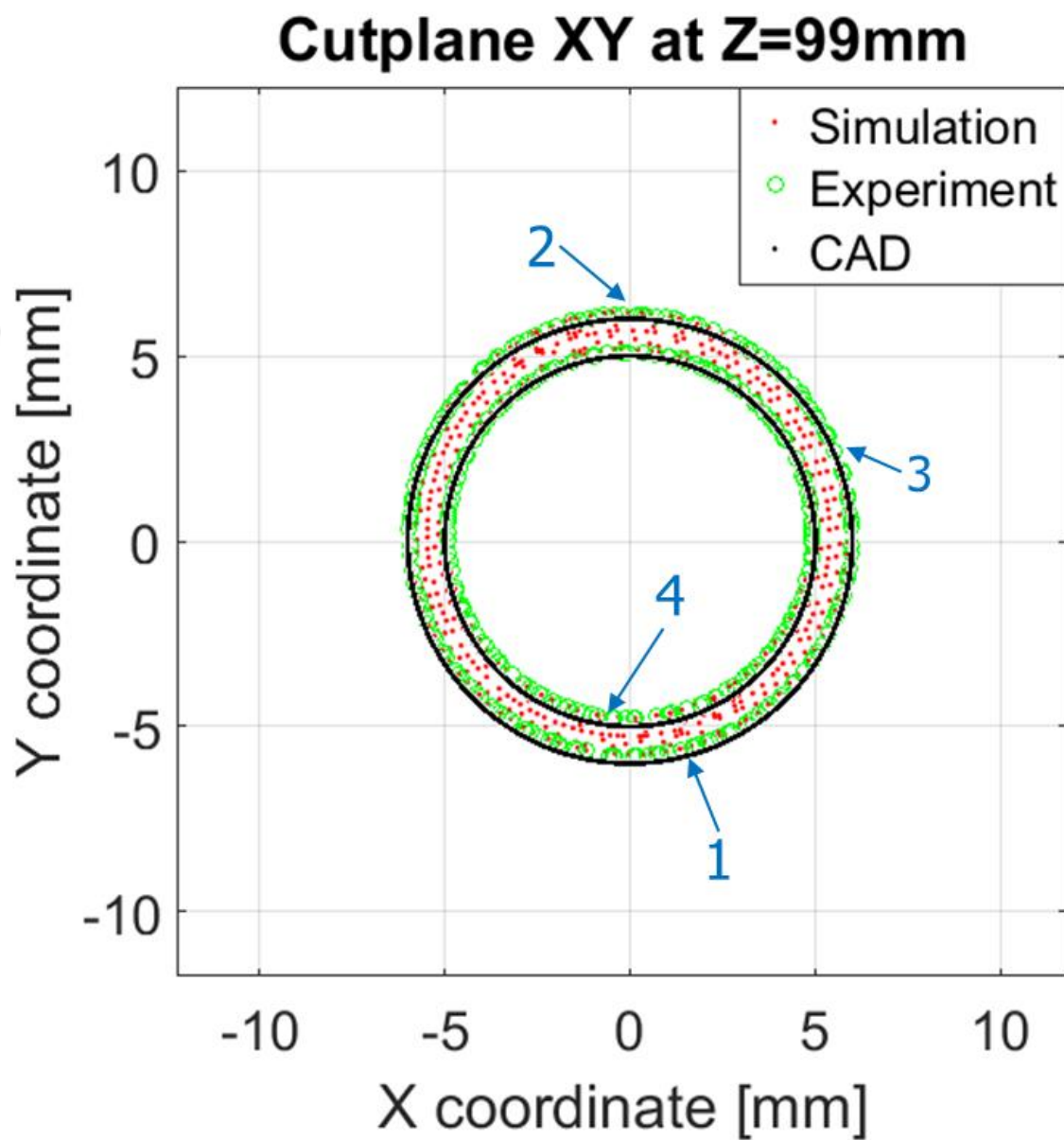


Figure 5-36- P7, Comparison of CAD, simulation and experimental results

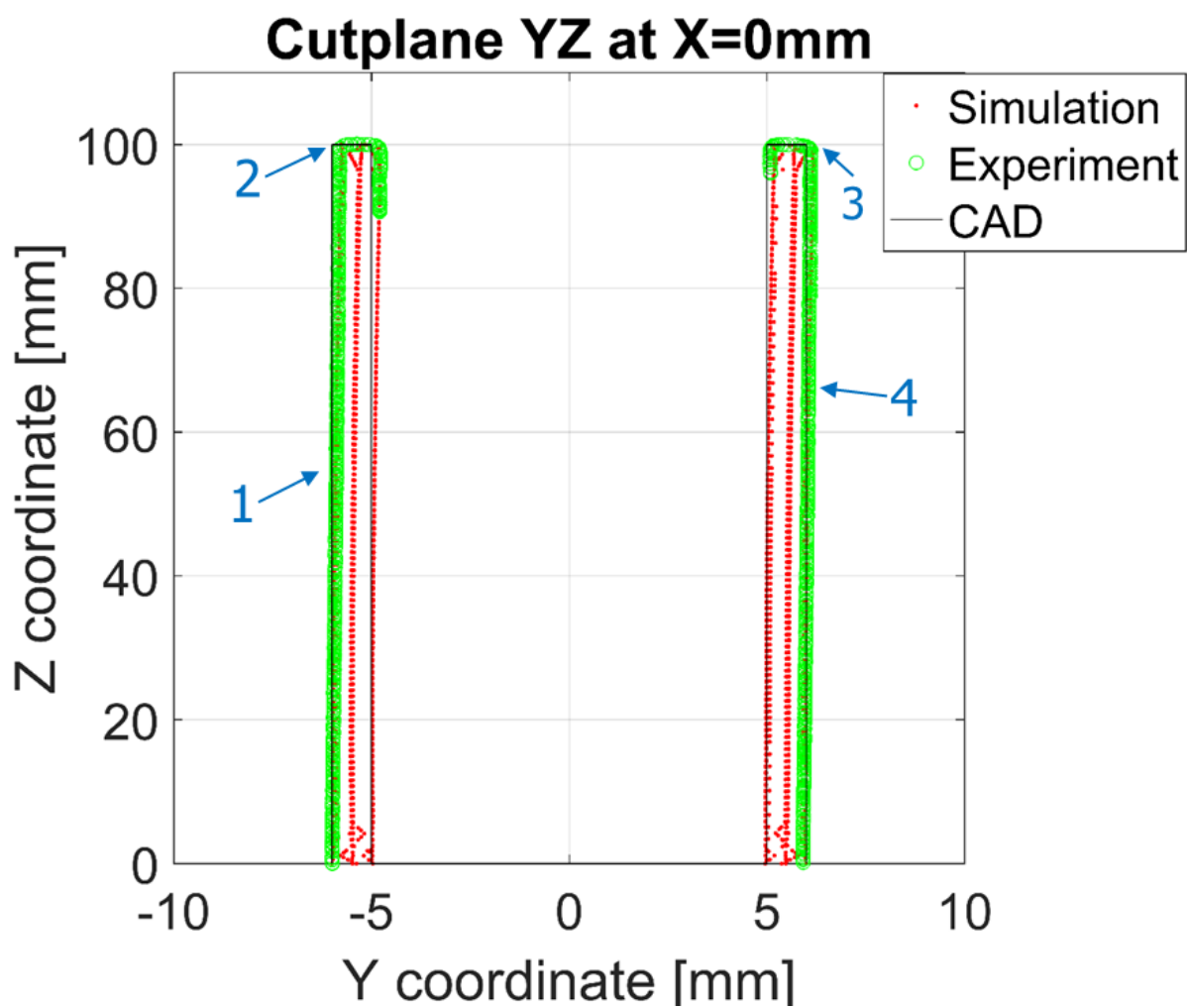


Figure 5-37- P7, Comparison of CAD, simulation and experimental results

Table 5-2- Comparison of the simulation and experiment for the impeller

Point Label	Experiment [μm]	Simulation [μm]	Prediction Error (%)
F1-CP_X1-1	75	70	6
F1-CP_X1-2	40	30	25
F1-CP_X1-3	40	50	25
F1-CP_X1-4	42	48	14
F1-CP_X1-5	16	17	6
F1-CP_X2-1	25	30	20
F1-CP_X2-2	95	120	26
F1-CP_X2-3	8	6	25
F1-CP_X2-4	92	102	10
F1-CP_X2-5	70	50	28
F1- CP_Y1-1	45	54	20
F1- CP_Y1-2	180	200	11
F1- CP_Y1-3	52	54	3
F1- CP_Y1-4	144	148	2
F1- CP_Y1-5	64	73	12
F1- CP_Z1-1	110	92	16
F1- CP_Z1-2	46	31	32.6
F1- CP_Z1-3	92	68	26
F1- CP_Z1-4	41	44	7
F1- CP_Z1-5	74	78	5

Table 5-3- Comparison of the simulation and experiment for the impeller_5Axis

Point Label	Experiment [μm]	Simulation [μm]	Prediction Error (%)
F2-CP_X1-1	20	26	30
F2-CP_X1-2	86	81	5.8
F2-CP_X1-3	52	71	36
F2-CP_X1-4	73	86	17.8
F2-CP_X1-5	26	23	11
F2-CP_Y1-1	4	3	25
F2-CP_Y1-2	13	17	30.8
F2-CP_Y1-3	3	2	33
F2-CP_Y1-4	22	18	18
F2-CP_Z1-1	55	73	32
F2-CP_Z1-2	86	81	5.8
F2-CP_Z1-3	52	71	36
F2-CP_Z1-4	73	86	17.8

Table 5-4- Comparison of the simulation and experiment for the fan blade

Point Label	Experiment [μm]	Simulation [μm]	Prediction Error (%)
F3-CP_X1-1	239	209	12
F3-CP_X1-2	306	308	0.7
F3-CP_X1-3	198	174	12
F3-CP_X1-4	149	143	4
F3-CP_X1-5	65	78	20
F3-CP_X2-1	240	221	7.9

F3-CP_X2-2	217	260	19,8
F3-CP_X2-3	150	180	20
F3-CP_X2-4	25	29	16
F3-CP_X2-5	19	25	31
F3-CP_Y1-1	383	302	21
F3-CP_Y1-2	330	277	16
F3-CP_Y1-3	80	81	1
F3-CP_Y1-4	120	70	41
F3-CP_Z1-1	150	148	1
F3-CP_Z1-2	221	179	19
F3-CP_Z1-3	95	93	2
F3-CP_Z1-4	60	70	16
F3-CP_Z1-5	109	122	11.9
F3-CP_Z2-1	184	218	18
F3-CP_Z2-2	293	276	5.8
F3-CP_Z2-3	203	221	8.9
F3-CP_Z2-4	235	188	20
F3-CP_Z2-5	224	228	1.8

Table 5-5- Comparison of the simulation and experiment for the fan blade

Point Label	Experiment [μm]	Simulation [μm]	Prediction Error (%)
F4-CP_Z1-1	213	147	30.9
F4-CP_X1-2	110	80	27
F4-CP_X1-3	135	90	33

F4-CP_X1-4	95	65	31.6
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Table 5-6- Comparison of the simulation and experiment for the pipe-6-2-60

Point Label	Experiment [μm]	Simulation [μm]	Prediction Error (%)
P1-CP_Z1-1	245	260	6
P1-CP_Z1-2	150	148	1.3
P1-CP_Z1-3	42	51	21
P1-CP_Z1-4	Not measured	270	-

Table 5-7- Comparison of the simulation and experiment for the pipe-8-2-80

Point Label	Experiment [μm]	Simulation [μm]	Prediction Error (%)
P2-CP_Z1-1	173	205	18
P2-CP_Z1-2	72	94	30
P2-CP_Z1-3	29	34	17.2
P2-CP_Z1-4	156	160	2.6

Table 5-8- Comparison of the simulation and experiment for the pipe-6-1-80

Point Label	Experiment [μm]	Simulation [μm]	Prediction Error (%)
P3-CP_Z1-1	21	26	23.8
P3-CP_Z1-2	65	80	23
P3-CP_Z1-3	25	32	28
P3-CP_Z1-4	83	71	14

Table 5-9- Comparison of the simulation and experiment for the pipe-8-1-100

Point Label	Experiment [μm]	Simulation [μm]	Prediction Error (%)
P4-CP_Z1-1	67	80	19
P4-CP_Z1-2	39	50	28
P4-CP_Z1-3	14	15	7
P4-CP_Z1-4	95	125	31

Table 5-10- Comparison of the simulation and experiment for the pipe-10-1-100

Point Label	Experiment [μm]	Simulation [μm]	Prediction Error (%)
P5-CP_Z1-1	369	456	23
P5-CP_Z1-2	113	125	10
P5-CP_Z1-3	20	26	30
P5-CP_Z1-4	433	420	3
P5-CP_X1-1	158	145	8
P5-CP_X1-2	447	442	1
P5-CP_X1-3	284	306	7
P5-CP_X1-4	214	191	10

Table 5-11- Comparison of the simulation and experimental for the pipe-10-2-100

Point Label	Experiment [μm]	Simulation [μm]	Prediction Error (%)
P6-CP_Z1-1	95	93	2
P6-CP_Z1-2	150	166	10
P6-CP_Z1-3	132	158	19
P6-CP_Z1-4	90	101	12

Table 5-12- Comparison of the simulation and experiment for the pipe-12-1-100

Point Label	Experiment [μm]	Simulation [μm]	Prediction Error (%)
P7-CP_Z1-1	199	184	7.5
P7-CP_Z1-2	123	160	30
P7-CP_Z1-3	76	64	15
P7-CP_Z1-4	222	193	13
P7-CP_X1-1	103	84	18
P7-CP_X1-2	214	239	11
P7-CP_X1-3	34	24	29
P7-CP_X1-4	94	115	22

Table 5-13- Average prediction % Error for each part (Stage I)

Part Name	Part Label	Average Prediction Error (%)
Impeller	F1	16.3
Impeller_5Axis	F2	23.2
Fan Blade	F3	13.8
Knee Implant	F4	30.8
Pipe-6-2-60	P1	9.6
Pipe-8-2-80	P2	17.2
Pipe-6-1-80	P3	22.4
Pipe-8-1-100	P4	21.6
Pipe-10-1-100	P5	11.2
Pipe-10-2-100	P6	11.9
Pipe-12-1-100	P7	18.4

5.4 Simulation – Experimental – CAD Comparison: Stage II

5.4.1 Simulation Results: Stage II

Stage II is the case where the parts are separated from the base plate. For each part, the developed model was implemented for Stage II and distortion results were obtained. The distortion results of the developed model are shown in Figure 5-38 to Figure 5-48.

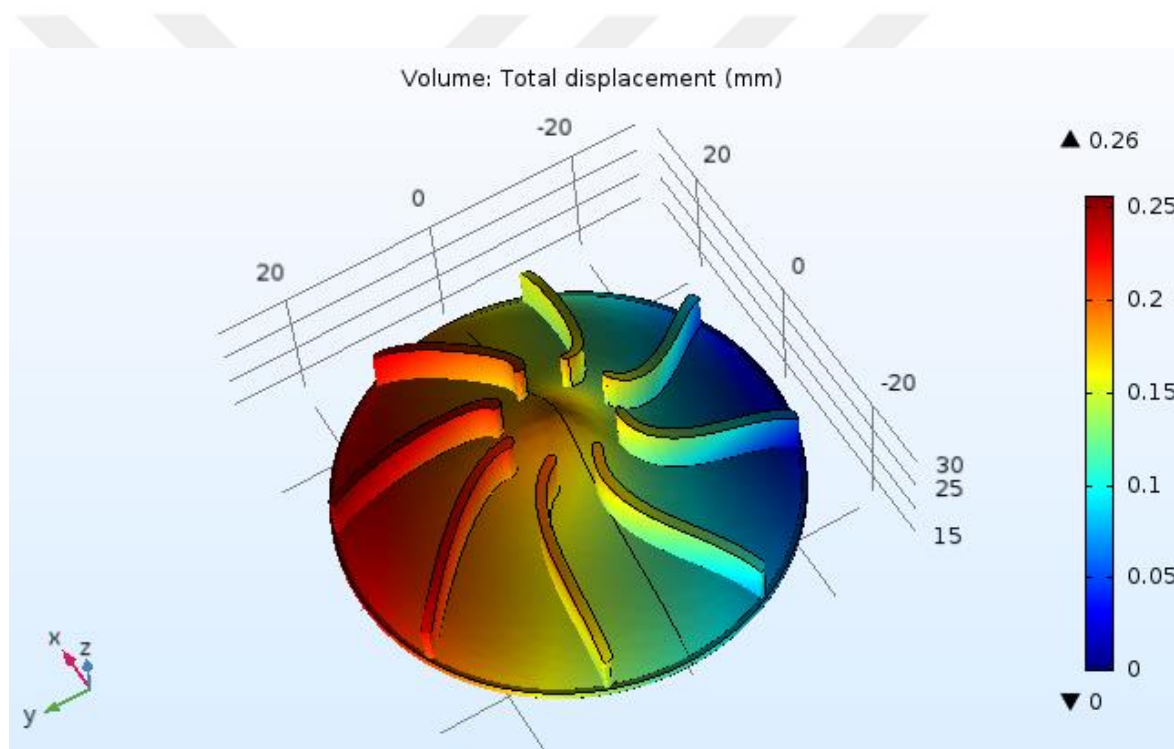


Figure 5-38- Impeller, Simulation Results (Stage II)

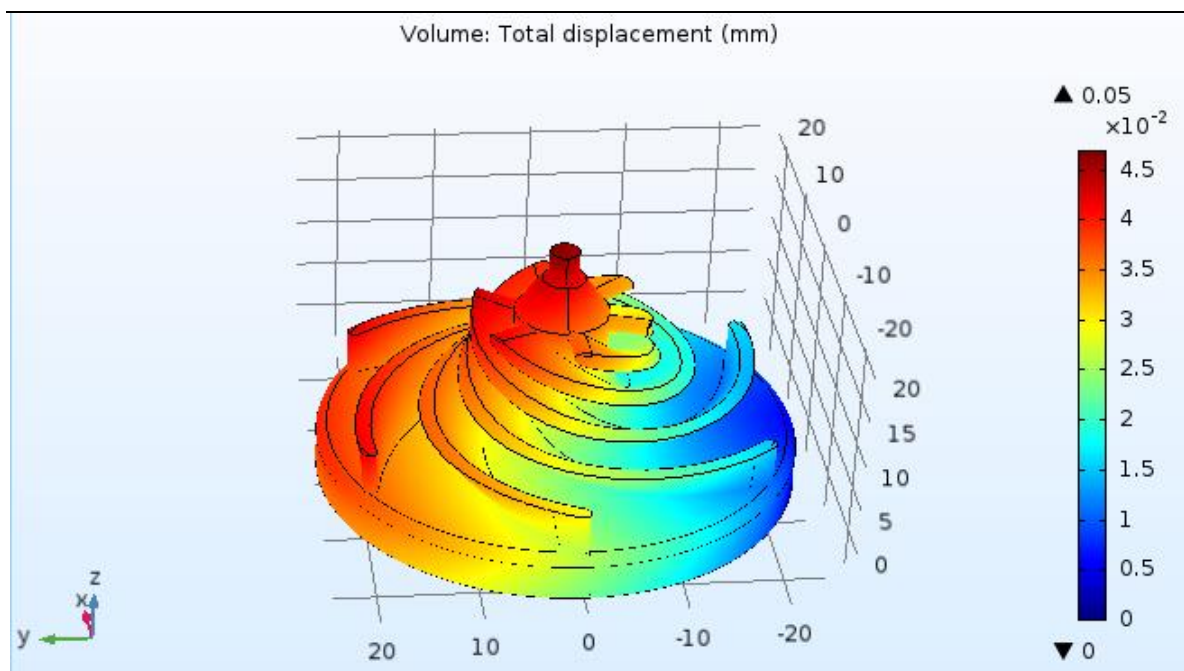


Figure 5-39- Impeller_5Axis, Simulation Results (Stage II)

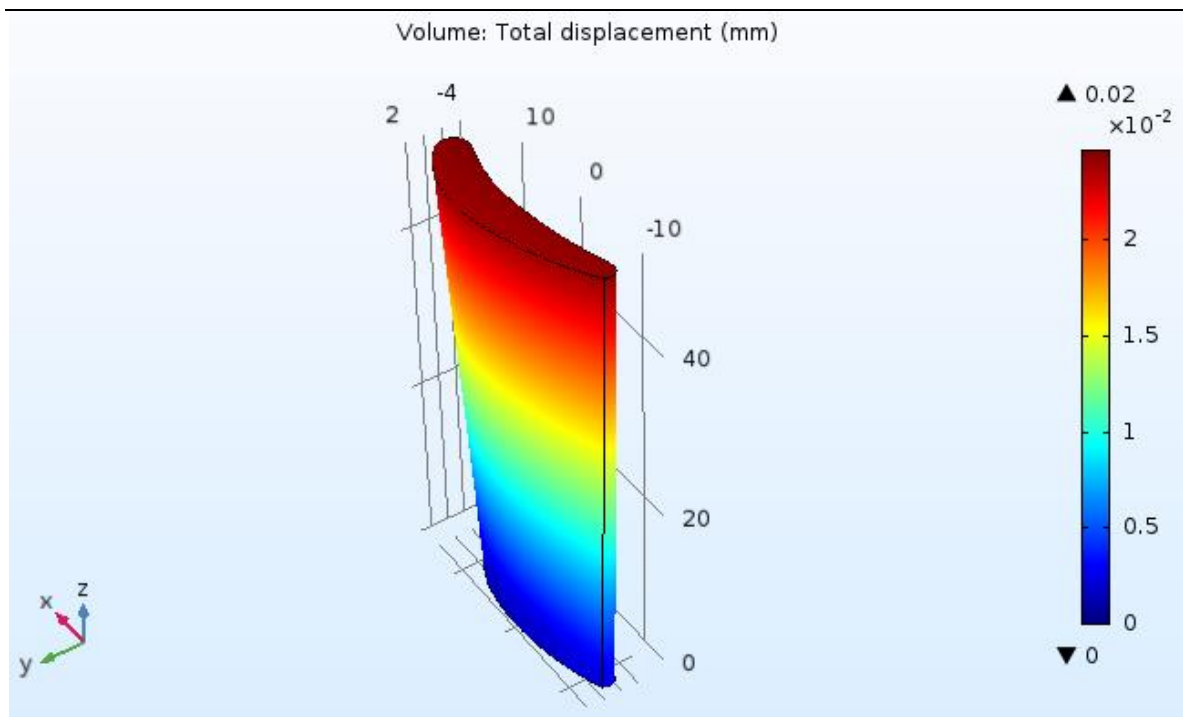


Figure 5-40- Fan Blade, Simulation Results (Stage II)

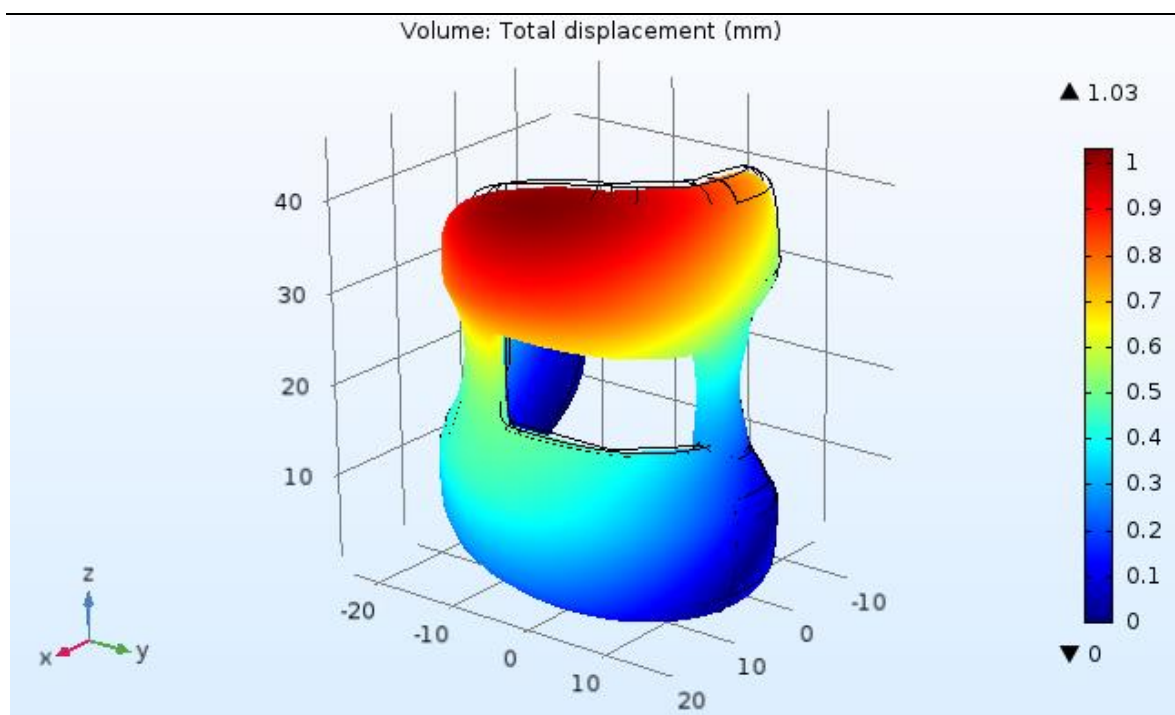


Figure 5-41- Knee Implant, Simulation Results (Stage II)

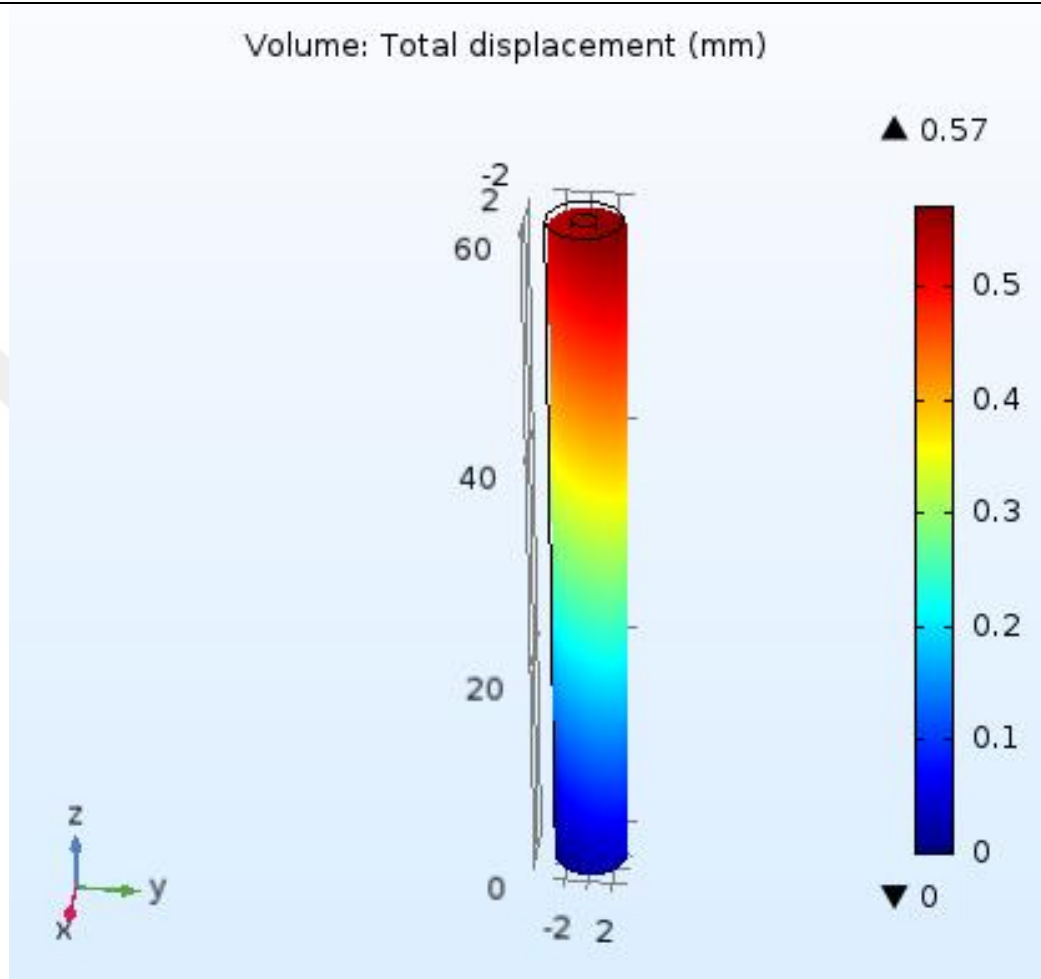


Figure 5-42- Pipe-6-2-60, Simulation Results (Stage II)

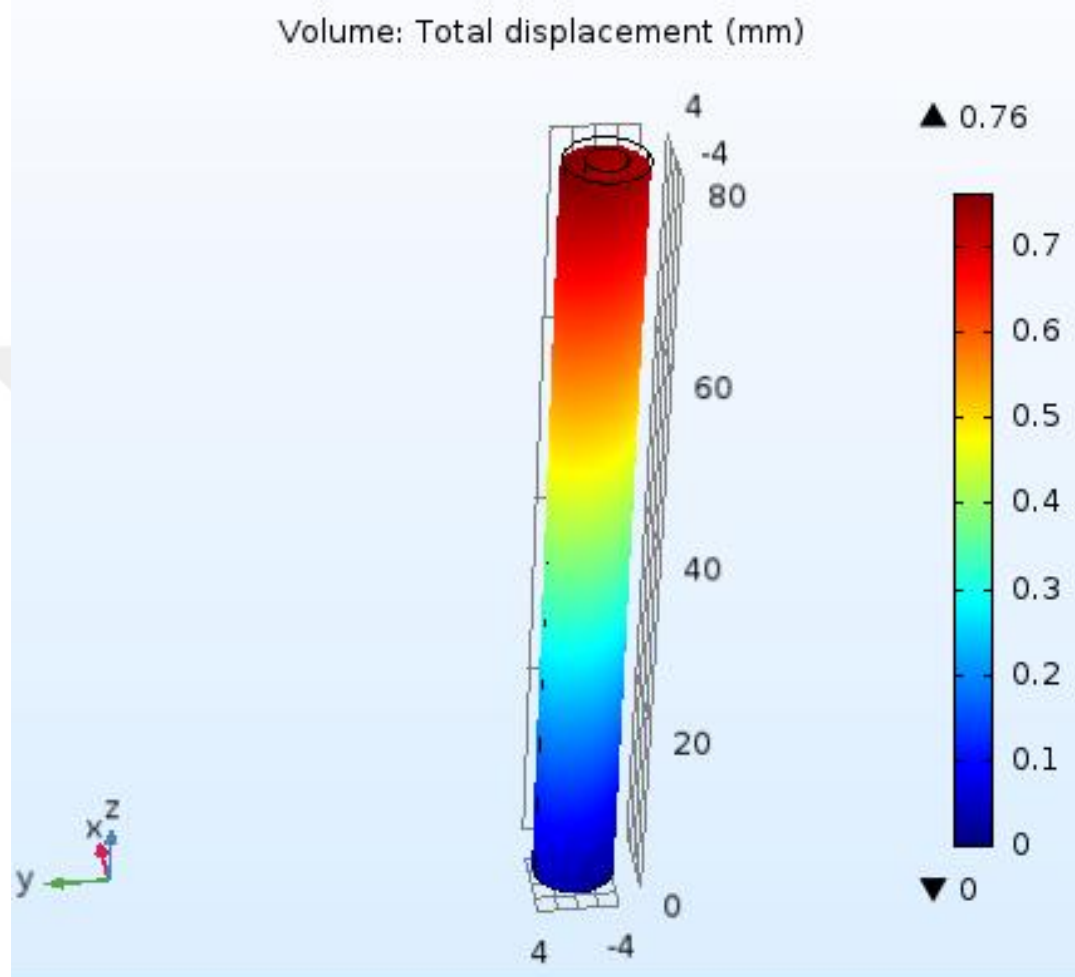


Figure 5-43- Pipe-8-2-80, Simulation Results (Stage II)

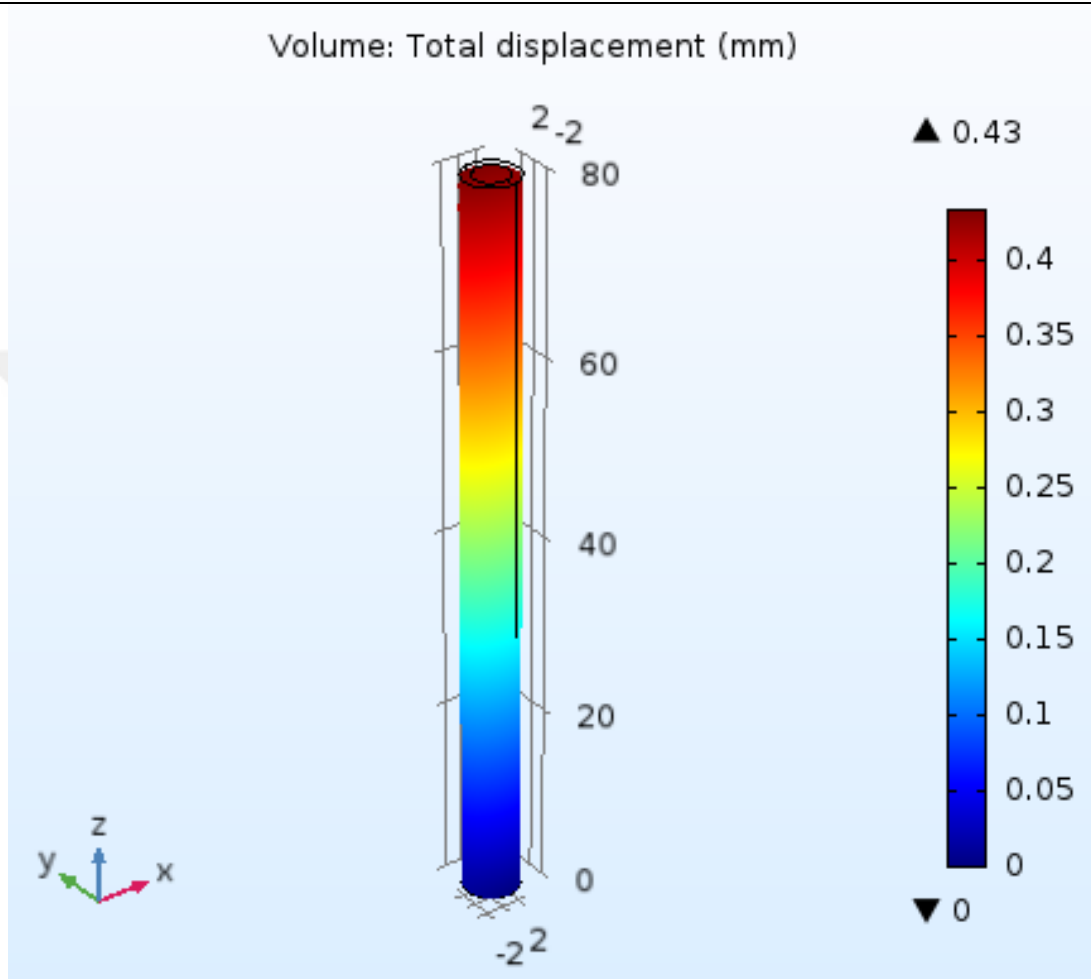


Figure 5-44- Pipe-6-1-80, Simulation Results (Stage II)

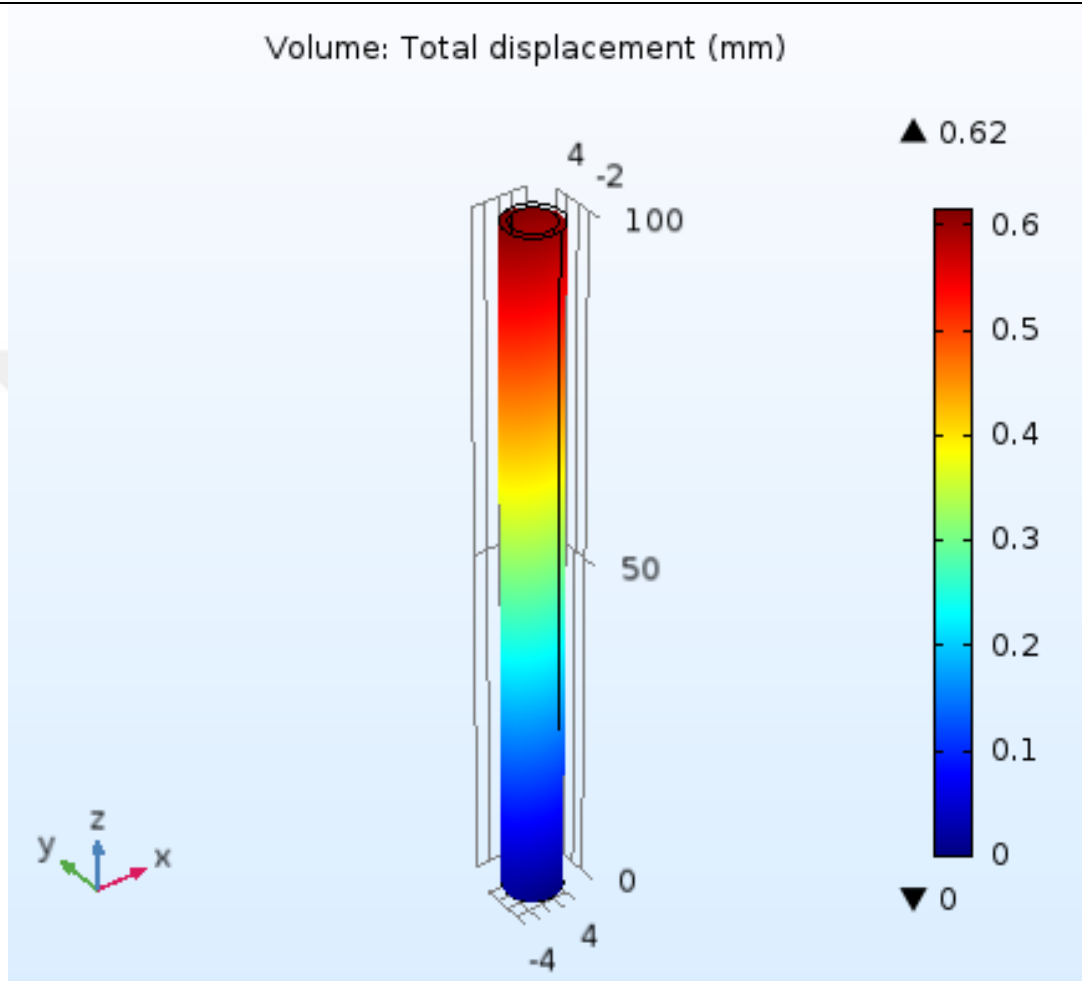


Figure 5-45- Pipe-8-1-100, Simulation Results (Stage II)

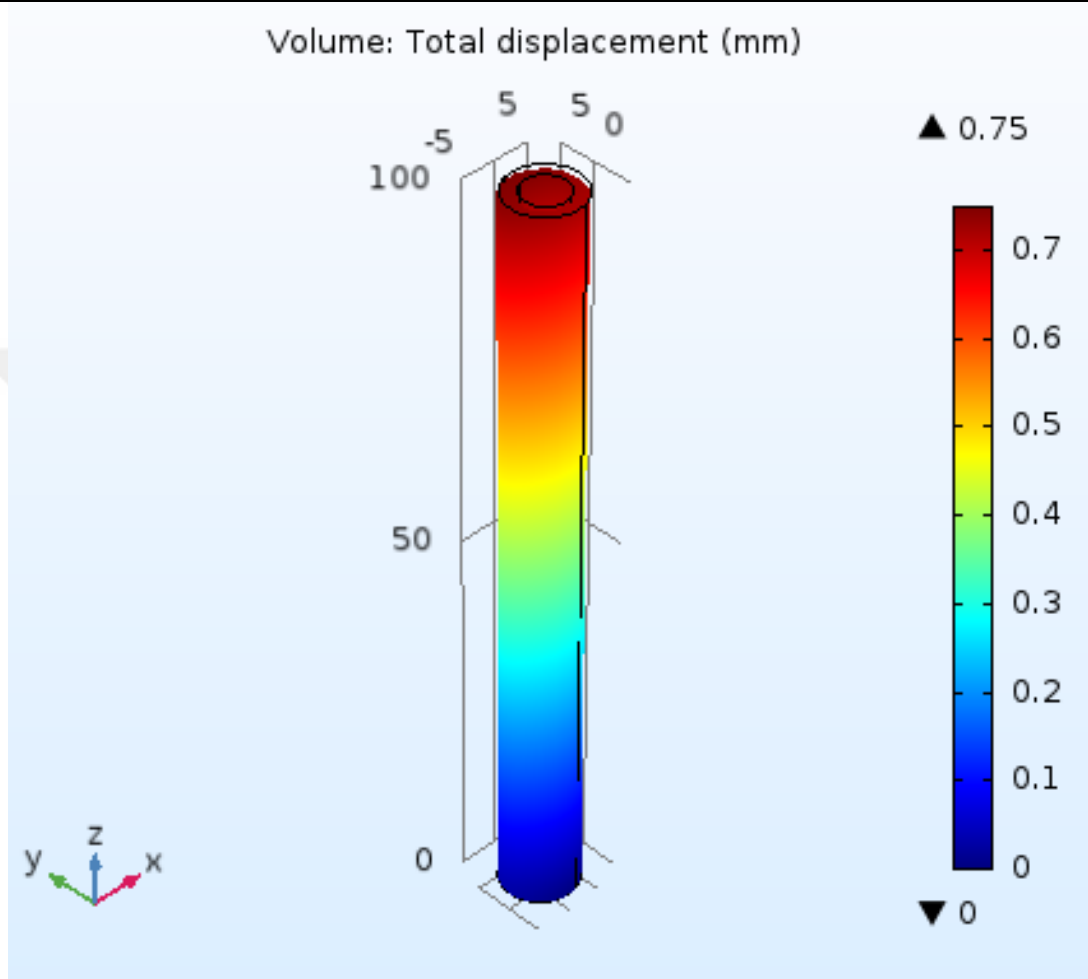


Figure 5-46- Pipe-10-1-100, Simulation Results (Stage II)

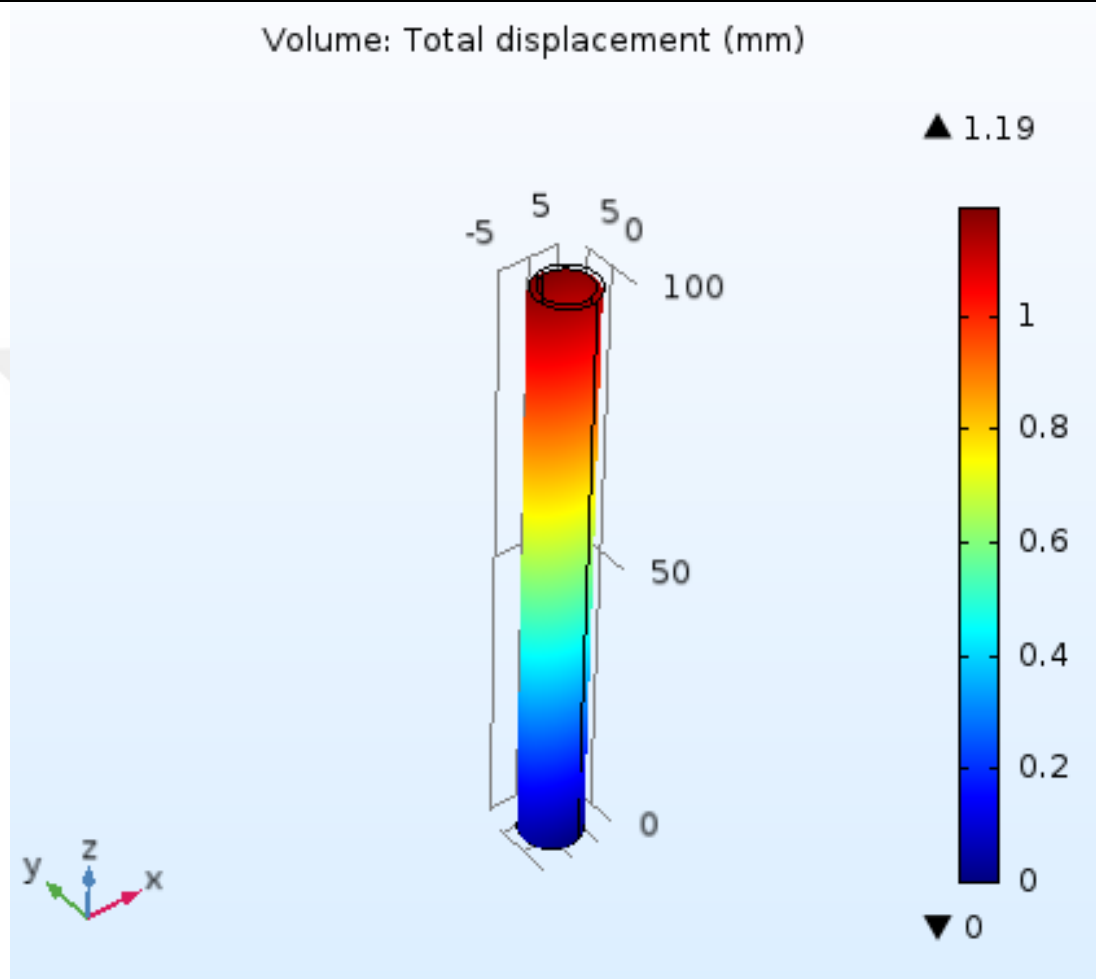


Figure 5-47- Pipe-10-2-100, Simulation Results (Stage II)

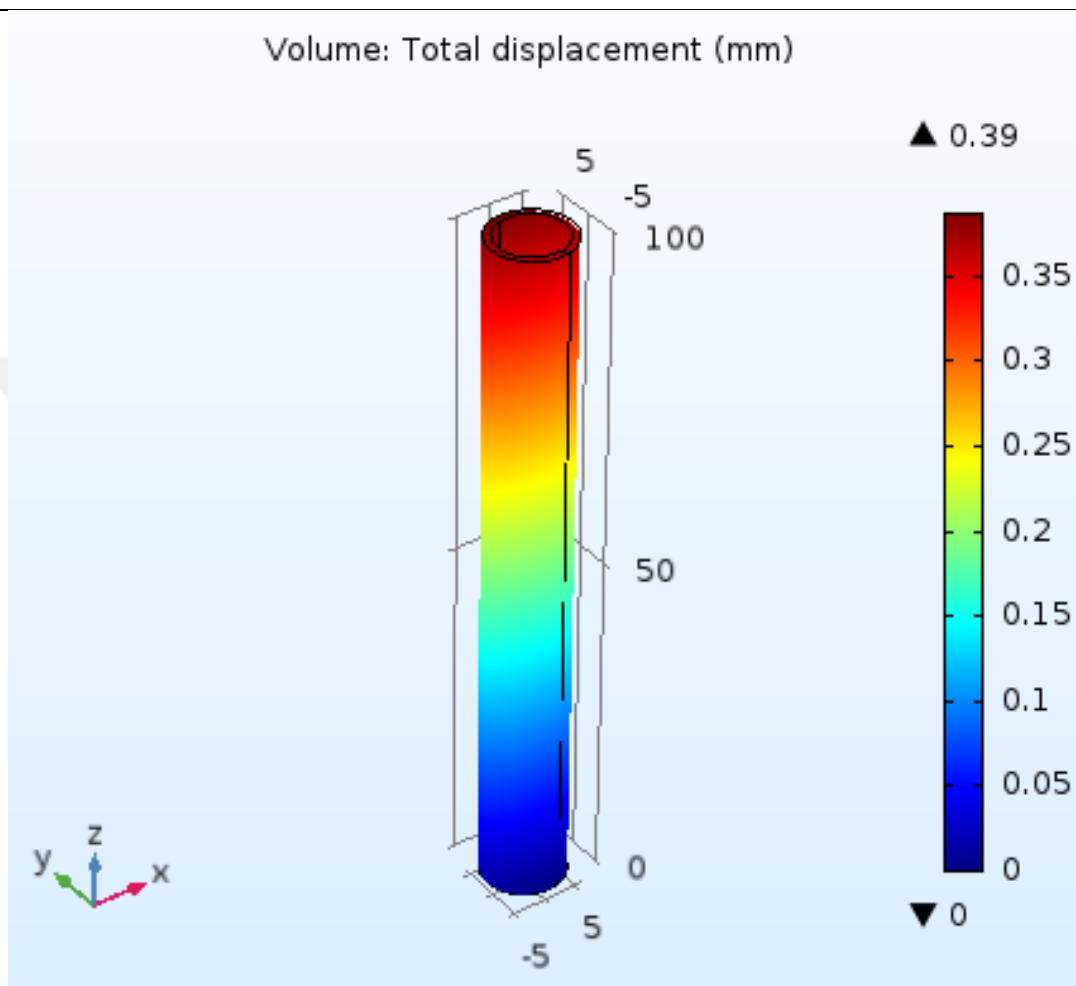


Figure 5-48- Pipe-12-1-100, Simulation Results (Stage II)

5.4.2 Experimental Results: Stage II

The parts were separated from the base plate via wire EDM. The cutting speed of the machine was chosen as 0.7 mm/min and the thickness of the wire was 0.25mm. The cutting speed was chosen as low as possible in order to eliminate the possibility of heating at the cutting zone which might affect the distortion results. Figure 5-49 and Figure 5-50 show the parts separated from the base plate.

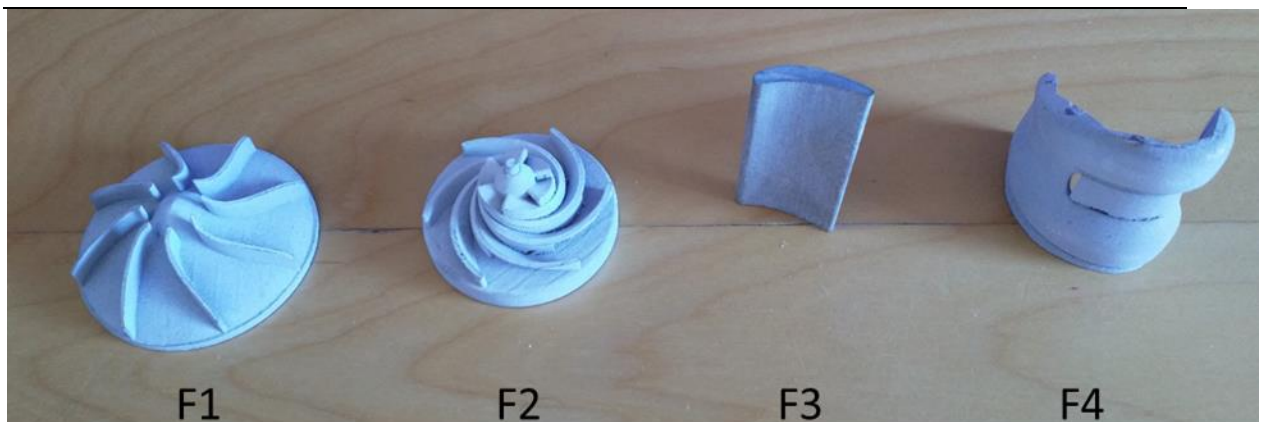


Figure 5-49- Impeller, Impeller_5Axis, Fan Blade and Knee Implant

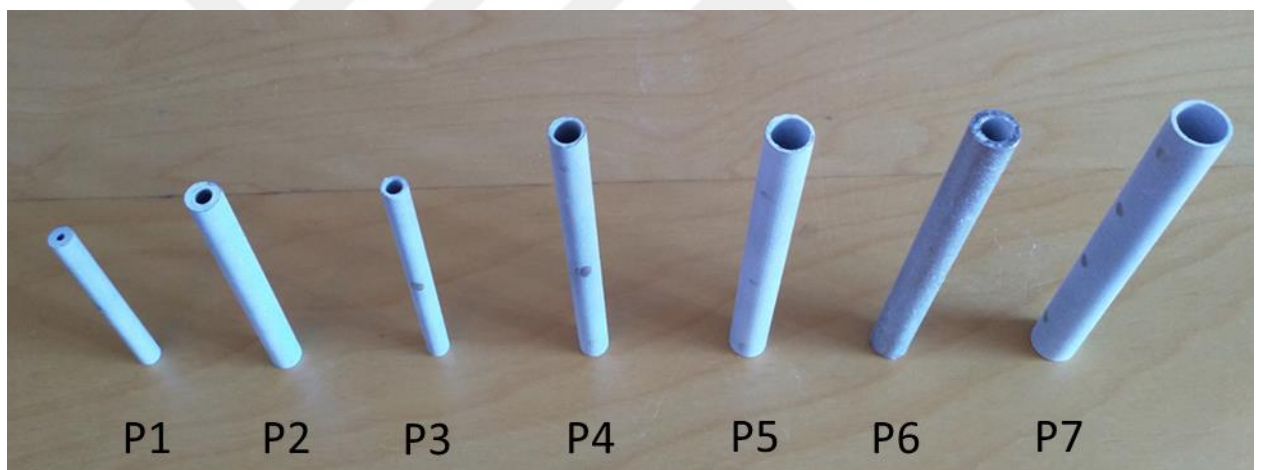


Figure 5-50- Pipe-6-2-60, Pipe-8-2-80, Pipe-6-1-80, Pipe-8-1-100, Pipe-10-1-100,
Pipe-10-2-100, Pipe-12-1-100

Experimental measurements were again performed using Comet 6 - High end 3D sensor.
The scan results of the parts are shown in Figure 5-51.

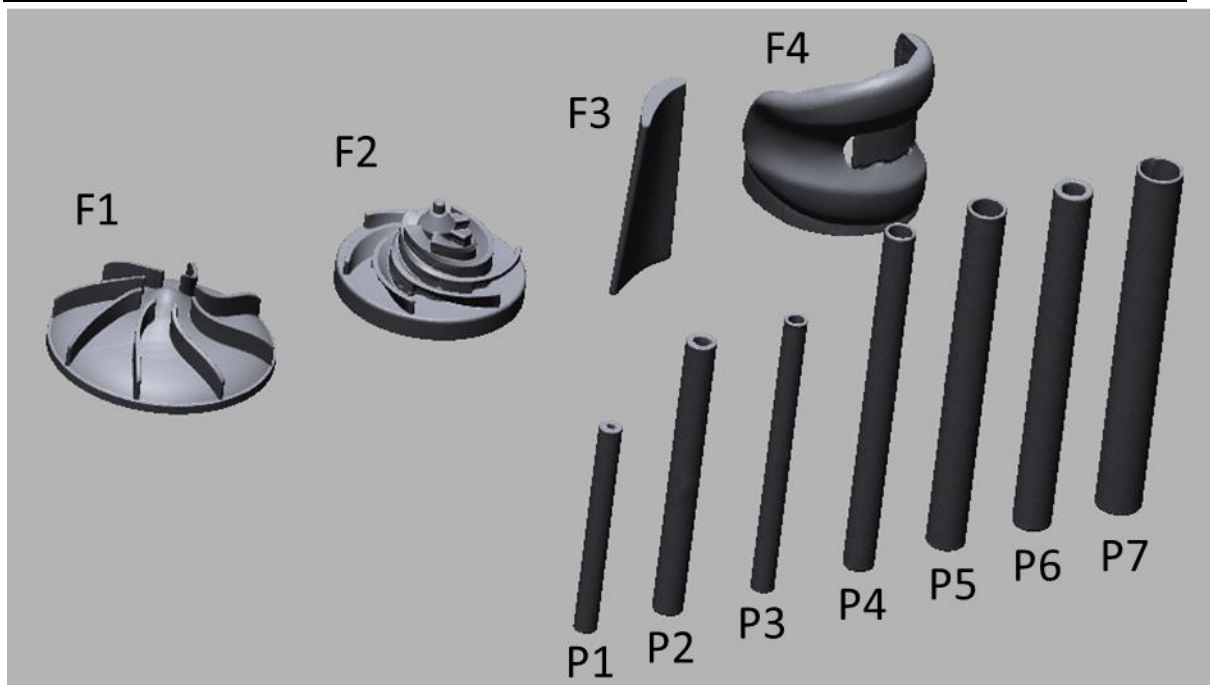


Figure 5-51- Experimental measurements (Scanned Data)

The circularity and perpendicularity of the pipes were obtained from the experimental results. Figure 5-52 demonstrates the deviation (c) in diameter and the deviation angle (β) of the pipes. It should be noted that the pipes (P1-7) have a deviation between 0.02-0.05 mm in diameter. The deviation angle of the pipes are given in Table 5-14.

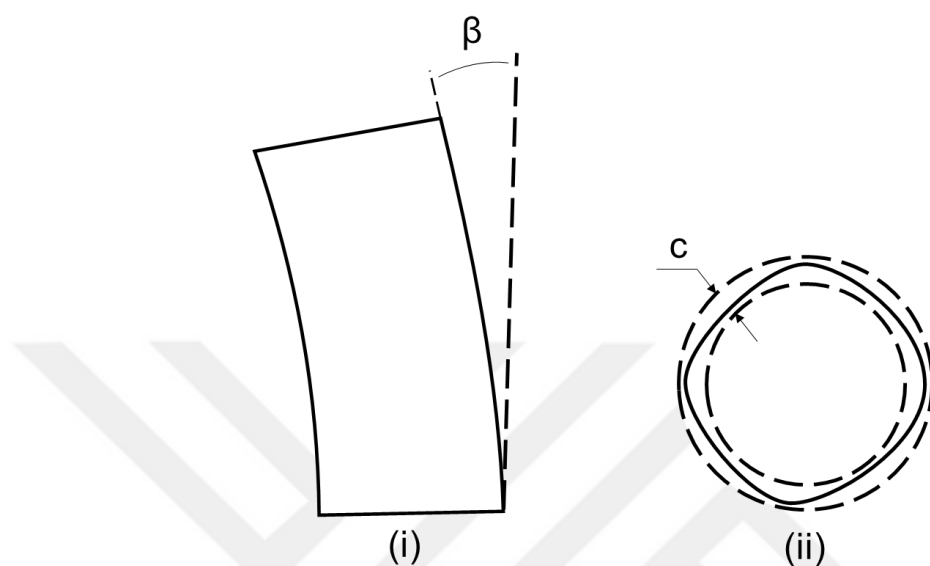


Figure 5-52-(i) Deviation angle (ii) circularity

Table 5-14- Deviation angle (β) of the pipes

Part Name	Part Label	Deviation angle [°]
Pipe-6-2-60	P1	0.46
Pipe-8-2-80	P2	0.47
Pipe-6-1-80	P3	0.35
Pipe-8-1-100	P4	0.39
Pipe-10-1-100	P5	0.58
Pipe-10-2-100	P6	0.38
Pipe-12-1-100	P7	0.27

5.4.3 Comparison: Stage II

For the comparison of Stage II results, Siemens NX was used. The simulation and experimental results are aligned and checked for deviations. The points, which have the highest deviations, are picked and compared. The comparison of the simulation and experimental results of Stage II are shown in Figure 5-53 to Figure 5-63. The comparison of the experimental and simulation results is given in Table 5-15 to Table 5-25. The average prediction errors for Stage II are given in Table 5-26.

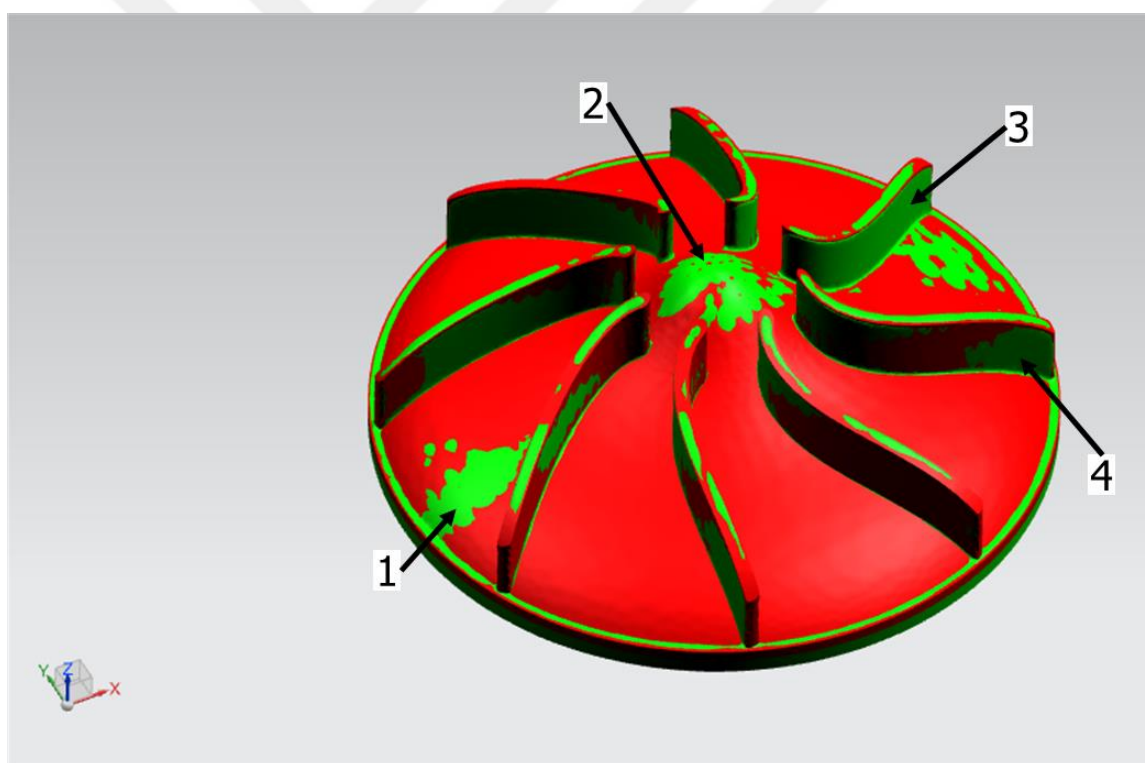


Figure 5-53- F1, Comparison of simulation (red) and experimental (green) results

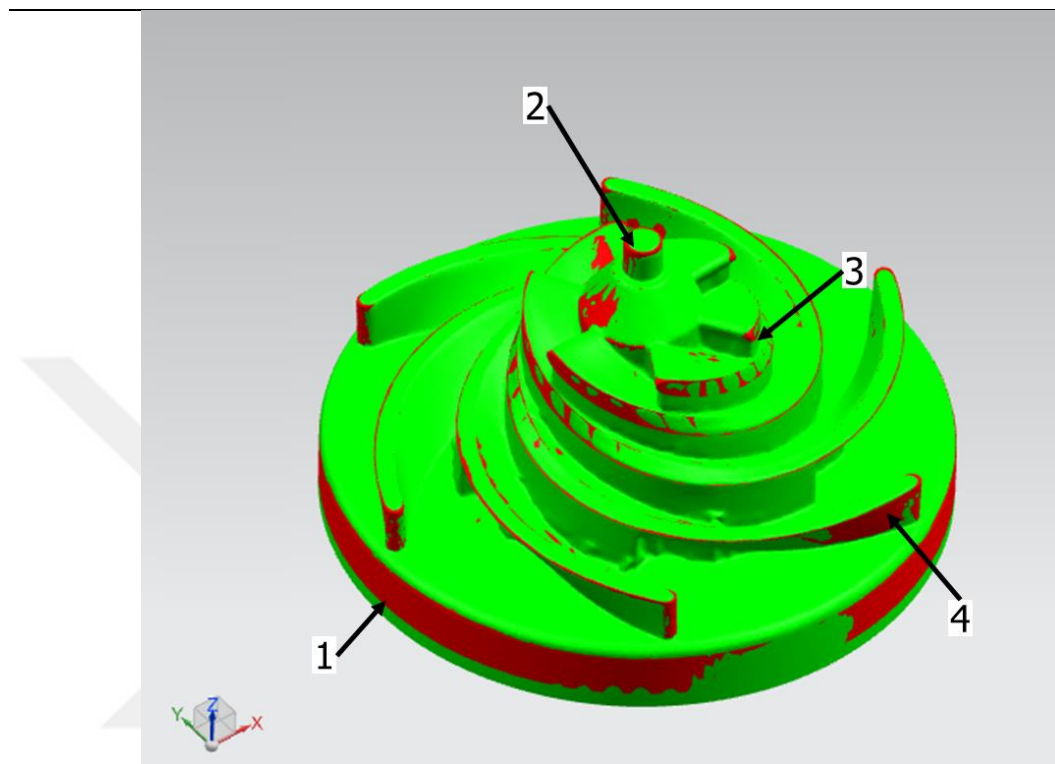


Figure 5-54- F2, Comparison of simulation (red) and experimental (green) results

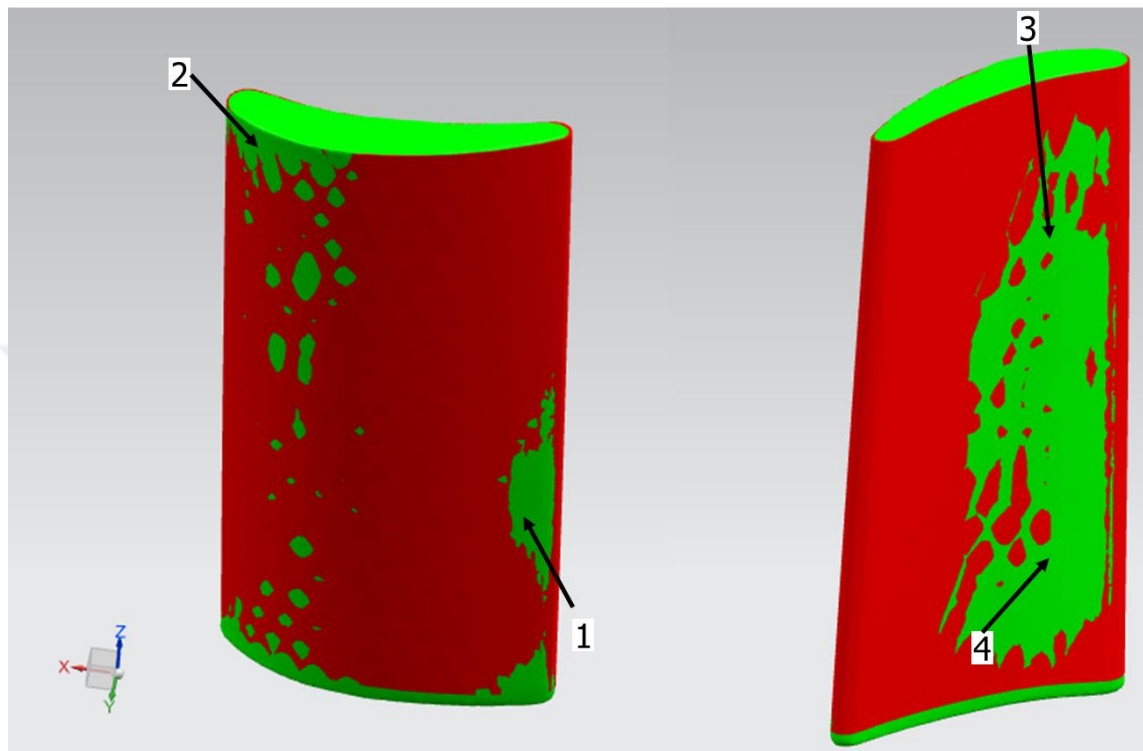


Figure 5-55- F3, Comparison of simulation (red) and experimental (green) results

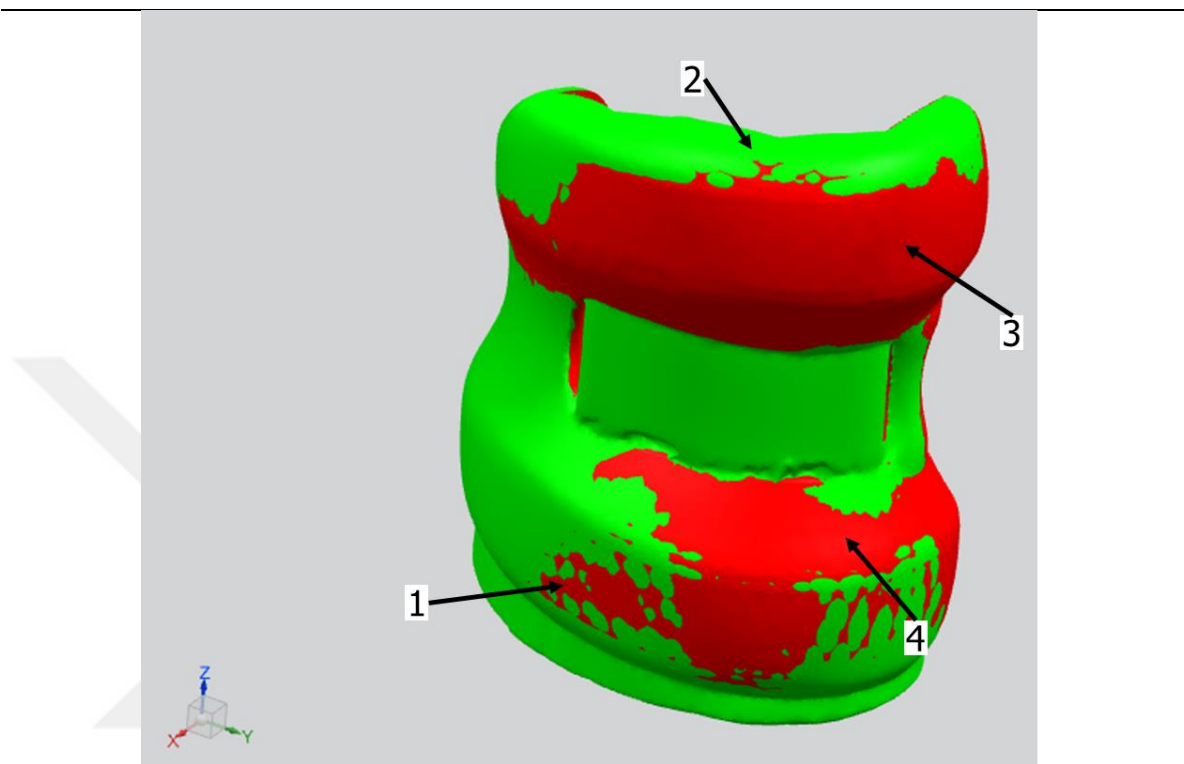


Figure 5-56- F4, Comparison of simulation (red) and experimental (green) results

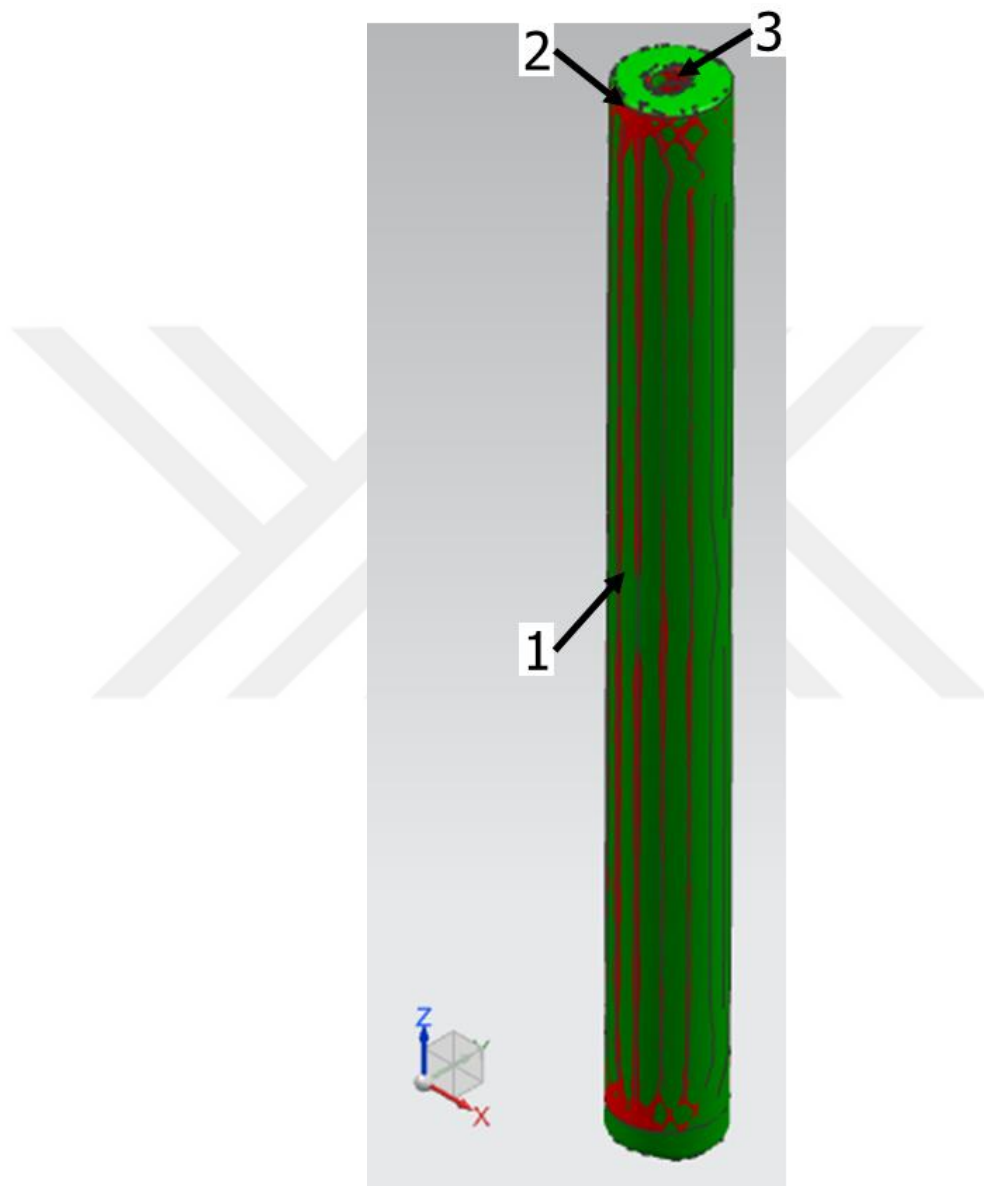


Figure 5-57- P1, Comparison of simulation (red) and experimental (green) results

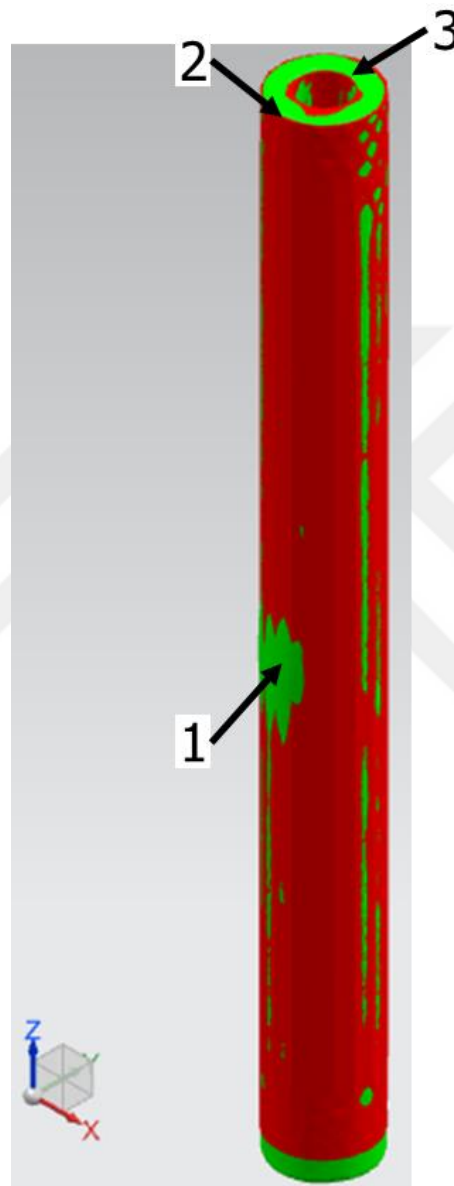


Figure 5-58- P2, Comparison of simulation (red) and experimental (green) results

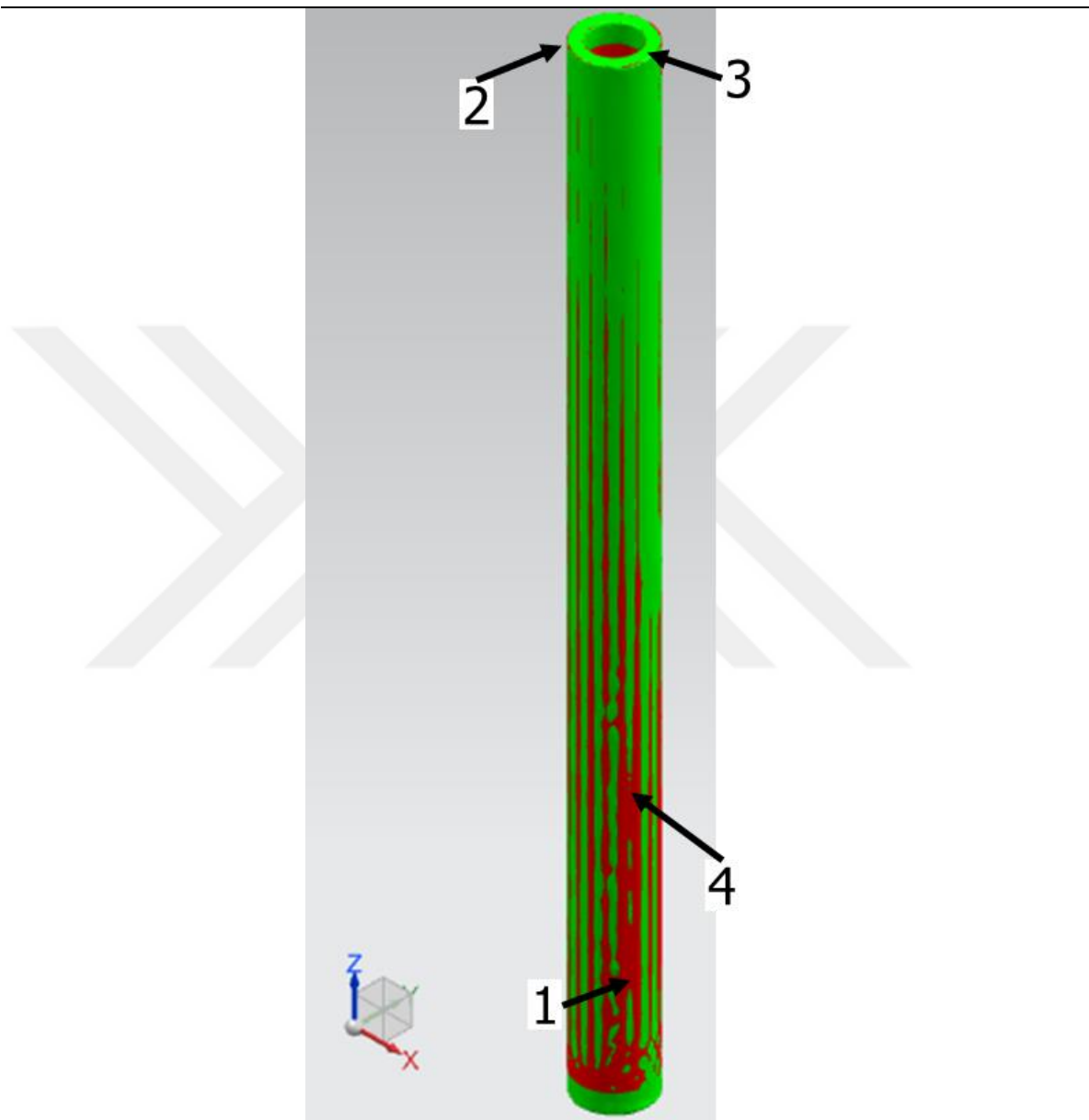


Figure 5-59- P3, Comparison of simulation (red) and experimental (green) results

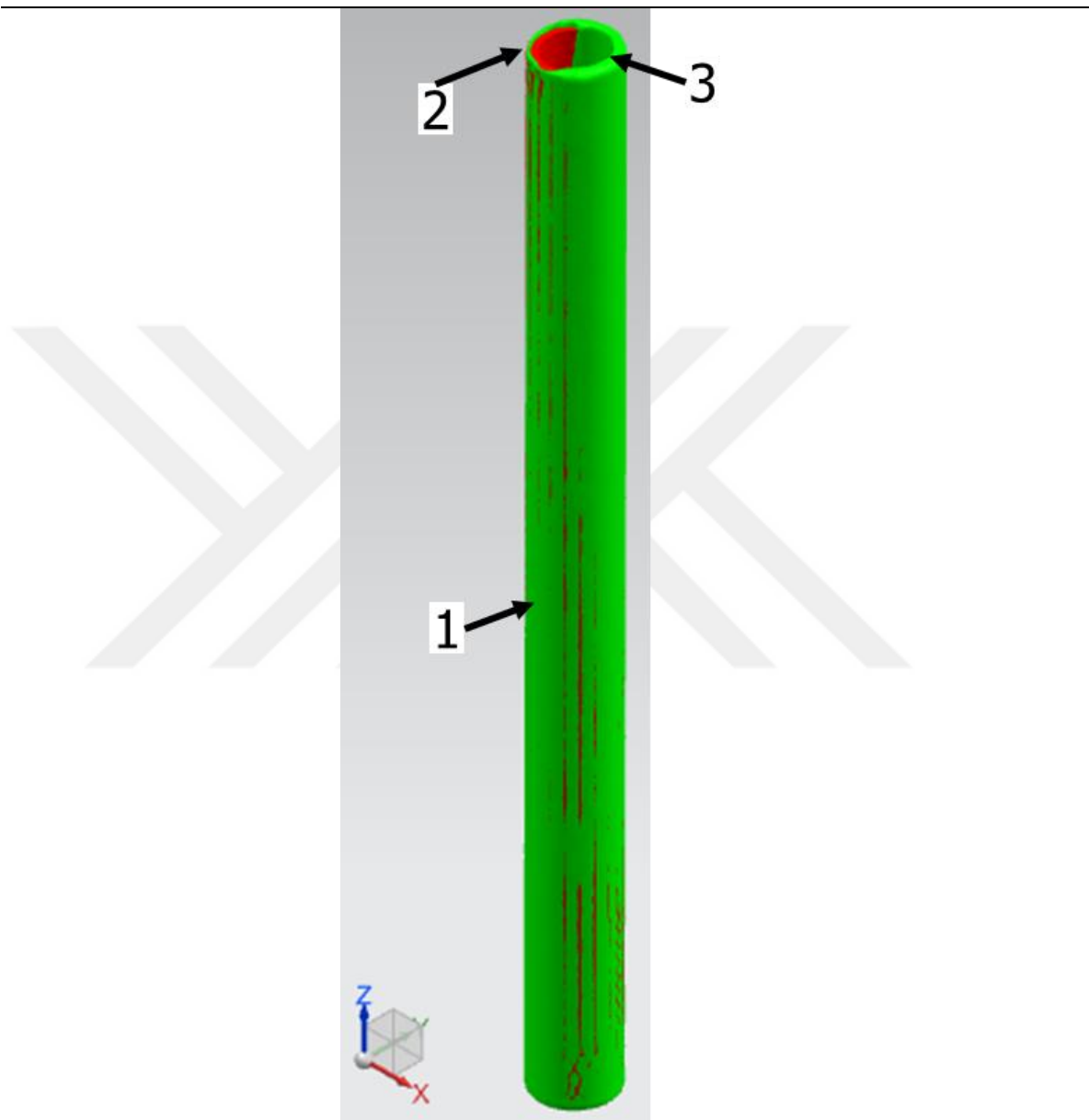


Figure 5-60- P4, Comparison of simulation (red) and experimental (green) results

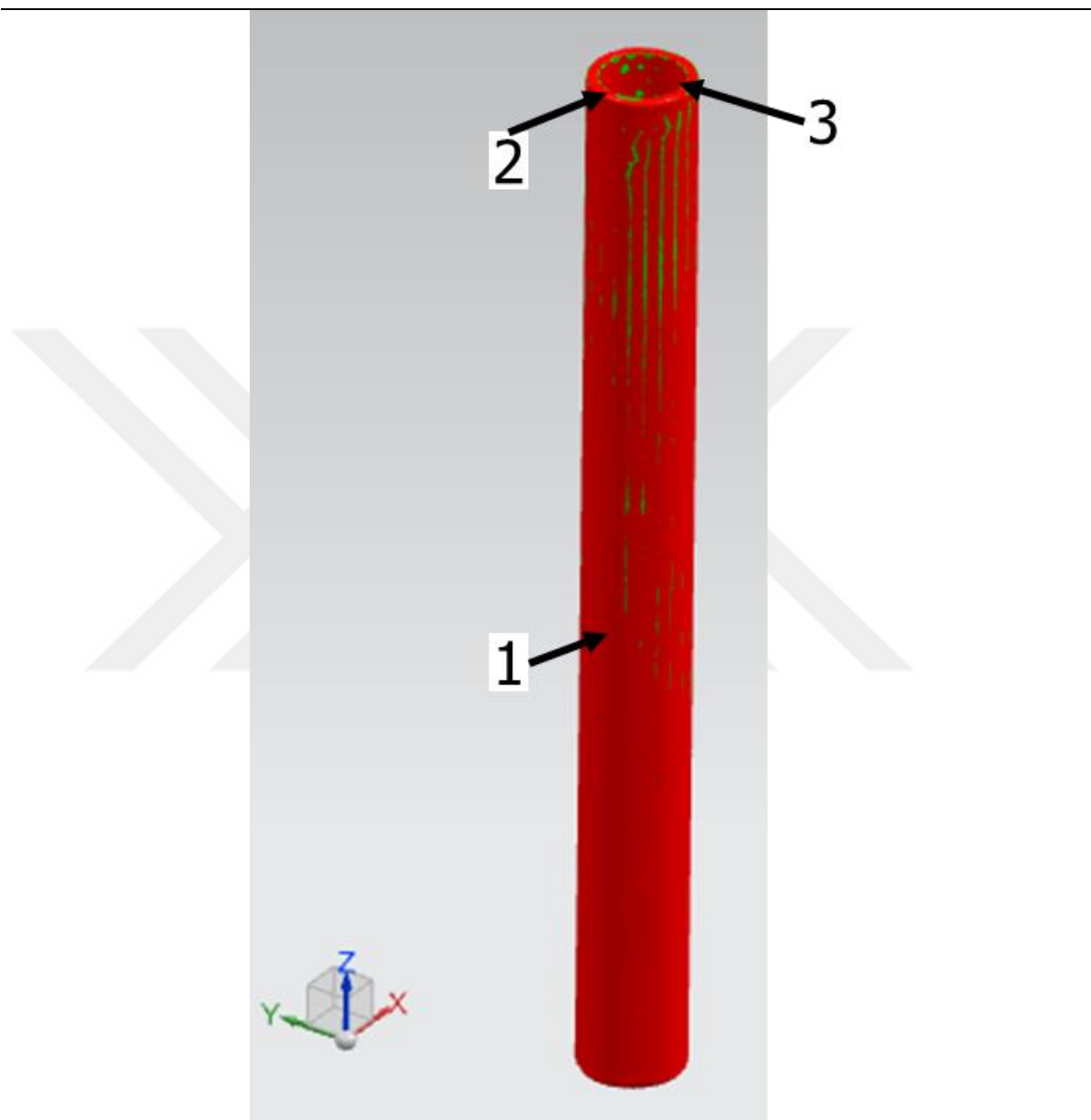


Figure 5-61- P5, Comparison of simulation (red) and experimental (green) results

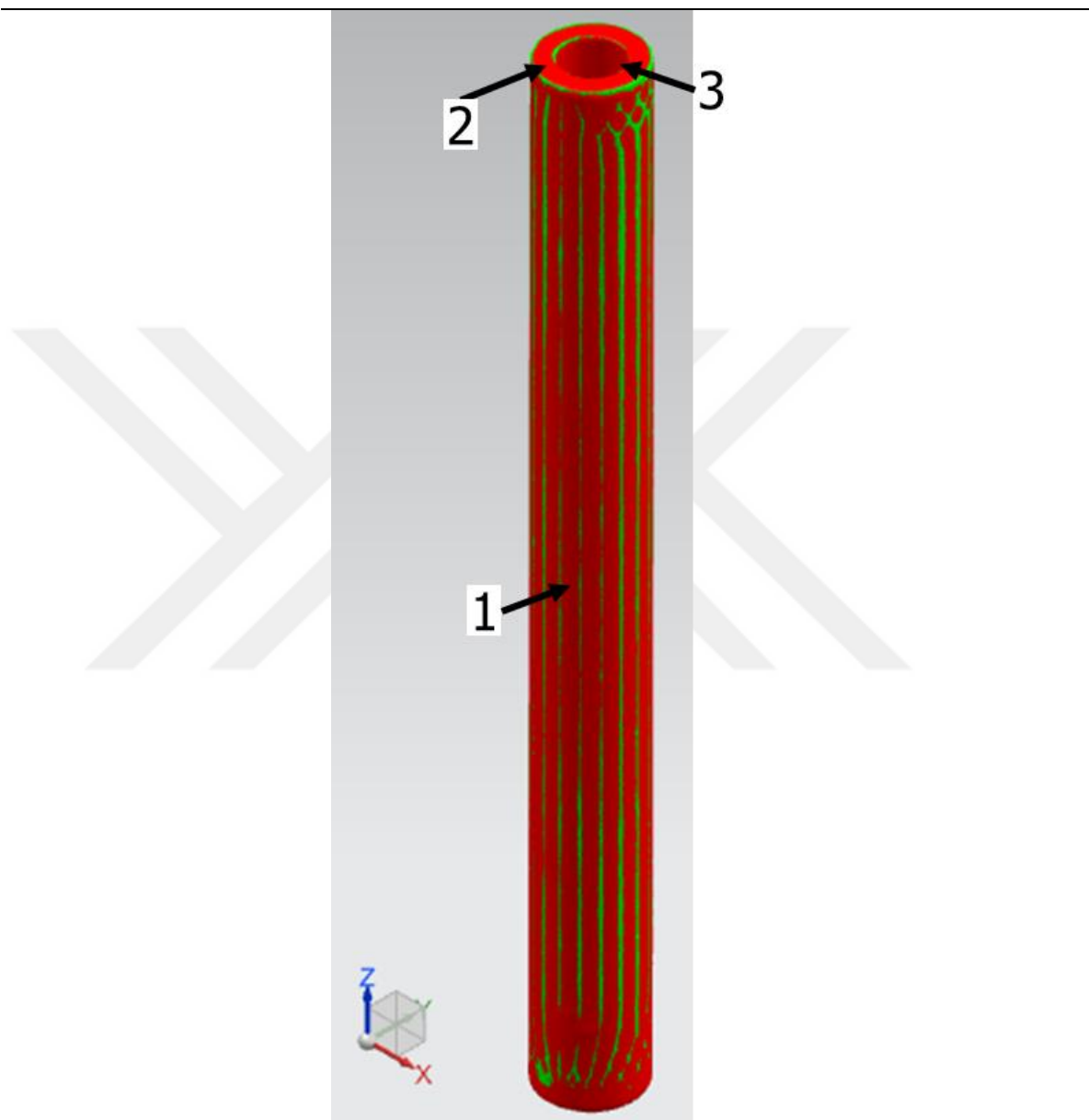


Figure 5-62- P6, Comparison of simulation (red) and experimental (green) results

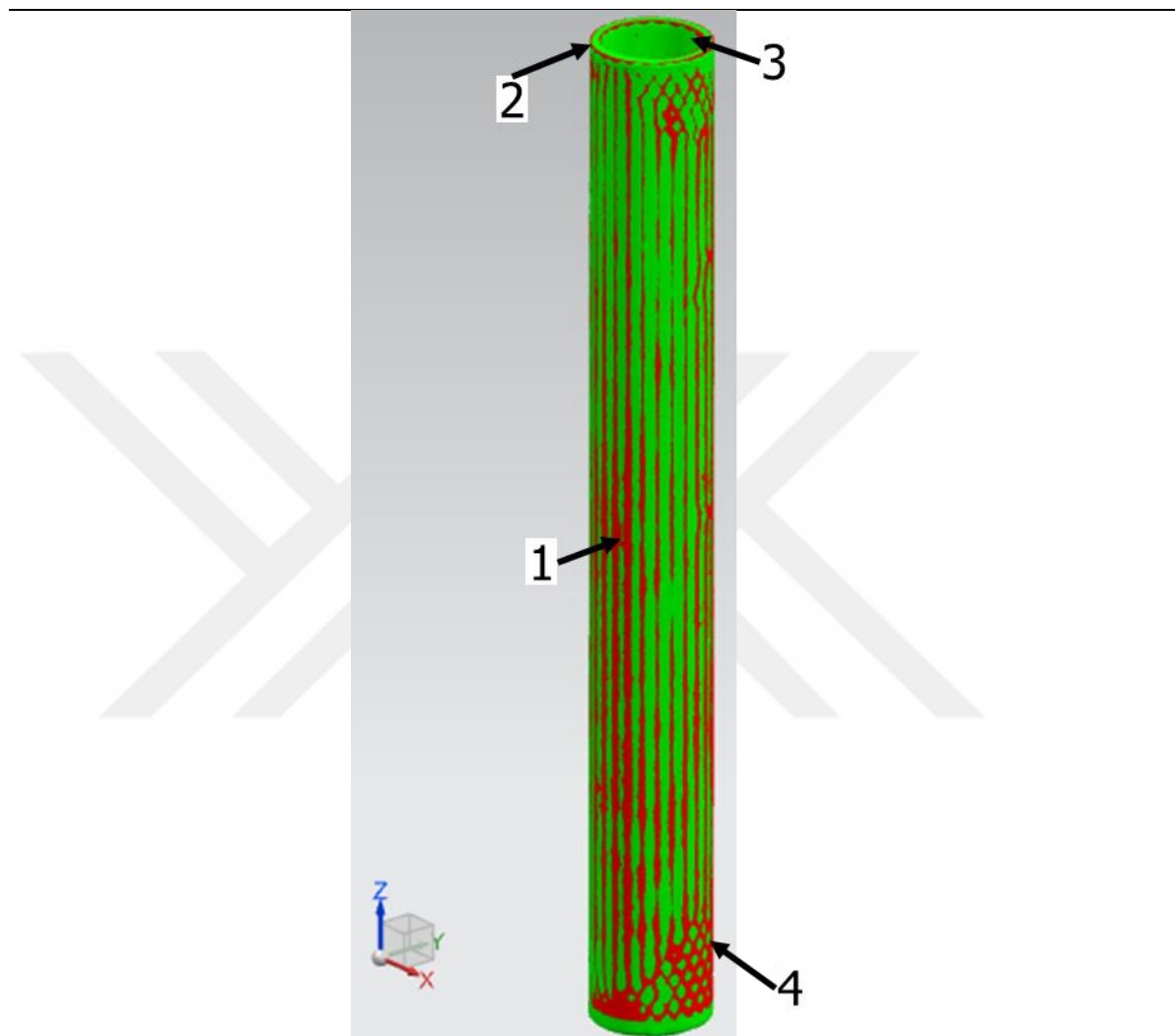


Figure 5-63- P7, Comparison of simulation (red) and experimental (green) results

Table 5-15- Comparison of the developed model and experiment for the impeller

Point Label	Experiment [μm]	Simulation [μm]	Prediction Error (%)
F1-1	136	123	10
F1-2	214	189	12
F1-3	248	211	15
F1-4	158	144	9

Table 5-16- Comparison of the developed model and experiment for the impeller_5Axis

Point Label	Experiment [μm]	Simulation [μm]	Prediction Error (%)
F2-1	18	22	19
F2-2	53	45	18
F2-3	28	33	17
F2-4	11	13	24

Table 5-17- Comparison of the developed model and experiment for the fan blade

Point Label	Experiment [μm]	Simulation [μm]	Prediction Error (%)
F3-1	14	11	21
F3-2	32	23	28
F3-3	22	18	18
F3-4	10	7	30

Table 5-18- Comparison of the developed model and experiment for the knee implant

Point Label	Experiment [μm]	Simulation [μm]	Prediction Error (%)
F4-1	245	322	31
F4-2	1157	1030	11
F4-3	713	834	17
F4-4	269	340	26

Table 5-19- Comparison of the developed model and experiment for the pipe-6-2-60

Point Label	Experiment [μm]	Simulation [μm]	Prediction Error (%)
P1-1	294	259	12
P1-2	478	564	18
P1-3	450	540	20

Table 5-20- Comparison of the developed model and experiment for the pipe-8-2-80

Point Label	Experiment [μm]	Simulation [μm]	Prediction Error (%)
P2-1	447	362	19
P2-2	638	734	15
P2-3	665	759	14

Table 5-21- Comparison of the developed model and experiment for the pipe-6-1-80

Point Label	Experiment [μm]	Simulation [μm]	Prediction Error (%)
P3-1	39	51	32
P3-2	496	422	15

P3-3	473	426	10
P3-4	112	142	27

Table 5-22- Comparison of the developed model and experiment for the pipe-8-1-100

Point Label	Experiment [μm]	Simulation [μm]	Prediction Error (%)
P4-1	362	308	15
P4-2	658	599	9
P4-3	697	614	12

Table 5-23- Comparison of the developed model and experiment for the pipe-10-1-100

Point Label	Experiment [μm]	Simulation [μm]	Prediction Error (%)
P5-1	506	603	19
P5-2	1014	1157	14
P5-3	1002	1130	12.7

Table 5-24- Comparison of the developed model and experiment for the pipe-10-2-100

Point Label	Experiment [μm]	Simulation [μm]	Prediction Error (%)
P6-1	305	382	25
P6-2	628	716	14
P6-3	672	740	10

Table 5-25- Comparison of the developed model and experiment for the pipe-12-1-100

Point Label	Experiment [μm]	Simulation [μm]	Prediction Error (%)
P7-1	214	186	13
P7-2	475	364	23.5
P7-3	314	384	22.2
P7-4	34	45	32

Table 5-26- Average prediction % error for each part (Stage II)

Part Name	Part Label	Average Prediction Error (%)
Impeller	F1	12
Impeller_5Axis	F2	20
Fan Blade	F3	24
Knee Implant	F4	21
Pipe-6-2-60	P1	16.6
Pipe-8-2-80	P2	16
Pipe-6-1-80	P3	21
Pipe-8-1-100	P4	12
Pipe-10-1-100	P5	15
Pipe-10-2-100	P6	16
Pipe-12-1-100	P7	19.5

5.5 Discussion

The average prediction errors are between 9.6 -22 % for hollow structures for Stage I and between 12-21% for Stage II (Table 5-13 and Table 5-26). It can be concluded that the prediction errors are in the acceptable range. For the freeform structures, the simulation and experimental results agree well for both stages except that the distortion results of knee implant for Stage I, are higher than expected (30%), which was due to the support structure that the simulation did ignore.

The reason behind a two-stage experiment is to see whether the developed model can predict the residual stresses during the additive manufacturing process.

Comparing Stage I results of the hollow structures, the orientations of the distortions are different from each other. The developed model predicts the orientation before the separation of the parts from the base plate. The fan blade is distorted about 293um (Simulation: 280 um) in Stage I. After detachment from the base plate, it was seen that the distortion of the fan blade was decreased to 24 um.

These results prove that the developed model not only predicts the deflection after the additive manufacturing process but also the residual stresses occurring during the process. It can be said that the developed thermo-mechanical model can be utilized for the optimization of the additive manufacturing process of freeform and hollow geometries in terms of residual stress and distortion.

5.6 Summary

In this chapter, a two-stage experiment was carried out in order to test the performance of the developed thermo-mechanical model. Four freeform geometries and seven hollow structures are additively manufactured in EOS M290 machine. After the manufacturing process, parts attached to the base plate were scanned by COMET 6 High end 3D sensor. After alignment of CAD, simulation and experimental data in Siemens NX environment,

comparisons were made in Matlab demonstrating that the distortions are lower compared to Stage II in terms of magnitude.

After Stage I, the parts were cut using wire EDM. It should be noted that the cutting parameters are taken in such a way as to eliminate the possibility of heating in the cutting zone. The comparisons are performed in Siemens NX environment. The experiment scan data and simulation results were aligned. Then, the deviations were checked and the highest deviation points were compared.

The calculated distortions of the developed model and the measured distortions of the experiments were compared for both stages for both structure types: freeform and hollow. For both types of structures, the prediction errors (for both stages) were in the acceptable range. Ignoring the effect of the support structure in the developed model led to the prediction error in Stage I distortion results of the knee implant.

This work introduces an analytical approach for simple geometries and a fast FEM based residual stress and distortion prediction tool that allows modeling of the large-scale complex parts in direct laser metal sintering.

Chapter 6

CONCLUSION

In this thesis, a wide literature review of additive layer manufacturing (focusing on direct laser metal sintering) was carried out to check the literature and industrial needs of process modeling of DMLS. It turns out that there is a need of a thermomechanical model for the accurate prediction of temperature field, residual stresses and distortions occurring during the direct laser metal sintering, which is quickly computable, applicable on freeform geometries, suitable for the optimization of process parameters.

A thermal model was developed, under the assumptions of the constant laser absorption coefficient, an isotropic material behavior, from which the effects the material properties and scanning parameters on the temperature distribution and molten pool geometry during the DMLS process can be predicted. Including the powder-liquid-solid transformation and a 3D heat source model, the developed model can predict the temperature evolution and the dynamic molten pool geometry. Two comparisons were made from the studies found from literature and two experiments were performed to validate the developed model. The developed thermal model accomplished to simulate:

- Powder bed model with a 3D heat source model,
- Different materials with temperature dependent properties,
- Freeform geometries,
- The temperature field and the dimension of the molten pool with a prediction error below 20%,

An analytical model was developed in order to investigate the mechanism between process parameters and residual stresses. Due to the geometrical limitation of analytical approach, four different FEM model were developed. Comparing these models in terms of

prediction accuracy, computation time and prerequisites, one of the models have been selected for experimental validation. Five different experiment sets were carried out: four of them focused on the residual stresses and distortions occurring after the DMLS process and one of them focused on the residual stresses and distortions occurring before and after DMLS process.

The developed mechanical model, under the assumptions of constant thermal expansion coefficient, neglecting the effects of phase transformations on residual stresses, can predict residual stresses and distortions occurring during and after the DMLS process. It should be noted that, in this study, support structures were excluded to compare the simulation and experimental results in order to see the effects of support structures on residual stresses and distortions. Providing the support geometries, the developed model can simulate the effect of support geometries as well.

The developed mechanical model accomplished to simulate:

- 3D mechanical model with an isotropic material model including plasticity (hardening mechanism can be added if it is available for the material)
- Simple, complex and freeform geometries,
- Simple, semi-complex geometries with a prediction error below 10% and freeform geometries with a prediction error below 24%,
- The different distortion orientations in the same DMLS build batch,
- The residual stresses and distortions for both cases:
 - During the DMLS process
 - After the DMLS process
- An industrial-sized part between 3 to 20 minutes depending on the geometrical complexity.

The developed thermal and mechanical models can be used as a platform for further research purposes such as optimization of scanning parameters, optimization of support geometries and compensation of CAD data.



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