JANUARY 2020 M.Sc. in Mechanical Engineering MEHMET BURAK ÖNAL

REPUBLIC OF TURKEY

GAZİANTEP UNIVERSITY

GRADUATE SCHOOL OF NATURAL & APPLIED SCIENCES

MELT POOL TEMPERATURE DISTRIBUTION ANALYSIS IN SELECTIVE LASER MELTING PROCESS

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IN
MECHANICAL ENGINEERING

BY
MEHMET BURAK ÖNAL

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M.Sc. Thesis

in

Mechanical Engineering

Gaziantep University

Supervisor

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by

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This is to certify that we have read this thesis and that in our consensus opinion it is fully adequate, in scope and quality, as a thesis for the degree of Master of Science.

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Mehmet Burak ÖNAL

ABSTRACT

MELT POOL TEMPERATURE DISTRIBUTION ANALYSIS IN SELECTIVE LASER MELTING PROCESS

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The main objective of this research is to investigate the importance of selective laser melting (SLM) process, with the application of laser on powder metals. SLM is one of the most popular methods to construct complex geometrical shape and advanced in additive manufacturing process for metallic materials. In the thesis, numerical modelling and simulations of temperature distribution of melt pool were analysed in SLM process. In this process, simulation of melting area and its situation in selected region by applied laser power is quite crucial to provide a better control. Temperature distribution of melt pool geometry can be defined by heat affected zone (HAZ), where is just before the phase transformation, melting region is obtained and this region is introduced the fusion of powders to complete needed geometry. There is a need for the control types and prediction. In order to distinguish the case of metallic powders, the simulation take an active role in this type of applications. In this study, demonstration of the dimensional simulation on the temperature distribution of melt pool is examined by user friendly customized methodology has been developed. According to laser interaction powder metals were instantly being affected of time and temperature with laser power. The results of the simulation have showed that the instantaneous position of laser beam effects for temperature distribution on the surface.

Key Words: Selective Laser Melting, Temperature Distribution, Melt Pool Temperature, Additive Manufacturing

ÖZET

SEÇİCİ LAZER ERGİTME İŞLEMİNDE ERGİME HAVUZU SICAKLIK DAĞILIMININ ANALİZİ

ÖNAL, Mehmet Burak
Yüksek Lisans Tezi, Makine Mühendisliği
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65 sayfa

Bu araştırmanın temel amacı, toz metallerin üzerinde uygulanan Seçici Lazer Ergitme (SLM) işleminin önemini araştırmaktır. Katı serbest şekilli üretim tekniği olan SLM, metalik malzemeler için birçok katkı üretim prosesi de dahil olmak üzere karmaşık geometrik şekil oluşturmak için en popüler yöntemdir. SLM işleminde eriyik havuzunun sayısal modellemesi ve sıcaklık dağılım simülasyonları çalışılmıştır. Bu süreçte daha iyi bir kontrol sağlamak için lazer gücü uygulanan erime alanının ve seçilen bölgedeki durumunun simülasyonu oldukça önemlidir. Ergime havuzu geometrisinin sıcaklık dağılım şekli, faz dönüşümünden hemen önceki ısıdan etkilenen bölge (HAZ) olarak tanımlanabilir; erime bölgesi elde edilen bu bölge, istenen geometriyi tamamlamak için tozların kaynaşmasını sağlar. Bu işlemde kontrol tiplerine ve tahmine ihtiyaç duyulmaktadır. Bu tip uygulamalarda metalik tozların durumunu ayırt etmek için, simülasyon aktif rol oynamaktadır. Bu çalışmada, kullanıcı dostu olacak şekilde uyarlanmış bir metodoloji ile SLM sürecindeki eriyik havuzunda gerçekleşen sıcaklık dağılımının boyutsal simülasyon gösterimi incelenmiştir. Lazer ile toz metal etkileşimindeki anlık sıcaklık, lazer gücü ve zamanla etkilenmektedir. Lazer ışınının yüzeydeki sıcaklık dağılımına etkisi, anlık olarak simulasyon sonuçlarında sunulmuştur.

Anahtar Kelimeler: Seçici Lazer Ergitme, Sıcaklık Dağılımı, Ergime Havuzu Sıcaklığı, Eklemeli İmalat

''Dedicated to my family''

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LIST OF SYMBOLS

Ti	Titanium
C	Specific Heat Capacity
K	Kelvin
k	Thermal Conductivity
q	Heat Flux
t	Time
β	Stability Factor

LIST OF ABBREVIATIONS

SLM	Selective Laser Melting
SLS	Selective Laser Sintering
AMP	Additive Manufacturing Process
MATLAB	Matrix Laboratory
RP	Rapid Prototype
3D	Three Dimensional
CAD	Computer Aided Design
HAZ	Heat Affected Zone
FEM	Finite Element Method

CHAPTER 1

INTRODUCTION

1.1 Introduction

In this section, the significance of the additive manufacturing process and its position in the manufacturing industry are presented in general. The purpose and content of this thesis are also presented in this section.

1.2 Additive Manufacturing Process in Industry

In the last years, the additive manufacturing process have been the most popular methods in manufacturing industry. Additive manufacturing process have been used to perform high complex shape and critical geometrical pieces manufacturing on industries applications, which is aeronautical, aerospace, automotive, architecture, consumer products, education, electronics, entertainment, nanotechnologies, repair, tooling, art-jewellery, visualization, medical: implants, orthopaedics and tissue engineering etc. [1].

Additive Manufacturing meaning is joining the material group on collect the required geometry process using from taken three dimensional (3D) model datas in compatible situation, roughly. Additive Manufacturing words meanings are explained by additive processes, layer manufacturing, additive layer manufacturing, additive fabrication, additive techniques, and freeform fabrications. All these meanings are adapted with every types of materials consisting of metals, polymers - thermoplastics, ceramics, biochemical, and composites, comprehensively [2].

In comparison with the other manufacturing processes, Traditional/Conventional manufacturing process fall short of the expectations about new style industrial manufacturing and applications of the complex part all geometrical shapes. All requirements of industrial high complexity products are manufacturing by layer by layer and efficient control to each layer with additive manufacturing method rather than removing material from the parts via conventional manufacturing process. Adding material layer upon layer to obtain desired shape of part without the needed external and internal parts and requirement for any tooling process [3].

Without outer process in machining and freeform, additive manufacturing pioneer the technology for these sectors to obtain high accuracy and much more complexity of needed shape of objects. When commonly using the additive manufacturing in manufacturing process, this method is covered the expenses of machining and its negative effect on this sector.

Especially manufacturing of the inner detail of complex part, AMP is often the exclusively technical solution.

1.3 Background on Additive Manufacturing and Applications

First additive manufacturing method was introduced in the beginning of 1990s and utilize to produce based models and prototypes. The Moral Right of “Selective Laser Sintering with assisted powder handling” has been taken from U.S. Patent by Beaman and Deckard [4]. Additive Manufacturing Process has been developed and used on rapidly changing and increase the effectiveness of advanced manufacturing technology day by day with commonly research, Since in 1990s. In Addition, this research will be increased with competing demand in some industries; especially biomedical, automotive, aircraft, defence and aerospace industrial applications.

Classification of Additive Manufacturing process can be declared into four category, that is shown as below by Figure 1.1.

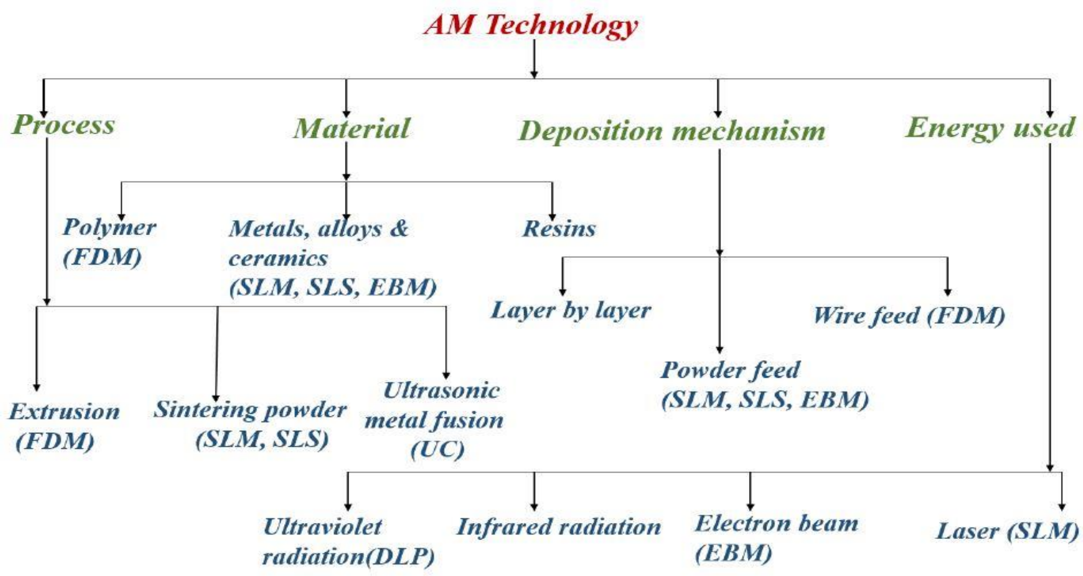

Figure 1.1 Category of the additive manufacturing technology [5]

1.4 Objectives of the Thesis

In this study, numerical modelling and simulations of temperature distribution of melt pool were done in selective laser melting (SLM) process. Temperature distribution of melt pool geometry can be defined by heat affected zone (HAZ), where is just before the phase transformation, melting region is obtained and this region is introduced the fusion of powders to complete needed geometry of shape. The simulation of melting region and the case of melt pool in selected zone by applied laser power is quite crucial to provide a better control.

Selection of appropriate process parameters are so critical phenomena in SLM process. The process parameters for SLM process describe as;

- Laser related parameter,
- Scan related parameters,
- Powder related parameters,
- Temperature related parameters.

Owing to parameters variety and much number of strategy, lots of study are needed to investigate the related parameters effects on the process. In this thesis, the effect of considered temperature related parameters are presented also the others related parameters. Essentially, temperature of the selected metallic powders, locally heated and melted zone, process time, size and dimensions of the model, on the thermal properties are theoretically investigated.

To research of locally laser melted of the powder metal is performed with linear movement on the axial midpoint of the surface. For this purpose, melt pool temperature distribution is modelled and simulated by using discrete element method with implicit and explicit method. Metallic powders sequences are utilized in mathematical form by central difference method. Modelling and simulations were performed to identify/designate the temperature distribution of HAZ by using MATLAB code (script) programming.

The SLM is repute in metal working industries as a significant method for many challenging additive or conventional manufacturing process. However, several quantities of experimental procedure take a long time and more expensive owning cost. Therefore simulation is a good method for cost reduction and to eliminate the samples for faster at long term and better results before the manufacturing. This situation is similar to rapid prototype process [6].

Furthermore, in this study the macroscopic inspections were implemented to interpret the meaning of simulation by computer programming. The effects of several parameters will be studied by considering some essential mechanical characteristics of the metallic powders fusion on the goal of topological optimisation and the heat affected zone of the selected region and its surrounding.

This thesis consist of six chapters: First chapter is related with the introduction section about the SLM process.

Second chapter deals with literature related with additive manufacturing process, selective laser melting and selective laser sintering (SLS) researches.

In chapter 3, theoretical knowledge and general information about SLM are mentioned. Additionally, this chapter mentions about the additive manufacturing process.

Chapter 4 describes the mathematical modelling of melt pool temperature distribution in SLM. Derivation of mathematical formulas and approach strategies are given in this chapter.

Chapter 5 deals with result and discussion of melt pool temperature distribution simulation model. The results of simulation model are presented in this section with illustrated frames, consecutively.

Mathematical modelling and simulation of melt pool results are presented and discussed in Chapter 6.

All conclusions drawn from the whole work are pointed in Chapter 7. Future works and recommendations are also given in this chapter.

CHAPTER 2

LITERATURE SURVEY

2.1 Introduction

In literature survey section, some of the prior studies about selective laser melting (SLM) are expressed in additive manufacturing process. Some of literature about using of different materials, laser heating, melt flow during the SLM, thermal phenomena on heated surface by a laser beam, selective laser sintering, nodes temperature simulation and importance of the thesis is also described inside of this chapter.

2.2 Literature Survey

Selective laser melting (SLM) method was developed as an importance industrial applications and has been prepared to organize serial production. Selective laser melting has got great capacity for fabricating complex geometries using directly CAD models providing metal-based powder-bed fusion system. Metal parts with complex geometries can be produced like in serial production providing an advantage. A number of materials used such as; Ni-based super alloys, Ti-based alloys, Al-based alloys, steels and composites. Many studies have been performed on the microstructures with mechanical properties. Problems seen in SLM processes were noticed as the thermal distortion of the model during forming period. Selective laser sintering (SLS) uses a laser to sinter powdered plastic material to a solid 3D model, bed fusion systems are plastic based. Thus, SLM process and SLS process differs in the way of the full melting of powders or their partial melting in a way.

This method was firstly patented by Fockele and Schwarze, in Germany Patent and Trademark Office in 1998s [6].

As far as the sectorial importance of selective laser melting in additive manufacturing process, the interest of researchers for this topic also rising up, day by day.

2.3 Survey on Laser Sintering and Selective Laser Melting

The studies are summarized on Laser Sintering (LS) and Selective Laser Melting (SLM) as the following.

Safdar et al. (2007) have analysed enhanced thermal conductivity approach for predicting melt pool geometry and temperature distribution for Laser Melting Process (LMP) of mild steel (EN-43A). Finite volume method has been applied to simulate the transient effects of a moving beam. An experimental set up was prepared using 1.5 kW fiber coupled high power diode laser (LDL 160-1500) in the range of 800-980 nm. A comparison was performed between the experimental melt pool profile and the cross-sectional melt pool profiles found by CFD. In place of the solving some types of equations, estimation method of the melt pool geometry and temperature distribution were preferred. The results were not accurate enough [7].

Contuzzi et al. (2011) have worked on the influence of process parameters on the temperature distribution in 3D model by FE analysis. AISI 316L was considered. The powder-liquid-solid change was simulated by showing the nodes temperature [8].

Zeng et al. (2012) have presented a review of thermal analysis methods in Laser Sintering (LS) and Selective Laser Melting (SLM). Review has included 75 studies on SLM and temperature measures with LS. Different models were derived for the influence of sintered part shrinkage molten pool liquid flow and binding mechanism. Solutions were performed using numerical methods, FE was the reliable one [9].

Kubiak et al. (2015) have performed 3D mathematical modelling of thermal phenomena and phase transformations for the solid state accompanying laser-heating process. The kinetics of phase transformations were studied for thin sheets made of S 355 steel. Simulations were performed by using 3 different welding speeds [10].

Qiu et al. (2015) have studied on the melt flow into the surface structure and porosity development during SLM. Ti-6AL-4V samples were fabricated by LSM with different laser scanning speeds and powder layer thicknesses. These samples have shown low porosity (<1%). Power layer thickness has increased porosity level and surface roughness [11].

Yap et al. (2015) have then presented a review for SLM process as an additive manufacturing technique. In recent studies high power laser have provided chance of using different metallic materials; copper, aluminium and tungsten for example even if ceramic and composites. This study covered more than 200 references [12].

2.4 Survey on Thermal Analysis for Laser Sintering and Selective Laser Melting

Zeng et al (2012) have performed a review on thermal analysis methods to analyse thermal behavior during processes. Rosenthal solution was applied as an analytical approach for example. Various models were studied. But the numerical methods were seen to be reliable using commercial software's. SLM simulation model was predicted the optimal process parameters to simple form for users of laser sintering technology. Basic Fourier heat transfer equations were using for characterize the temperature distribution effects. Interplay with the process elements between the laser and powder bed, and also nonlinear material properties were expressed the last section. A detailed literature survey of the thermal modelling procedure in SLS is mentioned in this study [9].

Lavery et al. (2014) have given an extensive review of computational modelling of additive layer manufacturing. A number of modelling areas were recognized as thermal modelling of melting and solidification, residual stress modelling and topological and shape optimization of components. Thermal modelling was performed typically finite element methods or codes like ANSYS, FLUENT, CFX, ABAQUS. Residual stress prediction in multi-scale modelling was given. Different case studies were included as; Marangoni convection, powder melting (FLUENT), 3D Lattice-Boltzmann code in FORTRAN and ANSYS [13].

Fu and Guo (2014) have developed 3D finite element model to simulate multi-layer deposition of Ti-6Al-4V in SLM. Prediction model and validation were performed for the melting pool shape and dimensions. FEA package Abaqus/St was used. The effects of laser powder and material properties on molten pool geometry and temperature gradient were studied [14].

Romano et al. (2015) have presented finite element (FE) simulation of thermal modelling of laser melting. Thus the melt pool geometry and temperature distribution are found. The characteristics of Ti-6Al-4V, Stainless Steel 316 L and 7075 Al powders were compared and findings were presented [15].

Meier et al (2017) have given a comprehensive overview of existing approaches; macroscopic (the determination of residual stresses or dimensional distortion effects), mesoscopic (excessive surface roughness, residual porosity) and microscopic (microstructure resulting from the high temperature and heating-cooling rated occurred). Simulation based characterization of SLM was done by the finite element method (FEM), the finite difference method (FDM) and the finite volume method (FVM) [16].

In a very recent study, Rosso et al. (2018) have proposed a FEM of the SLM process with validation. Two models of laser-heat source have been used. Model validation was performed with an experimental set up using AISI 36L stainless steel A comparison was included between the simulated and experimental results [17].

2.5 Place of this Work in Literature

In this research, temperature distribution of melt pool in selective laser melting (SLM) process has been studied on the Ti-6Al-4V alloyed-metallic powder at the instant interaction relation. The previous researches are often related with a period of time and control the thermomechanical properties. They have been simulated especially using the commercial software programs. However, Our research serves a very important purpose, alternatively. Since, the implementation of the own script codes are controllable and user-serviceable to modify. This program is independent of any other commercial package or program modules, wherever is applied according to mathematical and technical rules. By using strategic approaches on the codes, the epideictic main idea of the other programs has been solved, clearly. The capability of requirements are depended on the universal programs, But this type of original programs were not given enough place in the studies. The place of this research in literature, try to fill the gap of selective laser melting process modelling and temperature distributions simulations by individual code methods, supported with computer programming.

In consequence, this study will contribute to rapid manufacturing technology that aims to produce parts quickly with multiple metallic powders. By controlling the melted powders and defect-free produced products, this process will be effectively used for direct-part fabrication for aerospace, tooling, defense industry, biomedical and other technologies.

CHAPTER 3

THEORY OF SELECTIVE LASER MELTING PROCESS IN ADDITIVE MANUFACTURING

3.1 Introduction

This chapter describes the strategy of additive manufacturing technology in step by step, and general information about rapid prototyping is presented with selective laser melting process. Fundamentals of selective laser melting process, its equipment and classification are also presented in that section.

The following section presents mathematical modelling of the thesis according to SLM process. After the examined the mathematical model, the general functions and formulas of the process are derived by using finite difference method. And also attain to be explained in detail by implicit method in central difference method.

3.2 Rapid Prototyping (RP)

Rapid Prototyping (RP) is utilizing to preprocess for rapidly creating a manufacturing parts with needed design in order to obtain the last release a product before the mass production of sales. Final products is manufacturing according to based model and prototypes, which is using on the reverse engineering to convert from physical model to digital model by data format, sometimes. Nowadays, RP is not only using the prototyping, but also much more purposes in development technologies.

3.3 Additive Manufacturing (AM)

In additive manufacturing process uses less material than conventional or subtractive manufacturing and any other casting process with molding and casting supporter elements. Additive manufacturing (AM) facilitates structure of rapid prototypes, creation of much more complex geometry, integrity of design flexibility, design interior creation. Moreover, AM techniques are not only enable to maximum strength, but also minimum weight of materials on design of parts prepare to manufacturing. This type is similar to natural effects, which is consistence of organic structure of style in manufacturing. Conventional machining, milling operations, dies, and molds, etc. are not allowed these facilities. All these manufacturing methods require some parameters to order of production. This is required an attention and much more detailed analysis on the part geometry to designate Which process and What kind of process should be used, and What additional or subtractive equipment can be used?

Because of this is required on the manufacturing process. There are more changeable features depend on the tools and type of process is used. However, working principle of AM technology is simple and needs only dimensional details with boundary, and see background information necessary to How is it work during the build of part layer by layer, essentially? For this reason, AM method is preferred to instead of other manufacturing process. Thus, AM have more advantages to compare the others. As stated above, the seamlessness can be distinguished from the point of the reduce to production and process steps with also external applications, utilized in productions. Even if much more complex geometrical shape of the parts to be constructed by using an AM device is commonly performed in one step. This single step (which) is not feel the needed any other external process during the built to parts. When the system needs to modify for design via new features, AM technology does not need to multi and repetitive stage of production. Basic change and little modification of design cause is spent much more time required to construct with traditional type of production. Thus, AM might be seen as an inventive and efficient way to time approximation in production steps to obtain fabricate models regardless of what changes could be applied.

Additive manufacturing is called as rapid prototype and three dimensional (3D) printing process in general frequent meaning. In the beginning, according to current circumstances to create a simple model for the basic principle of this additive manufacturing technology on the program. This programing is called as three dimensional computer aided design (CAD) program, which is generally using for technical drawing on virtual platform and its modification by run based on computer, logically.

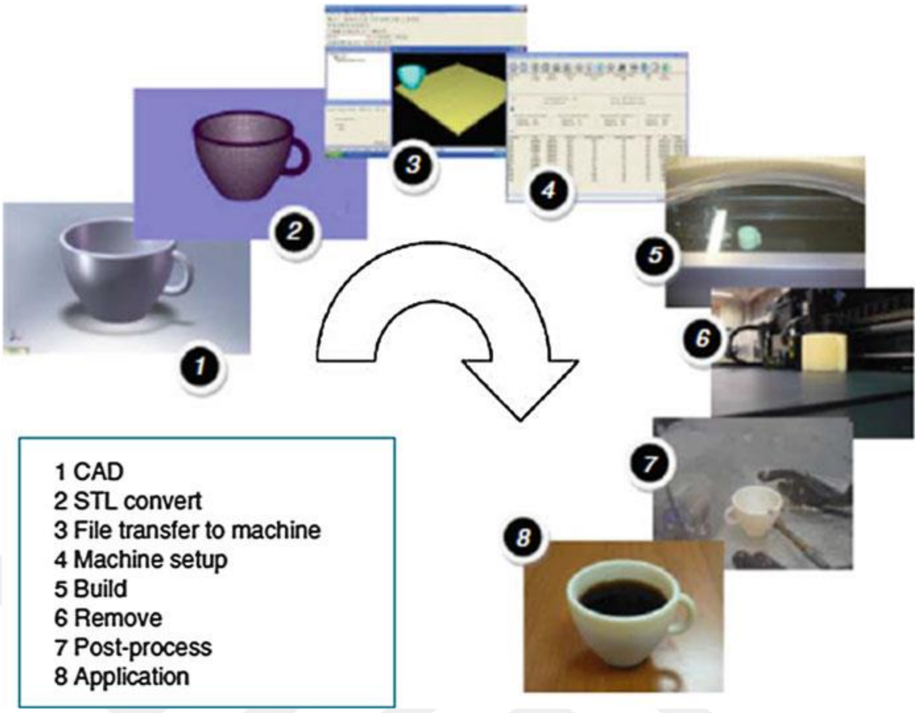

Figure 3.1 The eight stage of th AMP from CAD to end product [18]

Figure 3.2 Additive manufacturing process flow [19]

Get the bottom of AM process is adding material by using new layers, these are reffered a kind of sheet on the part of design. Since, this process is similar to textbook and layers assume each sheet / paper of textbook. On the beginning to explanation of AM process collect all sheets inside of design (into a book). After this collection, the needed book is obtained with step by step, and AM process is briefly resembles a book printing process. It can be described as if each page in the printing press merges into a new book. This similarity situation is adaptive planning on production, exactly the same process.

In generally AM process steps are collected in eight steps and these are illustrated in Figure 3.1 [18]. Some of them is spent short time and may be negligible with production situations. To be expressed in 5 subtitles like as Figure 3.2 [19]

3.3.1 CAD Modelling

In generic form, all additive manufacturing process needs to geometrical modelling with compatible 3D software, which could be described all geometrical shape not only external geometry but also internal geometry and inner shape of needed parts. Since, inner details are requested in some cases. Such as self-lubrication parts, tyre molds, jewellery industry, biomedical parts, turbine blades, self-cooling parts etc. Additive manufacturing process starts with 3D CAD data. The building part is modelled using CAD solid modelling software at the beginning. The designer can take advantage of pre-existing CAD file. In addition, to generate new model for prototyping objects.

After design process in CAD solid modelling software, to save as the file suitable to other programs or engineering process (e.g. laser scanning or any other reverse engineering equipment, etc.). Furthermore, to productive better design result can represent 3D objects using a solid modelling software is more definitively than a wire frame model [26].

3.3.2 Standard Tessellation Language – Stereolithography

There are many theories about the Standard Tessellation Language, which one is the originated initialism. The STL is an abbreviation of standard tessellation language or standard triangle language with stereolithography. The STL file is the standard file type of Additive Manufacturing machines, which was invented by Chuck Hull in 1986 [20]. STL file is defined as triangular declaration of 3D surface geometry of model in mathematical form. Each triangle is cover the 3D model by combination with a logical series. In addition, each triangle is included three points with a normal vector inside the vertex, where is explained as the side of inside face on design model and outside of the triangle, which is visible surface of model. This is shown in Figure 3.3. In other words, STL file from triangular facet data list, which is defined by a unit vector away from model sides and three vertices on the facet, according to Right-Hand Rule (Each vertices is oriented CCW direction), privately. In generally, STL file commonly uses in 3D software packages and their modules. STL files can be characterized the surface geometry of 3D model without any texture information, colour designation, and any other representations.

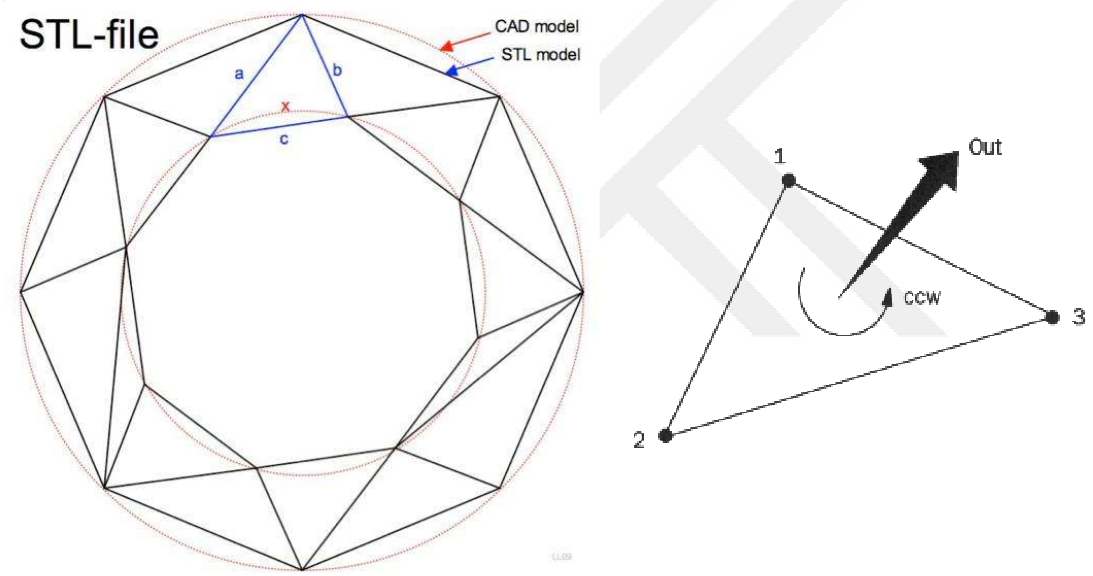

Figure 3.3 Objective desing and triangles shown in STL.

In plain language, STL format is transformed the design into a sharp edge, triangulated surface. Furthermore, similar situation with after many pixels collection, create a photo image. If there are more pixel in an image, It could be visible sharper and high resolution. The design resolution is effected by amount of generated triangles on the model. CAD programs usually use three type of resolution option. These are Coarse, Fine and Custom. Coarse and Fine options are directly depend on programs, but Custom option allows the users to control the resolution according to needed shape. In Figure 3.4, First shape is objective design, the others classified to number of triangles, respectively. Coarse resolution is seeing on the number 2. Fine resolution is seeing on the number 3 and very fine resolution is seeing on the number 4. Even if, Number 4 is high accurate type among these, Number 3 has optimal resolution to process in AM. Because, The Selection of Number 4 means that the file may be overly large and take so longer time to process than expected time [21].

Automatic STL file generation uses in AM machines, generally. This method is based on an algorithm to build parts by creating continuous slices on top of each layer.

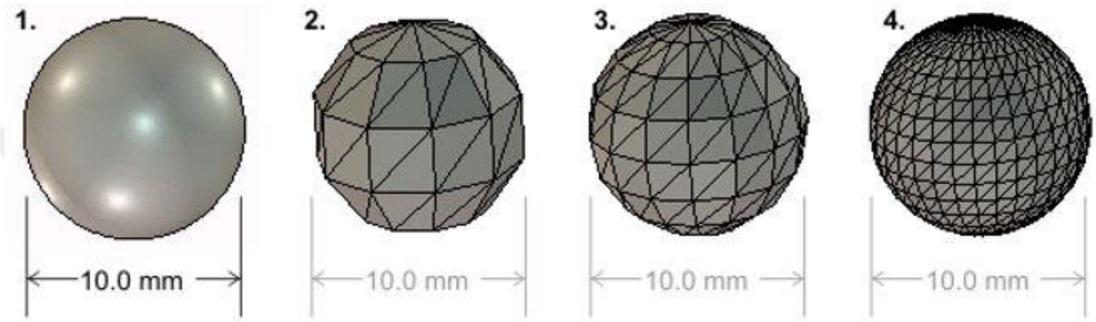

Figure 3.4 Resolution type of 3D model in STL or AMF format [21]

3.3.3 Slicing and File Manipulation

After the second step, the pre-processing program uses to construct STL file and prepared STL file is loaded on the system or additive manufacturing machine. There are using a program to adjust the position of the model, orientation, correct size, scale for building, and also slicing. Build orientation is necessary for coordinate direction. Because the process are generally less accurate in vertical direction than in horizontal direction on the platform. Thus, prototypes are stronger in X and Y direction than the Z direction owing to (since) build direction of each layer is construct throughout the vertical axis.

The orientation of part is acting on the time required to build the model without symmetrical geometry of all directions. In order to reduce number of layers in vertical direction, placing the part is needed with shortest dimension on the building process. The slicing program may use supporter to protect the specification of model during process especially in hollow shape or internal cavities situations. Sometimes, supports are so important for precision parts of the model. This can be seen on the unequal height of the layer, disordered structure, surface differences or under the hollow shape. The importance of supports are shown in Figure 3.5 and Figure 3.6.

The detail of CAD model is shown in part of Figure 3.5 (a). According to preparation data and information about part are evaluated to manufacturing time with vertical and horizontal orientation. To make a decision about the orientation is selected to the best possible orientation, which one is the effective and optimum for manufacturing part. Amount of support structure plays an important role during manufacturing process and machining operation time. Hence, the vertical orientation is selected on this type of part in Figure 3.5 (b). The lightening holes do not need to support structure and that shape can be modified by adapted design. Figure 3.5 (c-d) show the adding machining allowances with orientation of part and support structures on the surface.

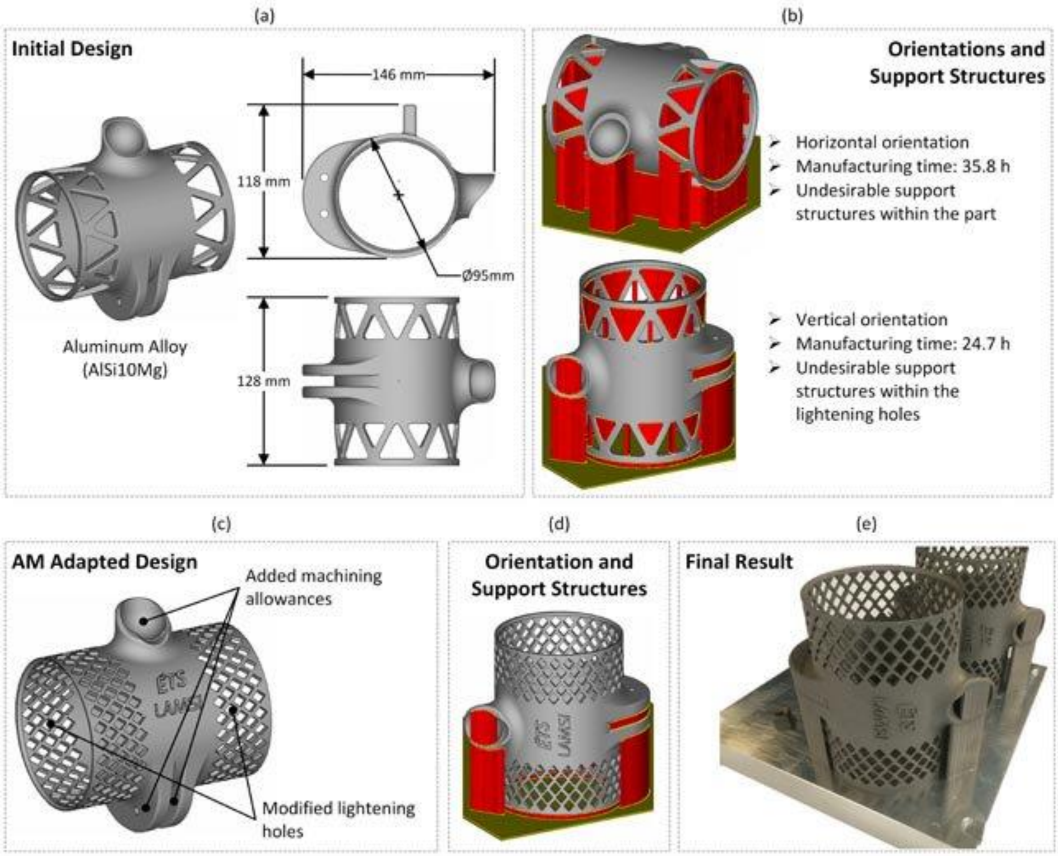

Figure 3.5 Preperation steps of selective laser melting process in a part [22]

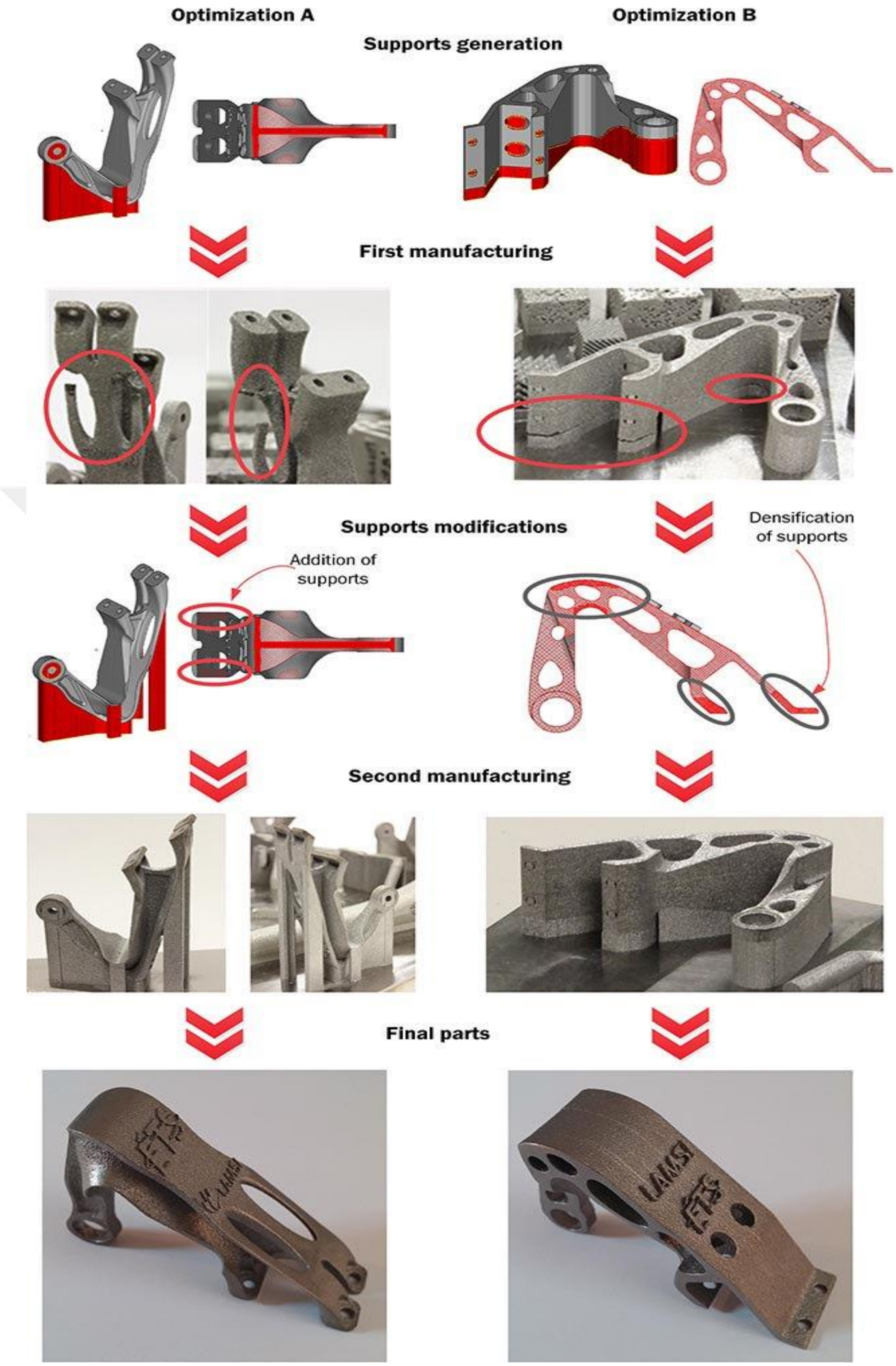

Figure 3.6 The importance of supports in manufacturing steps [22]

3.3.4 Build the Part Layer by Layer Manner

Additive manufacturing machines run automatically from beginning to end of layer on part production process. The sliced of CAD model is represented by each layer shape. Superposition technique is used layer by layer on the each layer during the build process until the 3D object is generated. Fusion of the metallic powder materials need to ensure a safe operation. Superficial monitoring can be used for this operation to coordinate the laser power, program and small technical problems.

3.3.5 Post Processing and Removal Part

After the machine has finished the construction process, the final step is completed with removing the object from the machine. In addition, the supporters must be removed and eliminated by some equipment or chemical compositions. After the cleaning operation, metallic part is ready to use.

3.4 Selective Laser Melting Processes

Selective Laser Melting (SLM) process is an evolving additive manufacturing technology with promising presence in high technological industrial applications and engineering in manufacturing process. SLM is a solid freeform fabrication technique in additive manufacturing process. Nowadays, Additive Manufacturing is famous from various industrial sectors since compare from traditional/conventional forming techniques. In generally, Additive Manufacturing is known as three dimensional (3D) printing, and it gives the more advantages to design significant part production and also complex geometrical shape.

Manufacturing business goal is developing on the rapid prototype and to deliver the new products to consumers, who use to be needed additive manufacturing. This method offers the great potential to manufacture various kinds of product and objects for practical application areas. Such as especially aerospace, automotive, aircraft, tool making industry, medical applications etc. High technological manufacturing industry wants to be use this type of technology [23].

At the end of the 1990s, SLM method is found by Fockele & Schwarze of Germany introduced its steel powder-based selective laser-melting system, developed in cooperation with the Fraunhofer Institute for Laser Technology [24]. SLM process can be partially similar to welding operations. Because of the each metallic powder is melted when the laser torch/power touches on the selected area. Melted powder is combined with neighbour powder and affected fusion process is done by laser beam energy. SLM process platform is shown in Figures 3.7.

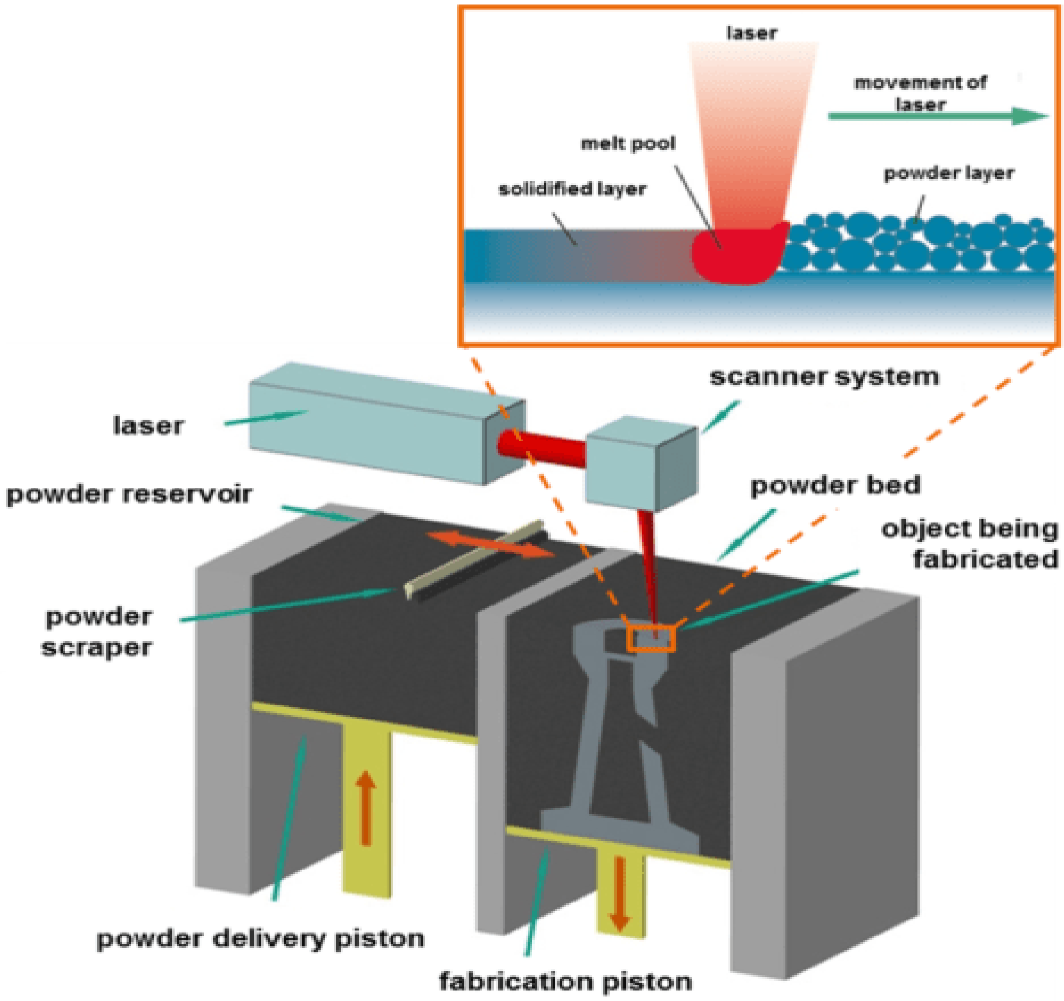

Figure 3.7 Powder Bed Fusion / SLM process platform. [25]

SLM process starts when metal powder is equally scattered across a balanced platform and directed energy is applied by means of a laser to melt and fuse the metallic powder so much so that melted areas solidify at the layer of platform. Laser scanning operation goes on across the layer of platform until the SLM process is completed the solidification of material forming. Each layer process continues by laser beam across on the platform step by step up to geometrical shape of material can be obtained. SLM uses three dimensional computer aided design (3D CAD) data without any external and conventional manufacturing process method. Desired part is designed by 3D CAD programs to obtain each layer dimensions. Slicing program is used in second step of SLM simulation process. The outline of SLM process is shown in Figure 3.8.

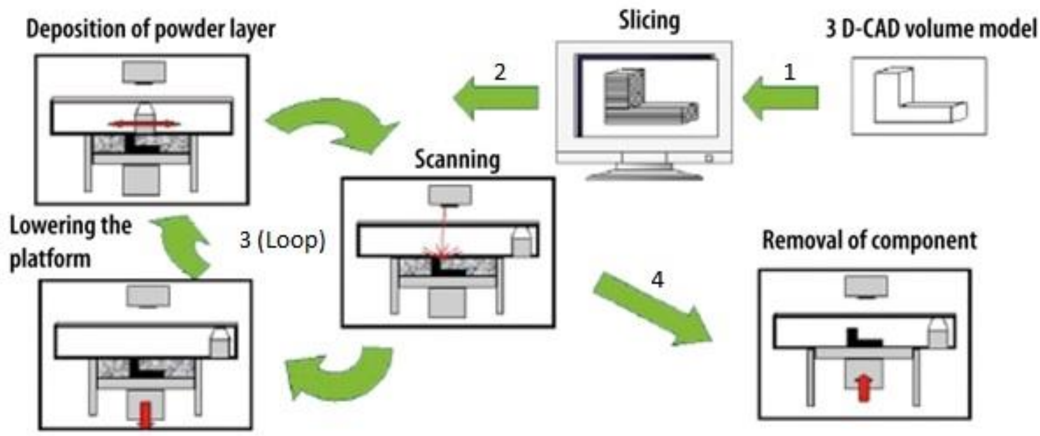

Figure 3.8 The steps of SLM working principle. [26]

After slicing operations, code is generated on the slicing software or program and loaded to SLM machine, which is running until complete the last layer operation. After than high energy laser beam scans the powders on the layer-powder bed to finish the melting path from computer data in each running. Where the metal powder solidifies and comes to a state of phase transition from bulk metal to solid metal, which is shown in Figure 3.9. The purpose of this process has been done (Figure 3.7 as upper mesoscale part). The first layer is melted on the other hand melted materials solidify quickly and get into desired shape. Then, the completion of the designed cross-section scan of a layer, the platform is lowered down by one-layer thickness for new powder layer deposition above the solidified powder metals (Figure 3.10). After the continuous loop process has been finished, required product can be taken from the platform. SLM process is not only complex form, but also a difficult process to control all parameters. SLM process is need to be exact preparation, before the running operation.

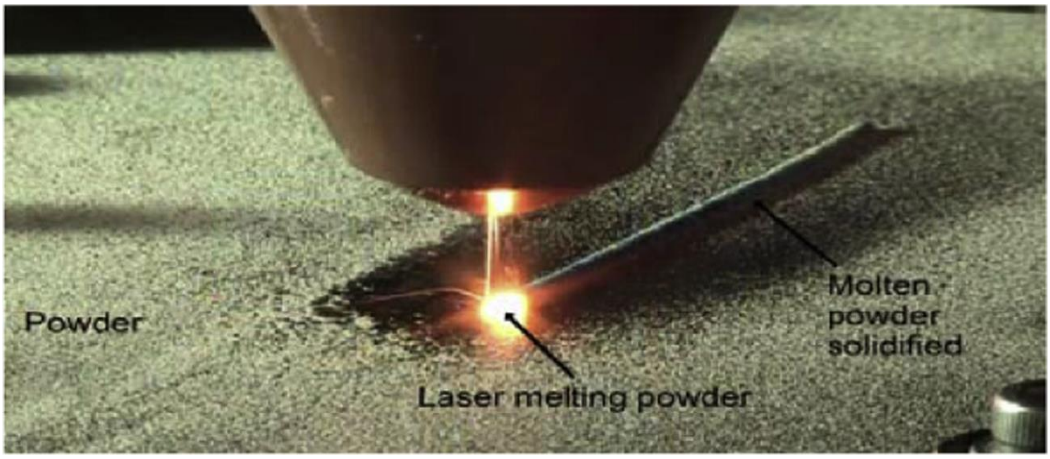

Figure 3.9 Laser beam melting powder in the SLM during the process [27]

Basic principle of this process is bases on the building of selected powder on the platform layer by layer. During this building operation, laser beam scans on the powder metals each layer according to design constructions. When the scanning process is completed, new metallic powder will be spread on the layer by the roller or any other blade surface in an attempt to spread of the metallic powder on the last layer. During the building operation, shape of design is taken from the CAD data of design software.

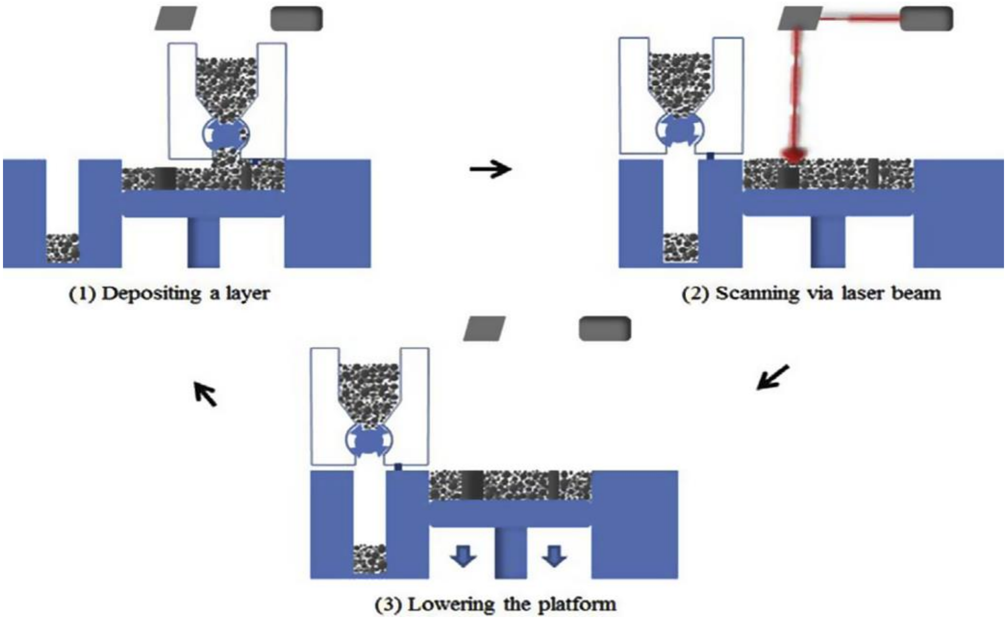

Figure 3.10 Selective Laser Melting (SLM) process loop in schematic form demonstration [27]

CHAPTER 4

MATHEMATICAL MODELLING OF MELT POOL TEMPERATURE DISTRIBUTION IN SLM

4.1 Introduction

This chapter includes four sections. The first section describes mathematical modelling, solution method, discrete element methods, and finite difference methods with implicit and explicit method.

4.2 Mathematical Modelling

Engineers deal with system and process in mathematics of change, continually. Because this change is an essential tool of engineering profession. Engineers use mathematical modelling to control system. Mathematical model can be defined as an equation the basic characteristic of a physical system or formulation of the process in mathematical terms. Dependent variable is equal to function of independent variables, parameters and forcing functions. Dependent variable reflects the characteristic of system, independent variables are dimensions according to time or space, the parameters reflect to properties of system, forcing functions are outer reflection acting upon it.

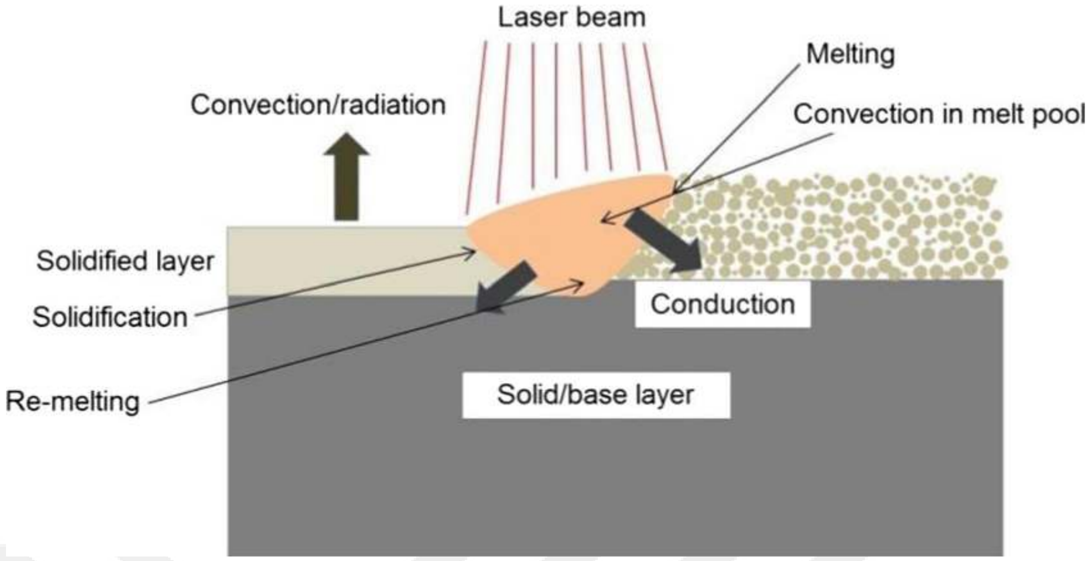

Figure 4.1 Physical schema in SLM [6]

Derivation performs by the rate of dependent variable with respect to an independent variable. In another case, mathematical models of systems may not be simple. It can be much more complex and cannot be solved accurately. In order to solve functions, to require more advanced mathematical techniques than basic calculus or algebra. Partly for this reason, make use of the combine mathematical models with another type of methods. Shortly, mathematical model method is set with partial differential equations and corresponding boundary conditions by using computers and numerical or graphical method on problem solving tools.

Rough model can be derived by just considering the temperature, thermal properties and coefficient, and also time. Modelling is taken upon oneself to utilize numerical or analytical solutions using self developed scripts by central difference method, discrete finite element based or another simple way using the commercial software's programs which are COMSOL, ANSYS, ABAQUS, FLOW3D, FLUENT etc. These are multi-physics programs and system requirements for the generic and wide ranging model. That should be involved melting and solidification, free surface reconstruction, all material phases (liquid, solid, gas), thermal conductivity, density, specific heat capacity, radiation properties, etc. Theoretical models can propose cost effective and controllable opportunity, for under the influence of laser surface analysis. In order to protect the system during the selective laser melting operations, thermal effects and laser beam are controlled by selective parameters.

Numerical solution of the problem is included much more arithmetical calculations. Therefore, the solution should be applicable and valid for the all situation and conditions. For this process, the required form of the problem is achieved by the dimensionless transform. Q_o is the first environmental heat effect on the pieces and initial conditions of the system, which is shown in Figure 4.2

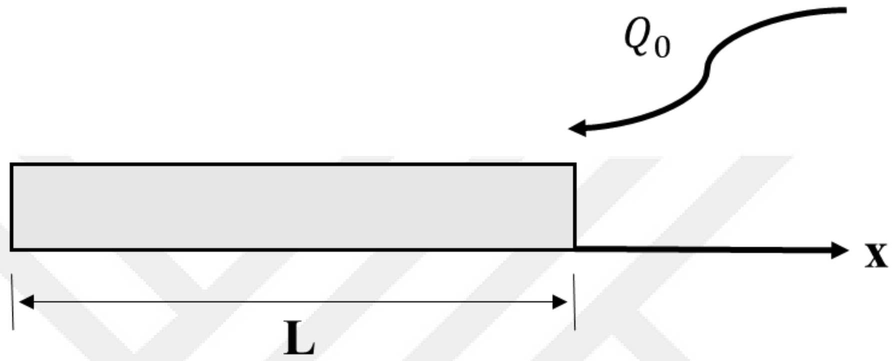

Figure 4.2 From dimensionless to one dimensional form of Heat-Temperature effects on the system

For the transformation of the system, dimensionless form should be defined. That is explained by in Eq.4.1.

$$x = \frac{X}{L} \rightarrow \; X = x.L \quad \equiv \quad q = \frac{Q}{Q_0} \rightarrow \; Q = Q_0.q \quad \Rightarrow$$

$$\frac{\partial q Q_0}{\partial T} = K\frac{\partial^2 q Q_0}{\partial (x.L)^2} \quad \Rightarrow \quad Q_0\frac{\partial q}{\partial T} = KQ_0\frac{\partial^2 q}{L^2\,\partial x^2} \quad \Rightarrow \quad \frac{L^2}{K}\frac{\partial q}{\partial T} = \frac{\partial^2 q}{\partial x^2} \tag{4.1}$$

$$\text{for } t = \frac{K.T}{L^2} \Rightarrow T = \frac{L^2}{K}t\;; \quad \frac{L^2}{K}\frac{\partial q}{\partial(\frac{L^2}{K}t)} = \frac{\partial^2 q}{\partial x^2} \quad \Rightarrow \quad \frac{\partial q}{\partial t} = \frac{\partial^2 q}{\partial x^2}$$

In order to see the temperature distribution of SLM process for one dimension, mathematical form of the heat transfer and cell structure of the heat distribution are given in Eq.4.2.

From there, the heat conduction in the moving part is described as:

$$q + k\left(\frac{\partial^2 T}{\partial x^2}\right) = \rho\, C\left(\frac{\partial T}{\partial t}\right) \tag{4.2}$$

In order to see the temperature distribution of SLM process for two dimension, mathematical form of heat transfer equation and cell structure of the heat distribution are given in Eq.4.3 and Figure 4.3, respectively.

$$q + k\left(\frac{\partial^2 T}{\partial x^2} + \frac{\partial^2 T}{\partial y^2}\right) = \rho\, C\left(\frac{\partial T}{\partial t}\right) \tag{4.3}$$

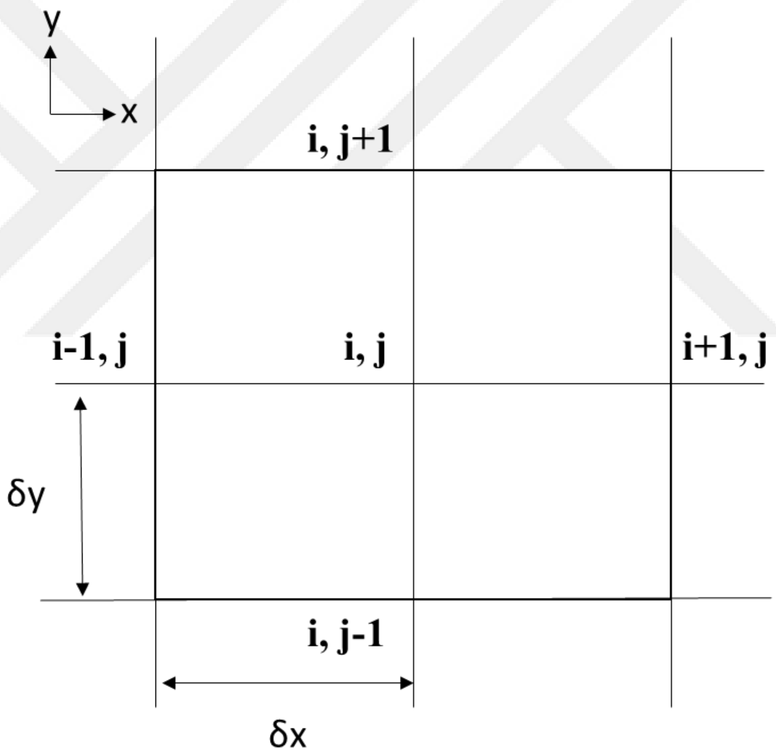

Figure 4.3 Two dimensional form of heat-temperature effects on the system

In order to see the temperature distribution of SLM process for three dimension for heat transfer equations, mathematical form of heat transfer equation and cell structure of the heat distribution are given in Eq.4.4.

$$q + k\left(\frac{\partial^2 T}{\partial x^2} + \frac{\partial^2 T}{\partial y^2} + \frac{\partial^2 T}{\partial z^2}\right) = \rho\, C(\frac{\partial T}{\partial t}) \qquad (4.4)$$

In given equations above; q, k, C, ρ, T, t denote the heat flux, thermal conductivity, specific heat capacity, temperature, and time respectively. x, y and z are declared to dimensions of distance and axis on the model.

All parameters and variables are used after attained mathematical equations. Time dependent temperature distribution results can be obtained on x, y, and z dimensions. To obtain these results, analytical and numerical methods are clarified in following sections.

4.3 Solution Methods

An overall introduction the solution methods for the selective laser melting in additive manufacturing process was mentioned by the improving the classical methods. Thermal basis Fourier transform or Navier-Stokes foundation equations have been utilized on the majority of the thermal modelling studies, in previous section. Therefore, some research groups evaluated scaling unit consideration from µm to cm and physical effects on the modelling. That is validation of these type of equations, partially.

Heat source, laser beam, characteristic and mechanical properties of metallic powders, boundary conditions, physical and thermomechanical parameters take an active role in solution methods. These solution methods are described by the heat transfer equations when the energy interaction happened between the laser beam and powders.

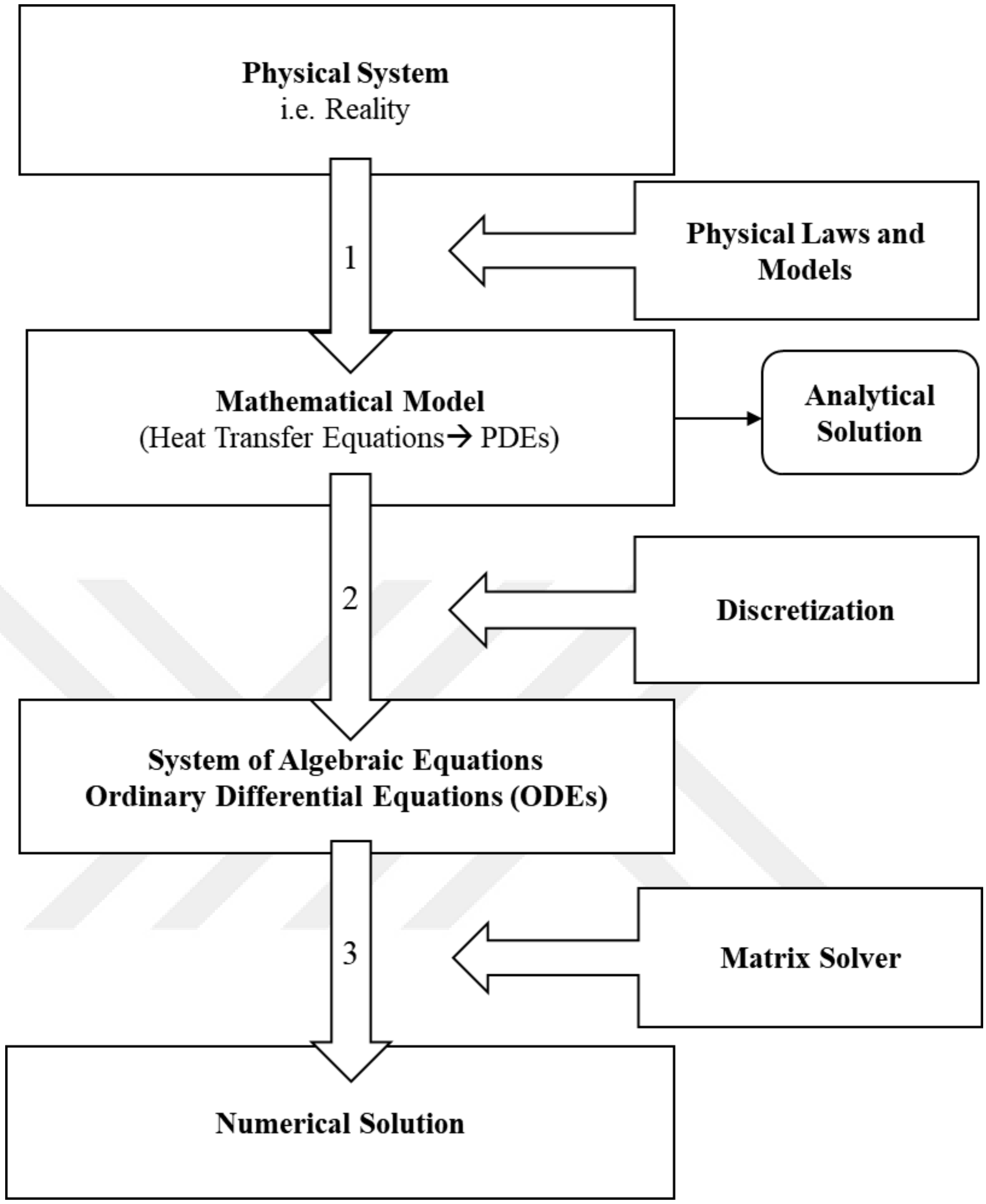

Figure 4.4 Numerical solution procedure

At the beginning, the problem is defined. Mathematical model is derived and by using mathematical theory, the problem is solved via code compiling or the problem solving tools are selected such as computers, statistics, numerical methods or graphical methods. Next step in flow chart is applied for attaining numeric or graphical results. After that, implementation and results are evaluated as in Figure 4.4.

Several methods are available for the solution of temperature distribution and moving the laser beam modelling. However, which one is the more accurate results can be presented? Answer of this question is represented with examples and references on the following steps.

Two methods are used for the solution of the differential equations as analytical and numerical form.

4.3.1 Analytical Solution

Thermal model analysis of the laser beam, heat source and metallic powders becomes rather complicated. The cerebration of moving elements (directly laser beam, indirectly heat source) with importance of the boundary geometry is describing by mathematical equations. Related articles and papers are researched for analytical solution may take days to execute or may have not solution for non-linear differential equations.

Nearly 15 years ago, computers have not high performance and computational modelling programs were so complicated. Moreover, analytical model for moving steady heat source on laser melting on the surface by volumetric heating has not been realize in literature. Nowadays, some researches to predict temperature distribution of the selective laser manufacturing part, by FEM. Other opinion, analytical models use under the semi-infinite media assumption in order to convenient the boundary conditions. In that, analytical method is closed form solution has not supported limitations circumstances. To use analytical solution, conditions are suitable for physical interposition [28].

In the foregoing section, it is explained that analytical solution method is not preferred to solve thermal distribution mathematical model equations which obtained in section 4.2. Therefore, the numerical solution is decided to solve attained equations.

4.3.2 Numerical Solution

Numerical solution of partial differential equation is obtained step by step in this section. Numerical solution procedure is explained by three steps. First one is the starting physical system, that was supported by physical laws and models. Second one is mathematical model, that refers to equation form and also analytical solution.

Next step is ordinary differential equation (ODEs) or system of algebraic equations, which are following the discretization of equation form of mathematical model. The matrix solver is using to obtained numerical solution.

The mathematical modelling of the problem is the degradation of the physical problem to set of each algebraic or differential equations topic to precise assumptions. The schematic chart of process of system modelling follows the demonstrated path in Figure 4.4, generally.

Components of a numerical solution method introduce the mathematical model and discretization method. Accuracy of numerical solution determine the form of functions and quality of discretization.

The Basic concept of finite element method is transformation technic from complicated problem to simple form, by using to find solution.

Since, the existing mathematical instruments are not equal to find the solution of the problem. In some cases, this instruments will be inadequate approximation of the exact solution on the practical operations. Therefore, Finite Element Method have to prefer to obtain approximate solution of the problem without another way or method. In addition, more computational work expending to find approximate solution get better and promote by finite element method. In order to applied FEM, need to mesh of object. So, three dimensional form of mesh is illustrated in Figure 4.5.

In this method, finite element can be defined as the little pieces like mesh on work part. Working area is imaged like a STL format. There are built up little pieces interconnected sub regions to each connection part inner and the outer. For clear detection of finite element can be described by controllable each part of the general system. FEM is illustrated by in Figures 4.5.

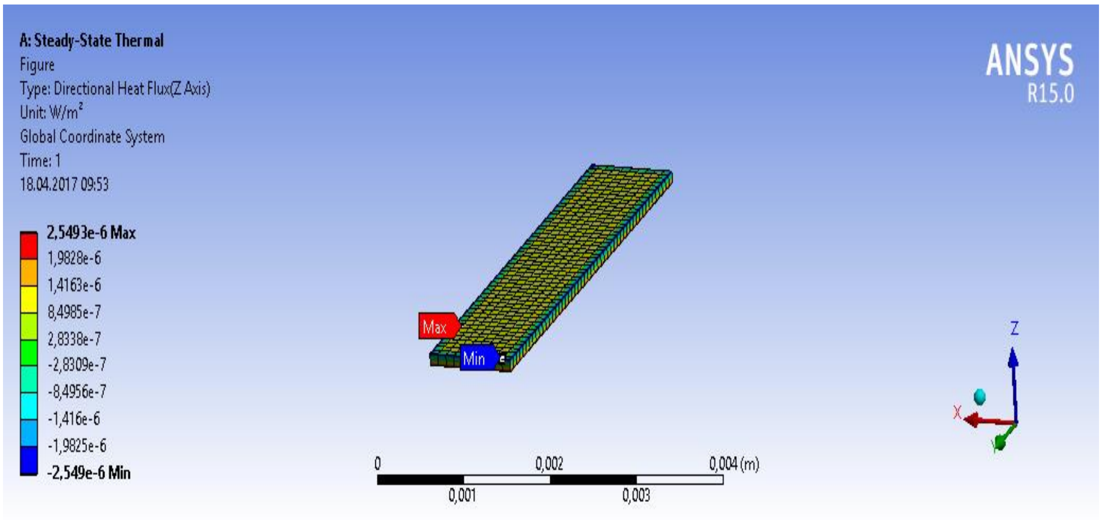

Figure 4.5 Mesh for computational analysis in 3D form.

Discrete locations at which the variables are to be calculated are defined by the numerical grid or mesh. Need to use a discretization method, which approximates the differential equations by a system from mathematical models for algebraic equations. This can be solved on a computer program by using matrix solver form or another forms. These forms and finite element equations can be expressed hybrid formation in mathematically as follows:

$$\text{for } T\ (x, t)$$
$$x = [0\Delta L, 1\Delta L, 2\Delta L, 3\Delta L, 4\Delta L, \dots, n\Delta L]$$

$$t = [0\Delta t, 1\Delta t, 2\Delta t, 3\Delta t, 4\Delta t, \dots, n\Delta t]$$

Set the initial temperature is $27°C\ (300\ K)$:

$$T\ (x, y, z, 27°C) = T_0$$

This explanation of the system is accenting initial temperature and preheated grid form of the area.

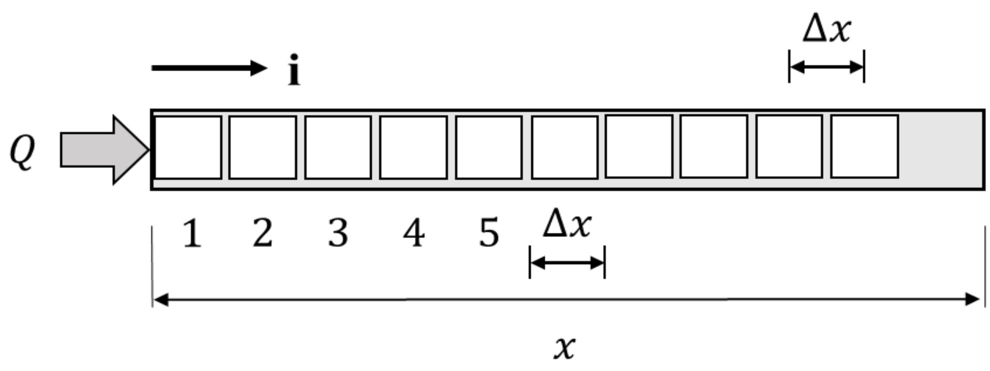

Figure 4.6 Mesh form for the geometrical demonstration of powders

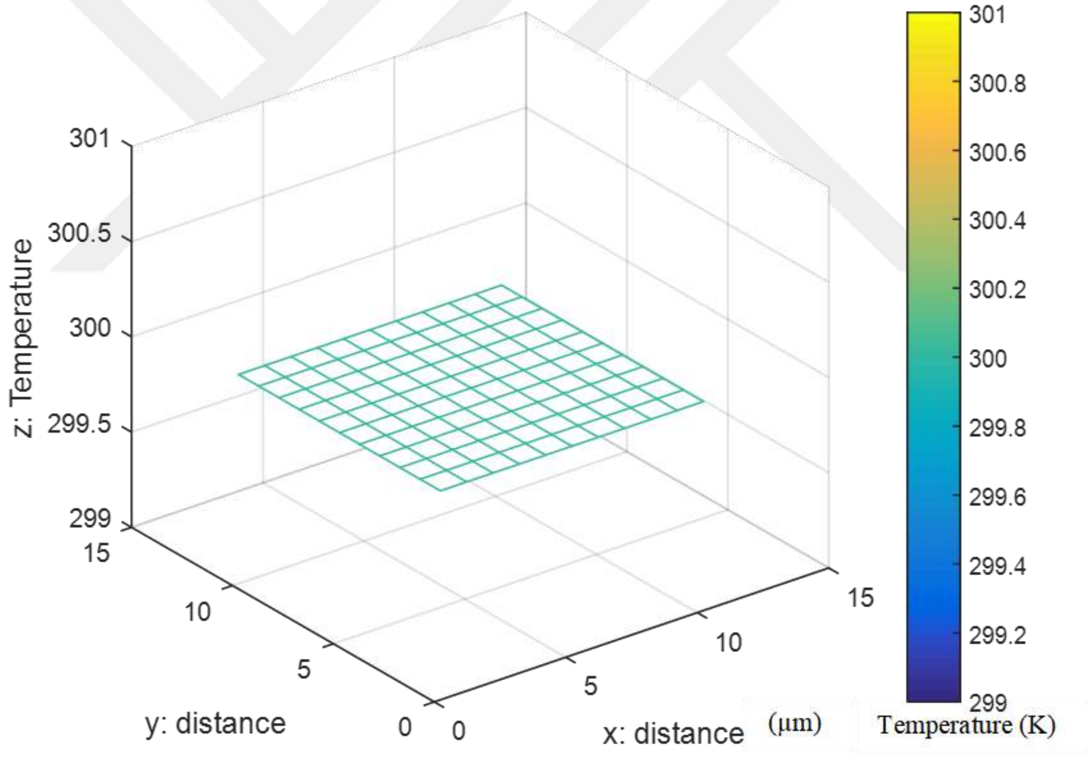

Figure 4.7 Grid formation of the initial temperature condition on preset area

Although explicit method was simple, but it has deficiency, which is time domain and its interval. Time step (Δt) and especially ∂t time must be taken infinitesimal.

Since, the calculations and modelling are suitable in $0 \leq r \leq \frac{1}{2}$ range, r is a factor of stability. So that ∂t was selected so small to obtain needed accurate value of the modelling. If the time interval was selected so small, the calculation process would be much more complex and have a long time. For this reason, Crank-Nicolson put forward to implicit method on 20 March 1946 [36].

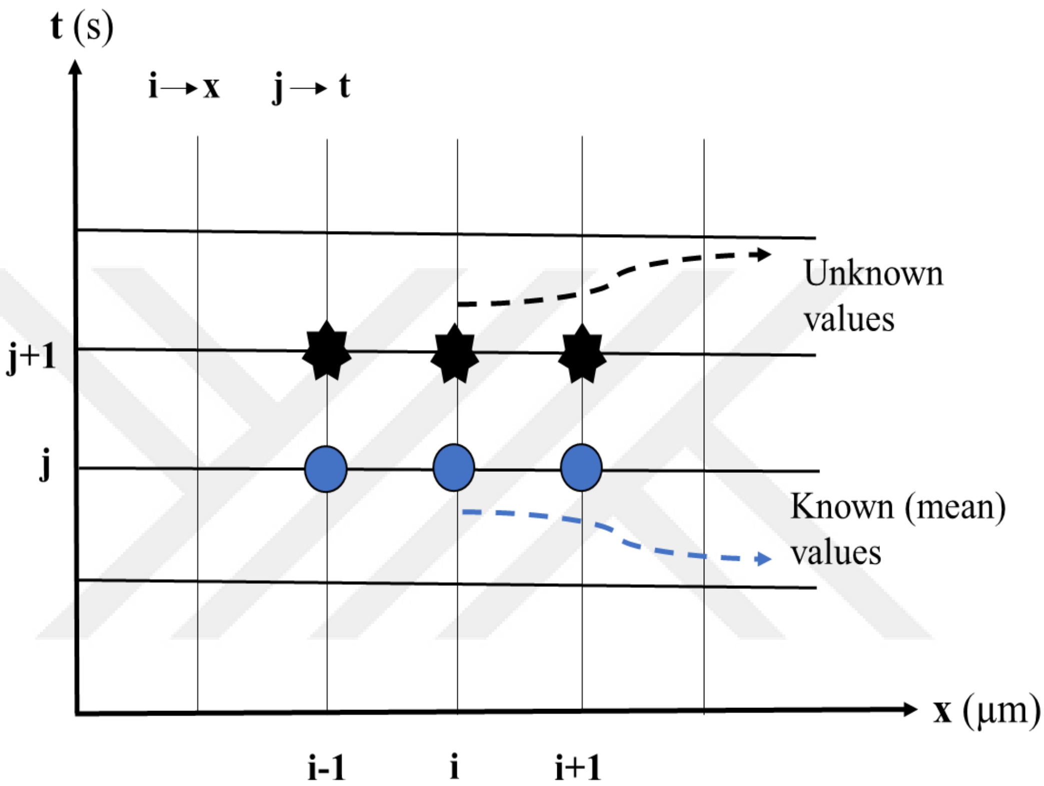

Figure 4.8 Crank-Nicolson / Imlicit Method for the grid size meaning.

Mesh/grid form of partial derivative equation is executed in the midpoint of grid size on the system by Crank-Nicolson method. Finite difference values are equal to convergence the average value of unknown and known values. That approach is shown in Figure 4.8. The symbolic form of T values in Figure 4.8 can be explained by mathematically as like here (Eq. 4.5);

$$\frac{\partial T}{\partial t} = \left(\frac{\partial^2 T}{\partial x^2}\right) \tag{4.5}$$

$$\left(\frac{T_{i,j+1} - T_{i,j}}{\delta t}\right) = \frac{1}{2}\left(\frac{T_{i-1,j} - 2T_{i,j} + T_{i+1,j}}{\delta x^2} + \frac{T_{i-1,j+1} - 2T_{i,j+1} + T_{i+1,j+1}}{\delta x^2}\right)$$

$$\frac{T_{i,j+1} - T_{i,j}}{\delta t} = \beta\left(\frac{T_{i-1,j} - 2T_{i,j} + T_{i+1,j}}{\delta x^2}\right) + (1-\beta)\left(\frac{T_{i-1,j+1} - 2T_{i,j+1} + T_{i+1,j+1}}{\delta x^2}\right)$$

$$\text{when,} \quad r = \left(\frac{\delta t}{\delta x^2}\right)$$

Table 4.1 For the factor value of explicit and implicit method

$\beta = 0$	Implicit Method
$\beta = \frac{1}{2}$	Crank-Nicolson Implicit Method
$\beta = 1$	Explicit Method

If the β value is equal to half of one for every r values ($\frac{\partial t}{\partial x^2}$) in order to stability of the system from Table 4.1, this equation will be explained in Figure 4.8, clearly.

$$-r.T_{i-1,j+1} + (2+2r)T_{i,j+1} - r.T_{i+1,j+1} = r.T_{i-1,j} + (2-2r)T_{i,j} + r.T_{i+1,j} \quad (4.6)$$

Left side (j+1) of the finite difference equation is express the unknown values of the temperature, in other words the right side of the finite difference equation has a j term, that is known values. If there is n-1 term inside the grid points (such as j=0 and i=1, 2 ,3, 4, …, n-1), The equation of the n-1 item will be attained. At the beginning point of (j=0) T value is the first limitations and boundary conditions of the system. Next value (j=1) is found from this boundary condition and the first value. This method is identified as implicit method.

For the differential boundary condition is supported to find the unknown values on the system. So that situation, hybrid form of implicit and explicit method is applied in this study. However the main modelling is based on explicit method. Because, one step closer than the other methods for the real time situations.

According to mention about hyperbolic equations, the situation can be assumed that the wave form equation.

$$\frac{\partial^2 T}{\partial t^2} = \frac{\partial^2 T}{\partial x^2} \tag{4.7}$$

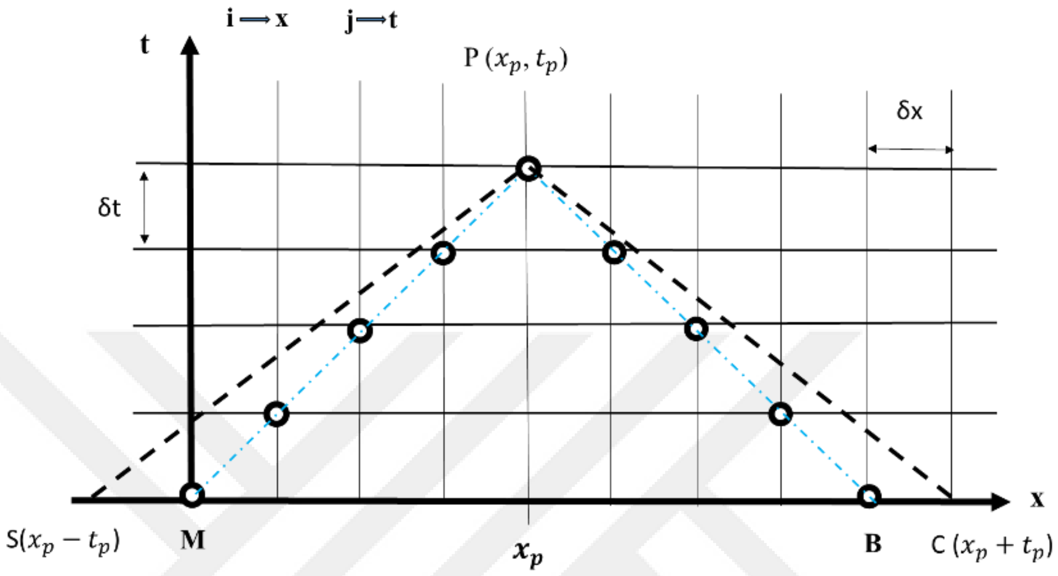

Figure 4.9 Courant-Friedrichs-Lewy (CFL) condition - explicit method for the grid size meaning.

$$T\,(x,t) = T_{i,j}\,;\ \ (\,i \rightarrow x, \qquad j \rightarrow t)$$

$$\text{for the initial conditions } \ t = 0 \Rightarrow \qquad T\,(x,0) = f(x)\ ;\ \frac{\partial T(x,0)}{\partial t} = g(x)$$

$$\left(\frac{T_{i,j-1} - 2T_{i,j} + T_{i,j+1}}{\delta t^2}\right) = \left(\frac{T_{i-1,j} - 2T_{i,j} + T_{i+1,j}}{\delta x^2}\right)$$

$$T_{i,j+1} = r^2.T_{i-1,j} + 2(1-r^2)T_{i,j+}r^2.T_{i+1,j} - T_{i,j-1}$$

$$\text{when,} \quad r = \left(\frac{\delta t}{\delta x}\right)$$

$$T_{i,1} = r^2.T_{i-1,0} + 2(1-r^2)T_{i,0+}r^2.T_{i+1,0} - T_{i,-1}$$

$$\text{for the initial conditions } \ t = 0\,;$$

$$T\,(x,0) = f(x) \qquad \Rightarrow \quad T_{i,0} = f_i$$

$$\frac{\partial T(x,0)}{\partial t} = g(x) \;\Rightarrow\; \frac{T_{i,1} - T_{i,-1}}{2\delta t} = g_i \;\Rightarrow\; T_{i,-1} = T_{i,1} - 2\delta t\, g_i$$

$$T_{i,1} = r^2.T_{i-1,0} + 2(1-r^2)T_{i,0+}r^2.T_{i+1,0} - (T_{i,1} - 2\delta t\, g_i)$$

where, $$T_{i,1} = \frac{1}{2}\left(r^2.T_{i-1,0} + 2(1-r^2)T_{i,0+}r^2.T_{i+1,0} + 2\delta t\, g_i\right) \tag{4.8}$$

D'Alembert solution of the wave equation is found by this form, analytically.

$$T(x,t) = \frac{1}{2}\left\{f(x+t) + f(x-t) + \int_{x-t}^{x+t} g(\xi)d\xi\right\} \tag{4.9}$$

If the equation is solved by the numerical solution, The point of P ($T_{i,j}$) value is dependent on the triangular form of Figure 4.9. If it is changeable for the first state of the system, analytical solution of point of P value is effected and can be changed inside the grid point of the MPB triangle. But the numerical solution of point P value is not changed and unaffected from this analytical effect. Although the modification of initial condition values, numerical solution is supported the system required. In this situation, numerical solution is not converged to analytical solution. Thus, the r value ($\frac{\delta t}{\delta x}$) should be selected the initial condition and related data to include according to the system, which is known as Courant-Frendrich Lewy Conditions. The r value must be equal and smaller than 1, in order to obtain the accurate results.

When the FEM is using for the solution of initial conditions of an unsteady or transient state of problem phenomena, the including linear differential equations are derived propagation problems, simultaneously [29].

CHAPTER 5

SIMULATON OF MELT POOL TEMPERATURE DISTRIBUTION MODEL

5.1 Introduction

In this section, the simulation procedure and process parameters during selective laser melting process are clarified in detail by figurative form. Also materials used, procedure and methods are expressed afterward.

Demonstration of the initial conditions in table, and preparing for the temperature distribution towards the laser beam path on the metallic powders are run on the MATLAB solution with instantaneous definition time.

5.2 Simulation of SLM

SLM has been widely applied with commercial materials such as stainless steel, Titanium and Nickel alloys and Aluminum alloys. Internal porosities, un-melted powder particles and poor fusion qualities between melted-solidified layers have been main drawbacks in SLM process. Such phenomenon causes final part quality and efficiency of the SLM process. In that sense melted material control in melt pool which is affected by many factors such as laser beam power, scan speed, powder properties, and material properties, is crucial in SLM process. Simulation has a strategic importance because of unknown parameters and prediction of the final steps on the experimental studies. The simulation of temperature distribution of melt pool is used during the SLM process under the high laser beam power by figurative form in this research. In this study, the material was using the Titanium alloys: Ti6Al4V is widely used in SLM for aerospace and aircraft industrial applications, also biomedical applications [30].

Simulation technique was applied and demonstration the similar one, general view of the system information in Figure 5.1. Here r is the effective radius, R is the radius of the circle on top view, r_b is the radius of the laser beam. In general cases, the preferred sizes of effective radius are taken as two times of the laser beam radius. So that, $r = 2r_b$ [31]. Metallic powders have been assumed to have homogenous form and interpolation between the maximum and minimum size of metallic powders in simulation. Mesh size has been assumed nearly metallic powder size in this simulation.

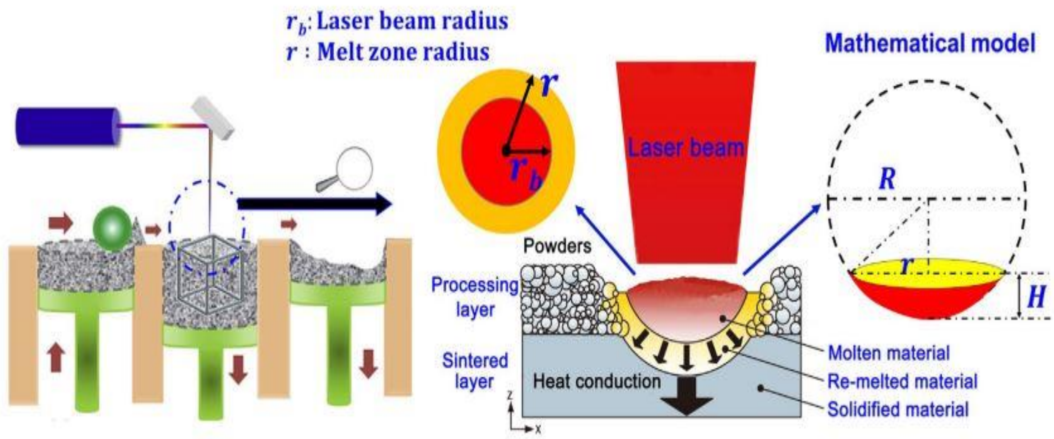

Figure 5.1 Selective Laser Melting (SLM) process in schematic form. [31]

In order to be able to do this type of study and accomplish the best results, many momentous preliminary grades are required. Acquisition of proper results from studies are other important factors to verification of the research. Price/performance ratio is minimized by script programing and developing a model to simulate the optimum level of parameters and powders are made under matrix laboratory (MATLAB). These methods are supported to eliminate the waste of time and reduction of the cost processing.

5.3 Material Selection

Before starting the simulation, set the values of physical parameter according to Table 5.1. After setting physical properties, thermal properties of Ti6Al4V alloy is defined into the programs via command windows to simulate the temperature distribution in heat conduction model, which is also visualized in the right side of Figure 5.1. In order to simulate the temperature distribution with terminological formulas, The defined program is used the data from Table 5.1, and Table 5.2.

Table 5.1 Physical properties of Ti6Al4V alloy [32-33]

Parameters	Values
Density (g/cm^3)	4.429-4.512
Melting Point (K)	1878-1933
Solidus Temperature (°C)	1605
Liquids Temperature (°C)	1655

Table 5.2 Thermal properties of Ti6Al4V alloy [32-33]

Parameters	Values
Specific Heat Capacity (J/kg K)	553-570
Thermal Conductivity (W/m K)	7.1-7.3

Physical and thermal properties of Ti6Al4V alloy used in this study are given in Table 5.1 and Table 5.2 respectively.

5.4 Simulation Setup and Parameters Selection

In our simulation studies set to program with selective parameters according to boundary conditions by self-developed hybrid modelling. That is include implicit/explicit method and mainly central difference methods via supported the explicit method to obtain the most accurate results. B is refer to the stability factor of system modelling.

$$T\,(x,t) = {T_i}^K;\;\; (K \rightarrow \text{time}, i \rightarrow \text{position})$$

$$\frac{{T_0}^{K+1} - {T_i}^{K+1}}{2\Delta t} = k\left(\frac{{T_{i-1}}^K - 2{T_i}^K + {T_{i+1}}^K}{\Delta x^2}\right) + BQ(0,t_K) \qquad (5.1)$$

$$\frac{T_i^{K+1} - T_i^K}{\Delta t} = k\left(\frac{T_{i-1}^K - 2T_i^K + T_{i+1}^K}{\Delta x^2}\right) + BQ(0, t_K) \quad (5.2)$$

$$T_i^{K+1} = T_i^K + \Delta t\left(k\,\frac{T_{i-1}^K - 2T_i^K + T_{i+1}^K}{\Delta x^2} + BQ(0, t_K)\right) \quad (5.3)$$

From there, k is equal to zero, $t_K = 0$. Thus, $T_1^0 = 27°C$, $T_2^0 = 27°C$, $T_3^0 = 27°C, \ldots\ T_n^0 = 27°C\ (300\ K)$. The main equation of temperature distribution can be defined as:

$$\frac{\partial T}{\partial t} = k\left(\frac{\partial^2 T}{\partial x^2}\right) + \frac{q}{\rho C} \quad (5.4)$$

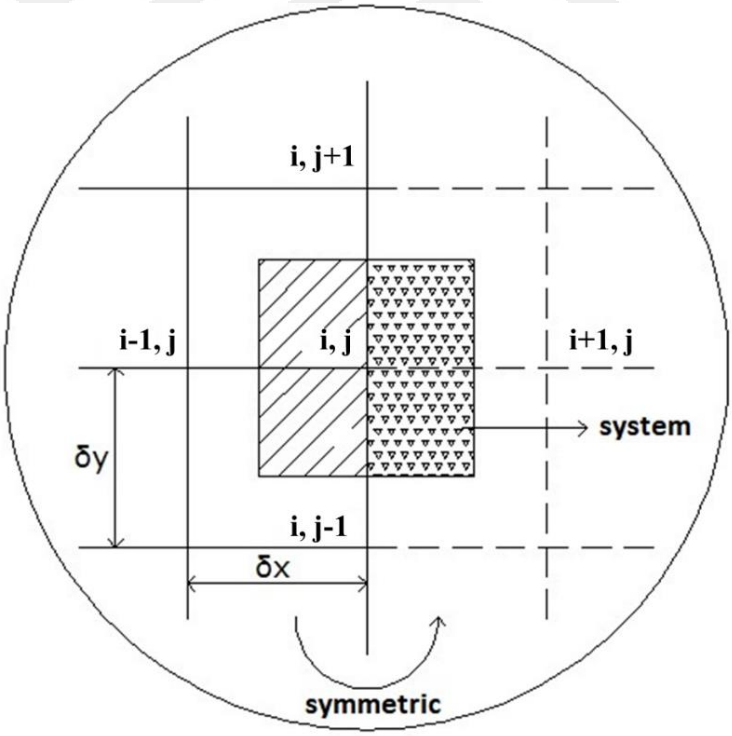

Figure 5.2 Heat transfer mechanism for temperature distribution on the selected mesh/ unit cell.

The condition according to the time and the elapsed time can be considered as the arrange of layers in the x and y direction.

$$\frac{T_{xy}{}^{t+1} - T_{xy}{}^{t}}{\Delta t} = k\left(\frac{T_{x-1,y}{}^{t} - 2T_{xy}{}^{t} + T_{x+1,y}{}^{t}}{\Delta x^2} + \frac{T_{x,y-1}{}^{t} - 2T_{xy}{}^{t} + T_{x,y+1}{}^{t}}{\Delta y^2}\right) + \frac{q}{\rho C} \tag{5.5}$$

In generated code (Lx=0.1;Nx=30+1;dx=Lx/Nx;x=0:dx:(Nx)*dx;), it is stated that there are 30+1 meshes in the each cell dimension in the x axis and dx in the Lx divided by the Nx parameters every mesh/grid dimension in other words, the units. The reasons behind adding (+) 1 to 30 are to find out the midpoint and to control the heat transfer at the beginning part.

(In the x axis, 30+1 mesh is present on the 0.1 dimension of the unit cell, and dx refers to proportion of Lx and Nx is defined the each mesh grid size of a unit.)

In this generated code (Ly=0.1;Ny=30+1;dy=Ly/Ny;y=0:dy:(Ny)*dy;), the same procedure applied for the x axis is applied to the y axis and the coordinate in every one grid/ unit mesh is found by starting from 0 at the part of “y=0:dy:(Ny)*dy” in other words, the lenght of the interval of the (row of) from zero to 32 (0, 1, 2, 3... 32).

The temparature values are fixed at the first layer as the amount of Nt plane temperature, which is x and y axis centroids (T=300*ones(Nx,Ny,Nt);).

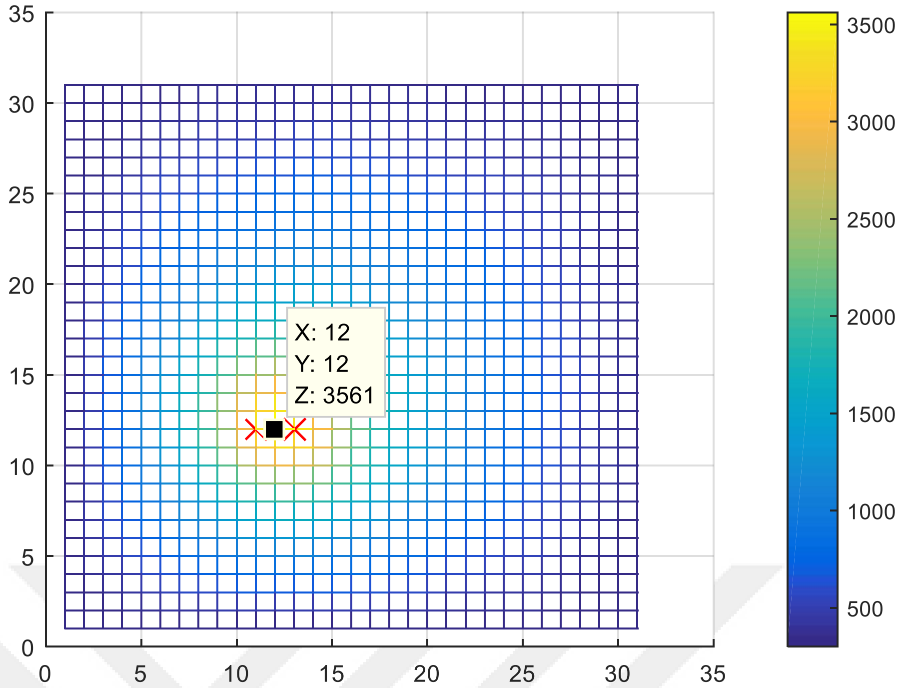

Figure 5.3 Schematic view of linear heat flux on consecutive points

Linear heat flux on consecutive points of the surface is shown in Figure 5.3. Thermal effects is demonstrated with peak temperature gradient on this area by Figure 5.7. Previous nodes temperature is effected on the next nodes, because of heat source and tracking time on the surface, as in Figure 5.6 and Figure 5.5.

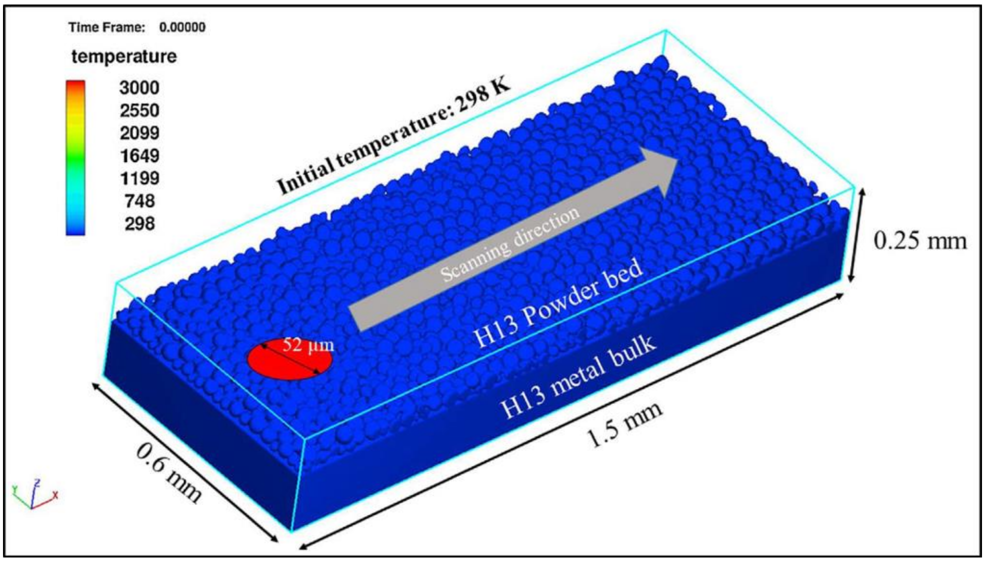

Figure 5.4 Schematic diagram of process parameters of scanning direction on the surface with defined area [34]

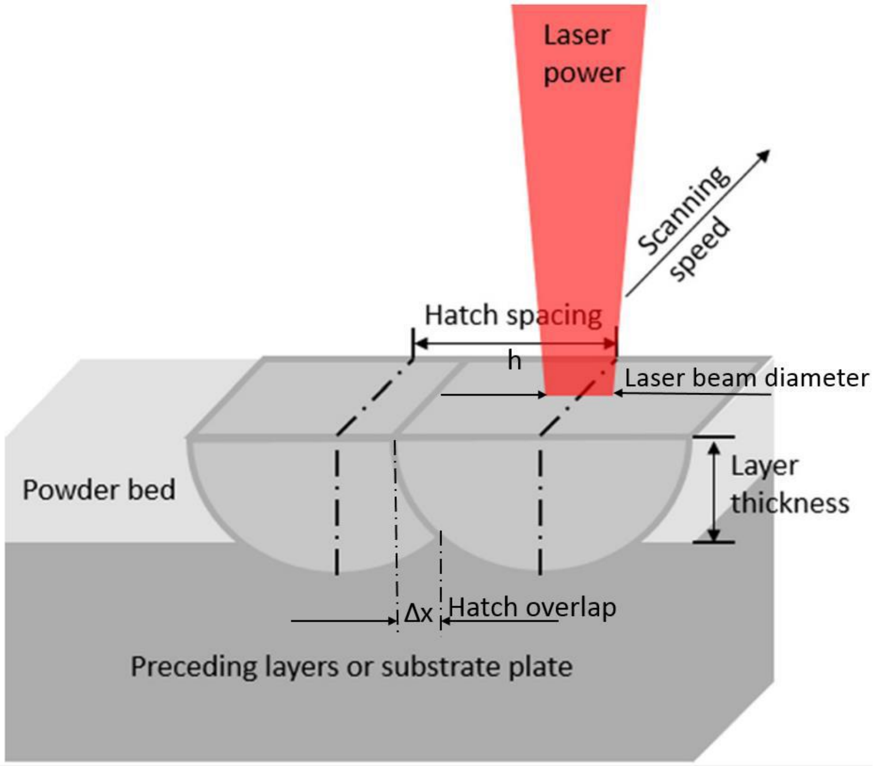

Figure 5.5 Shematic diagram of process parameters of direction on the model [35]

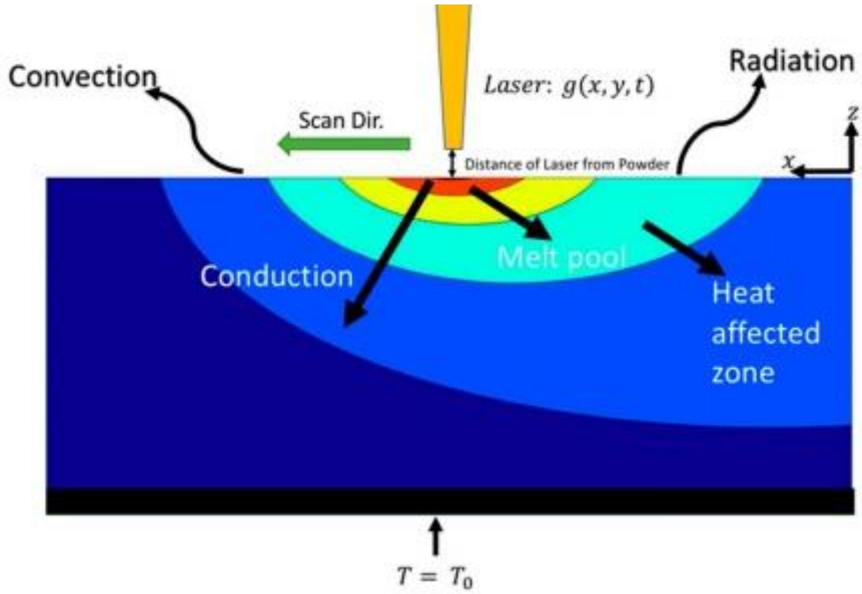

Figure 5.6 Heat Transfer mechanism when applied the laser force on the powder.

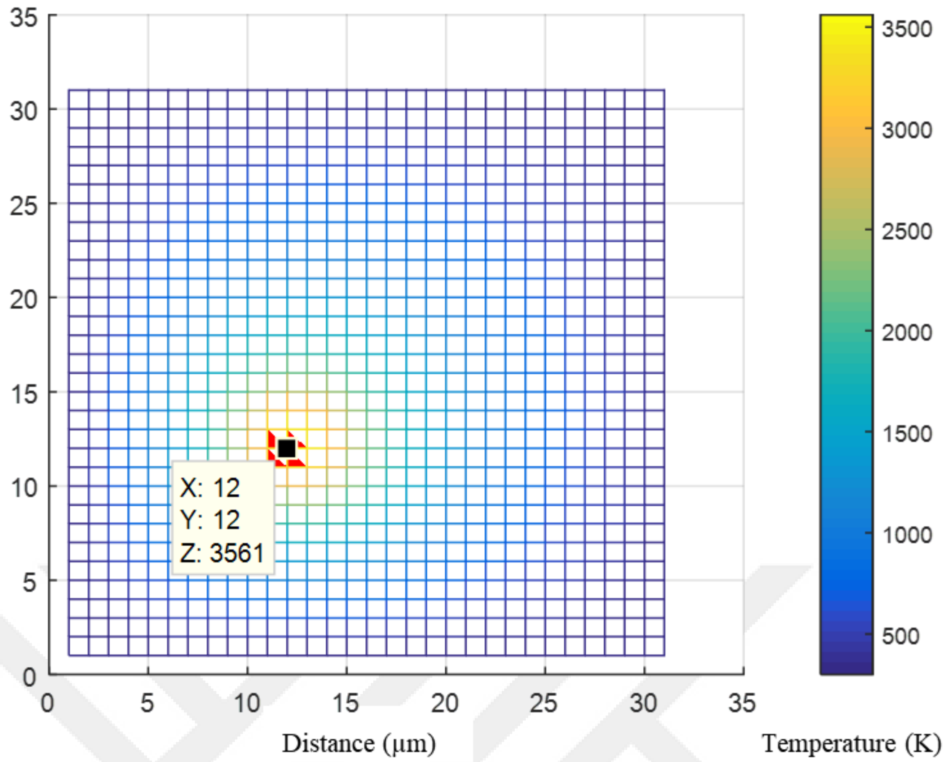

Figure 5.7 Simulation of linear heat flux on consequtive points around the (12,12) points.

In following simulation is described as decreasing the heat flux with using value of above the melting temperature suitable form in midpoint of the model, approximately. Its general view is shown in Figure 5.8.

For the 16 point is applicable on the system, and demonstration was done according to this strategy in Figure 5.9 and Figure 5.10.

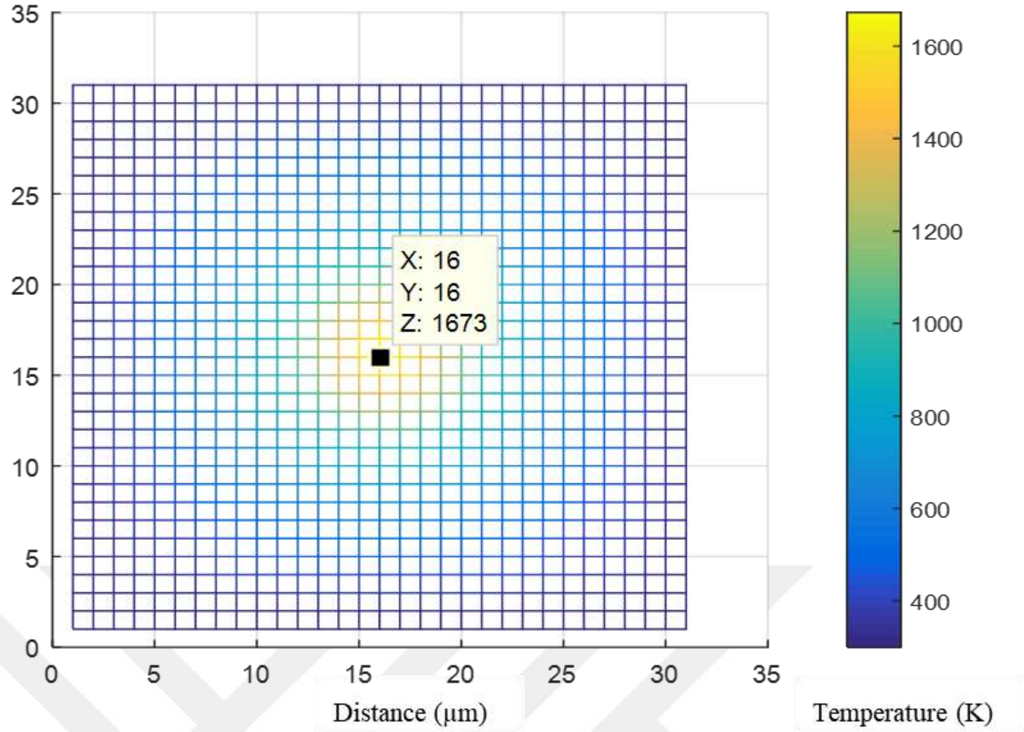

Figure 5.8 Simulation of temperature distribution on midpoints around the (16,16) points.

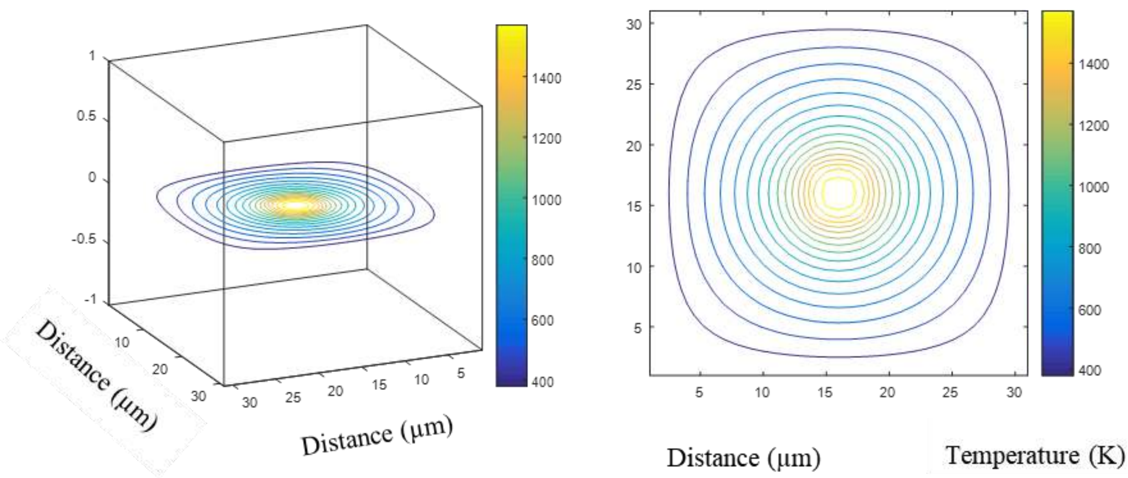

Figure 5.9 Simulation of temperature distribution of each point in wave form.

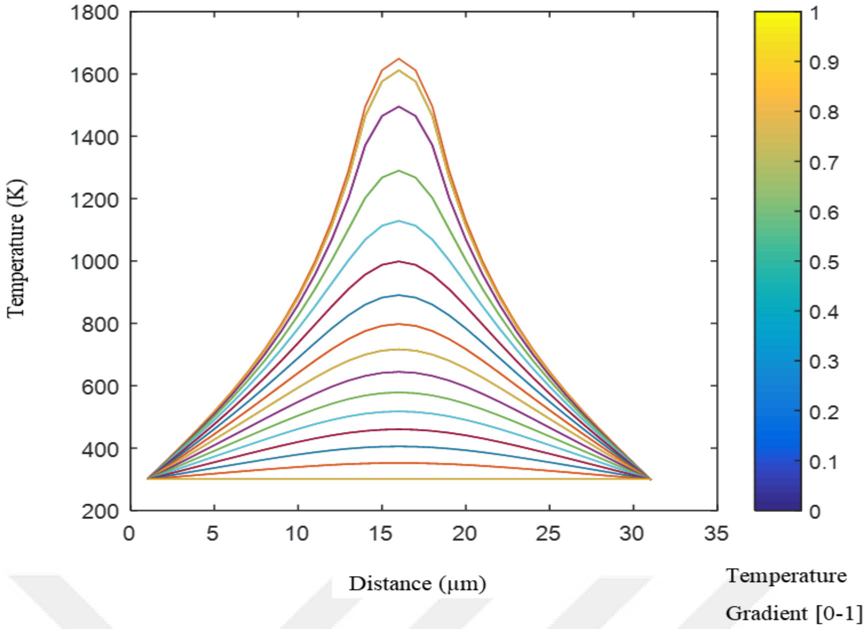

Figure 5.10 Simulation of temperature distribution of each point from 16 point at the starting point of the melting, consecutively.

CHAPTER 6

RESULTS AND DISCUSSION

6.1 Introduction

This chapter is about the analysis and evaluation of simulation results and involved discussion.

6.2 Simulation of Temperature Distribution Analysis

The simulation is useful for identifying the optimal type of process without extensive and expensive testing. Type of laser was selected as Gaussian distribution. Heat conduction will be seen in the following laser beam on the melted area, where heat affected zone is the most critical region in this process. Heat transfer has been done inside the metallic powder by conduction during the solidification. When the power of laser is increased, powder will be heated. However, Scan speed is defined the optimal changeable value when acting on this scenario. Since the scan speed can be controlled and depend on the melting process, directly fully melt or not. At this point simulation will definitely help to see. In first touching on the metallic powder, laser beam from preheated zone should wait for a while in order to transfer the energy to the neighbor powders zone. The preheated of the metallic powder under the melting and sintering temperature is achieved. This process might be supported the fusion process, and also the finishing the operations quickly. That is same as the preheating the hot bed of a 3D printer, when code is loaded on the 3D printer.

Figure 6.2 shows that when the laser beam is moved on the metallic powder, surface of the melted areas geometry is effected on the heat flux and energy density by the laser beam in SLM process. Melting temperature is the most critical difference in the heat transfer. The melting point of Ti6Al4V is 1933 K. Simulation core temperature is nearly 2036 K. Therefore, the fully melted area possibility is high. In order to determine the compatibility of the simulation, a comparative study should be performed by the experimental works. Unfortunately the experimental works is an uneconomic and most demanding process at the present moment.

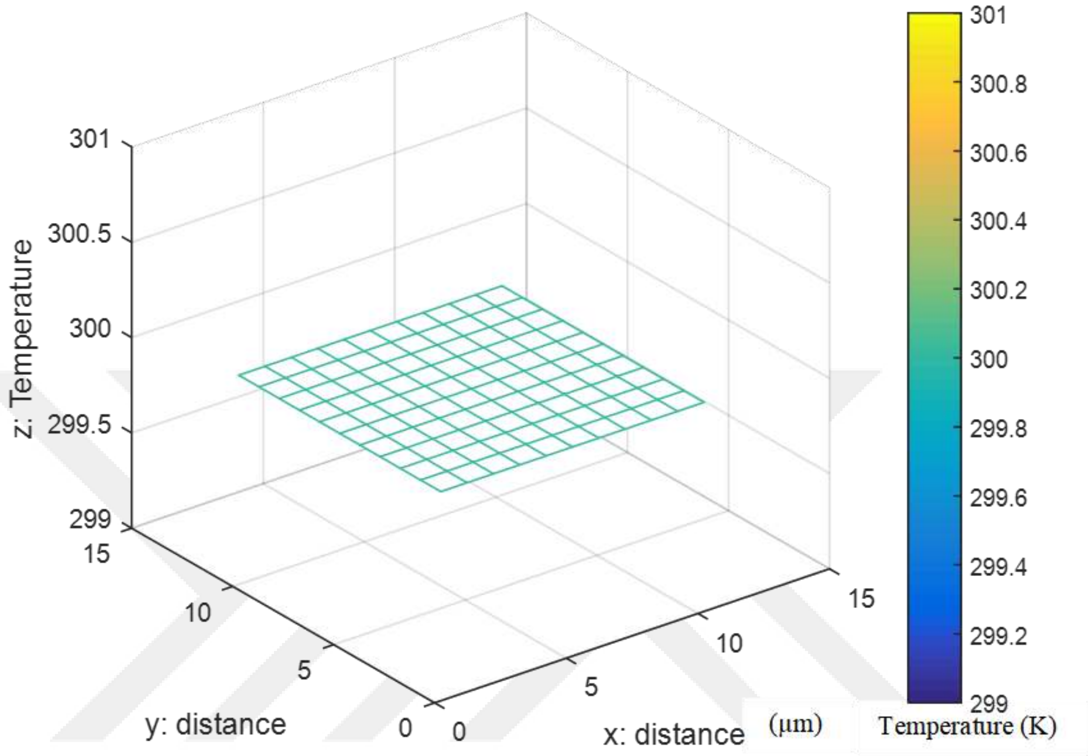

Figure 6.1 Initial condition of simulation

Initial conditions, temperature is set to $T_0 = 300$ K. Scan speed can be set by the distance and time relationship according to basic phsical phenomena. Z axis shows the temperature in Kelvin (K), and right side of the figure is defined as the temperature gradients colors label in Figure 6.1. The arrow refers to laser beam scanning direction in Figure 6.2. Where is shown simulation on an array of the nodes by SLM. This type is called as voxels in order to illustrated the simulation of moving heat source.

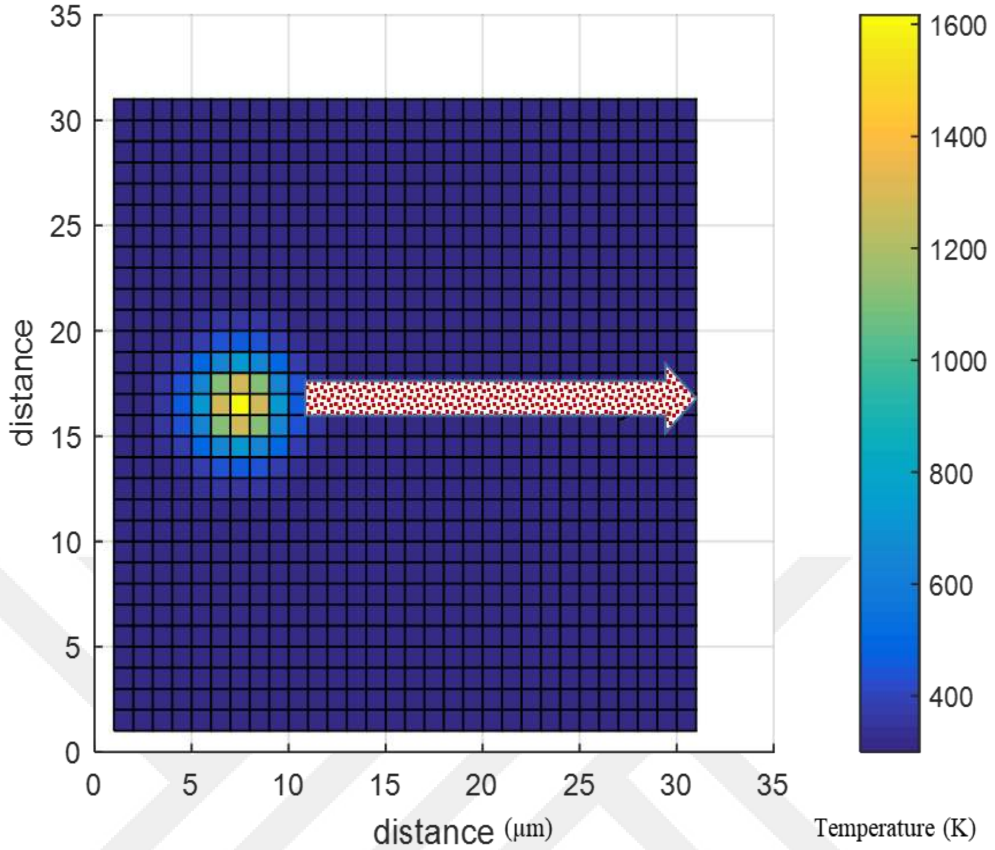

Figure 6.2 The scanning of laser beam step simulation on an array of the metallic powder.

Initial condition has been set the static heating. But the following steps are dealing with the moving motion of the laser beam or heat source.

Temperature values are given in Figure 6.3 (Step 1-2), Figure 6.4 (Steps 3-4), Figure 6.5 (Steps 5-6), Figure 6.6 (Steps 7-8) and finally Figure 6.7 (Steps 9-10). X and Y values are the coordinates of the position of the laser beam core in Figures. Here Z value refers to the temperature and in a rounabout way energy density because of the energy density is proportional with power. It is inversely correlated with the laser spot diameter and the scanning speed. From this point, conductional heat transfer is related with the interchange of heat between the metallic powders.

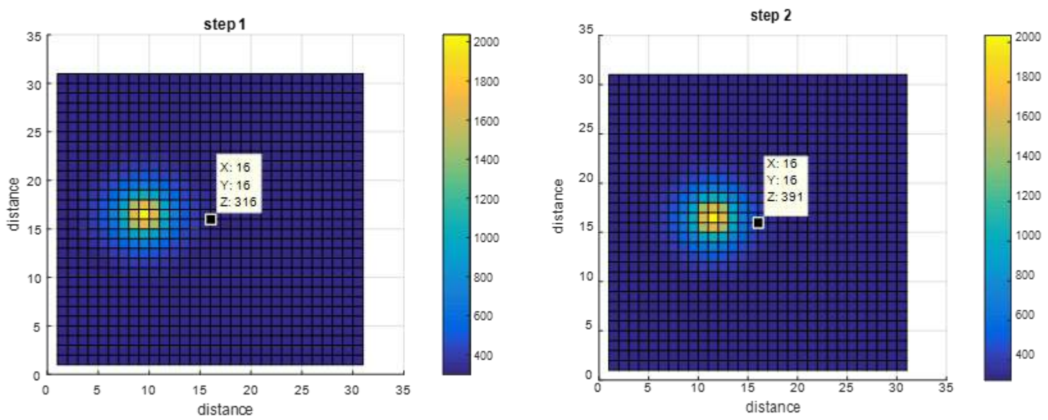

Figure 6.3 Step 1-2 and its temperature value in midpoint (16,16).

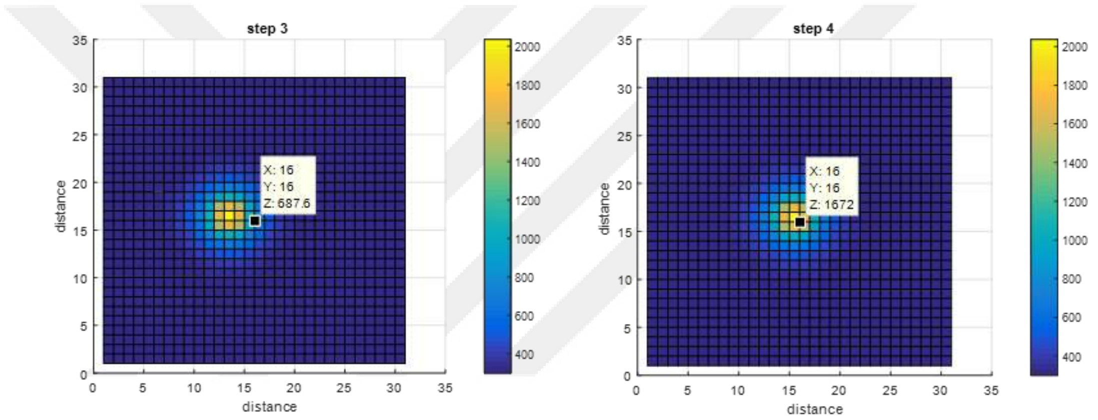

Figure 6.4 Step 3-4 and its temperature value in midpoint (16,16).

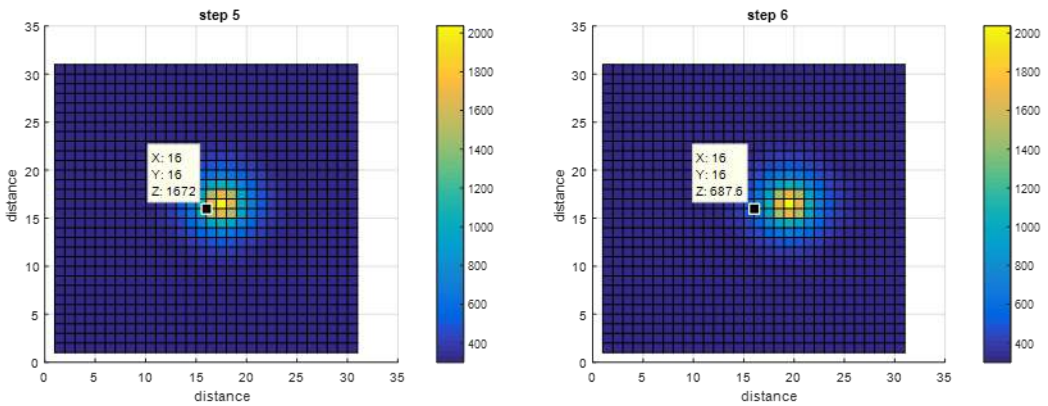

Figure 6.5 Step 5-6 and its temperature value in midpoint (16,16).

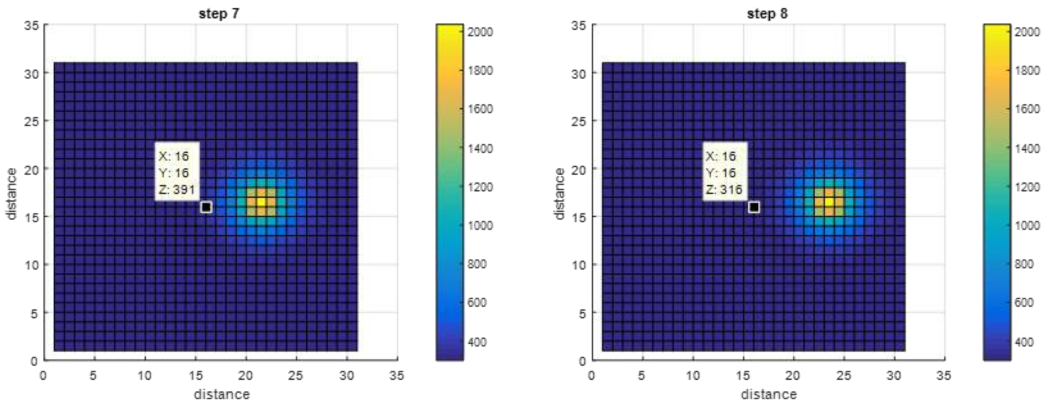

Figure 6.6 Step 7-8 and its temperature value with distribution in midpoint (16,16).

The core temperature in melt pool is supplier to heat and energy transfer to nearby in especially Heat Affected Zone (HAZ). Homogenous type of powder is supported the neatly cooling and continuosly solidification on the surface with body as shown in Figure 6.8.

All parameter and governing equations were solved in this simulation technique by using MATLAB.

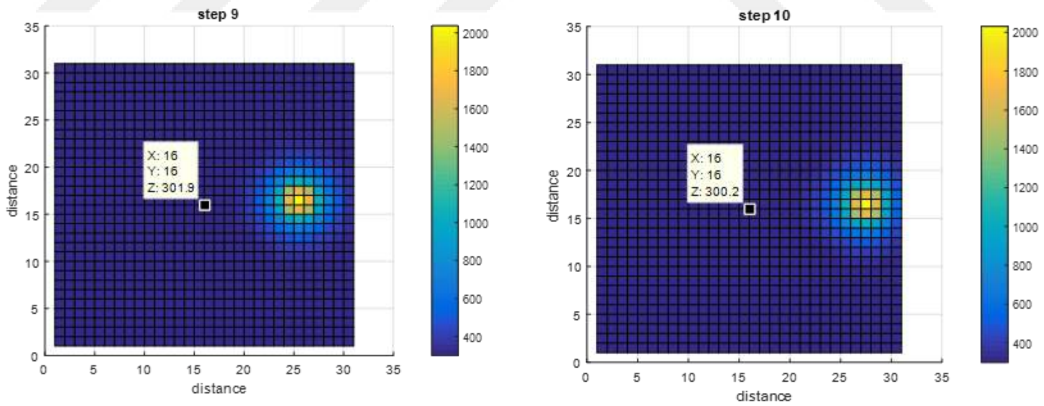

Figure 6.7 Step 9-10 and its temperature value in midpoint (16,16).

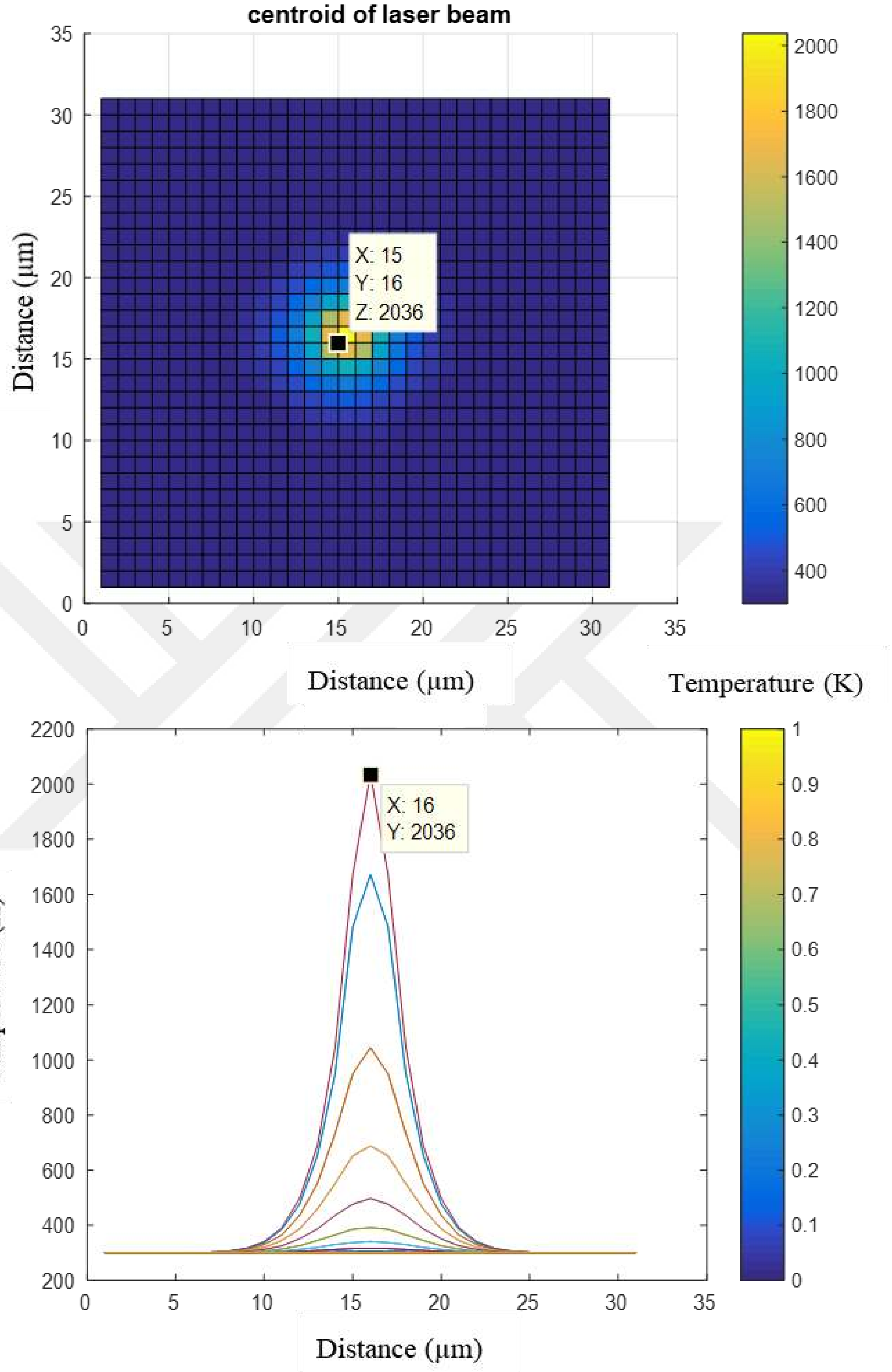

Figure 6.8 Centroid of the laser beam temperature value and pick temperature distribution

When laser torch was acting on x and y points in (3,3) at the beginning point of distribution of temperature. There is a trick and important point from this situation in Figure 6.9, in this figure points are starting from point (1,1) until the point (5,5) in Figure 6.10.

The origin point or the other points in order to starting laser torch touching on the powder. There was a critical situations and explanation of the figurative form is shown in Figure 6.11.

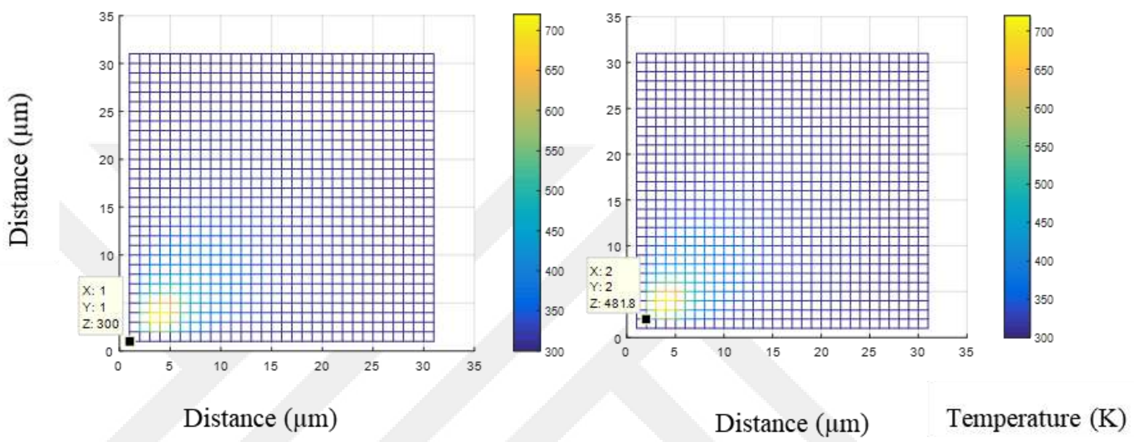

Figure 6.9 Starting point of the laser beam on the powders.

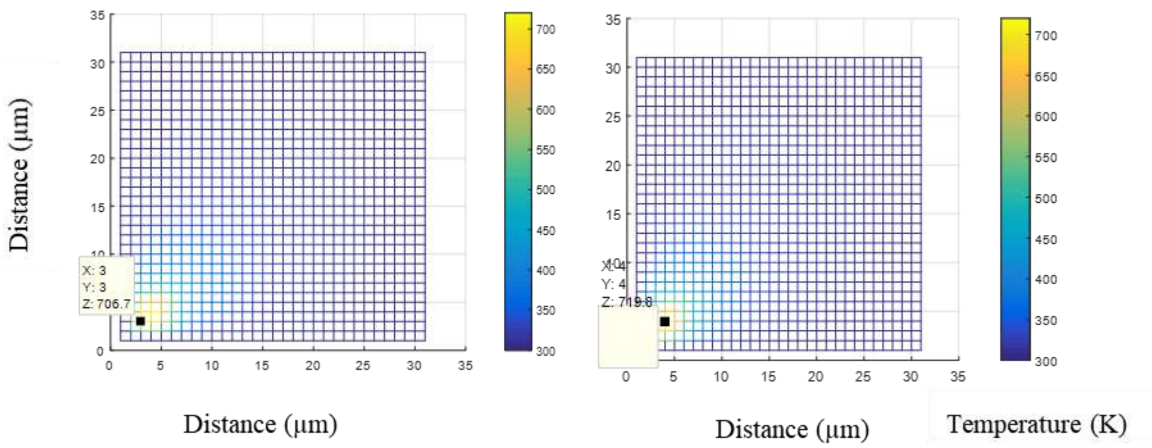

Figure 6.10 Starting point of the laser beam on the powders.

In Figure 6.11, temperature distribution is predictable to be observed after a unit offset is done.

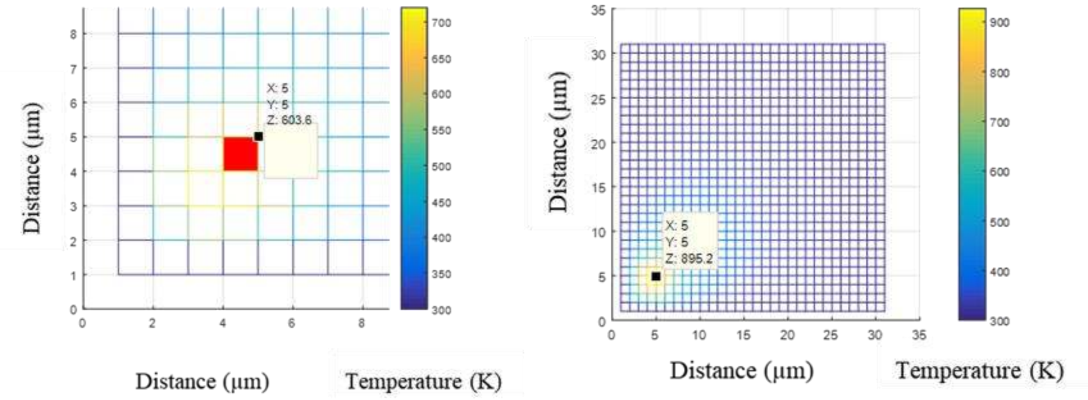

Figure 6.11 (5,5) point of the laser beam on the powders

If the algorithms are held invariably and limited in +/- 2 offset , the temperature distribution will not be much more detailed and it will be different at the new starting point. If this situation is assumed, the characterization of the temperature distribution will be accepted in a monotonous form. The resulting values are expected to be not effective enough.

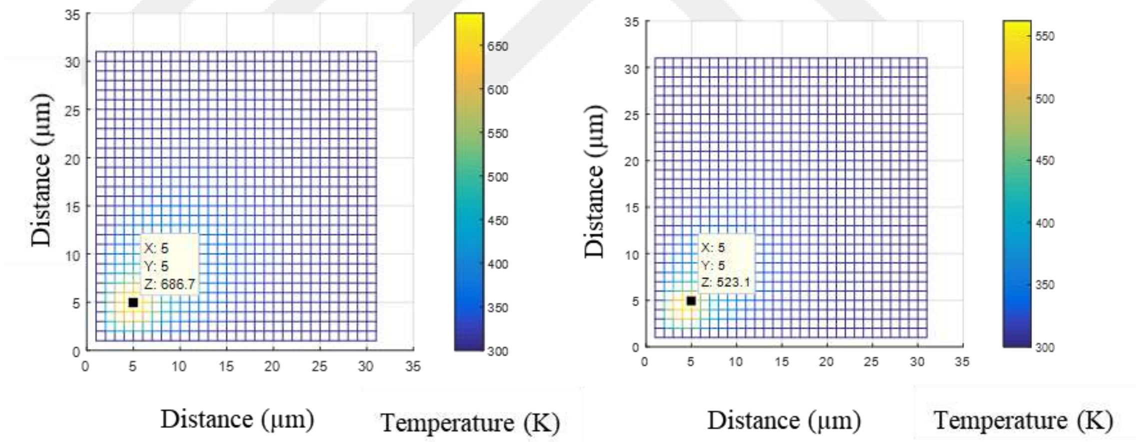

Figure 6.12 (5,5) point of the laser beam on the powders

The exact explanation is possible by Figure 6.12. The temperature became 523.1 K as a result of defining the X and Y values as (3,3). With the help of this limitation, the significance of the laser spot diameter and spot size are emphasized. The same rate of laser power is applied per unit powder metals. Therefore, the energy balance is provided on the metallic powders during the scaning operation. After this balancing operation, the effect of temperature distribution becomes more of an issue. Providing that the problem of the heat transfer at the boundry condition is neglected on the first line scaning operation. The heat conduction part of this process will be analyzed better with applying equal energy on each and every metallic powder. This condition is applicable solely at the beginning step.

When the laser power is increased %25 from the optimal starting point, Temperature distribution can be effected as in Figure 6.13. For instance, Laser Power is increasing from 100W to 125W.

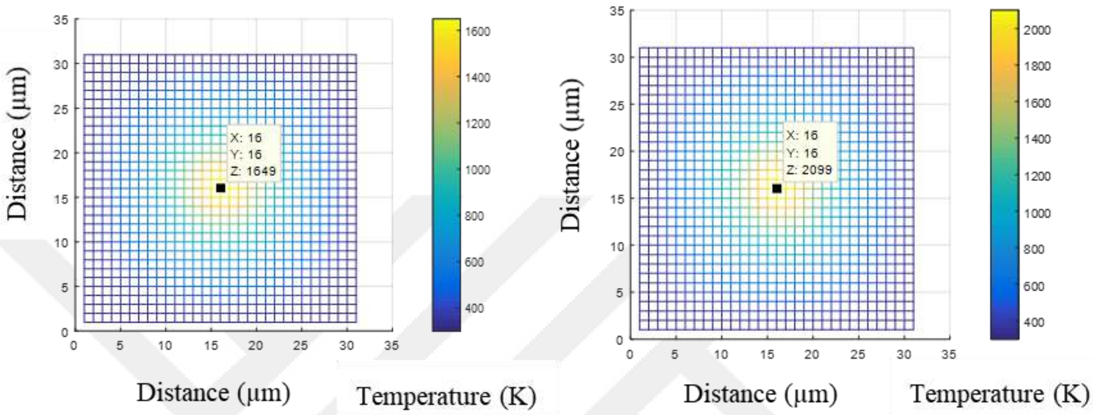

Figure 6.13 Different laser power on midpoint of the temperature distribution on the powders.

In Figure 6.14, the energy density of the core temperature effect is shown, when applied the incident laser source on the powder metals. This formation can be adopted the Heat affected zone (HAZ). There is midpoint of the laser spot sign on the powders. Temperature distribution form can be visiualized by Figure 6.15, statically.

Some studies are examined according to scanning speed and laser power in Figure 6.16. The result of the simulation has the similar characteristic properties of my results. Especially, after soldification temperature point and slope of the graph in Figure 6.17, that is so similar to my current simulation results, that are demonstrated in Figure 6.18. Temperature distribution is explained by symmetrical form. Therefore, the temperature distribution is covering on the area of selected line on the model. The midpoint of the temperature distribution for each units are explained incident temperature distribution of selected region. Actually, all conditions are combined each other the point by point in selected mesh or nodes. These are effected by heat transfer phenomena, which is shown in Figure 6.19 and Figure 6.20.

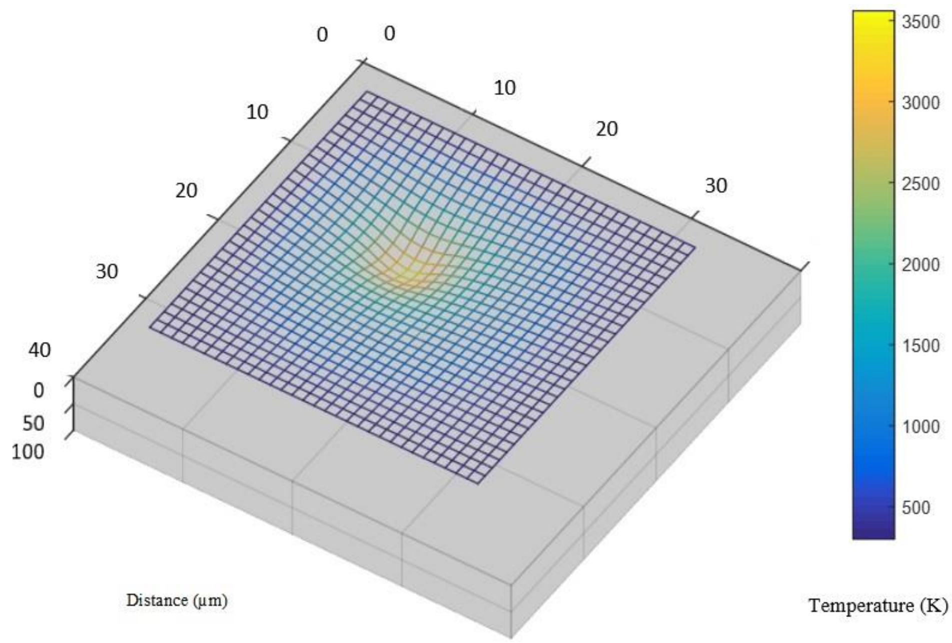

Figure 6.14 Heat affected zone at the midpoint of the system.

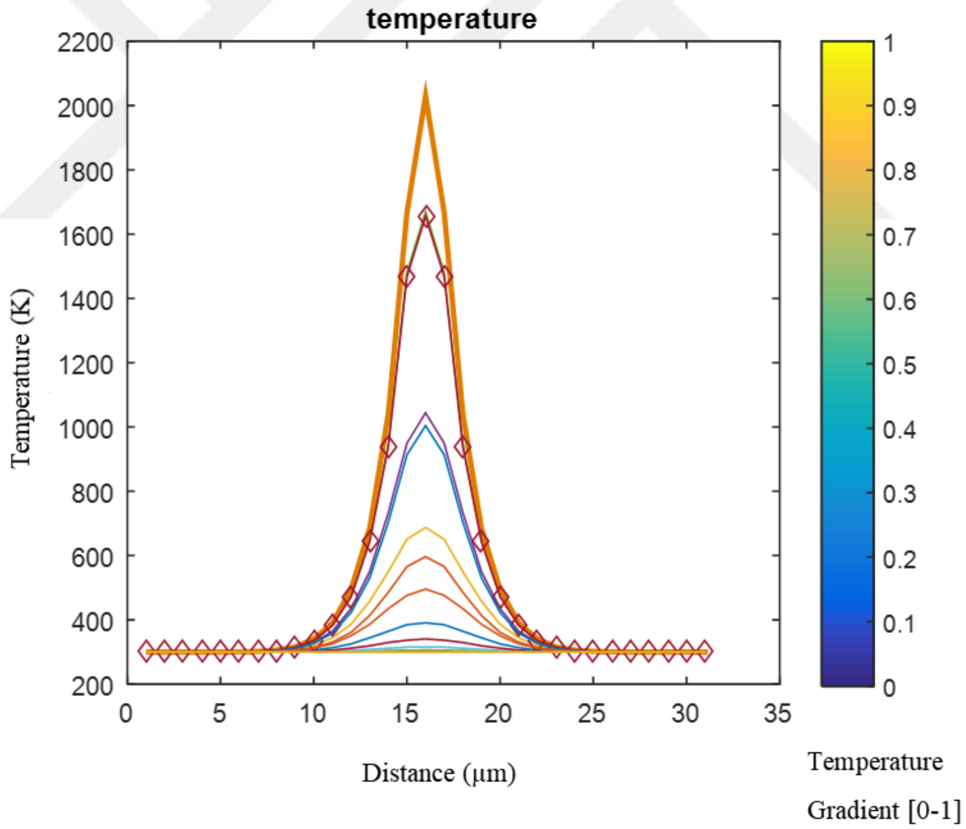

Figure 6.15 Midpoint of the temperature distribution for each units on the point by point, statically.

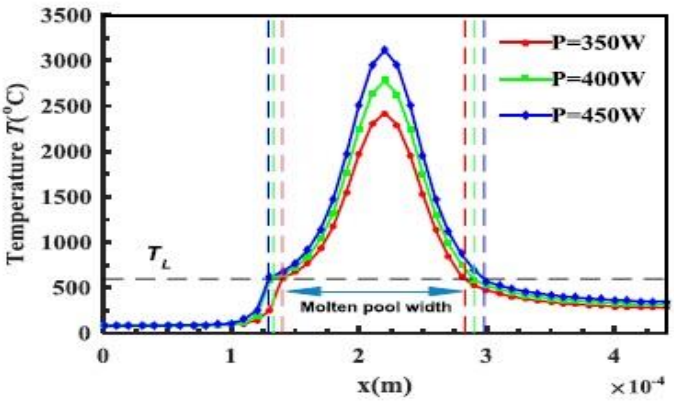

Figure 6.16 Temperature distribution of molten pool at central point [37]

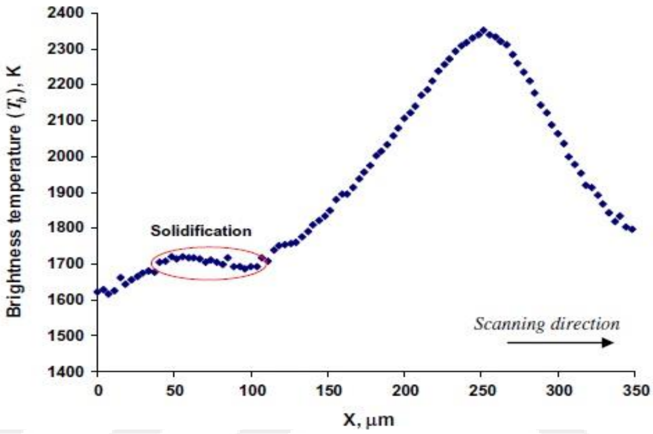

Figure 6.17 Distribution of the brightness temperature in the XY-plane along the laser scanning direction [38]

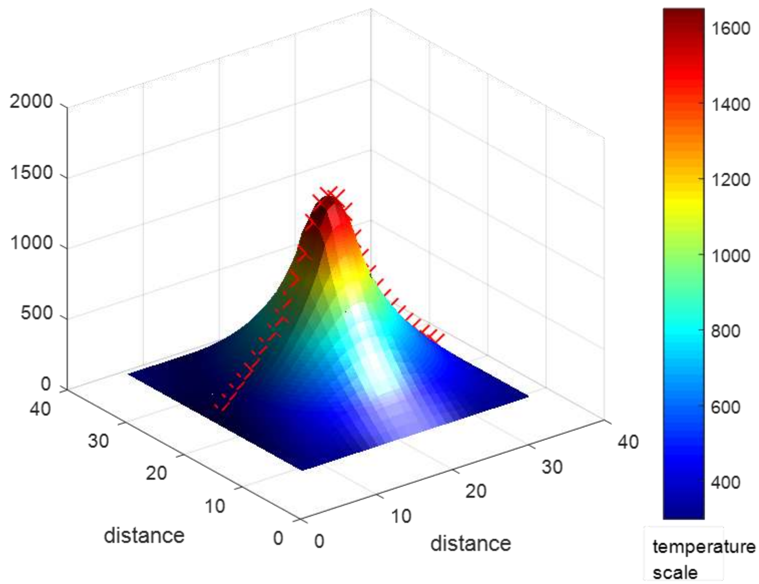

Figure 6.18 Distribution of the colorful definiation of sign on the selected powders.

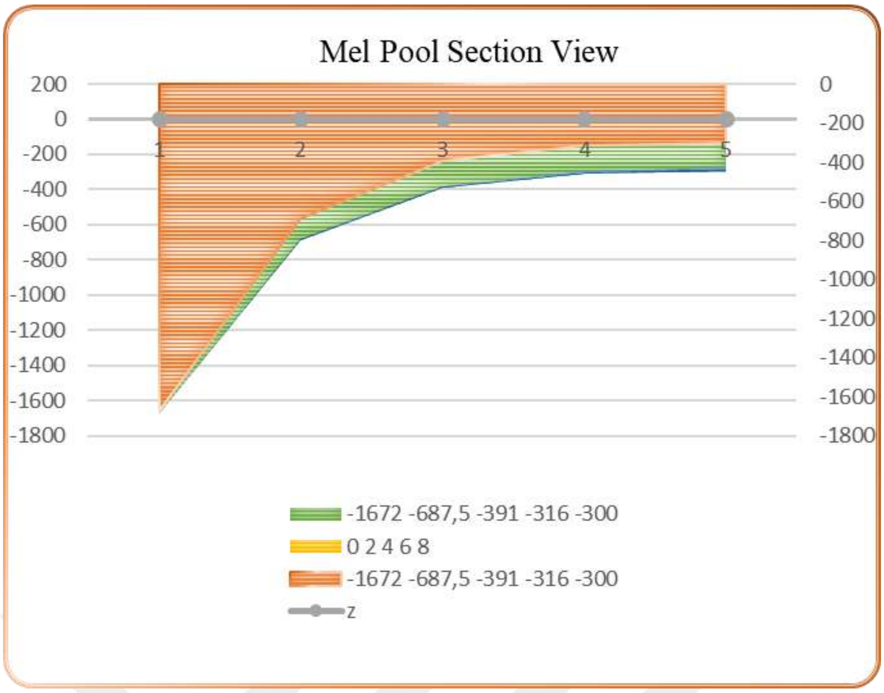

Figure 6.19 Temperature distribution of melt pool section in an adaptive form.

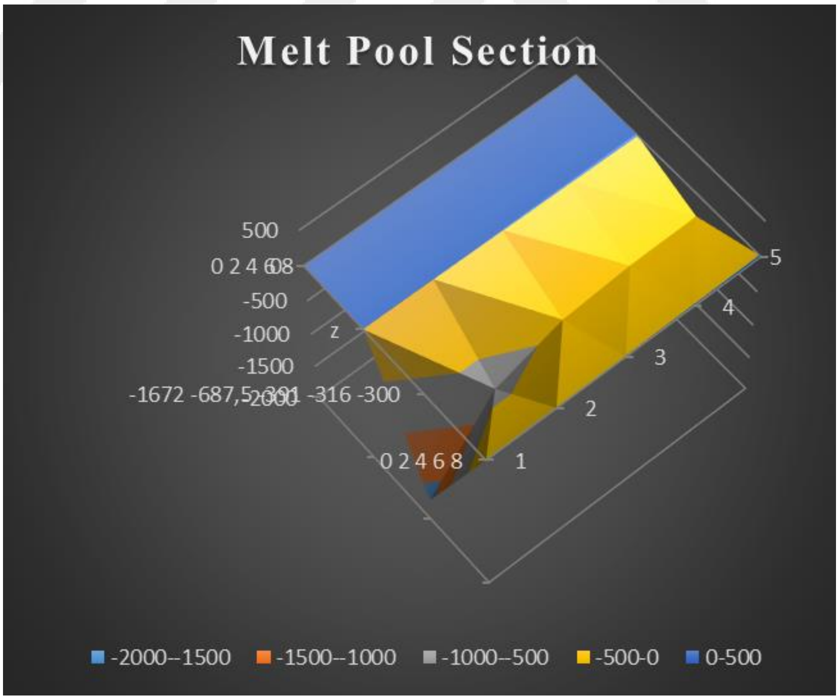

Figure 6.20 Temperature distribution of melt pool section in 3D form.

CHAPTER 7

CONLUSIONS AND FUTURE WORKS

7.1 Introduction

This chapter is about conclusions which are acquired from this work and the future works on the additive manufacturing process in selective laser melting method.

7.2 Conclusions

In this study, simulation based theoretical studies were carried out to investigate the temperature distribution of the selective laser melting process. User friendly customized methodology has been developed and modelling of the system used in the script programming in order to obtained simulation results, which are run by heat transfer mechanism. Heat conduction, convection and radiation are desired on this simulation. But, heat conduction take a main role during the process. Physical and thermal properties of Ti6Al4V alloy used in this study (taken by Table 5.1 and Table 5.2). That is shown that parameters control and programming can be successfully applied by using selective laser melting simulation technique.

A simulation study of selective laser melting process for temperature distribution in fixed point at center of the body is performed. This study has applied the heat transfer mechanisms from the metallic powder when adaptive scanning of the laser beam follows the direction of selected line. The evidence of findings and conclusion from the present simulation are as follows:

- The interval of starting point and final point of laser beam is nearly equal to each other.
- At the beginning point energy density is lower than the next step. However, previous powder energy from heat flux is increased the next unmelted powder temperature. For the first point, a laser power difusion can be applied a transient form because of the cluster of powder metals.

- Scanning speed depends on the distance from hatch spacing with laser pitch on the scanning direction. It is proportionally on the heat transfer and energy absorptivity above the powders.
- If the set temperature higher than or lower than the average of melting point, SLM process won't be done properly. If no presetting is reached, temperature distribution of melt pool could be extra ordinary.

7.3 Future Works

For future researches, it is suggested to simulate different type of materials for selective laser melting in additive manufacturing process. A mathematical model can be established on account of select the appropriate parameter sets for getting desired melt pool geometry control for good fusion process without any disturbance like keyholes, porosity, unfusion part, etc.

After the experimental and theoretical results, to analyse of the microscoping investigation on the material inside and outside. In addition, this process can be examined by image processing and also supported MATLAB programming and experimental photos.

If this study has an importance, modelling and simulation techniques can be applied on the topology optimisation for the most widely used in design studios.

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