

# **PROJECT REPORT ON**

## **MELT POOL ANALYSIS OF HIGH SPEED STEEL(M2) - FABRICATED THROUGH SELECTIVE LASER SINTERING USING COMSOL MULTI PHYSICS**

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## CERTIFICATE


This is to certify that the Project Report entitled “**MELT POOL ANALYSIS OF HIGH SPEED STEEL(M2) FABRICATED THROUGH SELECTIVE LASER SINTERING USING COMSOL MULTI PHYSICS**” being submitted by BOMMANA PAVAN KALYAN (317126520125), CHINTALA NARAYANA GOUTHAM (317126520127), NAGIREDDY RAMA VENKATA SATYANARAYANA (317126520155), PAILA BHARGAV (317126520156), in partial fulfillments for the award of degree of **BACHELOR OF TECHNOLOGY** in **MECHANICAL ENGINEERING**, ANITS. It is the work of bona-fide, carried out under the guidance and supervision of **MR.B.S.LAKSHMI PRASAD**, Assistant Professor, Department Of Mechanical Engineering, ANITS during the academic year of 2017-2021.

**PROJECT GUIDE**

  
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## **ABSTRACT**

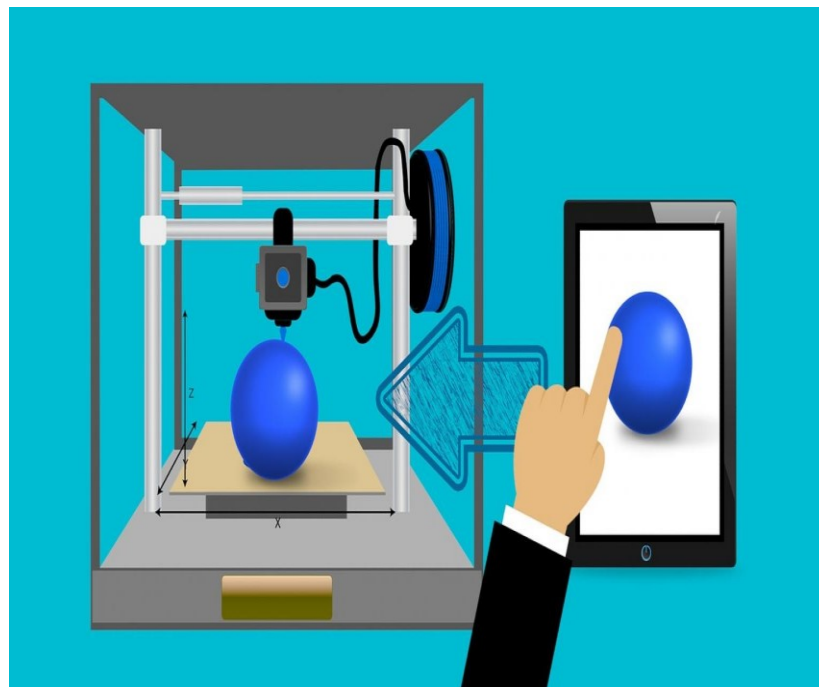
This report is about the introduction to the concept and process of Additive manufacturing. Using the Additive manufacturing techniques, simulation is done on a Metal(Steel) in this project. In this simulation of metallic powder bed additive manufacturing process we get the major findings like temperature field, residual stresses and melt pool characteristics that occur in a metal. Selective Laser Sintering is a famous metal additive manufacturing process that is used to melt powder metal on a bed and form a metal plate of desired material that is formed layer by layer with the melting of the metal powder. Based on many reviewed studies, a number of future directions are identified in the context of transforming simulation into a powerful tool for the industrial application of additive manufacturing. Smart modelling approaches should be developed, material and their properties should be further characterised and standardised in additive manufacturing simulation have to be developed and simulation needs to be a part of the modern digital production chains.

In this simulation of the laser melting powder bed fusion additive manufacturing process we use a multi-scale approach implemented with the COMSOL Multiphysics® software, Heat Transfer Module, and Structural Mechanics Module. COSMOL Multiphysics is the software which we use in this project for the process of simulation of STEEL.

# **CHAPTER - 1**

## INTRODUCTION

Additive manufacturing is the official industry standard term (ASTM F2792) for all applications of the technology. It is defined as the process of joining materials to make objects from 3D model data, usually layer upon layer, as opposed to subtractive manufacturing methodologies. Synonyms are additive fabrication, additive processes, additive techniques, additive layer manufacturing, layer manufacturing, and freeform fabrication.



This tool-less manufacturing method can produce fully dense metallic parts in short time, with high precision. Features of additive manufacturing like freedom of part design, part complexity, light weighting, part consolidation and design for function are garnering particular interests in metal additive manufacturing for aerospace, oil & gas, marine and automobile applications.

## CLASSIFICATION OF ADDITIVE MANUFACTURING :

A large number of different AM processes for fabricating metallic parts, utilizing different combinations of stock material form, material delivery and heat source have been developed over the years. In the powder-based processes, metallic powder is spread on the bed before scanned by the beam or being fed directly to the heat source affected region. The powder bed processes can be further classified based on physical state of raw materials and material fusion is used for consolidation.

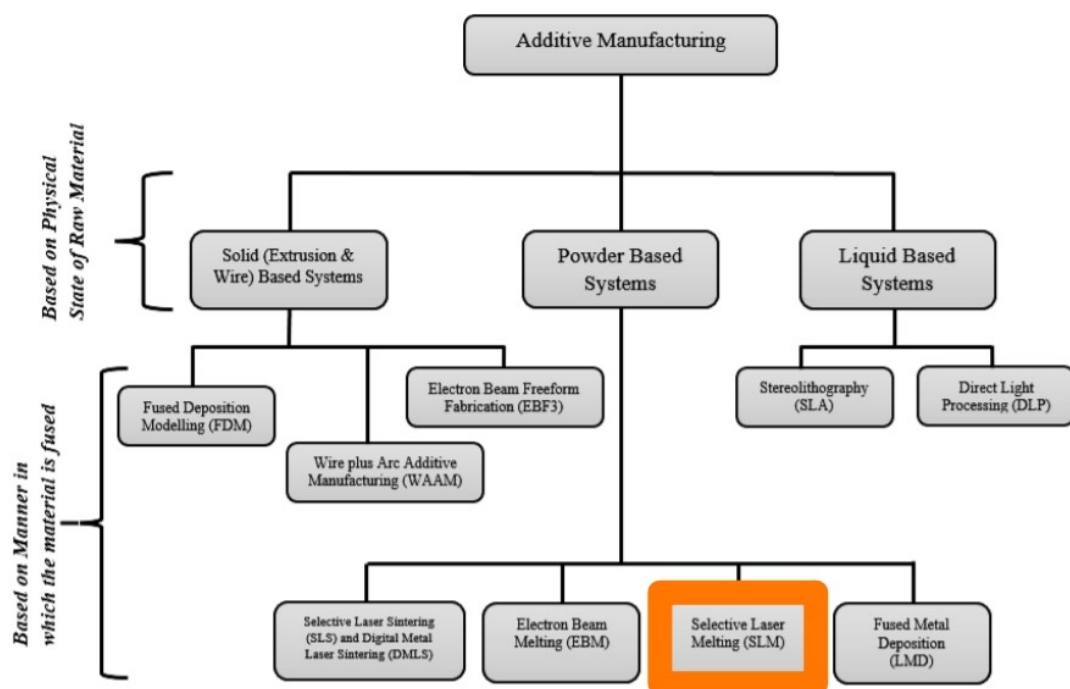


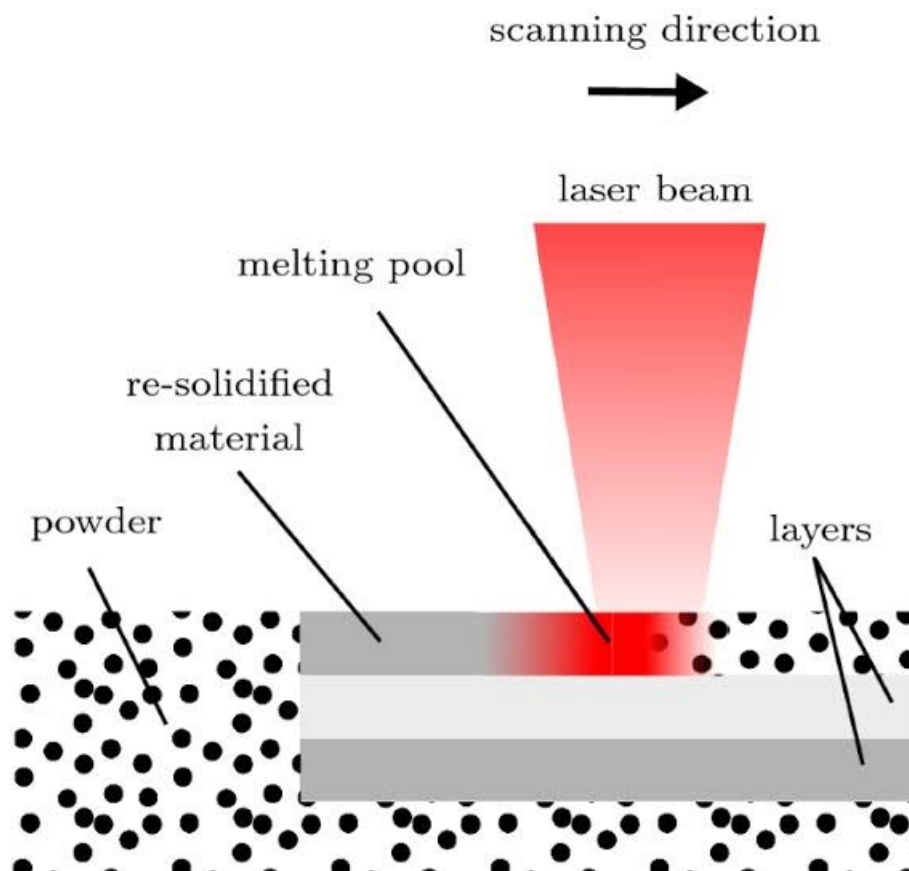
Figure 1: Classification of different AM processes.

Among the many different AM processes, according to the application in industry requirements are Selective Laser Sintering (SLS), Selective Laser

Melting (SLM), Electron Beam Melting (EBM) and Wire and Arc Additive Manufacturing (WAAM). These processes can produce extremely dense components without any post-processing with comparable mechanical and electrochemical properties to other conventional manufacturing methods. SLS and DMLS are in essence the same process. While SLS is used to produce parts using a variety of materials like plastics, ceramics, metals, DMLS can only be used to produce metal alloy parts. SLM can be used to manufacture with any material. It uses a high-energy laser beam to heat and melt the powdered material. The material oxidation and degradation is minimized by carrying out the process in protective environment. EBM uses a very high-energy density electron beam, produces dense, void-free parts, but can process only metals. It is emerging as a high-quality substitute to laser melting and is being used to manufacture and repair turbine blades. Friction Stir Additive Manufacturing (FSAM) is another AM technique and a study has shown that FSAM did not only improve the mechanical properties, but the properties attained were also different from those manufactured by conventional methods. Through FSAM, strength of 400 MPa and a ductility of 17 % were achieved for an Mg-based alloy as against the strength and ductility in the base material (357 MPa, 2.9 % ductility). In the aerospace industry, FSAM could be used for the fabrication of stiffeners/stringers, wing spars and longerons in skin panels. Electron Beam Freeform Fabrication (EBF3) uses an electron beam with a wire based system to fuse metals instead of powders. EBF3 can be used to produce structures with materials such as aluminum, high strength steels, titanium, titanium aluminides, nickel-base alloys, and metal matrix composites. Wire plus Arc Additive Manufacturing (WAAM) is another wire-based system that effectively delivers free-space unrestricted weld metal deposition. The process can produce vertical, horizontal and angled walls, mixed-material conic sections, enclosed sections, crossovers and intersections. The products obtained through WAAM are extremely high quality and are even better than those produced by normal welding procedures.



## SELECTIVE LASER MELTING PROCESS :

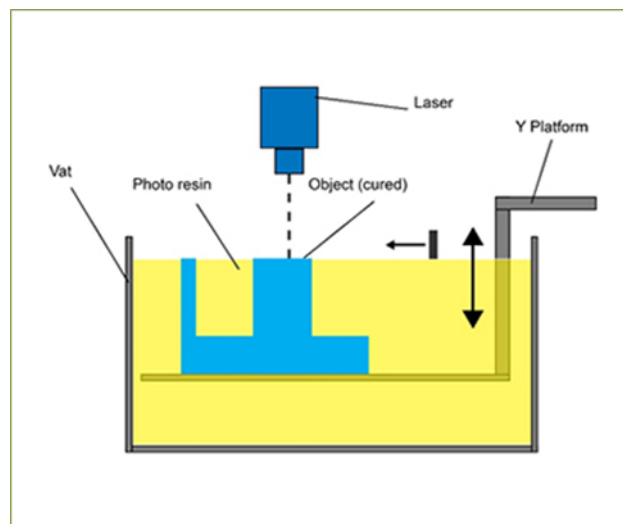


Selective laser melting (SLM) is a powder bed fusion-based metal additive manufacturing process. It has gained wide attention as a potential technology for making complex structures for aerospace, automotive and biomedical applications. The SLM process leads to a unique microstructure and mechanical properties due to extremely high cooling rates. The parts exhibit superior monotonic tensile strength and ductility compared to the conventionally manufactured parts. The SLM process involves several physical phenomena such as laser-matter interaction, melting/solidification, conduction-convection-radiation heat transfer and convective fluid flow in the melt pool. These physical phenomena are coupled usually and govern the microstructure, defects and mechanical properties of the manufactured part . Therefore, a detailed analysis of these coupled phenomena is essential to obtain the optimum processing conditions and parameters to manufacture high-quality parts through the SLM.

## Additive manufacturing techniques:

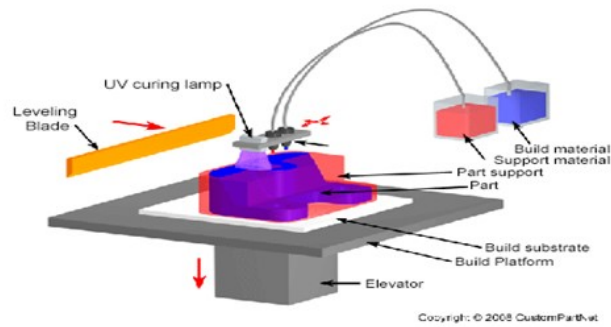
The term “3D Printing” as a synonym for all Additive Manufacturing processes, there are actually lots of individual processes which vary in their method of layer manufacturing. Individual processes will differ depending on the material and machine technology used. Hence, in 2010, the American Society for Testing and Materials (ASTM) group “ASTM F42 – Additive Manufacturing”, formulated a set of standards that techniques classify the range of Additive Manufacturing processes into 7 categories (Standard Terminology for Additive Manufacturing Technologies, 2012)

### 1. VAT Photo polymerisation:



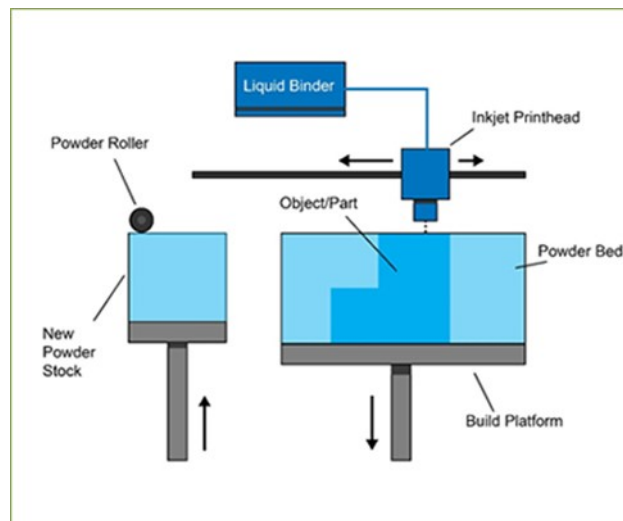
Vat polymerisation uses a vat of liquid photopolymer resin, out of which the model is constructed layer by layer. An ultraviolet (UV) light is used to cure or harden the resin where required, whilst a platform moves the object being made downwards after each new layer is cured, where the light is directed across the surface of the resin with the use of motor controlled mirrors . Where the resin comes in contact with the light, it cures or hardens.

## 2. Material Jetting:



Material jetting creates objects in a similar method to a two dimensional ink jet printer. Material is jetted onto a build platform using either a continuous or Drop on Demand (DOD) approach. Material is jetted onto the build surface or platform, where it solidifies and the model is built layer by layer. Material is deposited from a nozzle which moves horizontally across the build platform. Machines vary in complexity and in their methods of controlling the deposition of material. The material layers are then cured or hardened using ultraviolet (UV) light.

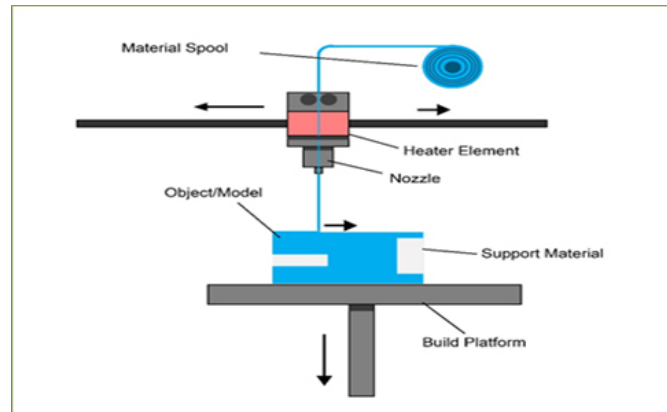
## 3. Binder Jetting:



The binder jetting process uses two materials; a powder based material and a binder. The binder acts as an adhesive between powder layers. The binder is usually in liquid form and the build material in powder form. A print head moves horizontally along the x and y axes of the machine and deposits

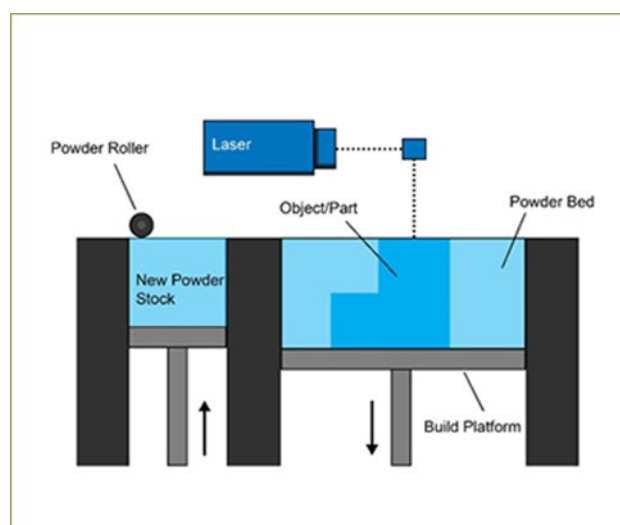
alternating layers of the build material and the binding material. After each layer, the object being printed is lowered on its build platform.

#### 4. Material Extrusion:



Fuse deposition modelling (FDM) is a common material extrusion process and is trademarked by the company Stratasys. Material is drawn through a nozzle, where it is heated and is then deposited layer by layer. The nozzle can move horizontally and a platform moves up and down vertically after each new layer is deposited. It is a commonly used technique used on many inexpensive, domestic and hobby 3D printers. Material layers can be bonded by temperature control or through the use of chemical agents. Material is often added to the machine in spool form as shown in the diagram

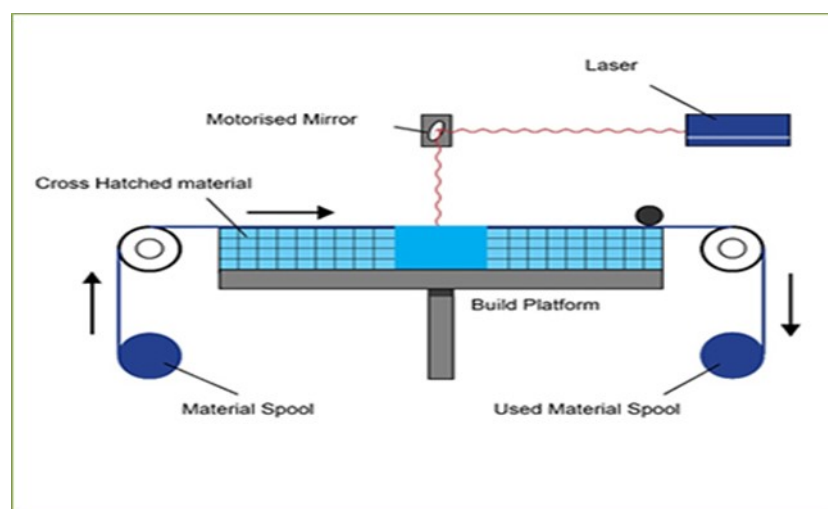
#### 5. Powder bed fusion:



Powder bed fusion (PBF) methods use either a laser or electron beam to melt and fuse material powder together. Electron beam melting (EBM), methods

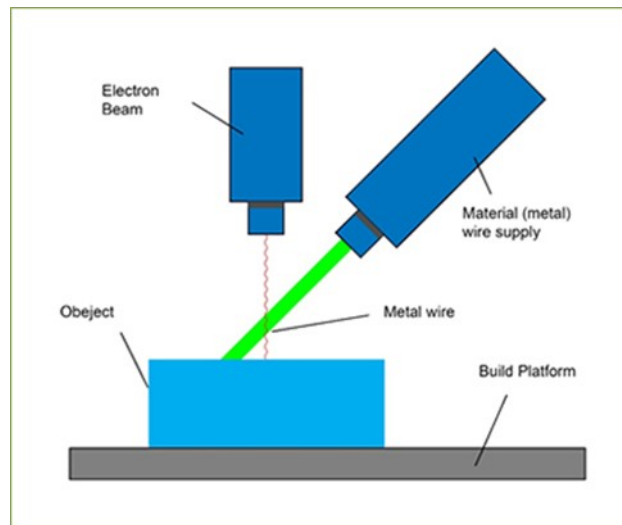
require a vacuum but can be used with metals and alloys in the creation of functional parts. All PBF processes involve the spreading of the powder material over previous layers. There are different mechanisms to enable this, including a roller or a blade. A hopper or a reservoir below or beside the bed provides fresh material supply. Direct metal laser sintering (DMLS) is the same as SLS, but with the use of metals and not plastics. The process sinters the powder, layer by layer. As before, layers are added with a roller in between fusion of layers. A platform lowers the model accordingly.

## 6. Sheet lamination:



Sheet lamination processes include ultrasonic additive manufacturing (UAM) and laminated object manufacturing (LOM). The Ultrasonic Additive Manufacturing process uses sheets or ribbons of metal, which are bound together using ultrasonic welding. The process does require additional CNC machining and removal of the unbound metal, often during the welding process. Laminated object manufacturing (LOM) uses a similar layer by layer approach but uses paper as material and adhesive instead of welding. The LOM process uses a cross hatching method during the printing process to allow for easy removal post build. Laminated objects are often used for aesthetic and visual models and are not suitable for structural use. UAM uses metals and includes aluminium, copper, stainless steel and titanium .

## 7. Directed energy deposition:



A typical Directed energy deposition machine consists of a nozzle mounted on a multi axis arm, which deposits melted material onto the specified surface, where it solidifies. The process is similar in principle to material extrusion, but the nozzle can move in multiple directions and is not fixed to a specific axis. The material, which can be deposited from any angle due to 4 and 5 axis machines, is melted upon deposition with a laser or electron beam. The process can be used with polymers, ceramics but is typically used with metals, in the form of either powder or wire.

## Applications of Metal Additive Manufacturing:

Additive manufacturing or 3D printing is an emerging manufacturing technology. AM technology allows for the direct transformation of digital data into a physical product. There are various printing technologies available. What all the printing technologies have common is that they all build 3D objects by adding material either layer-wise or deposition along a path.

### FIELDS OF APPLICATIONS:

The fields of application for additive manufacturing are manifold-here we focus on industrial usage of Metal Additive Manufacturing.

Metals are the fastest growing segments of 3D printing. Metal AM is increasingly being used to fabricate end use products for

### **1. Aerospace industry and suppliers:**

Aerospace contributes for almost 20% of AM revenue and has been growing annually at about 1.6%. This is mainly because AM produces parts that are lighter in weight, higher performing, reduced part count and reduced inventory. Boeing uses Metallic AM parts in both commercial and military aircrafts. AM allows the fabrication of parts of virtually any shape. Most commonly used Aerospace AM materials are Titanium, aluminium, nickel-based alloy, cobalt chrome, steel.

### **2. Automotive industry and suppliers:**

AM process has already been used in the industry for a range of different vehicle parts as its application is ideally suited to automotive. Unlike more traditional types of engineering and design, this process enables the production of automotive components more quickly. The different components of different usage are produced using this method are

- Aluminium alloys are typically used for Exhausts and emissions, via selective laser melting to create cooling vents.
- Selective laser melting and electron beam melting are utilised with aluminium alloys. These techniques can be used to make pumps and valves within the fluid handling system.
- Exterior: using selective laser melting, polymers are currently used to manufacture wind breakers and bumpers.
- In Manufacturing process.

### **3. Machinery ( e.g. turbines, special machinery):**

Improves the fatigue resistance of critical high performance AM components. along with additive manufacturing Hot Isostatic Pressing (HIP) has been successfully used by the manufacturers to eliminate pores and remove defects ,i.e. nitrides, oxides, carbides to increase the material properties.

### **4. Medical implants (dental, Orthopaedic ):**

One of the applications of additive manufacturing within medical which is already having a big impact is the ability to practice before procedure.

Surgeons can use data taken from MRI and CT scans to build 3D models of the patient's anatomy they will operate on.

5. Handling and robotics
6. Lifestyle & sports (e.g. jewellery, biking)
7. Custom parts (e.g. classical car parts, surgical tools)



## About Comsol muptiphysics software:

Engineers and scientists use the COMSOL Multiphysics® software to simulate designs, devices, and processes in all fields of engineering, manufacturing, and scientific research. COMSOL Multiphysics® is a simulation platform that encompasses all of the steps in the modeling workflow — from defining geometries, material properties, and the physics that describe specific



phenomena to solving and post processing models for producing accurate and trust worthy results. The import of all standard CAD and ECAD files into COMSOL Multiphysics® is supported by the CAD Import Module and ECAD Import Module, respectively.

## **CHAPTER - 2**

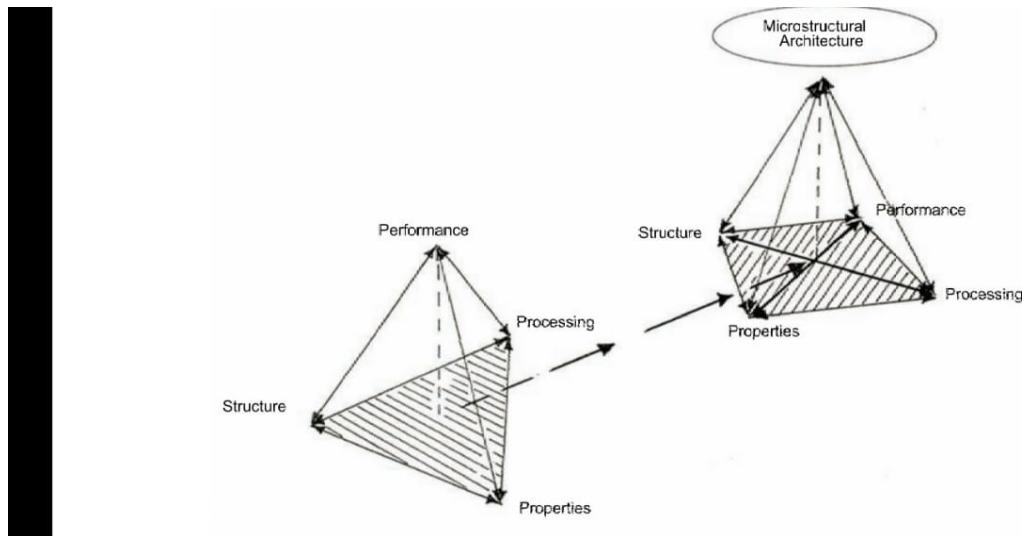
### **LITERATURE SURVEY :**

1. Laser and power bed based manufacturing (i.e, selective laser sintering/melting or its variants) holds a special place within all the Layer Manufacturing processes, no other technique is providing processing for polymers, metals, ceramics, as well as many composites and it also provides different mechanisms like solid state melting, liquid state melting, phase melting, partial melting, full melting, chemical binding etc. This paper described which type of laser-induced process can be used for which type of material. Even though this Selective Laser Melting can process different materials it still had some limitations and problems. There is still a long way for a common applicability of this SLM method to be used very frequently. This paper mainly provided the survey of Selective Laser Melting when processed on different materials with different mechanisms how are the influences and the importance of material properties and composition played an important role. This paper stands as a source of R & D for expanding of the applicability of SLM process.

**By (J.P.KURTH, 2007)**

2. Selective laser melting (SLM) and electron beam melting (EBM) are relatively new rapid, additive manufacturing technologies which can allow for the fabrication of complex, multi-functional metal or alloy monoliths by CAD-directed, selective melting of precursor powder beds. In this study, comparative examples for SLM and EBM fabricated components from pre-alloyed, atomized precursor powders are presented. These include Cu, Ti-6Al-4V, alloy 625 (a Ni-base super alloy), a Co-base super alloy, and 17-4 PH stainless steel. These systems

are characterized by optical metallography, scanning and transmission electron microscopy, and X-ray diffraction. Especially the prospects for creating metal or alloy products with controlled microstructural architectures. This could fundamentally alter or extend the traditional materials science and engineering paradigm relating structure-property-processing (synthesis)-performance in a tetrahedron to a pyramid including microstructural architecture as illustrated schematically in Fig.



**By (J. Mater, 2012.)**

3. During the development of a processing route for the selective laser Melting (SLM) powder-bed fabrication of the nickel super alloy CM247LC it has been observed that the 'island' scan-strategy used as standard by the Concept Laser M2 SLM powder-bed system strongly influences the grain structure of the material. Optical and SEM micrographs are presented to show the observed grain structure in the SLM fabricated and Hot Isostatically Pressed (HIPped) material. The repeating pattern shown in the grain structure has been linked to the overlapping of the 'island' pattern used as standard in the Concept Laser M2 powder-bed facility. Optical and sem analysis has isolated a 1mm repeating square pattern caused by the moving of 5mm island pattern of the SLM powder fabricated CM247LC when using the island scan strategy.

**By ( Luke N. Carter, 2014 )**

4. A combined computational–experimental study is performed to investigate the effect of melting modes (conduction, transition and keyhole) on 316L stainless steel parts fabricated by selective laser melting. The developed model helps to understand laser/matter interaction, melting of particles, the effect of recoil pressure and the formation of fusion zone .It was found that the defocusing has a prominent effect on the SLM process. For focused laser beams, the keyhole mode of melting occurs where both the thermo capillary force and recoil pressure play a dominant role resulting in a narrow and deeper melt pool and if the mode of melting is stable keyhole, then porosity-free single-track deposition can be achieved having better mechanical and microstructural properties .The mechanical testing results of the bulk specimen show that the stable keyhole mode results in substantially higher micro hardness . Nano hardness and elongation to failure compared with the conduction mode.

**By ( Akash Aggarwal, 12 December 2018)**

5. The successful fabrication of dense iron-based parts by selective laser melting (SLM) is still limited to a narrow range of materials. This study aims at gaining an understanding of the effect of elements such as oxygen, carbon, silicon, titanium and copper on the quality of two-dimensional and three-dimensional iron based objects. Carbon ameliorates the surface quality of single layers in contrast to 3D parts. Randomly distributed pores are present in the Fe – 0.8% C parts. Spherical pores result from entrapped CO or CO<sub>2</sub> gas formed by oxidation of C. The lower melting point, higher solidification range and lower amount of iron oxides, which improves the wetting behaviour, tend to reduce the irregular porosity. Silicon and titanium have a negative effect on the surface quality of single layers and three-dimensional Fe-based parts. Both elements increase the irregular porosity. Their detrimental effect is attributed to their high tendency to form oxides and carbides. Copper does not affect the melt pool behaviour of Fe – 0.8% C during SLM of a single layer. Laser radiation but a positive

effect if added in pre alloy form.

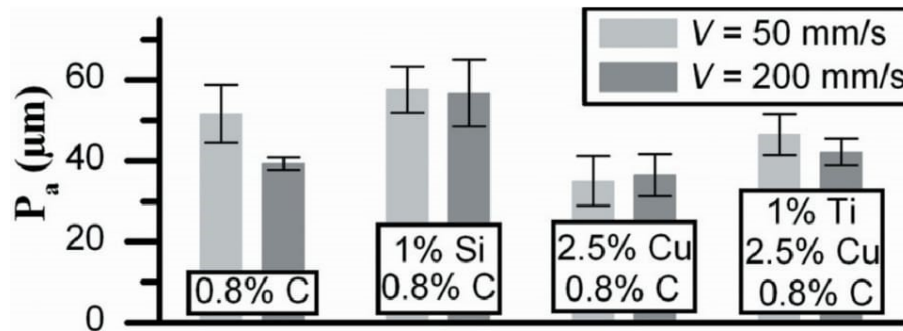
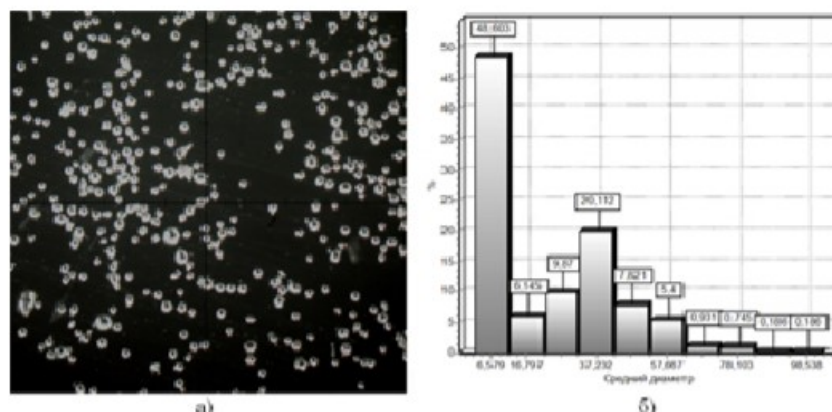


Figure 18: Roughness of the top surface of Fe-based parts produced at  $P = 95 \text{ W}$ ,  $l = 70 \text{ }\mu\text{m}$ ,  $S = 0.14 \text{ mm}$  and  $\%O_{atm} = 0.5\%$ .

By ( M. Rombout, 2007 )

6. In this article the results of the experimental study of the structure and mechanical properties of materials are obtained by selective laser melting (SLM), metal powder steel 316L was carried out. The study of the surface and the particle size analysis is made before the process of cultivation of samples as input control. Also, 3D X-ray quality control of the samples were carried out in order to detect hidden defects and qualitative & quantitative assessment. There are strict requirements imposed for metal powders from the surface a good surface finish is expected and particle size distribution.



a) The surface morphology of the powder particles; b) The size distribution of the powder

From the figure it is observed that the particle surfaces have sufficiently correct spherical powder particles in a small amount of visible growths. Results

show that the particles has visible growths and a average size of 37 microns. 3D X-Ray quality control of manufactured samples shows that the material has internal pores of 38-41mm.

**By (V G Smelov, A V Sotov , A V Agapovichev,T M Tomilina)**

7. To solve the problem that the thermal behaviour of powder bed during SLM process is difficult to be analyzed by direct test measurement. predicting the temperature field of AlSi10Mg molten pool in SLM process was established based on the finite element method. In the prediction model ,the thermal properties of the material and the variation of laser power absorptivity with temperature were taken into account. The experimental results were in eminent agreement with the predicted results, and the prediction error was lower than 7%. Based on this model ,the process parameters can be optimized according to the obtained law of variation of the thermal behaviour of the molten pool, reduce the number of intensive tests and improving process stability of SLM. This paper propose temperature prediction model through selective laser melting and analysed the result soft the single layer temperature field. On this basis ,the effects of different process parameters on the thermal behaviour of molten pool were discussed ,and carried out the corresponding test verification. The powder at the front end of the SLM in molten pool is not completely melted ,and the effective thermal conductivity of the powder is very small ,the heat can not be transmitted rapidly, which results in high temperature gradient and leads to the density of the front end .The other distribution of powder bed appears the phenomenon of “corner”.

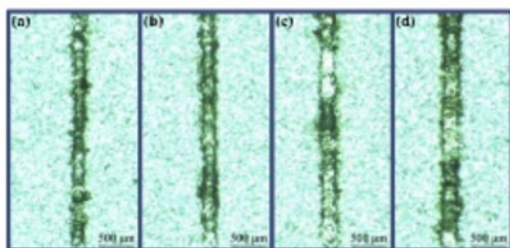


Fig. 12. Single Track scanning Contour at different laser power constant (250 W, 300 W, 350 W and 400 W).

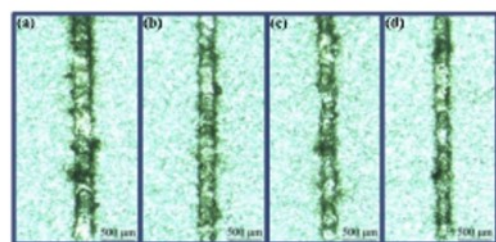


Fig. 13. Single Track scanning Contour at different scanning speed (600 mm/s, 800 mm/s, 1000 m/s and 1200 mm/s).

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**By (Yang du, March 2019)**

**PROBLEM STATEMENT :**

To simulate on Additive Manufacturing process (Selective Laser Sintering) of High Speed Steel (M2) to obtain its Mechanical Behaviour and Temperature Distribution using Cosmol Multiphysics Software.

# CHAPTER - 3

## Why COMSOL is used for Simulation?

Additive manufacturing has a wide array of applications, such as creating custom medical devices, aerospace components, and artwork. With the list of potential uses continuing to grow, it's important that this type of manufacturing can keep up with the demand. Additive manufacturing is the process of creating a 3D object by adding one or more materials on top of each other layer by layer.

Since additive manufacturing is a complex process, it can be difficult to study. This technique varies based on the materials involved and the specific type of additive manufacturing. Studying this process also requires accounting for many different effects, such as:

- Multiple phase transformations
- Transfer of energy, mass, and momentum
- Sintering
- Photopolymerization
- Drying
- Crystallization
- Deformation
- Stress

To account for these factors, engineers can use the COMSOL Multiphysics® software, which is a unique software that has great advantages in the simulation of additive manufacturing.” The software helps engineers to not only “optimize the additive manufacturing process but also to predict the mechanical and microstructural consequences on the product. Through this, engineers can include all of the relevant physics and determine the ideal manufacturing conditions and part geometries that balance the needs of stiffness, weight reduction, and heat dissipation. A challenge is that analysing

the additive manufacturing process while coupling the relevant physics can result in large model sizes and long computational times. To overcome this issue, COMSOL contains several different simulation strategies, such as activating mesh properties, using adaptive re-meshing, and performing sequential simulations.

## **Reasons why COMSOL is used for simulation :**

### **1. Streamline the Modelling Workflow :**

COMSOL Multiphysics enables you to simulate electromagnetics, structural mechanics, acoustics, fluid flow, heat transfer, and chemical phenomena in one environment, following one workflow. All simulation apps are created with the same tool, the Application Builder, independent of the type of physics involved. Completing the optimized modelling workflow, apps are deployed with the click of a button and anyone can benefit from the insights provided by the simulation results.

### **2. Understand Product Behaviour :**

Non-specialists or Learners can run their own tests without needing to comprehend the complexities of the actual simulation. As a result, there project/work can benefit from simulations, which in turn leads to an increased understanding of how their product will behave in the real world. The results that obtain are more understandable and can be identified by a beginner or a student without any professional help.

### **3. Provide Answers Quickly :**

COMSOL software contains a limited amount of inputs, making it easy to set up the analysis. Experts might have fine-tuned a mesh, solver, or other conditions to solve a specific simulation fast. People with different backgrounds can run these simulations without having to ask the experts to do the job for them, or waiting for a full model to converge, helping them to get answers more quickly. Computation of the results of the model are easy to obtain even for a learner or student who is trying to work on the software for the 1<sup>st</sup> time.

### **4. Remove the Learning Curve :**



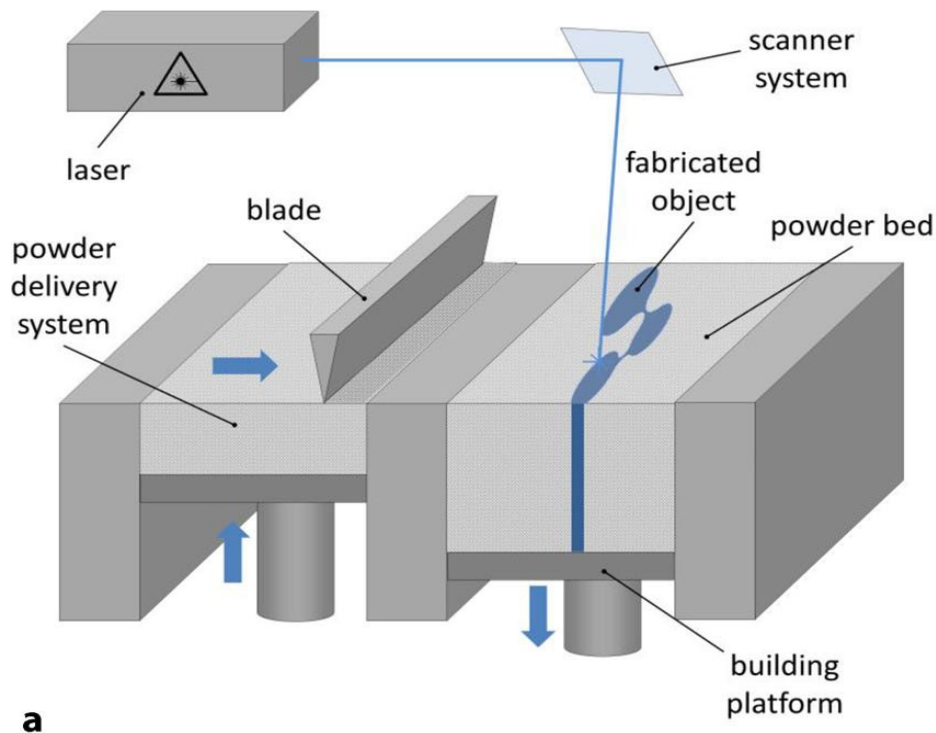
App users don't need to understand the underlying technology of the simulation software to run an analysis with an app, as the inputs and outputs are restricted to what is pertinent to the analysis.

By using simulation apps, anyone can test different configurations and designs without needing to learn a new software tool. Many relations, formulas that are required for the analysis that happen in the back stage of the software need not to be known by the users which helps in the easy usage of the software. There is no necessity to get all the lengthy and tricky relations that are needed to solve the problem or get the analysis results.

So, COSMOL multiphysics software has its reasons for it to be used for the simulation of Additive Manufacturing Process. Any model or component when needed to be designed can be analysed in this software to get the best results of heat distribution, solid mechanics properties and other many tests that required for a better understanding of the project can be easily obtained in this software without much complications for any student or learner who does some work or project. Large companies also use this software for the simulation of their products to get the best result on the behaviour of their products before they get manufactured, satisfy the needs of customers and get into the market.

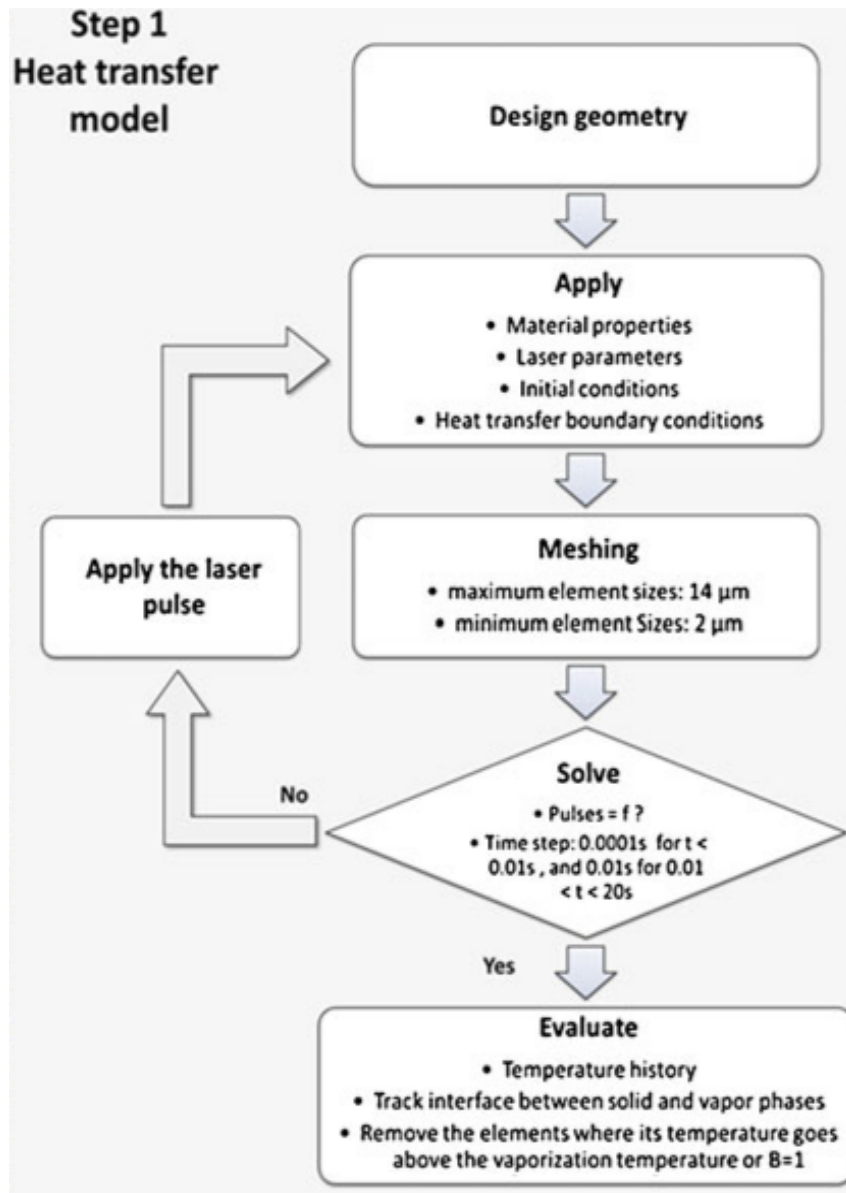
## Multi-physical simulation of selective laser sintering:

The multi-physical simulation model for SLS is based on the computational Thermal stress stresses and the heat transfer module of the finite element (FE) software package Comsol Multiphysics. It includes the absorption of laser radiation on the metal surface, conductive and convective heat transfer, the thermal stress is one the consideration of structural mechanics, it give von-misses stresses in results according to the process some surfaces should be fixed as shown this fig.



The model geometry consists of a powder bed like a rectangular plate. The energy of the laser beam is absorbed on the surface of the metal. The metal heats up, a melt pool is formed, and the melt wets the base plate as well as the neighbouring powder particles. If the energy input is high enough, evaporation occur and the metal vapour expansion leads to the deformation of the melt pool surface. When the laser moves on, the melt pool cools down,

resolidifies, and a molten track formed. The below flowchart explain Step by step simulation model in Comsol Multiphysics software.

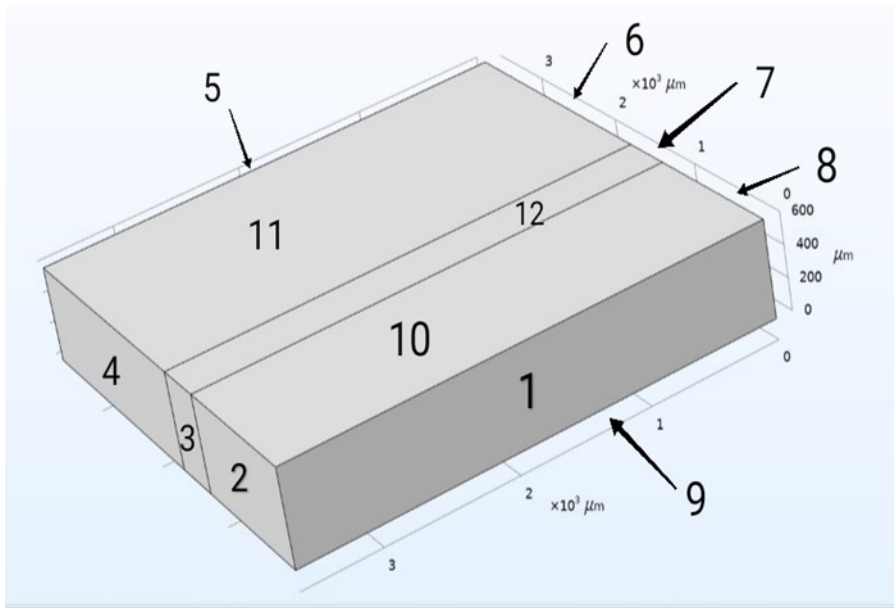


## CHAPTER - 4

### SIMULATION PROCESS :

#### 3D GEOMETRY OF BLOCK :

According to the Selective laser melting process as shown in fig1 a rectangular high speed steel (M2) metal block should be considered for simulation process.



Construction of a block with 3.6(mm) length, 3.6(mm) breadth, 0.6(mm) width. It's divided into 3 layers as shown in this fig. Add HSS (M2) material to the block which is already exist in software. It contains all properties except poisson's ratio which should be given in between 0.27 to 0.3 .Laser beam travels on the center layer so the part contains three parts. According to software every surface should have numbers as shown in this fig. according to the process select the surface manually for laser beam, conduction and radiation .



## Definitions of Laser Machining Parameters:

### 1. Number of Laser Pulses :

Pulsed operation of lasers refers to any laser not classified as continuous wave, so that the optical power appears in pulses of some duration at some repetition rate. This encompasses a wide range of technologies addressing a number of different motivations. Some lasers are pulsed simply because they cannot be run in continuous mode.

### 2. Pulse Energy :

The **pulse energy**  $E_p$  is simply the total optical **energy** content of a **pulse**, i.e., the integral of its optical power over time. For regular **pulse** trains, the **pulse energy** is often calculated by dividing the average power (measured e.g. with a power meter) by the **pulse** repetition rate.

### 3. Pulse Width :

The **pulse width** is a measure of the elapsed time between the leading and trailing edges of a single pulse of energy. The pulse repetition interval measures the time between the leading edges of two pulses but is normally expressed as the pulse repetition frequency (PRF), the number of pulses in a given time, typically a second. The duty cycle expresses the pulse width as a fraction or percentage of one complete cycle.

### 4. Beam Diameter :

The use of large beams in the Laser Powder Bed Fusion (L-PBF) process has been receiving increasing attention for the past few years and may widen the dissemination of this technology in the industry. The beam diameter refers to the **diameter** of the **laser beam** measured at the exit face of the laser housing. The beam diameter can be defined in several different ways, and for Gaussian beams it is typically described by the  $1/e^2$  width.

### 5. Vaporising temperature :

Vaporization temperature is the temperature at which liquid is converted into vapour without any change in temperature. Vaporization temperature is the temperature at which liquid is converted into vapour without any change in temperature. This is the maximum temperature of the metal at which the metal melts and vapours are created.

### 6. Latent Heat Of Melting :

The heat required to change a substance from a solid to a liquid state. Also called latent heat of fusion. After a particular temperature the heat that turns the solid into liquid of a metal is called Latent Of Melting.

### 7. Latent Heat Of Evaporation :

Latent heat of vaporization is a physical property of a substance. It is defined as the heat required to change one mole of liquid at its boiling point under standard atmospheric pressure. It is expressed as kg/mol or kJ/kg.

### 8. Coefficient Of Thermal Expansion :

The Coefficient of thermal expansion is a material property that is indicative of the extent to which a material expands upon heating. Over small temperature ranges, the thermal expansion of uniform linear objects is proportional to temperature change.

Label: Parameters 1

Parameters				
Name	Expression	Value	Description	
Pw	0.5[ms]	5E-4 s	pulse width	
D	0.6[mm]	6E-4 m	beam diameter	
emi	0.7	0.7	emissivity	
h1	10[W/m^2/K]	10 W/(m^2·K)	heat transfer coefficient	
A1	0.25	0.25	absorptivity	
t	30[K]	30 K	half width of the curve	
x0	-D	-6E-4 m	reference point to repres...	
xd	100[um]	1E-4 m	standed deviation of the...	
Ta	293.15[K]	293.15 K	ambient temperature	
H1	D^2	0.0012 m	Height of the sample	
W1	D^6	0.0036 m	sample width	
Vin	10[mm/s]	0.01 m/s	laser scan speed	
t_stop	(2*D+W1)/Vin	0.48 s	single pass duration	
B1	D	6E-4 m	sample depth	

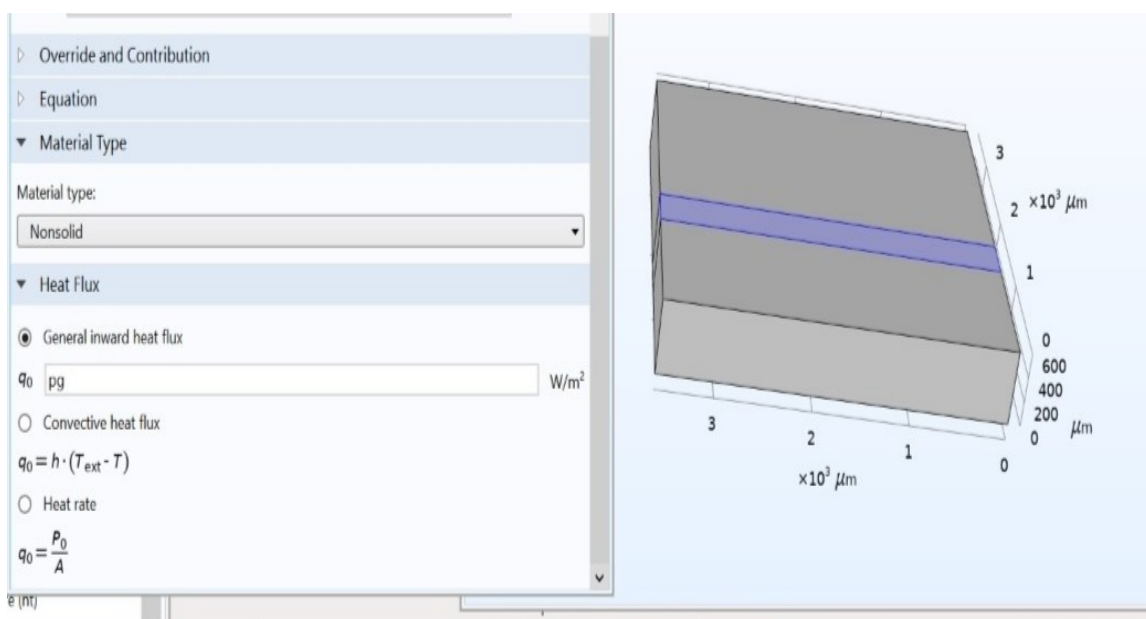
# VARIABLES :

Variables			
Name	Expression	Unit	Description
Ed	$E_p / (P_w \cdot (\pi \cdot 0.25 \cdot D^2))$	W/m <sup>2</sup>	energy density
G_space	$\exp(-(((x-xr)^2)/(2 \cdot xd^2)))$		gaussian distibution
pg	$A1 \cdot Ed \cdot G\_space$	W/m <sup>2</sup>	laser heat sourcde
xr	$x0 + Vin \cdot t$	m	laser beam position

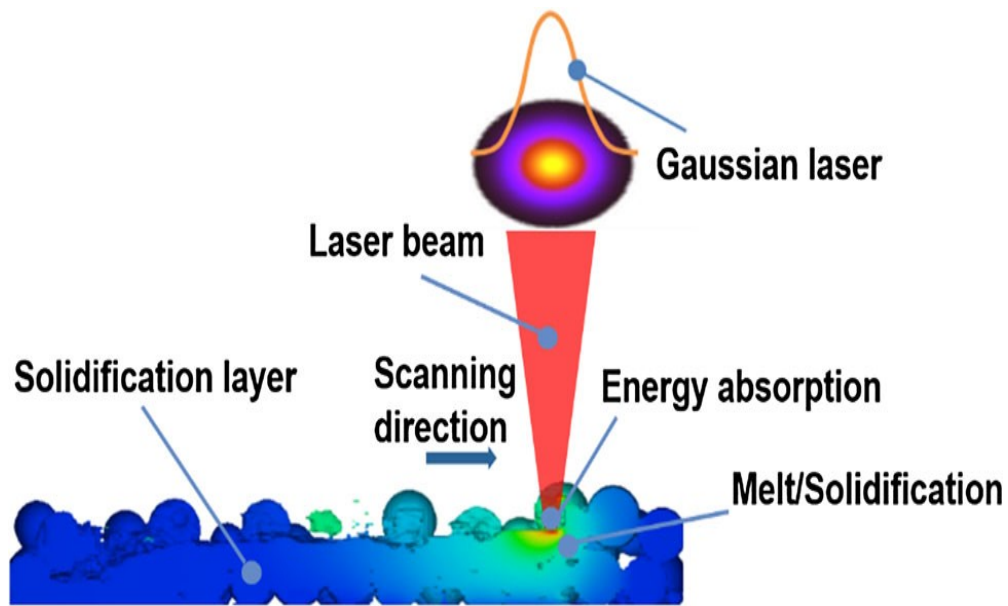
Variables are used to simplify the Gaussian distribution for laser heat source.

# LASER HEAT SOURCE :

Adding the Laser Heat source to the 12<sup>th</sup> layer on the solid makes the laser move in that path where the heat travels in that direction. The principle of the Laser Heat Source is the Gaussian Distribution.







Laser beam is travels using Gaussian distribution is denoted by **P<sub>g</sub>**. The function expressed in variables. Laser beam travels in center layer as show in the above fig.

In simulation, the laser is defined as energy source term and described by radiation source with a Gaussian distribution function.

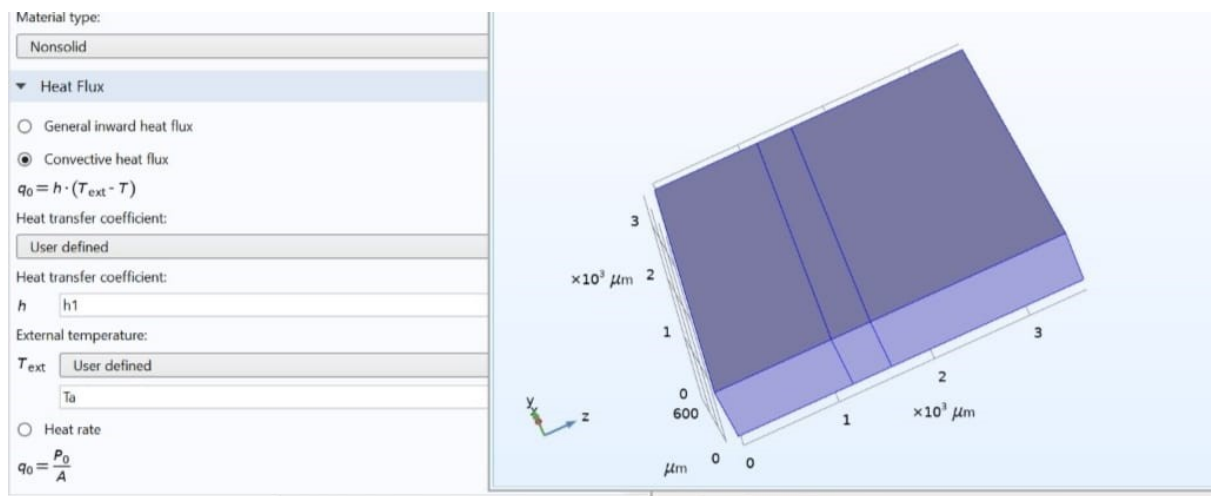
$$P_g = A [E_p / (P_w (\pi/4) D^2)] \exp [-(x-x_r) / 2 \times r_0^2]^2]$$

All values are expressed in parameters using variables this expression simplified and apply in heat source.

## COOLING :

Laser beam gives high temperature to the body for bond between the particles .So after that solidification purpose two types cooling are there in nature for creating the real atmosphere around the body. So, the total surface of 3D body react with this except the lower surface, it consider as insulator.

Heat loss = convection + radiation



After adding the heat laser source to the 12<sup>th</sup> layer then add the cooling effect to the sides 1,4,7,11,12,13,14,15 and 16 of the model.

### Convection:

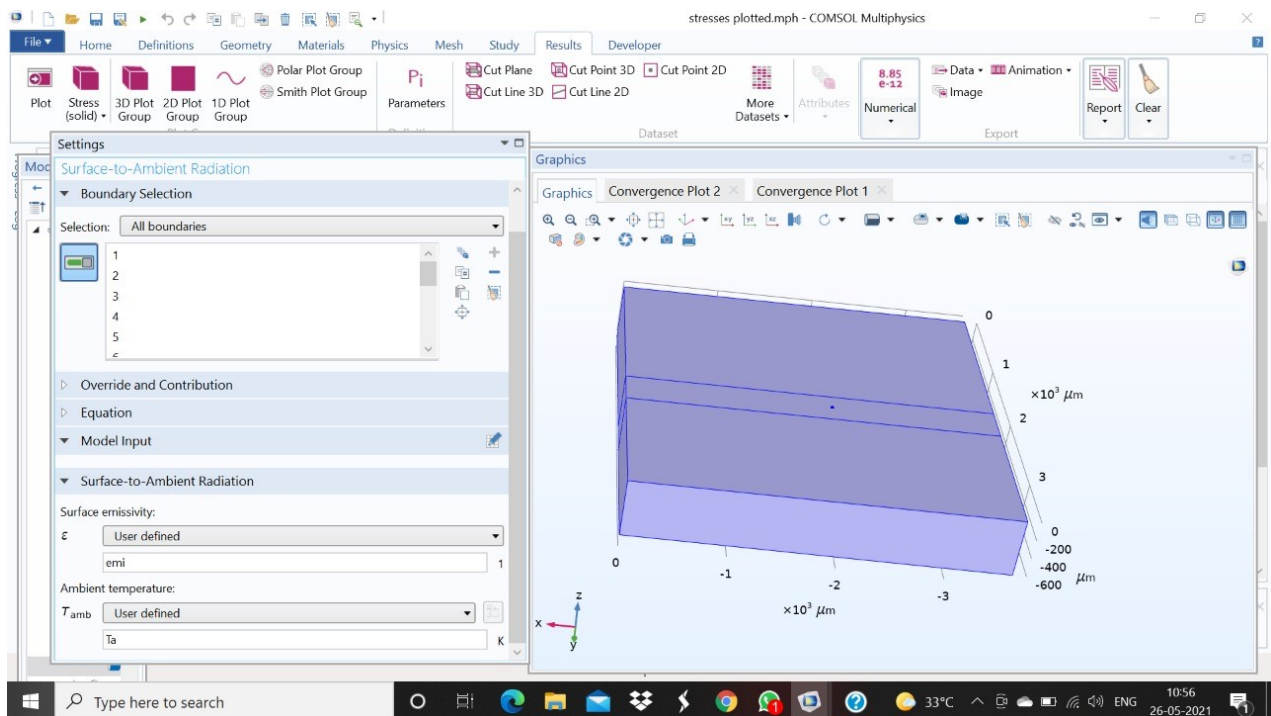
Cooling is the process of convection in metals. Where  $h_1$  is heat transfer coefficient ,  $h_1$  value is expressed in parameters it's a free convection process, so  $h_1$  have small value. Function used in cooling,

$$\text{Heat transfer} = h_1(T - T_{\text{atm}})$$

$$\text{where, } h_1 = 10 \text{ W/m}^2 \cdot \text{k}$$

$$T_{\text{atm}} = 293\text{k, and } T \text{ is depends on laser heat}$$

# RADIATION :



Radiation is one of the heat loss process. It's used to create actual conditions around the block (body).

Radiation formula Surface to ambient radiation =

$$e \times A \times (T_{\text{body}}^4 - T_{\text{atm}}^4)$$

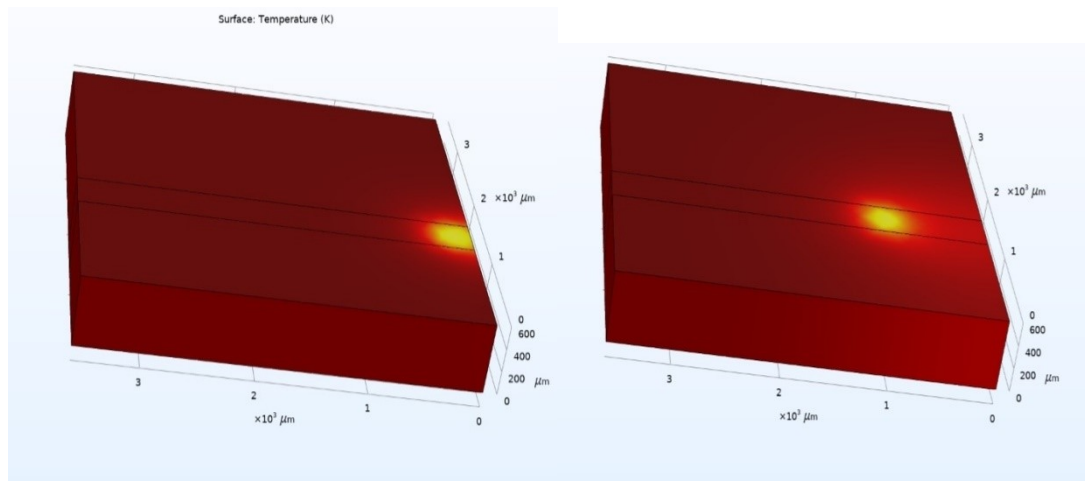
Where  $e$  is Stefan-Boltzmann constant , temperatures are given in the parameters. Radiation effects total body as Show in this fig.

# CHAPTER - 5

## SIMULATION RESULTS :

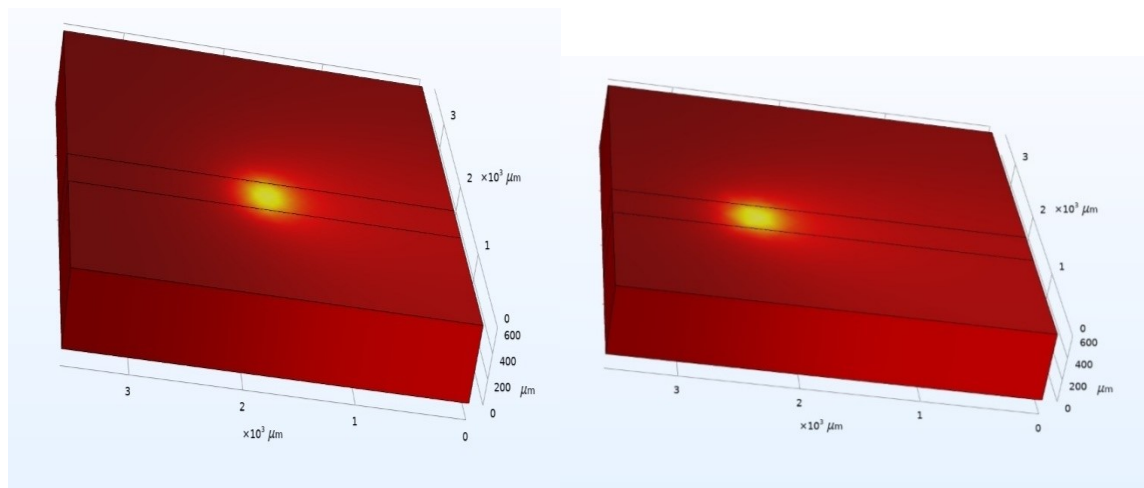
### 1. Temperature Distribution :

The block consist traveling laser beam and cooling, radiation heat losses. Traveling laser beam according to time as show in the fig.



(a) 0.08 sec

(b) 0.16 sec

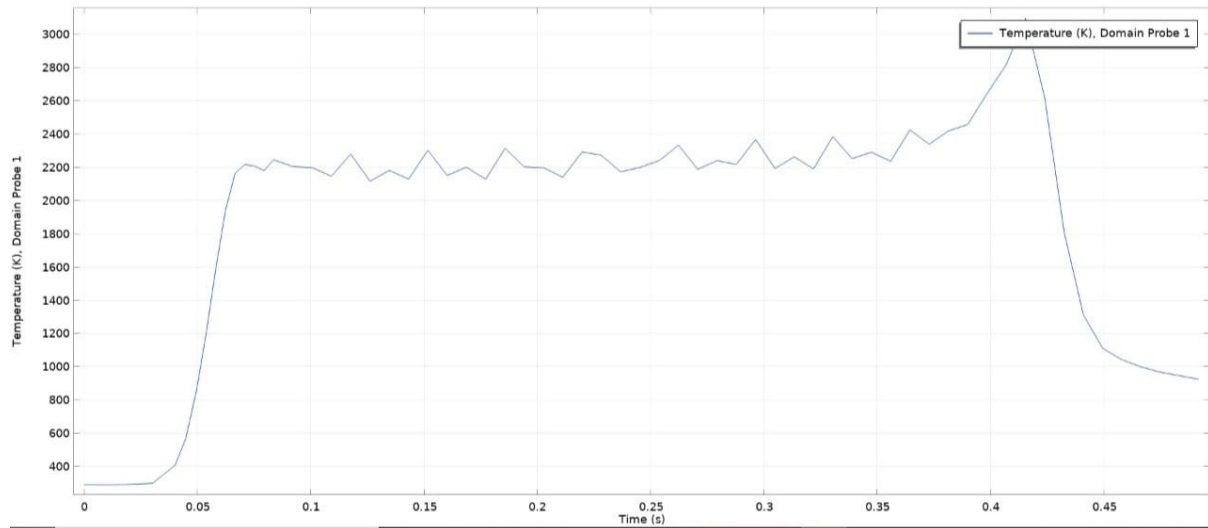


(c) 0.24 sec

(d) 0.30 sec

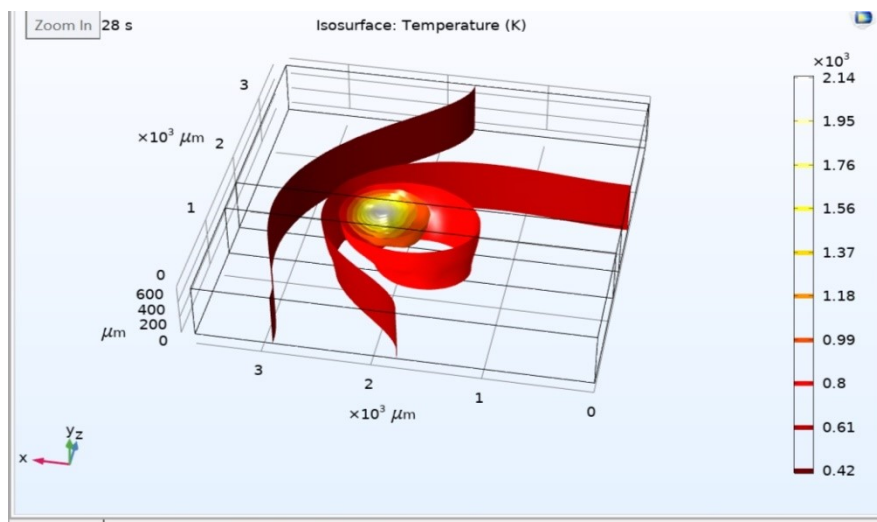
The time depends on laser speed and length of block.

Graph plot between time vs. temperature.



Maximum temperatures of the body is depends on the input heat given in joules.

### Isothermal contour :



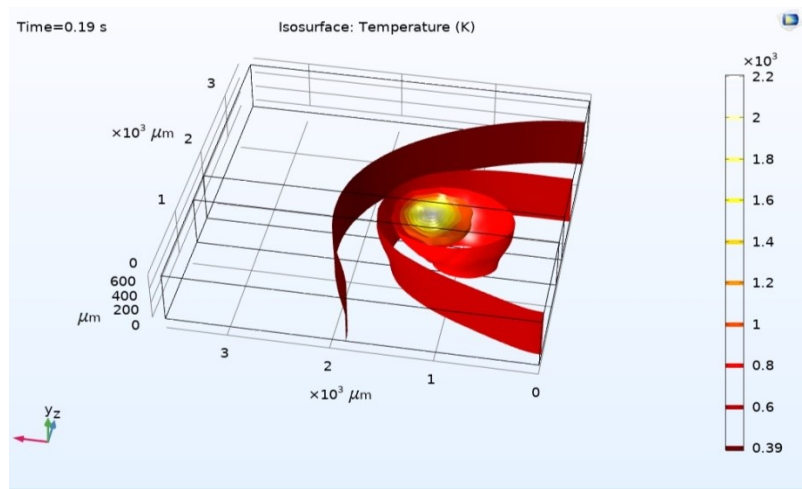


Figure describes the isothermal contour of temperature distribution of phase change phenomenon through solidification process at particular time. It has been described the temperature reduction in down layer through release the heat by down heat flux. These values of temperature Variable from 2200k at the top centre layer to 297k of outside layers.

Temperature Distribution depends on three parameters

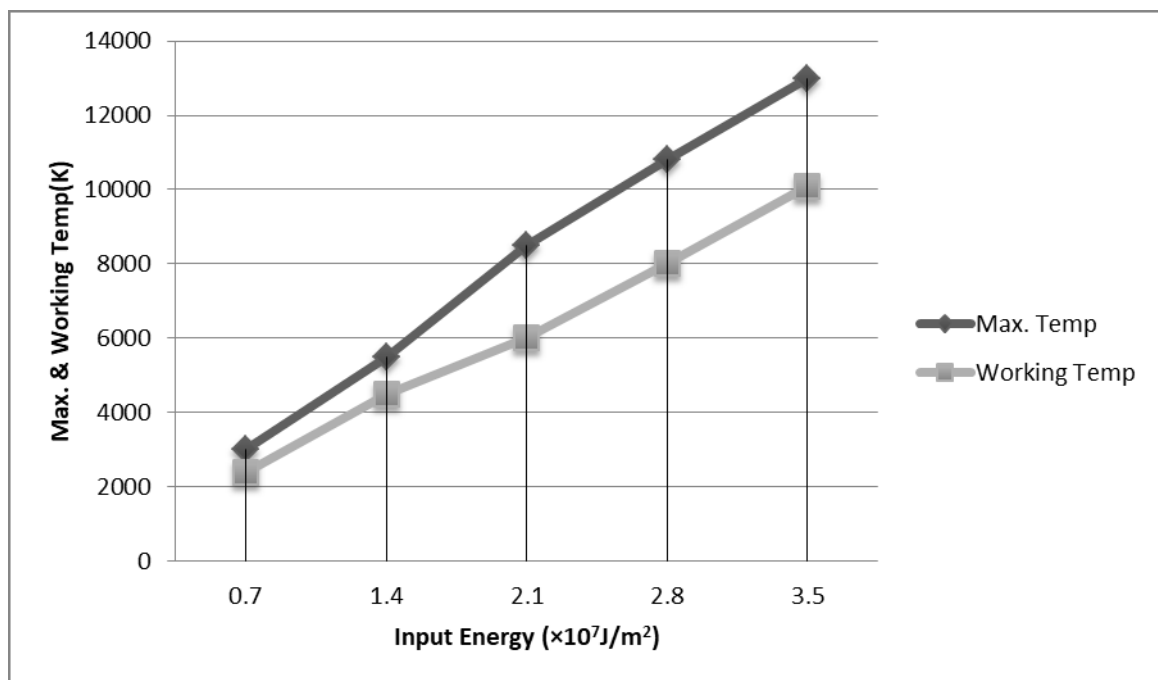
1. Input Energy ( $E_p$ )
2. Speed ( $V_{in}$ )
3. Diameter of Laser Beam ( $D$ )

The Temperature Distribution on the following parameters, and now let's see how the temperature distribution changes with different values of this three parameters.

- Firstly let's keep the speed and Diameter be constant and the values of Input Energy changes. The Values of Temperature are taken in the form of Table.

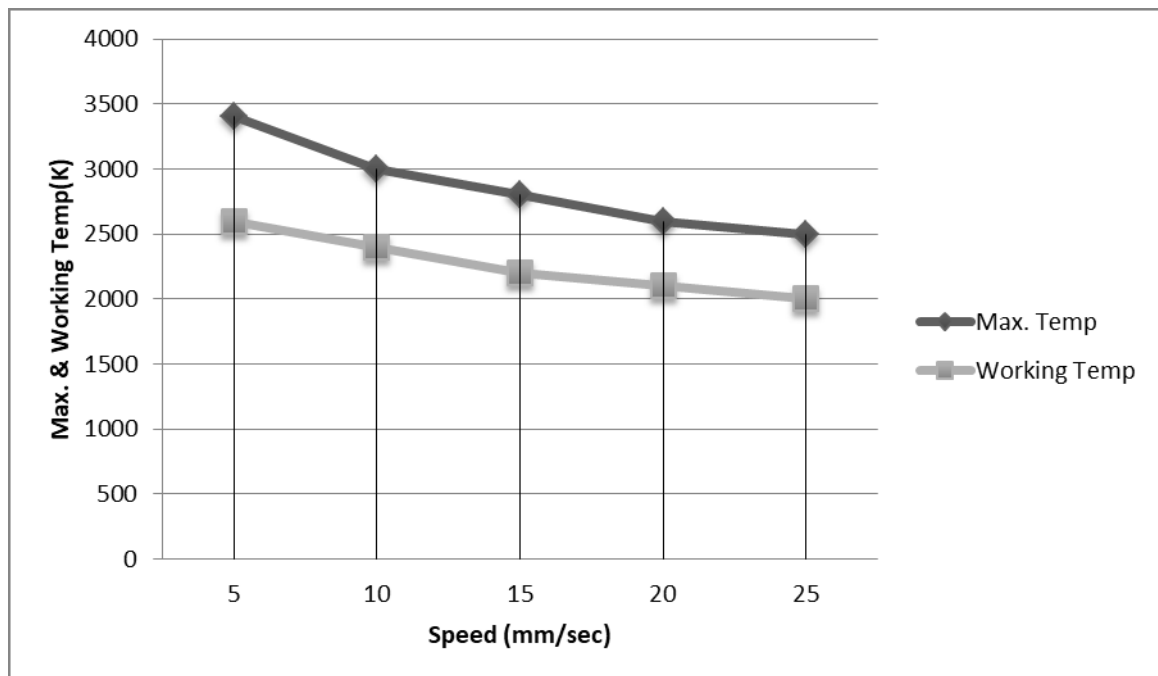
Taking the Values of Speed ( $V_{in}$ )=10mm/s and Diameter (D)=0.6mm

Input Energy	Max. Temperature(k)	Working Temperature(k)
$0.7 \times 10^7 \text{ J/m}^2$	3000K	2100 to 2400K
$1.4 \times 10^7 \text{ J/m}^2$	5500K	3800 to 4500K
$2.1 \times 10^7 \text{ J/m}^2$	8500K	5500 to 6000K
$2.8 \times 10^7 \text{ J/m}^2$	10800K	7400 to 8000K
$3.5 \times 10^7 \text{ J/m}^2$	13000K	9000 to 10100K



- Now keeping the values of Input Energy ( $E_p$ ) =  $0.7 \times 10^7 \text{ J/m}^2$  and Diameter (D)=0.6mm and varying the values of Speed ( $V_{in}$ ). We got the Following values :

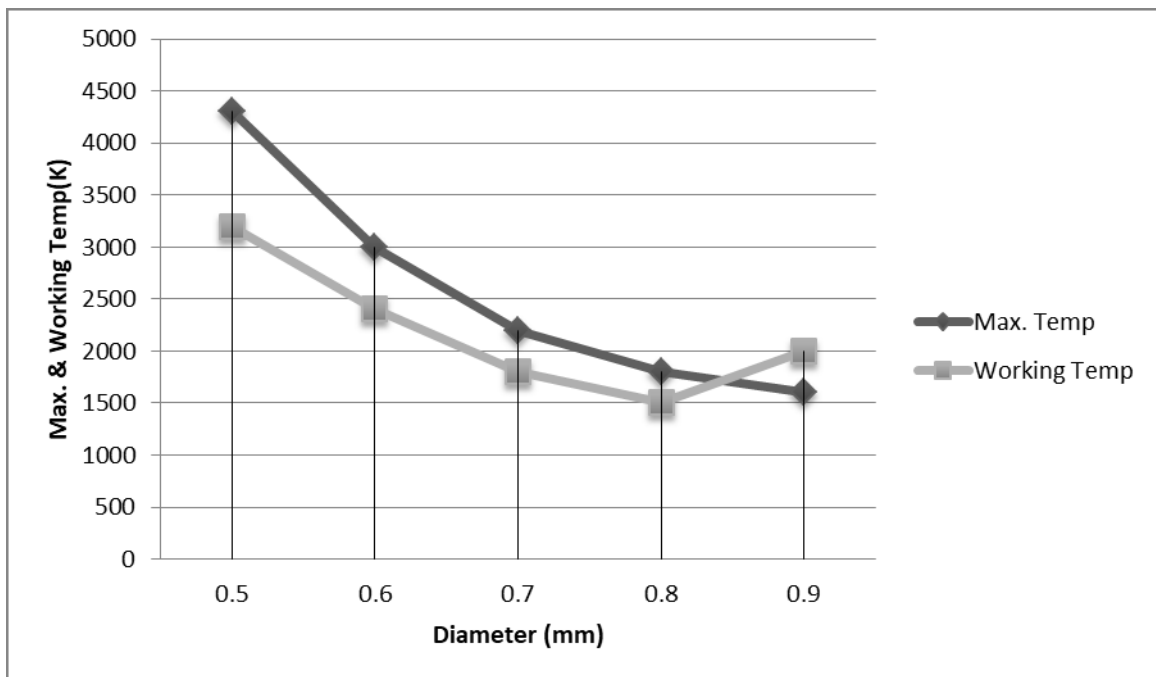
Speed	Max. Temperature(K)	Working Temperature (K)
5 mm/s	3400 K	2300 to 2600 K
10 mm/s	3000 K	2100 to 2400 K
15 mm/s	2800 K	2000 to 2200 K
20 mm/s	2600 K	1900 to 2100 K
25 mm/s	2500 K	1800 to 2000 K



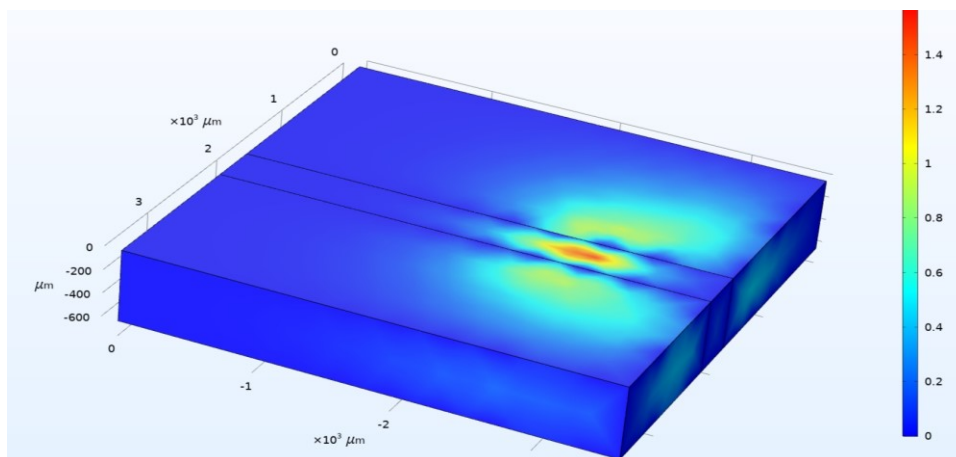
- Now keeping the values of Input Energy ( $E_p$ ) =  $0.7 \times 10^7$  J/m<sup>2</sup> and Speed ( $V_{in}$ ) = 10mm/s and now keeping the value of Diameter constant. We got the following values :

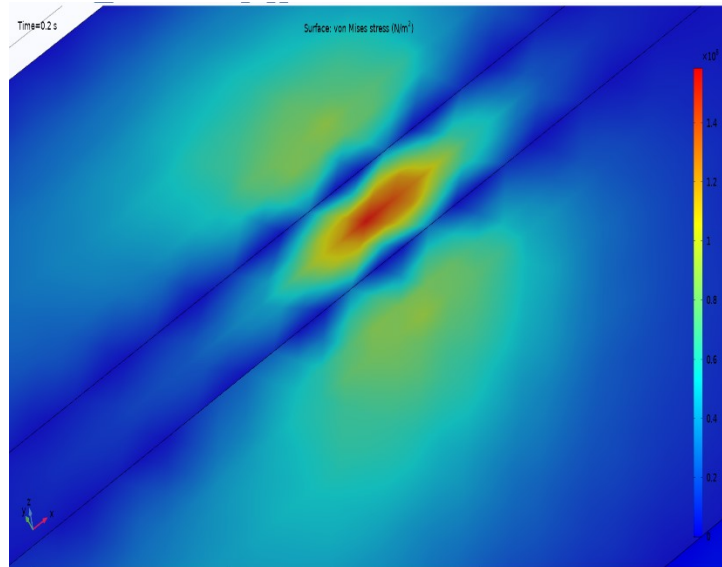


Diameter mm	Max. Temperature (K)	Working Temperature(K)
0.5 mm	4300 K	2900 to 3200 K
0.6mm	3000 K	2100 to 2400 K
0.7mm	2200 K	1600 to 1800 K
0.8mm	1800 K	1300 to 1500 K
0.9mm	1600 K	1100 to 1300 K



## THERMAL STRESSES :





Laser beam contains very high temperature, so this temperature distributes to total body. Stress is the force acting per unit area. The force can be of any form. When the applied force is in the form of temperature the resultant stress is called Thermal stress. It is observed when an object expands or contracts due to a change in temperature. Thus, we can define Thermal stress. According to above diagram each colour have certain value of thermal stress in  $\text{N/m}^2$

The scale (right side of the diagram) have different colours according to the colour thermal stress acting on the body as show in the fig. Comsol multi-physics software gives von-misses stress.

### **Von-misses stresses:**

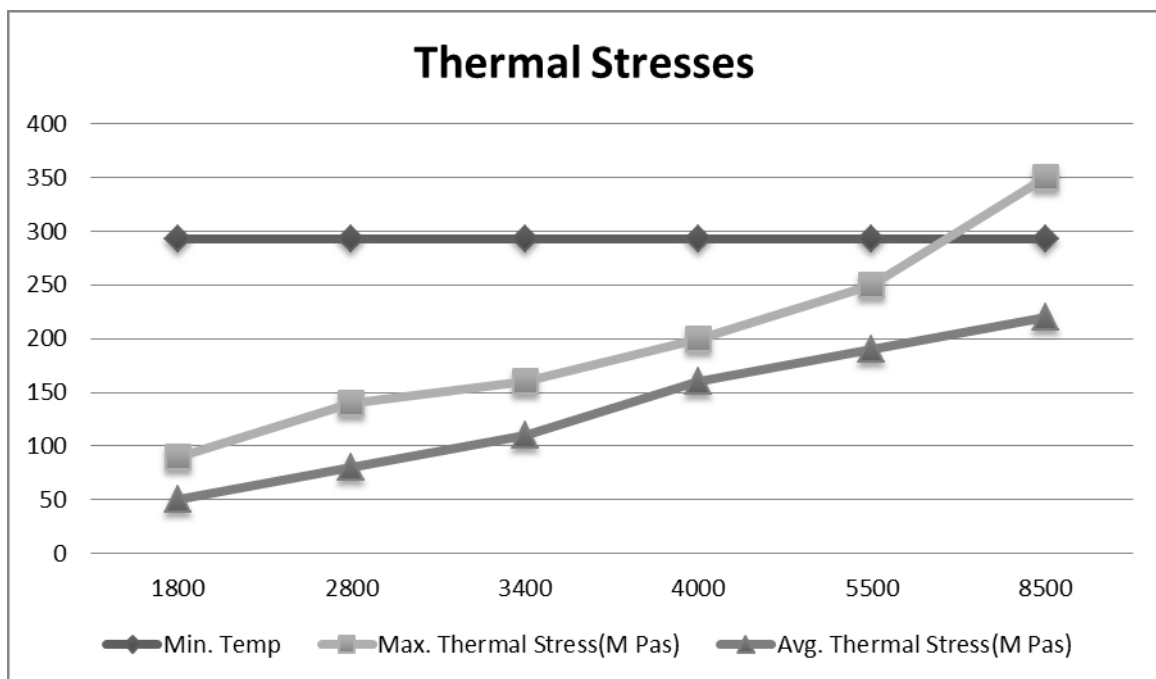
Von Mises is credited with coming up with what is arguably the most accepted yield criterion (way of resolving these stresses). He designed an equation that takes in each shear and principal stress value, and in turn spits out a single “von Mises stress value”, which can be compared to a yield strength of the material. If the value is greater than the yield strength, the part is failing according to his criteria. If it is less, then the part is said to be within the yield criteria and is not failing (for yield failure only). The equation for von Mises stress is shown below.

$$\sigma = \sqrt{0.5 \left[ (\sigma_x - \sigma_y)^2 + (\sigma_y - \sigma_z)^2 + (\sigma_z - \sigma_x)^2 \right]} + \sqrt{+ 3(\tau_{xy}^2 + \tau_{yz}^2 + \tau_{zx}^2)}$$

Note the sigma's ( $\sigma$ ) correspond to normal stress values, and the taus ( $\tau$ ) are the shear stress values.

According to the all consideration thermal stresses depends on temperature difference.

Maximum temperature(k)	Minimum temperature(k)	Maximum thermal stress (M pa)	Average thermal stress (M pa)
1800	293	90	50
2800	293	140	80
3400	293	160	110
4000	293	200	160
5500	293	250	190
8500	293	350	220



## Conclusion:

In this paper temperature and thermal stress distribution of high speed steel was present. While modeling the simulation of SLS process, the maximum and working temperatures and thermal stresses of powder bed were analyze. The following observation were found in the selective laser sintering process. Temperatures are depends on input heat energy, laser beam velocity and diameter. Thermal stresses are depends on the temperature difference. So the below values gives good results in laser sintering process according to model and considerations for high speed steel (M2).

<b>Laser beam diameter (mm)</b>	<b>Input energy (J/m<sup>2</sup>)</b>	<b>Laser velocity (mm/sec)</b>
0.6	$0.7 \times 10^7$	10

At this condition we get 3000k maximum temperature and 2100 to 2400 working temperature. This temperatures are in between melting temperature (1700k) and boiling point (3273.15k), so its gives good bonding between particles and this condition we get less thermal stress (140 M pa) with compare to maximum thermal stress (1000 M pa) of high speed steel (M2).

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