Analysis of Laser Sintering Process in 3D Metal Printer

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Abstract- *The Additive Manufacturing (AM) is one of the important techniques included in Industry4.0. Industry 4.0 is commonly referred as fourth industrial revolution. This technology helps to create 3D models / end use parts from 3D CAD data using layer bylayer approach. This helps designers to develop complex yet functional parts in various industries which are very difficult to manufacture by conventional manufacturing methods as time, cost and worker fatigue concern. Initially it started with the plastic prototype later it has been used on metal and its alloys by using the concept of Selective Laser Sintering (SLS), Selective Laser Melting (SLM) and Direct Metal Laser Sintering (DMLS). In laser sintering process the study of parameters such as effective thermal conductivity, total emissivity of powder bed, specific heat, absorptivity, relative density and other thermal properties of powder material and laser properties are necessary to analyses the laser sintering process. These parameters are determined by analytically and experimentally so understanding of analytical or numerical models to predict those parameters. By using the temperature dependent powder material properties as input for simulation in ANSYS APDL in which it should achieve the sintering temperature (For copper sintering temperature range 800˚C to 900˚C) in a field to determine the further results. Gaussian beam model has been used to determine the temperature distribution along the x, y and depth directions. By keeping laser power and powder bed thickness constant the laser speed is determined to achieve the sintering temperature in a field. This whole laser sintering process analyses by using heat transfer model with boundary conditions.*

Keywords– Additive manufacturing (AM), Numerical Thermal Model, Effective Thermal Conductivity (Keff), Selective Laser Sintering (SLS), Total Emissivity of Powder Bed (ε).

I. INTRODUCTION

The strengths of Additive Manufacturing lie in those areas where conventional manufacturing reaches its limitations. Additive Manufacturing allows for highly complex structures which can still be extremely light and stable. It provides a high degree of design freedom, the optimization and integration of functional features.

Powder Bed Fusion (PBF) processes were among the first commercialized AM processes. Developed at the University of Texas at Austin, USA, Selective Laser Sintering (SLS) was the first commercialized powder bed fusion process. Rapid Prototyping (RP) and Rapid Manufacturing (RM) technology is a relatively new technology such that three-dimensional parts can be fabricated directly from computer aided design (CAD) data without using any traditional tooling. Complex parts that cannot be manufactured by a traditional process can be produced with a very short lead-time. There are many RP techniques, such as SLS (Selective Laser Sintering), SLA (Stereo lithography), 3D printing, FDM (Fused Deposition Modelling) and DMLS (Direct Metal Laser Sintering) that are able to produce prototypes in many kind of materials. DMLS means laser-sintering using a metal powder, in which metal parts are produced directly in the building process. This technique was developed by EOS GmbH of Munich, Germany, and has been available commercially since 1995.

So far manufacturing sector has seen subtractive manufacturing using activities such as cutting, drilling, machining etc. A desired object was formed from a stock of material. Over the period of time as manufacturing sector evolved, complex but functionally important parts came into application. Manufacturing of such parts was a time consuming process. To reduce the complexities, worker fatigue, time taken and cost involved, a new efficient digital technology is making its mark / impact in the manufacturing sector. The technology is widely known as Additive Manufacturing (AM). Scientist named Carl Deckard developed 3D Metal printer based on laser sintering in 1986, but such printer found its commercial application in 1992 through DTM Corporation. Figure 1 shows the overall metal printing process. In Metal printer, a re-coater is used to deposit the layer over a build chamber. This layer is first scanned by laser with the help of galvano mirrors. After scanning, the laser applies its intensity to melt or sinter the metal powder in its region. Surrounding loose powder provides necessary support to the melted / sintered powder. This whole process is conducted in an inert gas or vacuum chamber so as to avoid oxidation (Shielding) of metal / metal alloys. The downward movement of build chamber & upward movement of powder chamber are controlled by a computerized program that ensures the act will happen as per a selected layer thickness. This process is repeated until the desired object is built in the build chamber.

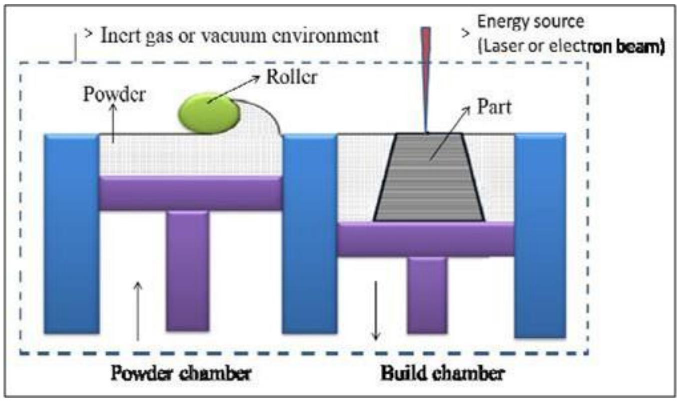

Fig. 1: Selective Laser Sintering Process in 3D Metal Printer

Many researchers have conducted work to emphasize the importance of laser based layer-by-layer manufacturing for metals with high density and excellent mechanical properties. Masanari Shiomi et.al [1] has conveyed the various methods used so far since last decade or so to implement laser processing technologies such as selective laser sintering (SLS), selective laser melting (SLM) and 3-D laser cladding to make functionally applicable metal components.

Aulus Roberto Romão Bineli et.al [2] proposed that, complex parts that cannot be manufactured by a traditional process can be produced with a very short lead-time. There are many RP techniques, such as SLS (Selective Laser Sintering), SLA (Stereo lithography), 3D printing, FDM (Fused Deposition Modeling) and DMLS (Direct Metal Laser Sintering) that are able to produce prototypes in many kind of materials. DMLS means laser-sintering using a metal powder, in which metal parts are produced directly in the building process.

After working on the concept of SLS I.A.Roberts et.al [3] has explicitly pointed out that the thermal interaction between consecutive layers affects the thermal gradients which lead to the heat transfer and thermal stress development mechanisms. They pioneered the simulation of sintering of metal powder using laser based technique known as element birth and death.

During the sintering of metals with high melting points, high temperature gradients get formed which directly leads to different stresses such as thermal & residual as well as thermal distortion. Rahul B. Patil et.al [4] investigated during rapid solidification process; thermal distortion affects the dimensional & part surface quality. Mr. Patil went on to develop a transient finite element method-based thermal model which helps to determine the temperature distribution in a single layer. Different researchers have put forth their studies & subsequent results in the same field to generate the numerical & simulation model for SLS.

In laser sintering process to determine the temperature distribution in a field is important, so Ahmed Hussein et.al [5] used 3D finite element simulation to calculate temperature distribution & stresses across in single layer of 316L stainless steel. A non-linear transient model based on sequentially coupled thermo-mechanical field analysis code was developed in ANSYS parametric design language (APDL). It is found that the predicted length of the melt pool increases at higher scan speed while both width and depth of the melt pool decreases. The cyclic melting and cooling rates in the scanned tracks result high Von Mises stresses in the consolidated tracks of the layer.

Numerical modelling of laser sintering process which contain the all heat losses like convection and radiation are formulated by Babis Schoinochoritis et.al [6]. Authors work to develop a various approaches in the numerical modeling of the processes and the selection of powder materials properties. He has asked researchers to develop smart modelling approaches & materials. For the betterment of AM, he expects researchers to characterize and standardize properties of applicable materials.

Laser sintering process in a metal printing is a transient thermal analysis problem in which consider the temperature dependent properties of powder material. L. Dong et.al [7] develop a transient three-dimensional finite element model to simulate the phase transformation during the selective laser sintering process; taking into account the thermal and sintering phenomena involved in this process. A bi-level structure integration procedure is chosen, in which the temperature dependent thermal conductivity, specific heat, and density are integrated at the outer level then used as material constants for the integration of the heat equation in the inner level.

Jie Yin et.al [8] proposed that, the finite element analysis (FEA) adopted the ANSYS μMKS (MicroMKS) system of units for the transition from powder to solid and the utilization of moving laser beam power with a Gaussian distribution model. By exploiting these characteristics a more accurate model could be achieved. The effects of the process parameters, such as laser beam diameter, laser power and laser scan speed on the temperature distribution and molten pool dimensions have been preliminarily investigated. It is shown that temperature increases with the laser power and decreases with the scan speed monotonously. For the laser beam diameter during single-track, the maximum temperature of the powder bed increases with the decrease in the laser beam diameter, but far from the centre of the laser beam area, the temperature increases with the laser beam diameter.

Daniel Moser et.al [11] has worked extensively in the same field to make random particle packing structures of spherical particles and to determine heat transfer between the particles. Model that Daniel has suggested is based on 3 different heat transfers through conduction:

1) A particle–particle contact conduction model,
2) A particle–fluid–particle conduction model, and
3) A view factor radiation model

The model helped to determine the effective thermal conductivity (Keff) from the steady state temperature distribution. Authors further suggested the key parameters that could affect the effective thermal conductivity. Those parameters were very high temperatures, finite bed depth and relative density of powder bed, emissivity and gas conductivity.

To analyse the sintering process for copper powder, it's necessary to determine the effective thermal conductivity of copper bed which is different from bulk material of copper. Kanan Bala et.al [12] investigated and measures the effective thermal conductivity of copper powders of different particle size experimentally at room temperature and normal pressure using the transient hot strip method. A variation in the values of the effective thermal conductivity of these powders with their porosities is observed. Theoretical calculations of the effective thermal conductivity of powders using this model and a model developed by Hadley (volume-averaging formalism) have been carried out. It has been found on comparison that the theoretical results are in good agreement with the experiment.

II. NUMERICAL ANALYSIS OF LASER SINTERING PROCESS

As per the first law of thermodynamics, the general energy balance equation in the closed system is [3],

$$Q_L = Q_{CD} + Q_{CV} + Q_R \qquad (1)$$

Where,

Q_L = Laser heat flux, (W/m2)
Q_{CD} =Heat vector due to conduction, (W/m2)
Q_{CV} =Heat vector due to convection (Heat Loss), (W/m2)
Q_R =Heat vector due to radiations (Heat Loss), (W/m2)

Transient heat conduction is an essential parameter that should be considered in a thermal analysis. Thermal field is a scalar function of spatial coordinates (x, y, z) and time t.

$$T = f(t, x, y, z)$$

Assumptions:

1. The heat flux from laser beam is a Gaussian distributed and applied to the top of the powder layer. The input heat flux due to laser irradiation is an internal heat generation in the powder layer.
2. Since the thickness of the powder layer is very small, the powder layer is subjected to plane stress type of temperature variation.
3. Laser beam spot is circular in shape.
4. To make calculation simpler, the all powder layers are homogeneous and continuous.
5. All the powder particles are spherical in shape and of same size dimensionally.
6. The effective thermal conductivity of the powder layer is used in the calculation which is a function of solid thermal conductivity, thermal conductivity of the surrounding gaseous environment (i.e. air) and initial relative density of the powder bed [4].

Governing equation for the heat transfer problem is time-dependent [8]:

$$\rho C_p \frac{dT}{dt} = \nabla (K_{eff} \nabla T) + Q \qquad (2)$$

Where,

ρ=Density of material, (Kg/m^3)
K_{eff} =Effective Thermal conductivity, (W/mK)
C_p = Specific heat of material, (J/KgK)
Q = Internal heat generation due to laser irradiation, (W/m3)

As mentioned earlier to understand SLS, the study of input parameters is important. Those parameters are explained in details as follows:

A. Absorption of Powder Material

Material's laser energy absorptivity depends on number of factors such as nature of surface, level of oxidation, wavelength of laser, surface temperature, etc. Granular characteristics of powders, particle size and size distribution, particle shape and roughness influence on the reflection, absorption and scattering are crucial factors that affect the laser powder interaction efficiency.

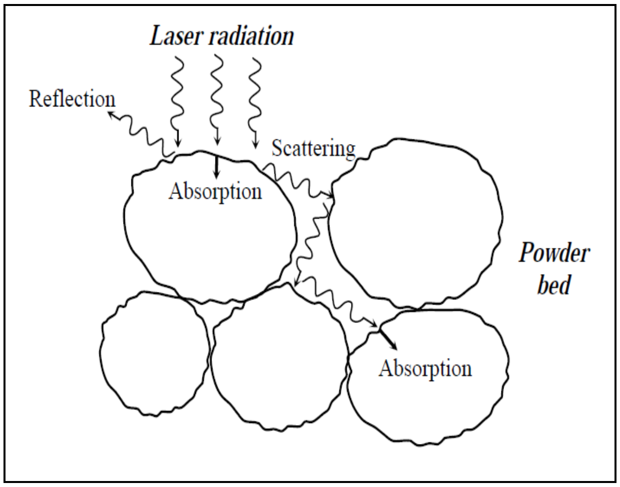

Fig. 3. The mechanism of interaction of laser radiation with a powder medium [13]

The absorptivity of metal power particles is always higher than the same material in a solid form. This is because there are multiple reflections in powder particles which leads to scattered radiations. But that is not possible in a solid form because parcticles are compactically packed with no room for any movement. This leads to conclude that there will always be higher amount of laser energy absorption in powder form when compared to a solid block of same metal [13].

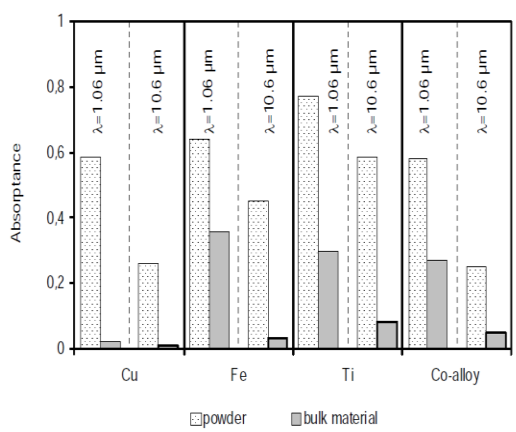

Fig.4. Absorptance of powders and bulk materials at the Nd:YAG and CO2 laser wavelengths [13]

B. Laser Load

The laser intensity distribution across the beam diameter closely follows a Gaussian relationship. Usually beam profile in the laser material processing is the Gaussian distribution of energy:

$$I(r) = I_0 \exp(\frac{-2r^2}{w^2}) \quad (3)$$

Where

I=Laser intensity of beam at r=0 (Maximum Intensity) ,(W/m^2)

r=Radial distance from the beam centre, (m)

w=The characteristic radius of the beam at which $I = I_0 \exp^{-2}$

Maximum intensity at the centre of laser spot is given by

$$I_0 = \frac{2AP}{\pi w^2} \quad (4)$$

So total equation of intensity of laser beam

$$I(r) = \frac{2AP}{\pi w^2} \exp(\frac{-2r^2}{w^2}) \quad (5)$$

The characteristic radius w, is related to the total beam diameter D,

$$w = \frac{D/2}{2.146} \quad (6)$$

For eq. (4) ,(5) & (6)

A=Absorptivity of powder material

P=Power of laser beam, (P)

Here, q(r) is the input heat flux at a distance r from laser beam centre,

$$q(r) = q_0 \exp(\frac{-2r^2}{w^2}) \quad (7)$$

Q = internal heat generation in the powder layer, (W/m3)

Then

$$Q = \frac{q(r)}{S} \quad (8)$$

Where,

q(r) =The input heat flux, (W/m^2)
r = radius of the laser beam, (m)
q_0 =Laser heat flux at the centre of beam, (W/m^2)

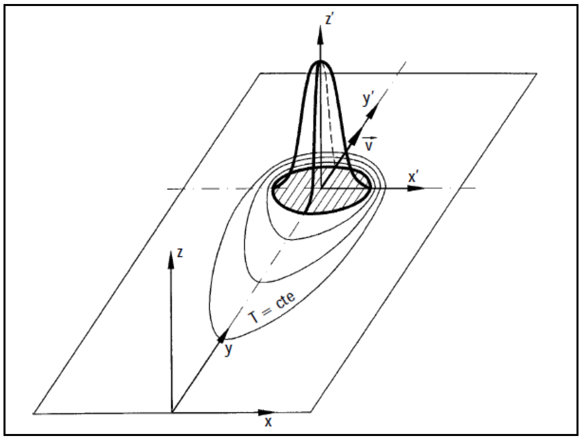

Fig.5. a) Gaussian Beam Profile

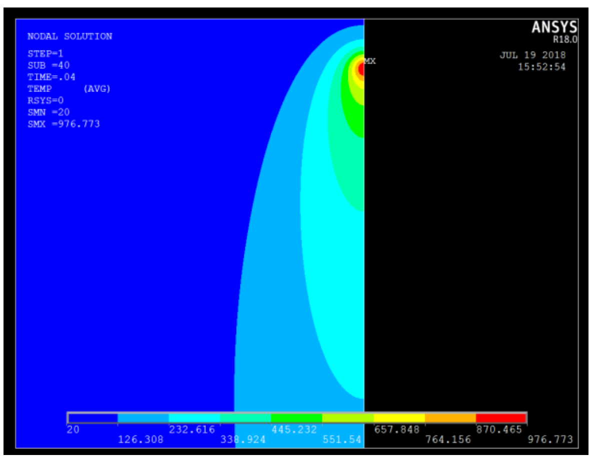

Fig.5. b) Gaussian Beam Profile

Laser beam that moves in the y direction with a constant velocity v. Owing to the movement of the laser beam this is a transient problem. Nevertheless, it can be transformed into a steady problem with a change in the coordinate axes of the problem. This change consists of using a local coordinate system cantered at the laser beam. The new system of coordinates is the following:

$$X' = X$$
$$Y' = Y - Vt$$
$$Z' = Z$$
$$t' = t$$

C. Effective Thermal Conductivity of Powder Material

Thermal conductivity is nothing but the ability of the material to conduct the heat. The thermal properties of the powder that affect the heat transfer results are considered in this model. The effective thermal conductivity of metal powder is dependent on the fractional porosity of the powder bed, temperature, and solid properties.

Density of powder bed is given by,

$$\frac{\rho}{\rho_0} = 1 - \varphi \qquad (9)$$

Where,

ρ = Density of powder bed, (Kg/m^3)
ρ_0 = Density of solid material, (Kg/m^3)
φ = Fractional porosity of the powder bed

For a given set of metal powder & bulk metal, the specific heat remains the same but density changes since it is a function of the porosity of a metal powder. At times the information of parameters such as density, specific heat required & laser properties to be controlled can be available, but thermal conductivity of metal in powder form needs to be calculated. This thermal conductivity for the same metal in solid form may be obtained from the manufacturer, but for the powder form it cannot be obtained beforehand since it decreases due to contact resistance between the powder particles.

Heat transfer takes place in 3 possible ways of conduction: particle–particle conduction (Qr), particle–fluid–particle conduction (Qpfp), and radiation (Qrad). The net heat exchanged in a particle is summation of all the heat being exchanged with all other particles across all three mechanisms as shown in Fig.5

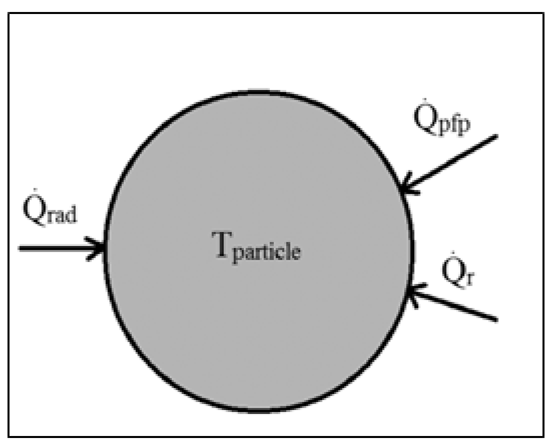

Fig.5. Particle model [11]

Different models can be used to determine the effective thermal conductivity of powder bed.

Hadley Model

The powder is considered to be a simple binary system that (solid particle & surrounding fluid) consists of loose particles of different size surrounded by a single pore fluid. The ratio of the material thermal conductivity K_s to the fluid thermal conductivity K_f, i.e $\frac{K_s}{K_f} = K$ is of the order of 10^4, allowing Hadley model to be used. The basic averaging formalism as given by Hadley [12],

$$K_{eff} = K_f \frac{\varphi f + K(1-\varphi f)}{1-\varphi(1-f) + K\varphi(1-f)} \quad (10)$$

Where,

K_{eff} =Effective thermal conductivity of powder material, (W/mK)
K_f =Thermal conductivity of a fluid, (W/mK)
K =Ratio of material thermal conductivity to the fluid thermal conductivity
φ=Porosity of powder material
This model is mainly used for copper powder as it satisfies the Hadley's criteria that is $\frac{K_s}{K_f} = 10^4$.

Yagi-Kunii's equation

This model does not consider the particle-particle contact conduction, so this model is given by [5],

$$K_{eff} = \frac{\rho_R K_s}{1 + c\frac{K_s}{K_g}} \quad (11)$$

Where,

ρ_R = the initial relative density of the powder layer,
K_s = temperature-dependent solid thermal conductivity, (W/mK)
K_g = thermal conductivity of the surrounding gaseous environment, (W/mK) i.e. air and is empirical coefficient $c = 0.02 \times 10^{2(0.7-\rho_R)}$

Zehner-Schlunder's equation

This model considers all 3 types heat transfers through conduction i.e. Qr, Qpfp, and Qrad. So this model is given by [10],

$$K_{eff} = \left(1-\sqrt{1-\varphi}\right)\left(1+\frac{\varphi K_R}{K_g}\right) + \sqrt{1-\varphi}$$
$$\left\{(-\varphi)\left[\frac{2}{1-\frac{BK_g}{K_s}}\left(\frac{\frac{B}{\left(1-\frac{BK_g}{K_s}\right)^2}\left(1-\frac{K_g}{K_s}\right)}{\ln\frac{K_s}{BK_g} - \frac{B+1}{2} - \frac{B-1}{1-\frac{BK_g}{K_s}}}\right) + \frac{K_R}{K_g}\right] + \frac{\varphi K_{contact}}{K_g}\right\}$$

(12)

Where,
K_{eff} =Effective thermal conductivity of the powder bed, W/m-K
K_g =Thermal conductivity of the continuous gas phase, W/m-K
K_s =Thermal conductivity of the skeletal solid, W=m-K
φ =Porosity of the powder bed

$$K_R = 4F\sigma T^3 X_R$$
(13)

Where,

F =View factor
σ =Stefan boltzman constant in W/m^2K^4;
T =Mean absolute temperature of the powder bed, in K
X_R =Effective length for radiation between particles, or the particle diameter of powder in m.

The view factor F is a function of powder bed emissivity various forms of the view factor from Damk Aohler's equation.

TABLE II Various Forms Of The View Factor [10]

References	F=View factor
Damk Aohler	1/3
Argo & Smith	$\varepsilon/(2-\varepsilon)$
Wakao & Kaguei	$2/(2/\varepsilon - 0.264)$

Yagi-Kunii's equation and Zehner-Schlunder's equation gives in comparison the approximately close results.

D. Total emissivity of powder bed material

Since the total emissivity of the surface of a powder bed is a function of the bed porosity and solid emissivity, these two are considered to generate the model [10].

Assumption made here is that most bodies are considered to be "gray" with no transmission of radiation. This leads to the assumption that α=ε. Emission from solid particles (ε_s) and emission from the cavities in the powder bed (ε_H) are responsible for the emission of radiation to ambient from a hot porous surface, such as the powder bed. The emissivity of the hole is dependent on its geometry, particularly the fraction of total cavity surface that is cut away by the emitting hole,

$$\epsilon_H = \frac{\epsilon_S}{\epsilon_S + f(1-\epsilon_S)} \quad (14)$$

Where,

ε_s =Emissivity of the solid particle

ε_H Emissivity of the hole

f =Fraction

Emissivity of the powder to be slightly higher than that of the solid, and to follow the expression,

$$\epsilon = A_H + (1 - A_H)\epsilon_S \quad (15)$$

Where,

A_H =Area fraction of the surface that is occupied by the radiation emitting holes.

ε_H does not depend on particle diameter and is a function of only solid emissivity and the bed porosity. The calculated ε_H decreases slightly as the bed porosity increases and also increases as ε_s increases.

$$A_H = \frac{0.908\varphi^2}{1.908\varphi^2 - 2\varphi + 1} \quad (16)$$

Where,

φ=fractional porosity of the powder bed

Now, Fraction f also a function of porosity is calculated by,

$$f = \frac{(\frac{\varphi}{1-\varphi})^2}{2(\frac{\varphi}{1-\varphi})^2 + 3.082} \quad (17)$$

Then by using these values f, A_H, ε_H and ε_s, calculate the total emissivity (ε) of the powder bed.

As per metal powder, emissivity & effective thermal conductivity change.

TABLE III Different Metal Powders Effective Thermal Conductivity And Emissivity

Metal or Alloy Powder	Relative Density	Effective thermal conductivity (in Argon environment)	Total emissivity
Stainless steel 316L	0.60	0.186	0.4230
Copper	0.35(150μm)	0.3025	0.7962
	0.62(250μm)	0.512	0.8610

E. Governing equation and its boundary conditions

1) Governing equation

In order to simplify the simulation work for the heat transfer, 2D transient heat transfer model is considered with co-ordinates as T (x, z & t).

$$\rho C_p \frac{\partial T}{\partial t} = Q(x,z,t) - K_{eff}\left\{\frac{\partial^2 T}{\partial x^2} + \frac{\partial^2 T}{\partial z^2}\right\} \quad (18)$$

Where,

Q (x, z, t) = The input energy.

K_{eff} =Effective Thermal conductivity

ρ=Density of material

C_p=Specific heat of material

The change in enthalpy is given by,

$$dH = C_p dT \quad (19)$$

so equation is as follows,

$$\rho \frac{\partial H}{\partial t} = Q(x,z,t) - K_{eff}\left\{\frac{\partial^2 T}{\partial x^2} + \frac{\partial^2 T}{\partial z^2}\right\} \quad (20)$$

The value of enthalpy (H) is different for different methods. For sintering process, it only considers the sensible heat of metal powder by considering proper sintering temperature of material and for melting process it consider both sensible and latent heat of powder material.

Boundary Conditions

The Boundary conditions is considered at different places:

a) Heat loss at the top of the surface element
b) No heat loss at the bottom of the surface

a) First boundary condition: At the top surface area energy irradiated by the laser beam, the boundary condition is [5],

$$K_{eff}\frac{\partial T}{\partial t}=Q(x,z,t)-\grave{o}\sigma\left(T_S{}^4-T_\infty{}^4\right)-h\,A(T_S-T_\infty) \quad (21)$$

For the remaining area of the sample, the boundary condition is

$$K_{eff}\frac{\partial T}{\partial t}=-\grave{o}\sigma\left(T_S{}^4-T_\infty{}^4\right)-h\,A(T_S-T_\infty) \quad (22)$$

The initial conditions are

T(x, z, 0) =T□ & T(x, z, □) =T□

Where,

Q(x, z, t) is the input energy,

$K_{eff}\frac{\partial T}{\partial t}$ = Heat conduction

$\grave{o}\sigma\left(T_S{}^4-T_\infty{}^4\right)$ Heat loss via emission and radiation

$hA(T_S-T_\infty)$ =Heat loss via convection

Q_{conv} is a heat loss due to convection, h is a heat transfer coefficient, A is a heat transfer area, Q_{Rad} is a heat loss due to radiation, ε = Emissivity of material, σ = Stefan Boltzmann constant, T_s =Surface temperature, T□=Surrounding temperature

b) Second Boundary Condition: The second boundary condition satisfies the requirement that no heat is lost though the bottom of the powder bed (z = 0).

$$K_{eff}\left.\frac{\partial T}{\partial t}\right|_{z=0}=0 \quad (23)$$

By considering all the parameters, appropriate equations and boundary conditions mentioned herewith, we can find the output parameters such as laser power (P), scan rate (v) provided the sintering temperature for the given metal powder is available.

Temperature Dependent Properties

1. Relative Density

he thermal properties of the powder are considered in this model, which may have an impact on the heat transfer results. For the mechanical properties of the powder the properties of the powder are considered to depend on the fractional porosity of the powder bed, temperature, and solid properties. However, in this work, the relation between the powder properties and corresponding solid properties are assumed to be independent of temperature.

$$\frac{\rho}{\rho_0}=1-\varphi$$

Where, φ is the fractional porosity of the powder bed.

The relative density of powder bed with respect to temperature is improving within the time domain due to microstructure evolution and/or increase in grain size.

2. Effective Thermal Conductivity

It was also found that for low conductivity materials, effective conductivity depends primarily on porosity, while for high conductivity materials, effective conductivity depends primarily on the material and is independent of porosity.

The local effective heat conductivity, $K^{T+\Delta T}$, is given by Childs et al. (1999) as function of the heat conductivity of the solid material Ks and the porosity φ. By using Yagi-Kunii's equation we found out the effective thermal conductivity for different temperatures.

$$K_{eff}=\frac{\rho_R K_s}{1+c\dfrac{K_s}{K_g}}$$

By putting the different values properties with respect to temperature like solid thermal conductivity, Relative density then find the effective thermal conductivity of copper powder with different temperature.

The conductivity Ks of the solid copper is given by,
Ks= 420.75 – 6.8493x10^{-2} T (W/mK).

3. Specific Heat

The specific heat of polycarbonate material is assumed to be a linear function of the temperature in the solid, the temperature dependence of the specific heat is,

$$Cp^{T+\Delta T} = 316.21 + 0.3177T - 3.4936x10^{2} + 1.661*10^{3}$$

III. SIMULATION OF LASER SINTERING

Laser sintering process is a transient thermal analysis type of problem in which laser is used as moving heat source.

To create a Gaussian beam model in the APDL develop a code. In this code define the all temperature dependent material properties as input. By putting this temperature dependent properties of material develop a code for Gaussian beam with heat flux.

Simulation is performed in ANSYS APDL by coding the laser track along the y direction. by considering laser power to determine the laser heat flux of Gaussian beam approach. In Gaussian beam approach at TEM_{00} mode the laser intensity is maximum at centre and decreases along the radial direction.

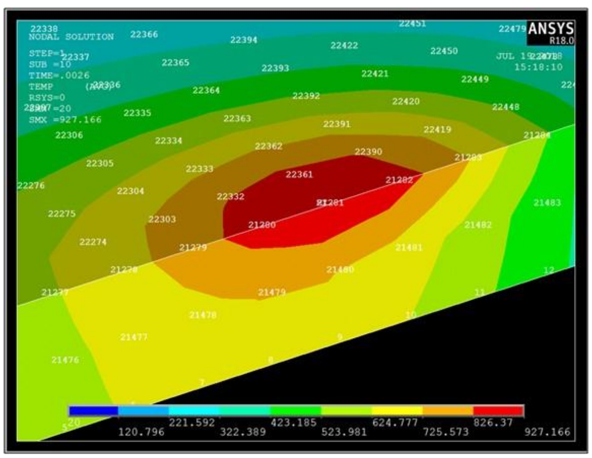

Figure 3: Temperature Distribution of Laser Beam Spot in a Temperature Field

To simulate the Laser Sintering process temperature dependent properties like density, Effective thermal conductivity, Specific heat, Poisson ratio, Yield Strength, Young's modulus and other useful material properties should used because this is a nonlinear or Transient Thermal Analysis type problem. These properties which are given in Table 3.5 used as input for simulation. Different types of lasers are available but mostly CO_2 type of laser is used with 0.4mm diameter. By using the Gaussian beam approach first find out the laser intensity or heat flux which is to be incident on the powder bed.

IV. RESULTS AND DISCUSSION

4.1 Temperature Distribution Along X, Y and Depth direcion

Fig. 4 and 5 shows the surface plot of top surface temperature distribution of the area in the powder layer from X =0 to 0.2mm and from Y=0 to 0.2 mm. These figures shows that the maximum surface temperature 910˚C is observed at the center of the laser beam. Some peaks are observed in the area, which comes under the laser beam. Both figures shows that the temperature distribution along the radial distribution decreases gaussianally.

In Fig. 6 shows the temperature distribution along the depth direction, in which temperature decreses along the depth direction.

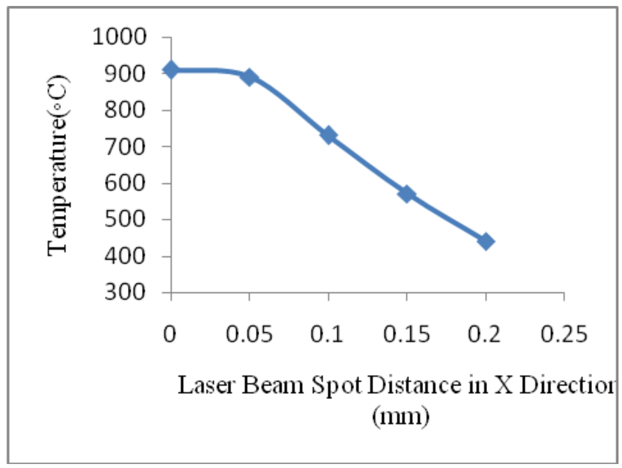

Fig. 4: Variation of Top Surface Temperature Along X Direction

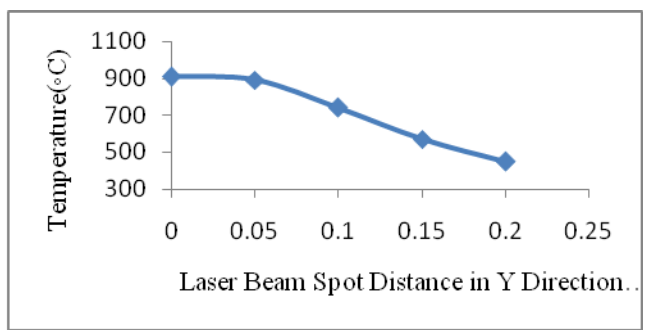

Fig. 5: Variation of Top Surface Temperature along Y Direction

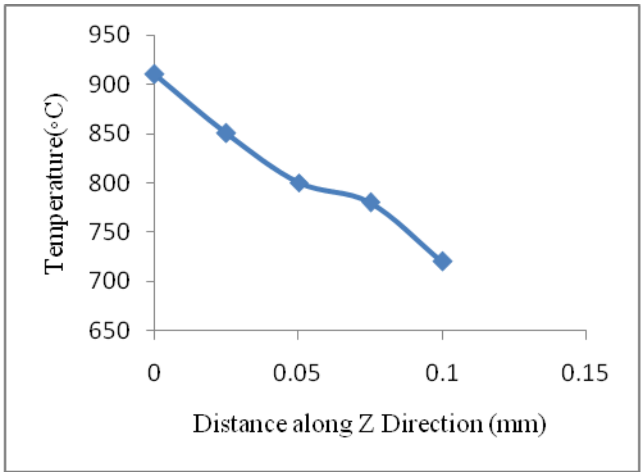

Fig. 6: Variation of Top Surface Temperature Along Depth Direction

4.2 Laser speed and Laser Power

Laser speed variation by keeping laser power constant and by considering the temperature dependent properties like effective thermal conductivity, specific heat, emissivity, environment temperature and other thermal properties.

Es is a key factor which affects quality of the laser sintered structure. A laser energy density is defined by the laser power, laser scan speed and laser beam spot size:

$$Es = \frac{P}{v\delta} \qquad (24)$$

Es = Laser Energy Density
P = Laser Power
V = Scan speed
δ = Laser beam spot

By keeping Laser power constant equ.(24) shows that laser power is directly proportional to laser speed. So in Fig. 7 indicates that laser power is directly proportional to laser speed.

So 150 Watt laser power and 0.1 mm thickness of powder bed is required for 150 mm/s laser speed to achieve laser sintering temperature in a field for fusion mechanism of particles, without considering the radiation effect, but experimentally 150 Watt laser power is required 200 mm/s.

For 400 Watt laser power and 0.1mm thickness of powder bed is required for 2.6 m/s laser speed to achieve laser sintering temperature in a field for fusion mechanism of particles, without considering the radiation effect.

Experimentally standard which are given by EOS (Electro optical system) is 400 Watt laser power and 0.1 mm thickness of powder layer required 3m/s without considering the effect of radiation and with radiation loss it requires 0.06, 0.08, 0.120m/s .

It indicates that huge amount radiation loss takes place in system as compared with convection.

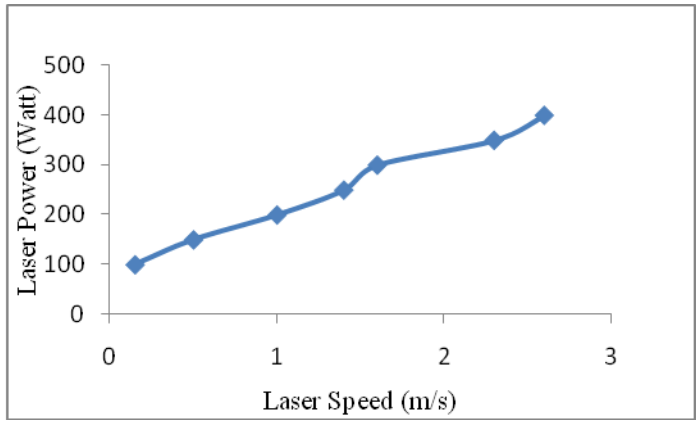

Fig. 7: Laser Power with respect to Laser Speed

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