Simulation of Laser Surface Hardening of Ti-6AL-4V

M.Tech. Thesis

by

Piyush Chand
(1902103002)

DEPARTMENT OF MECHANICAL ENGINEERING

INDIAN INSTITUTE OF TECHNOLOGY INDORE

June 2021

Simulation of Laser Surface Hardening of Ti-6AL-4V

A THESIS

Submitted in partial fulfilment of the
requirements for the award of the degree
of

Master of Technology

in

Mechanical Engineering

with specialization in

Production and Industrial Engineering

by

Piyush Chand

DEPARTMENT OF MECHANICAL ENGINEERING

INDIAN INSTITUTE OF TECHNOLOGY INDORE

June 2021

INDIAN INSTITUTE OF TECHNOLOGY INDORE

CANDIDATE'S DECLARATION

I hereby certify that the work which is being presented in the thesis entitled **Simulation of Laser Surface Hardening of Ti-6AL-4V** in the partial fulfilment of the requirements for the award of the degree of **MASTER OF TECHNOLOGY** and submitted in the **DEPARTMENT OF MECHANICAL ENGINEERING, Indian Institute of Technology Indore**, is an authentic record of my own work carried out during the time period from May 2020 to June 2021 under the supervision of **Dr. Yuvraj K Madhukar,** Department of Mechanical Engineering, Indian Institute of Technology Indore.

The matter presented in this thesis has not been submitted by me for the award of any other degree of this or any other institute.

Piyush Chand
(1902103002)

04-06-2021

This is to certify that the above statement made by the candidate is correct to the best of my/our knowledge

Dr. Yuvraj Kumar Madhukar

Dr. Yuvraj K Madhukar

Piyush Chand has successfully given his M.Tech. Oral Examination held on 04-06-2021

Dr. Yuvraj Kumar Madhukar

Signature of the Thesis Supervisor
Dr Yuvraj K Madhukar
Date: 06/06/21

Signature of Convener, DPGC
Dr. S. Patel
Date: 07/06/2021

Signature of PSPC Member 1
Dr. Girish Verma
Date: 07/06/21

Signature of PSPC Member 2
Dr. Abhijit Ghosh
Date: 07/06/21

ACKNOWLEDGEMENT

I would like to thank my guide **Dr. Yuvraj K Madhukar** for his guidance throughout the course of the project. I am highly indebted to **IIT INDORE** for providing me the opportunity to be part of the project which provided me a great learning experience and helped me in equipping many skills.

I want to take this opportunity to thank my PSPC members **Dr. Girish Verma and Dr. Abhijit Ghosh**, for their valuable suggestions in assessing my work during the mid-term and end-term presentations.

I also want to thank all my professors who were a part of my journey in IIT INDORE who helped me gain knowledge and insight which helped me gain better understanding of Mechanical Engineering.

I express my sincere gratitude to **PhD Scholar Mr Anas Ullah Khan** for his initial technical assistance to my project.

Piyush Chand

Dedicated

To

My Family

And

My faculties

ABSTRACT

Laser hardening aims to improve the wear behaviour of various component. The advantage of using laser as a heat source in this surface hardening method is that its region can be controlled. In laser surface hardening the source of heat is laser which is made to fall on the surface of the material. The surface layer is heated such that phase transformation occurs and the cooling rate would decide the hardness achieved. To study this, simulation of laser hardening of Ti6AL4V was carried out using ABAQUS and JMatPro software. Optimized parameters of laser were taken such as the laser power, scanning speed and beam spot diameter. Measurements of Vickers microhardness was done through simulation in ABAQUS and it was found that there was increase of surface harness after the laser hardening process, from (324 HV to 448 HV) measured on top surface of Ti6AL4V. The simulation for Vickers hardness was challenging as the properties of material which was changed due to heat interaction has to be evaluated. The change in material properties such as yield stress and corresponding strain values are calculated based on cooling rates. To find the cooling rate Rosenthal equation was used and for particular cooling rate the material properties was calculated from JMatPro software which takes account the phase transformations in it. The hardness decreases with increase of depth from surface. It was found that as we increase distance from centre of beam spot the hardness value decreases. The laser surface hardening was performed on different thickness of sheets as 1.5 mm and 3 mm. The effect of sheet thickness was also studied in this research. The main aim was to get maximum harness at top surface of Ti6AL4V. It was seen that with increase of cooling rate, the harness was enhanced. In this research, the enhancement of cooling rate was studied using the concept of heat sink. The effect on cooling rate with thermal contact resistance at the interface of Ti6AL4V and heat sink was also studied.

TABLE OF CONTENTS

TABLE OF FIGURES

Chapter 1 Introduction

1.1 Surface Hardening

Surface Hardening is the process of hardening the surface of component so as to increase its wear resistance properties. The core of the material remains soft but the top surface has a thick layer. Generally, these processes are used in those applications in which metal components are subjected to sliding contact with hard or abrasive materials. Since the hard layer is formed at the top so the surfaced is more resistant to wear as compared to before. One more advantage to it is that the core remains the soft, so it can absorb stresses without cracking. The unique benefit of titanium is its high strength to weight ratio as well as it's coefficient of thermal expansion is low. Moreover, it is corrosion resistant. The most common titanium alloy is Ti6AL4V, which is used in this research. The main drawback of this alloy is that it has low resistance to wear. So, to get rid of this, laser irradiation for surface modification can be done. There might be different surface hardness methods but the reason to choose laser surface hardening is that it induces compressive stress in the material due to which load carrying capacity of the material is enhanced.

There are a lot of surface hardening techniques which are given below

- Flame or induction Hardening
- Carburizing
- Nitriding
- Cyaniding
- Carbonitriding
- Laser surface Hardening

1.2 Flame or induction Hardening

Flame Hardening is the process in which the surface of material is heated very rapidly to high temperature. The heat source in this process is oxy- gas flame or induction coil. After heating the component, it is cooled rapidly using water which creates a martensitic surface. **Fig 1** shows the flame or induction hardening process.

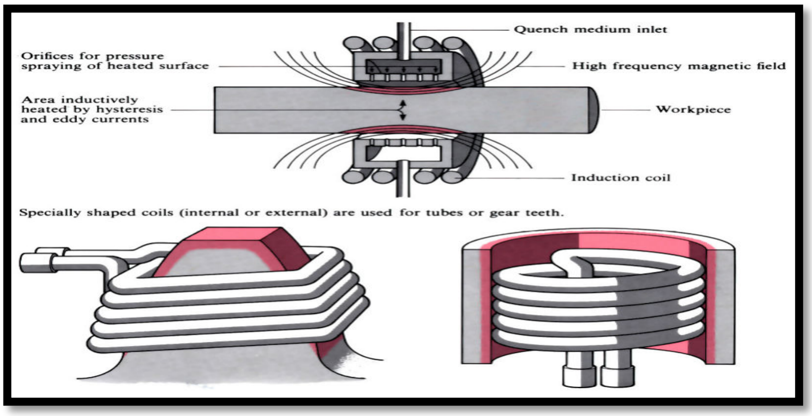


Figure 1: Induction Hardening (Source: Wikipedia)

1.3 Carburizing

Carburizing is the surface hardening process which is used to case harden steel. In this the carbon is made to diffuse inside the surface. This process is generally used for low carbon steel having Carbon content between 0.1 and 0.3% C. In this the material is kept inside the carbon rich environment at the high temperature for certain time period. After some time, the component is quenched so that carbon gets trapped in the structure. **Fig 2** shows the carburizing process.

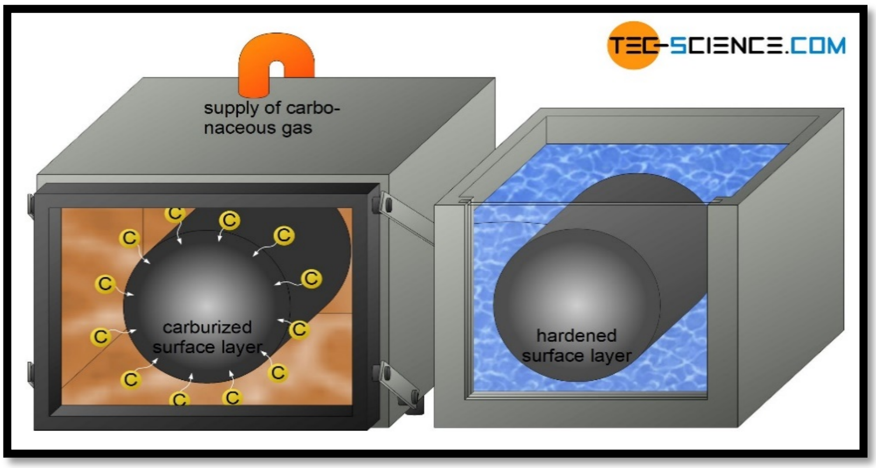


Figure 2: Carburizing Process (Source: Tecscience.com)

1.4 Nitriding

Nitriding is the process in which the component is placed in an atmosphere which is rich of ammonia. In this we can use either the ammonia gas or NaCN. The time for which the component is made to placed decide the depth of case. Nitrides are formed in this process which are responsible for increase in hardness value. The advantage of using this process is that no quenching is required.

1.5 Laser Surface Hardening

Laser hardening is a surface hardening process which aims at improving the component's wear behaviour. The advantage of using laser as a heat source in this surface hardening method is that we can control our region of interest and the cooling rate will decide the hardness achieved. In case of Ti-6AL-4V, the laser surface hardening is done by selecting the laser parameters (Laser power, scanning speed, beam spot) such that the temperature is reached at which alpha phase transforms to Beta phase. **Fig 3** shows the laser hardening process.

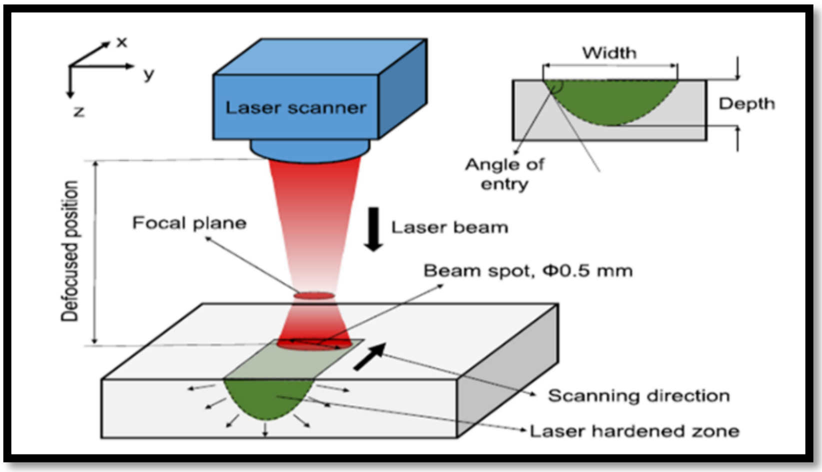


Figure 3: Laser Surface Hardening (Source: Wikipedia)

1.6 Why Laser Surface Hardening Important over others?

1. There are less HAZ due to which the distortion will be less.
2. The process is more flexible and accurate as we can control area of interest.
3. This process does not require any quenching medium.
4. The wear resistance of material is increased to much extent.
5. This process induces compressive stress on the material, so its fatigue strength is also increased.

1.7 Important applications of Ti-6Al-4V

Major applications *in aerospace, marine, biomedical, thermal energy power plants, and chemical processing industries* because:

1. Greater strength to weight ratio,
2. Low specific density.
3. Extraordinary corrosion and wear resistance.
4. Capacity to withstand reasonably high temperatures without creeping.

1.8 Phase Transformation of Ti-6AL-4V

- Titanium exists in two crystals alpha (HCP) and Beta (BCC).
- There are different types of alloy, the Ti-6AL-4V belongs to alpha +Beta alloy category.
- If we heat treated in Beta region and air cooled, we get different colonies of alpha. These colonies have different orientation due to which properties changes.
- We have to take care that not much alpha precipitates on grain boundaries because if it so, it will have impact on mechanical properties.
- In case of Ti-6AL-4V, to make globular structure, it is not possible simply by heat treatment as in case of steel.
- So, in this case we have to deform the Ti-6AL-4V in alpha + beta region.

1.9 Organisation of Thesis

Chapter 2 presents the detailed literature review on the past work reported in the relevant field of Laser surface hardening, Thermophysical properties of Ti-6AL-4V, process parameters evaluation, the objectives of research and research methodology used in the present work.

Chapter 3 includes the simulation of Vickers Hardness before and after Laser surface Hardening process. A detailed analysis was performed using FEA based ABAQUS software. The results were validated from past work reported so far.

Chapter 4 presents the analysis of various objectives which were mentioned in chapter 2. These objectives were successfully validated from previous researches which people tried to perform. This chapter highlights the importance of cooling rate to enhance the hardness. Various techniques are listed so as to increase the cooling rates, one of them is application of Heat sink.

Chapter 5 highlights the conclusions of the present work and marks the scope for future work based on the limitations of the present work.

Chapter 2: Literature Review and objective formulation

This chapter presents the detailed literature review on the past work reported in the relevant field of Laser surface Hardening, limitations, various assumptions taken, models taken to find various properties of material. With the help of these past work the simulation results were validated.

2.1 Parameters of Laser Surface Hardening

Many studies have been implemented and it was found by **Borowski et.al. [1]** that in case of Aluminium alloy, the surface properties are enhanced by laser hardening process. It was studied by them that the wear resistance and hardness was improved and was dependent on laser power and scanning speed. There was increase in hardness value when laser power increases and scanning speed decreases.

Ming-der et al. [2], have used the Taguchi method so as to minimize wear rate in case of Cast Iron. They had also concluded that in case of Cast Iron the most significant parameters affecting the wear resistance is the scanning speed.

B.kar et al. [3] used the Taguchi method used the Taguchi method so as to minimize wear rate in case of Pure Titanium. They observed that the scanning speed and laser power are most important factors to be controlled for laser transformation of pure titanium.

From these studies it was concluded that whatever be the material, the laser surface hardening process depends mainly on laser parameters like scanning speed, power and beam spot diameter.

2.2 Thermophysical properties of material

Since this laser surface hardening process involves the heat transfer analysis so thermophysical properties of material must be known to simulate the heat transfer analysis. For this **L. Lolli et.al. [4]** investigated on Low Temperature Thermal Conductivity of Ti-6Al-4V Alloy and they found out that for low temperature, Thermal conductivity of Ti-6Al-4V Alloy increases as the temperature rises. It was also concluded that the relationship between thermal conductivity and temperature is almost linear for this low temperature variation.

L. Johnson et. al. [5], Studied the various Thermo-physical properties of Ti-6Al-4V which was found to be dependent on Temperature range and was found that for a temperature rise up to 1800 K, specific heat increases with temp and beyond 1800 K it remains almost constant. The density was found to decrease as temperature increases.

2.3 Hardness evaluation- materials properties

A.K. Nath et al. [6], Studied the repetitive and continuous laser pulse heating and cooling and found that the surface hardening depends on pulse duration and frequency. They found that when the repetitive laser pulse is used the depth of hardness is much more as compared to the continuous laser heating.

D.W. Jung et.al. [7] studied about Flow Stress Equations of Ti-6Al-4V and Ludwick`s hardening law had been used to find out yield stress corresponding to plastic strain. The effect of temperature on flow stress was studied. The Ludwick's hardening law depends on material to evaluate constants. Hence constants of Ludwick's law for Ti-6AL-4V had been evaluated in their research.

J. D. Hahn et.al. [8] predicted the hardness by using kinetic model. In this model they determined the phases which are present on the material when it is heated to a particular temperature and cooled. By using the amount of alpha and beta phases and their respective hardness, the overall hardness of material can be obtained. They have given the phases transformation and cooling rate dependence for the formation of martensite which will increase the hardness of material.

Simon Pauly et.al. [9] determined the cooling rate in case of laser surface hardening. They predicted that if we increase the power of laser the cooling rate tend to decrease. According to them the cooling rate was 10^4 K/s when high laser power (300 W) was used. At the lower laser power (200 W) the cooling rate comes was found to be 10^5 K/s.

Ramesh Raju et.al. [10] has given the mathematical relation for determining the cooling rate during laser hardening operation. According to them the cooling rate was observed increasing when the scanning speed was increased, however, the temperature rise in the specimen was found to be decreased. **Dao et al. [11]** had analysed the FE- based simulation using 2D axisymmetric modelling instead of the real configuration.

Hyung son Ki et.al. [13] studied the thermal contact resistance and concluded that in most of practical applications the value of thermal contact resistance varies from $5*10^{-6}$, $5*10^{-5}$ and $5*10^{-4}$ $m^{\wedge 2}K/W$. **Yan-Jun et.al.[14]** predicted that if clearance is up to 1mm, it is assumed that the thermal contact resistance is very large i.e., thermal conductance value is zero. If no clearance is present, it is assumed that thermal contact resistance is less i.e., thermal conductance value taken as larger one (200,000).

2.4 Objectives of the Present Research

I. Simulation and comparison of continuous and repetitive laser pulse heating and cooling cycles.

II. Selection of Laser parameters for achieving maximum surface hardness.

III. Simulation of Vickers Hardness Before laser Hardening.

IV. Simulation of Vickers Hardness after laser Hardening.

V. Variation of hardness along depth.

VI. Variation of hardness on moving away from centre of beam spot.

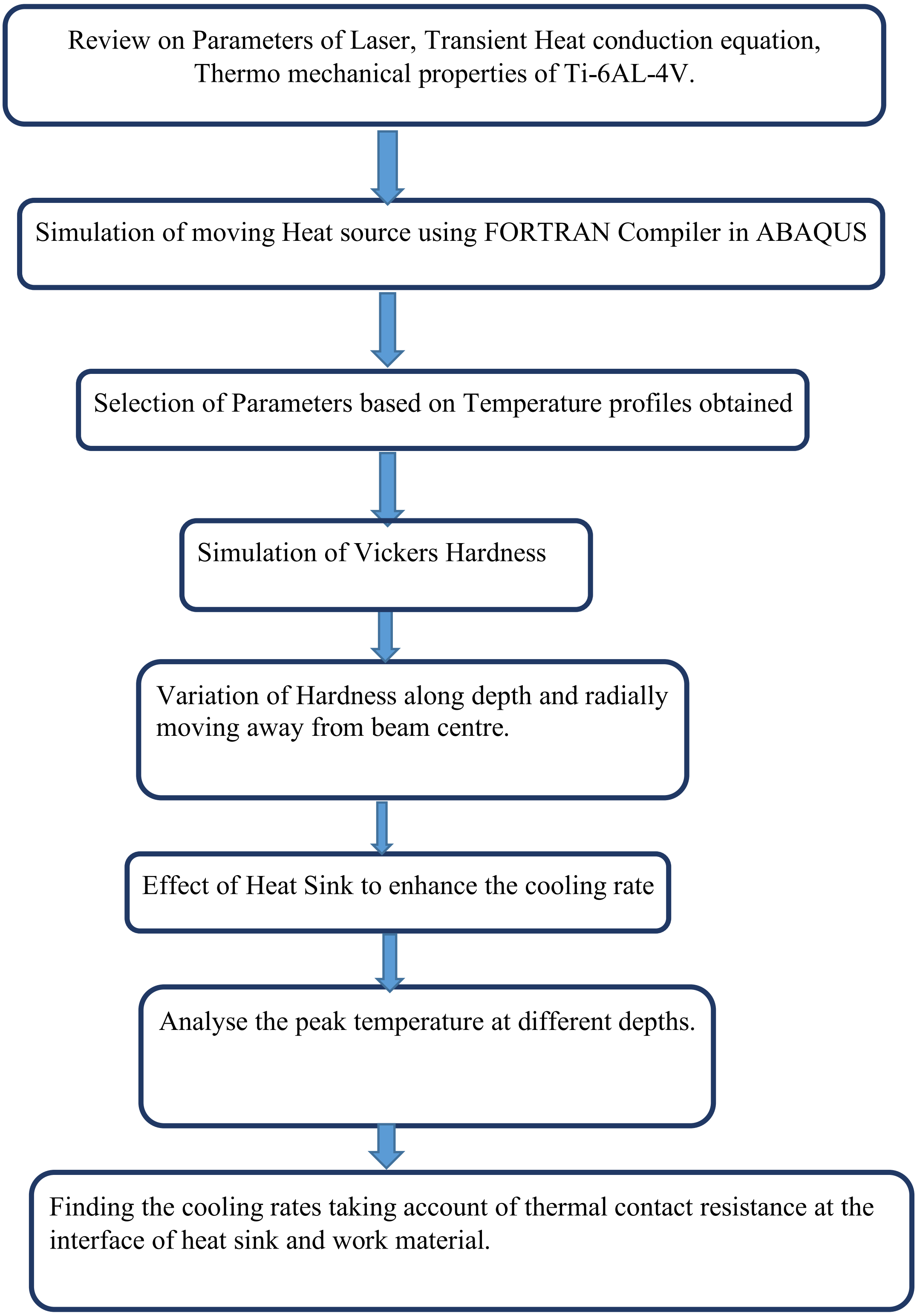
VII. Simulation to study the effect of Heat Sink to enhance the cooling rate.

VIII. Simulation to study the effect of plate thickness to enhance the cooling rate and to analyse the peak temperature at different depths.

IX. Simulation to study the effect of plate thickness by analysing the Time History of temperature on surface of Ti6AL4V sheet.

X. Effect of contact resistance between Ti6AL4V sheet and sink material.

2.5 Research Methodology



Chapter 3: Simulation of Vickers Hardness Using ABAQUS and JMatPro

3.1 Vickers Hardness

It is the process to evaluate hardness of material. Pyramid shaped diamond indenter is used to produce the indentation on the surface to be tested. The indenter's opposite sides meet at the apex at an angle of 136°. The force is applied on the indenter which varies and the size of the impression is measured. In this case the diagonal length is measured. The Vickers number (HV) is calculated using the following formula:

$HV = 1.854(F/D^2)$, where F is in Kg-f, D diagonal of impressed shape in mm.

3.2 Modelling in ABAQUS and using Boundary Conditions

Fig 4 shows the 2D analysis of Vickers hardness. The Vickers indenter is not axisymmetric but to reduce the complexity of simulation it was studied by different authors that the result was close to real situation. **Dao et al. [11]** had analysed the FE- based simulation using 2D axisymmetric modelling instead of the real configuration. Since in past works done so far there were not any information about finding the hardness value after laser surface Hardening process. Since the material region where the laser is made to focus, its properties will change due to increase of temperature. This study will take into account of those limitations and can be used in future.

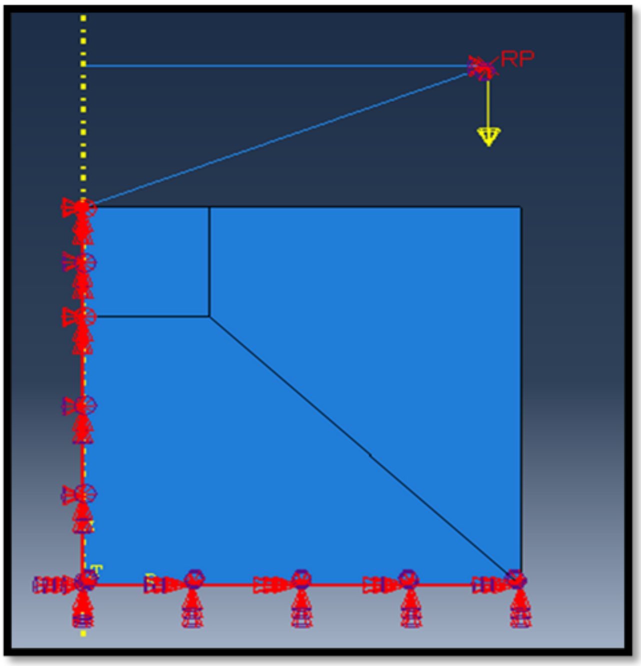


Figure 4: Shows the Boundary conditions Used while simulating

3.3 Methodology

Fig 6 shows the methodology adopted for simulating Vickers Hardness. In this the material has to be chosen as custom material so that its material properties can be given according to cooling rates. To find the Vickers Hardness, since the load is applied to the material there will be deformation in the material. We need to calculate the strain and corresponding yield stress using Ludwick's Hardening Law. According to this low the yield stress and corresponding strain are related as **$\sigma_0 = \sigma_y + K (\epsilon_{pe})^n$** ; where **$\sigma_0$** : yield stress corresponding to strain value. K and n are constants which depend on material. For Ti-6AL-4V, K= 492.709 MPa, n= 0.3159 These values are taken from literature. For different strain values the yield stress was calculated and is mentioned in Fig 7.

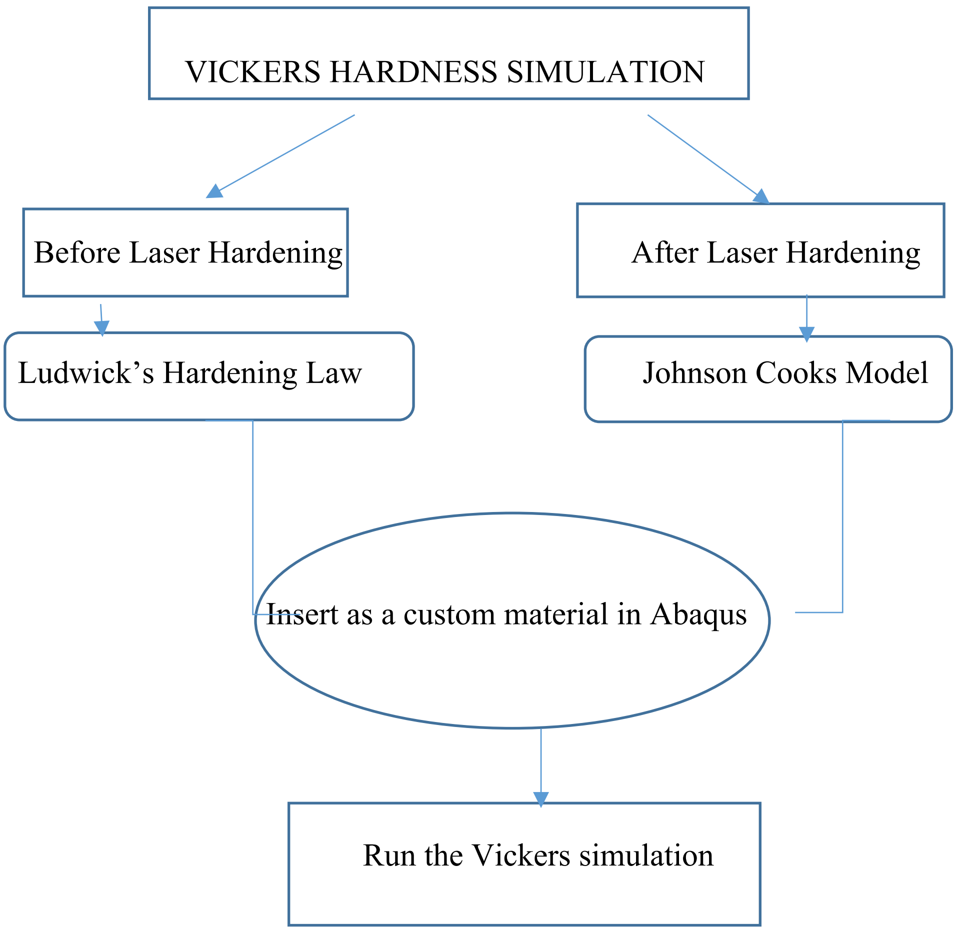


Figure 5: Shows the Methodology adopted while simulating Vickers Hardness

Ϭ0 (MPa)	Єpe
1000	0
1055.57	0.001
1092.40	0.005
1115.02	0.01
1191.24	0.05
1238.05	0.1
1395	0.5
1492.70	1
1560.02	1.5

Figure 6: Shows yield stress corresponding to strain values.

3.4 Calculations for Vickers Hardness before Laser surface Hardening

Load of 25N acts on the indenter for time of 15 sec and is released. The indentation was analyzed using FEA based simulation ABAQUS. As the force is applied the indenter will penetrate into the material and the value is obtained through Fig 9. From Fig 9 the depth of penetration is recorded as 19 microns. Using Pythagoras theorem, the length of diagonal of indentation can be calculated as 118.8 microns. Using the formula of Vickers, the Vickers Hardness is found to be close to 334 HV.

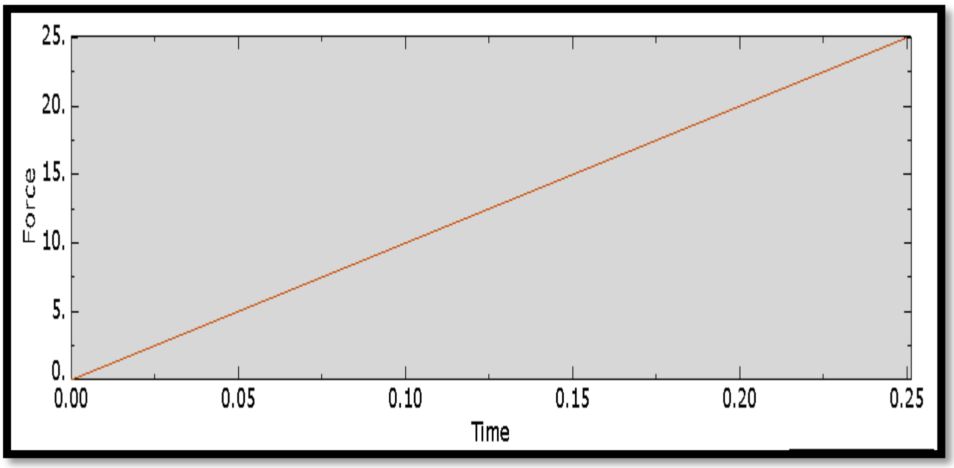


Figure 7: Shows Load variation when applied for 15 sec (0.25 min)

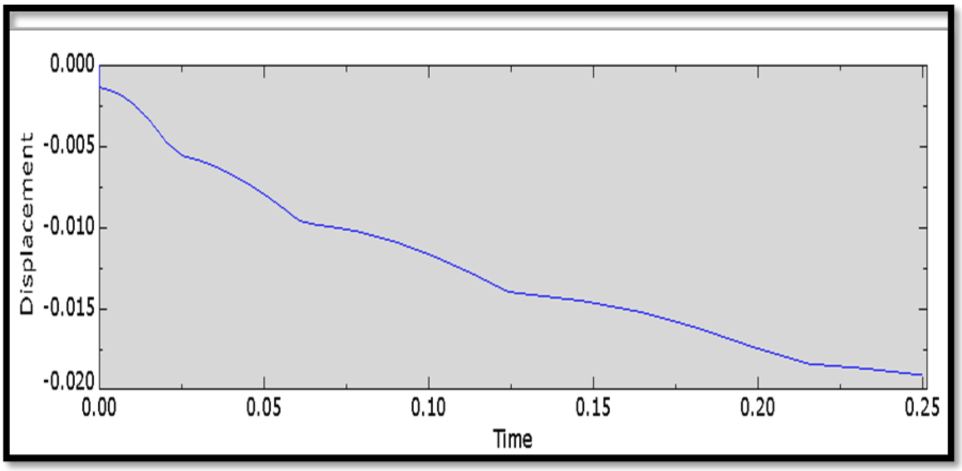


Figure 8: Shows the position of indenter when load acts on reference point

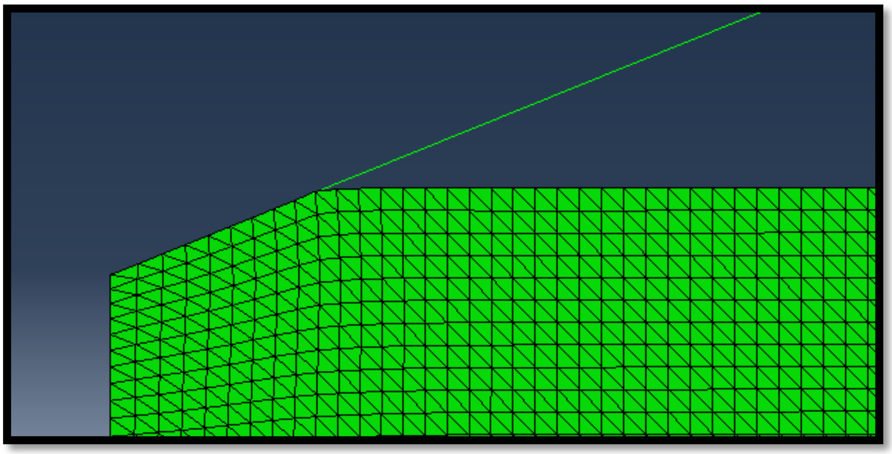


Figure 9: Shows the deformation along the different layers and the front view of impression obtained

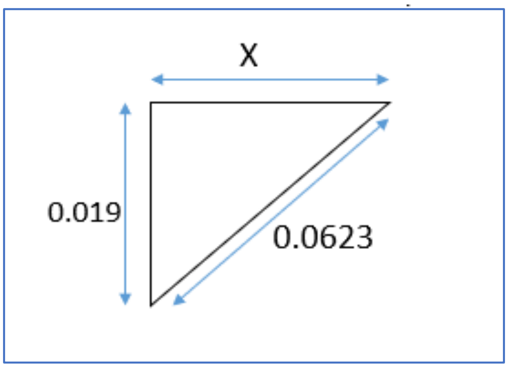


Figure 10: Shows the calculation for diagonal of indentation (in mm)

Calculations: X= 0.0594 mm

Length of Diagonal= 0.1188 mm

HV= (2F sin68)/D^2

Where F in kgf, D in mm

Substituting F= (25/9.81), D=0.1188 mm

We get HV= 334.83

3.5 Calculations for Vickers Hardness After Laser Surface Hardening

The main challenge was to find the changes in material properties due to phase transformation occurring when material is heated to such an elevated temperature. The properties needed in evaluating the Vickers hardness in the simulation is yield stress and corresponding strain values. For this, two approaches were used.

I. Using Johnson cooks model to find yield stress and corresponding strain values.

II. Using JmatPro, which take the input as cooling rate and accordingly plot the flow stress strain curve using the phase transformation curves inbuilt in it.

Both of these results give approximately same value of hardness after laser surface hardening.

3.5.1 Using Johnson Cooks Model

The Johnson Cook model gives the relation between the yield stress and corresponding strain as:

$$\sigma = [A + B\,(\varepsilon_p)^n]\left[1 + C\,\ln\left(\frac{\dot{\varepsilon}_p}{\dot{\varepsilon}_{p_0}}\right)\right][1 - (T^*)^m]$$

$$T^* = \left(\frac{T - T_{\mathrm{ref}}}{T_{\mathrm{melt}} - T_{\mathrm{ref}}}\right) \qquad T_{\mathrm{ref}} = 23\ ^\circ\mathrm{C} \text{ and } T_{\mathrm{melt}} = 1630\ ^\circ\mathrm{C}$$

m: Thermal softening rate (0.8 for Ti-6AL-4V) ε_{p_0}, is set at 1 s^{-1}.

Єp: strain

n: hardening exponent (0.55)

A: yield stress (680MPa)

B: strength coefficient (1200 MPa)

C: strain rate sensitivity parameter (0.0157)

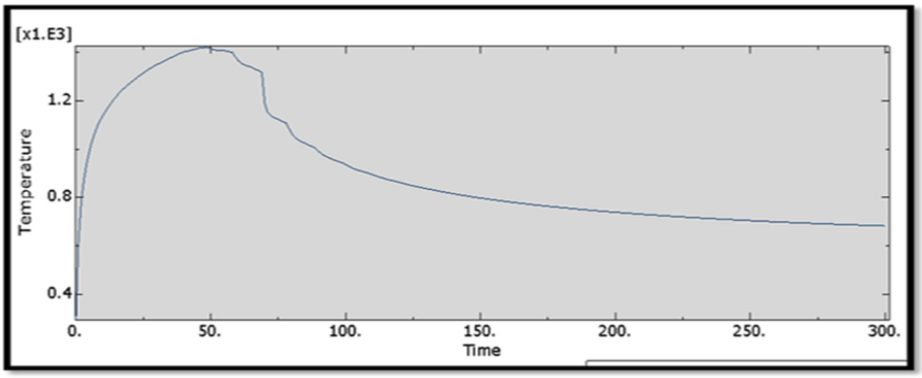


Figure 11: Shows the Temperature time plot for particular case of Process parameters. In this case P=600W, Scanning speed = 2000mm/min Beam spot= 5mm

From the **Fig 11** it is clear that maximum temperature rise is 1424 K. using T= 1424 K and substituting all constant for Ti-6AL-4V, in Johnson cooks model we get following values of stress corresponding to strain values as shown in below table.

σ (MPa)	Єp
230	0
258.78	0.001
273.069	0.005
281.07	0.01
308.70	0.05
327.48	0.1
404.67	0.5
463.42	1
509.331	1.5

Figure 12: Shows the value of yield stress and strain using Johnson Cooks model.

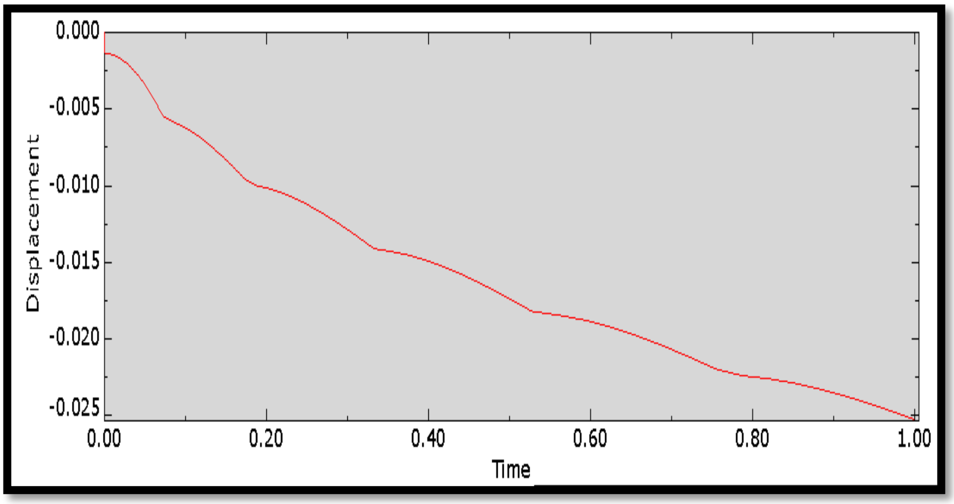
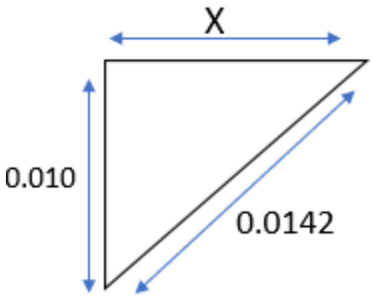


Figure 13: Shows the position of indenter when load acts on reference point

From **Fig 13** the displacement of indenter is 25 microns when load of 100gf acts on the indenter at reference point for 15 sec. Using this as one of the lengths of triangle as shown in Fig 17, the value of length of diagonal using Pythagoras theorem comes to be 20.34 microns.



X=0.01017 mm

d= 0.02034 mm

HV= (2Fsin68)/d^2

=448

Where F in kgf, d in mm

3.5.2 Using Flow stress curve obtained through JMatPro software

Hardness was also calculated using the results from JMatpro. The basic requirement in finding the Vickers hardness was to find the change in properties of material after laser surface hardening. It was studied that the hardness depends on the phases present during phase transformation of Ti6AL4V. To calculate the phases present JmatPro was used. The input required in JmatPro is cooling rate, which can be calculated using Rosenthal equation. *For a Particular set of optimized parameters, the cooling rate was found using Rosenthal equation and imported in JmatPro which takes the effect of TTT diagram inbuilt in i*t. The flow stress curve can be plotted using this method and hence the simulation of Vickers hardness can be performed.

To find the Vickers hardness we need the flow stress equation or the value of stress corresponding to different strains. For this JMatPro software was used in which the inputs are cooling rate and phase transformation temperature. From various iterations done for an optimized parameter of laser the Transformation Temperature was close to 1286 K - 1342 K. The cooling rate corresponding to these optimized parameters are calculated as 80,000 K/s. Substituting these values the flow stress strain curve is obtained as shown in **Fig 14.**

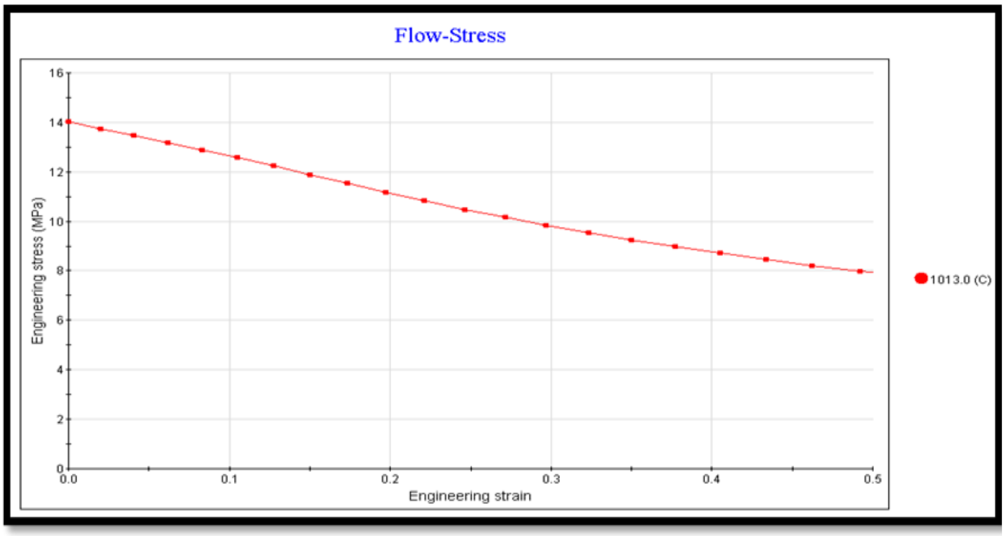


Figure 14: Shows the Flow stress curve at 1286 K, cooling rate 80,000 K/s

Chapter 4 SIMULATION RESULTS AND DISCUSSIONS

4.1 Experimental Detail

To study the laser surface hardening process the optimize parameter of laser had to be taken. **Borowski et.al [1]** suggested that the parameters on which the surface hardening depends only on laser power, scanning speed and beam spot diameter. It was investigated by **J. D. Hahn et.al.[8]** that the absorptivity of material is 0.61 which is constant up to 1350 K but above this temperature it follows as 0.0003(T) +0.205. In this paper the mean absorptivity is taken as 0.75 The materials properties are temperature dependent as investigated by **L. Johnson et. al**. **Fig15** shows the different properties which were used during simulation.

Temperature (˚C)	**Thermal Conductivity (kW/m K)**	**Density (g/cm^3)**	**Specific Heat (J/g K)**
25	6.09	4.41	0.55
200	9.83	4.39	0.6
400	13.31	4.36	0.65
600	16.52	4.33	0.79
800	19.13	4.31	0.84
1000	24.28	4.31	1.04
1200	27.55	4.28	0.70
1400	30.69	4.24	0.74

Figure 15: Shows Thermo-physical properties of Ti-6Al-4V

4.2 Selection of Laser parameters for achieving maximum surface hardness

Fig 16-18 shows different iterations performed for selecting optimized parameters of laser. The selection of laser parameters was made on the basis of phase transformation. **J. D. Hahn et.al.[8]** suggested that the Ti6AL4V is alpha beta alloy in the material had to be heat treated so that the temperature should cross the Beta transus line (Temperature close to 1200 K). The rate of cooling will decide the hardness achieved. In this paper the air cooling was used and the cooling rate was calculated for a particular process parameter using Rosenthal Equation given by $dT/dt = -2\pi k(v/p)\Delta T^2$

Where K is thermal conductivity (W/m K), V is scanning velocity(cm/sec), P is laser Power (W).

Cases	Laser Power (W)	Scanning speed (mm/min)	Absorptivity	Beam spot diameter (mm)	Max Temperature (K)	HV (at top surface)	Phases Alpha (%)	Beta (%)
I	400	2000	0.75	5	1166	427.42	60.14	38.86
II	500	2000	0.75	5	1286	448.80	0	100
III	600	2000	0.75	5	1465	448.89	0	100
IV	800	2000	0.75	5	1713	448.89	0	100
V	900	2000	0.75	5	1822	448.89	0	100
VI	1000	2000	0.75	5	1923 (beyond melting Temperature)	-	0	100

Figure 16: Shows the maximum Hardness of 448 achieved at Temperature 1286K for Laser Power 500W, scanning speed 2000 mm/min.

Cases	Laser Power (W)	Scanning speed (mm/min)	Absorptivity	Beam spot diameter (mm)	Max Temperature (K)	HV (at top surface)	Phases Alpha (%)	Beta (%)
I	400	3000	0.75	5	878	403.69	94.48	5.52
II	500	3000	0.75	5	1007	407.93	90.23	9.77
III	600	3000	0.75	5	1295	448.89	0	100
IV	800	3000	0.75	5	1583	448.89	0	100
V	900	3000	0.75	5	1687	448.89	0	100
VI	1000	3000	0.75	5	1785	448.89	0	100

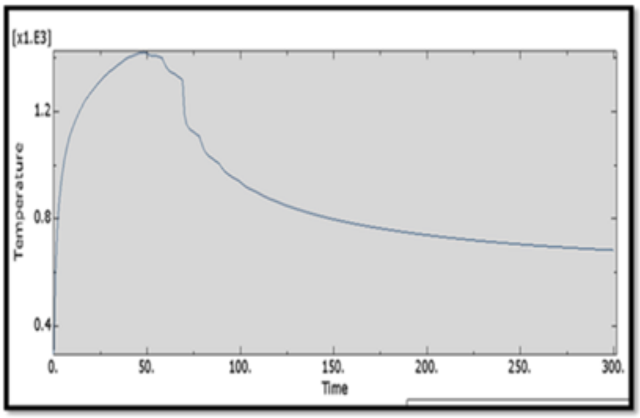
Figure 17: Shows the Maximum Hardness achieved for Laser Power 600W and Scanning speed 3000 mm/min

Cases	Laser Power (W)	Scanning speed (mm/min)	Absorptivity	Beam spot diameter (mm)	Max Temperature (K)	HV (at top surface)	Phases Alpha (%)	Beta (%)
I	400	4000	0.75	5	773	401.62	95.37	4.63
II	500	4000	0.75	5	873	403.59	94.55	5.45
III	600	4000	0.75	5	1041	410.18	87.58	12.42
IV	800	4000	0.75	5	1342	448.89	0	100
V	900	4000	0.75	5	1463	448.89	0	100
VI	1000	4000	0.75	5	1642	448.89	0	100

Figure 18: Shows the Maximum Hardness achieved for Laser Power 800 W and Scanning speed 4000 mm/min

4.3 Variation of hardness on moving away from center of beam spot.

In this Present work the variation of Hardness radially as we move away from centre of beam spot was studied. The temperature profile was generated through ABAQUS and the peak Temperature was calculated as shown in **Fig 19**. It also shows the nodes selected at a distance of 10 mm. The hardness value at these nodes were predicted as 448HV at node A, 410HV at node B, 383HV at node C and 361 HV at node D. A graph was plotted for Vickers Hardness with respect to radial distance and it was found that the hardness decreases as we move away from centre of beam spot as shown in **Fig 20**.



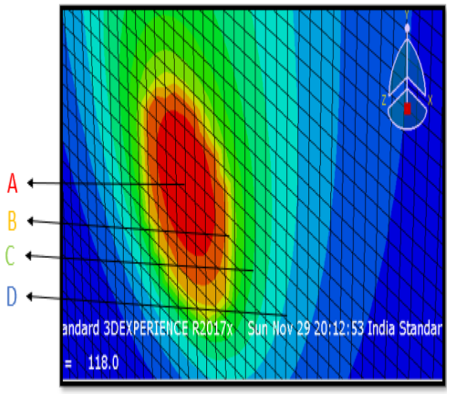


Figure 19: Shows Temperature profile for Laser power 600W scanning speed 2000mm/min and beam spot 20 mm

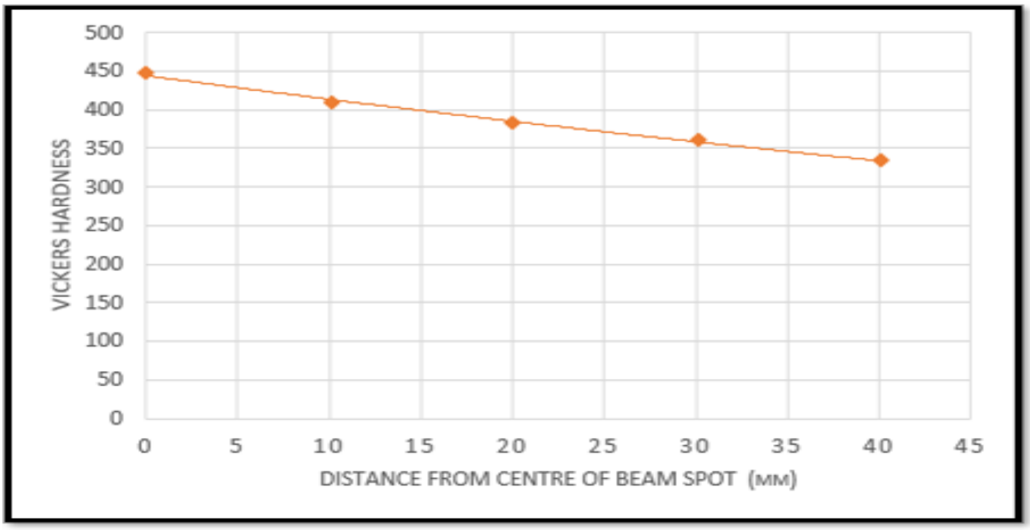


Figure 20 Shows the Decrease in Hardness as distance from centre of beam spot increases.

4.4 Variation of hardness along depth

The variation of Hardness along depth was also measured and it was predicted to decrease. **Fig 21** shows the variation of Hardness along depth. It was predicted that there was increase in hardness up to depth of 0.36 mm from surface, beyond which the hardness remains same as it was before laser hardening process.

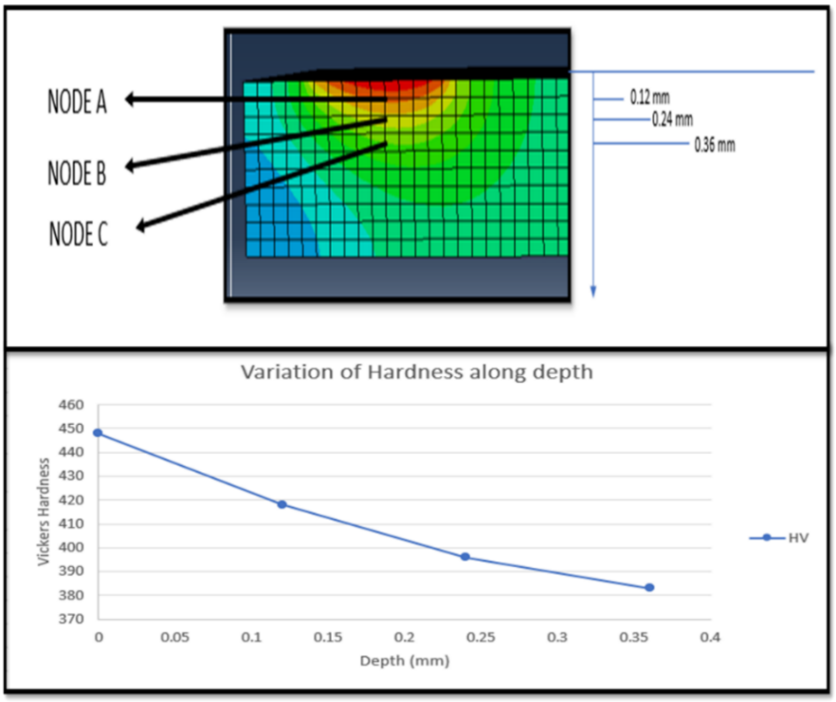


Figure 21 Shows the variation of Hardness along depth

4.5 Methods To increase the Surface Hardness

To increase the surface Hardness of material various methods were developed so far and it was concluded as per literature the hardness depends on cooling rate. To increase the cooling rate the concept of Heat Sink was taken into account. Heat sinks of different materials like Cu and SS was joined with Ti6AL4V specimen as shown in **Fig 22** and the Temperature profile was plotted using ABAQUS as shown in **Fig 23**.

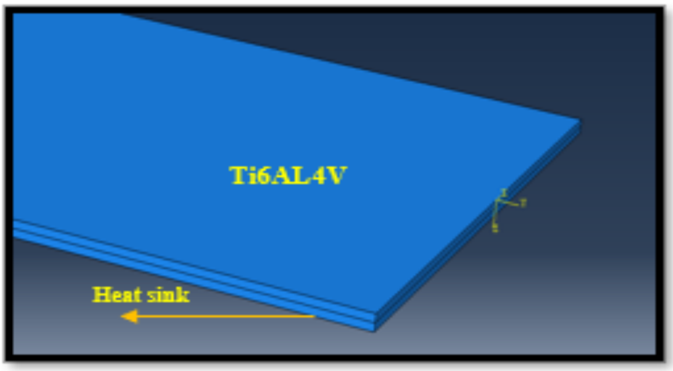


Figure 22 : Shows the Ti6AL4V sheet with heat sink

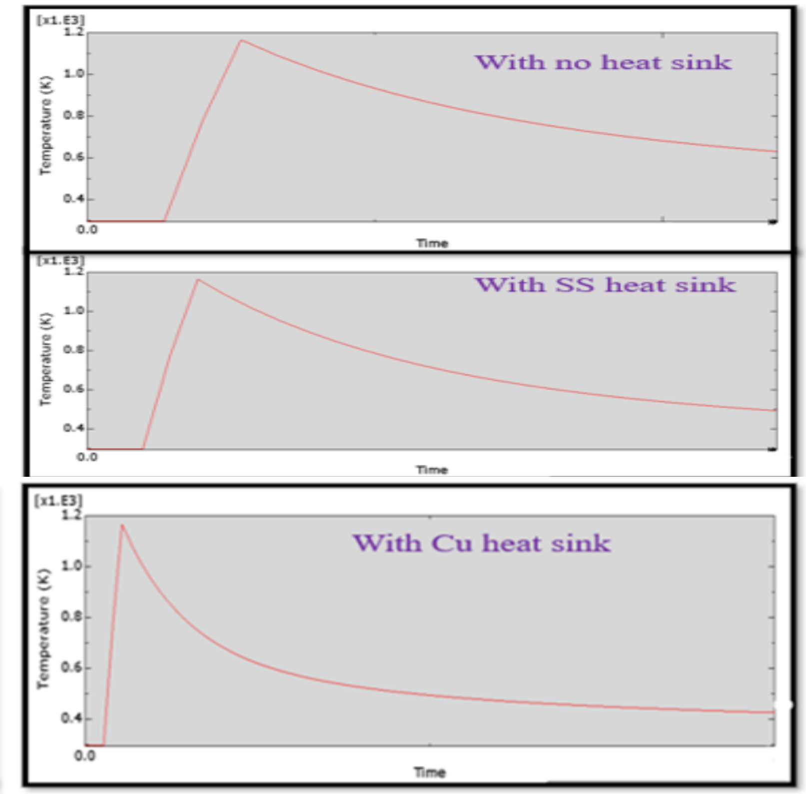


Figure 23 Shows the effect of Heat sink in cooling rate

When the Heat sink material was attached to the Ti6AL4V, the thermal contact resistance between the two sheets should also be taken into account. For this the effect of thermal contact resistance on cooling rate was studied in this paper. **Fig 24** shows the modelling taking into account thermal contact resistance.

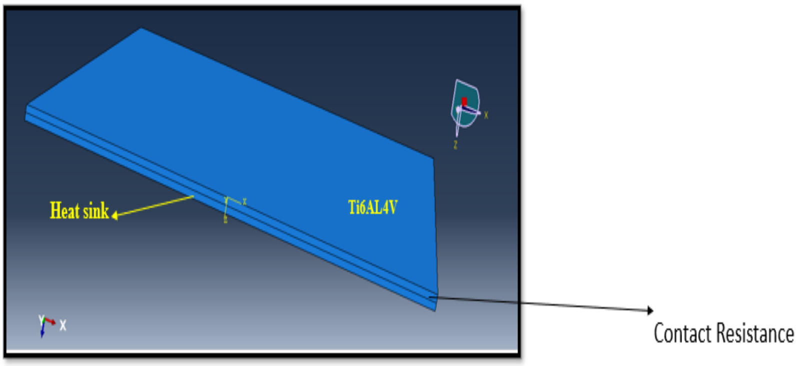


Figure 24: shows the modelling taking into account thermal contact resistance.

Hyung son Ki et.al. [13] studied the thermal contact resistance and concluded that in most of practical applications the value of thermal contact resistance varies from $5*10^{-6}$, $5*10^{-5}$ and $5*10^{-4}$ $m^{\wedge 2}K/W$. **Yan-Jun et.al.[14]** predicted that if clearance is up to 1mm, it is assumed that the thermal contact resistance is very large i.e., thermal conductance value is zero. If no clearance is present, it is assumed that thermal contact resistance is less i.e., thermal conductance value taken as larger one (200,000). Using thermal contact resistance as $5*10^{-6}$ $m^{\wedge 2}K/W$ the temperature profile obtained is shown in **Fig 25**. The cooling rate using Rosenthal equation is given as $2.1*10^{5}$ K/s. Similarly cooling rates were calculated for other values of thermal contact resistances. A graph was plotted as shown in **Fig 26** which shows the variation of cooling rate with thermal contact resistance. To enhance the cooling rate the thermal contact resistance should be as small as possible.

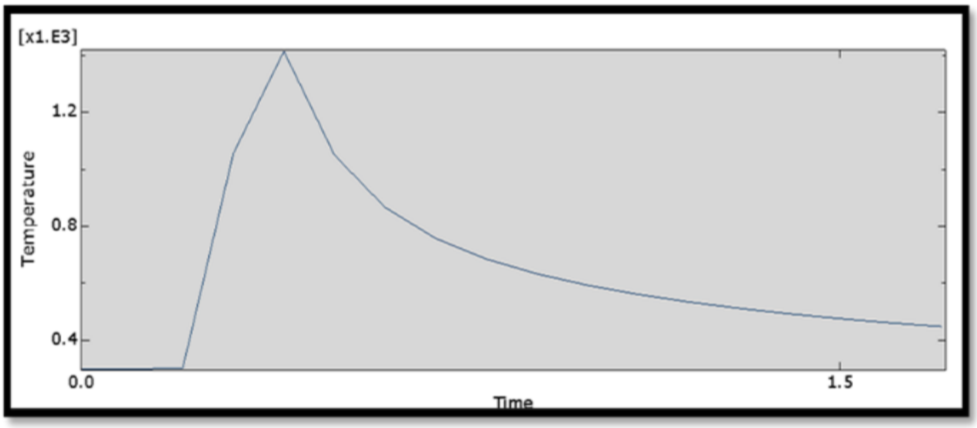


Figure 25 shows the temperature profile when low value of thermal contact resistance is taken into account.

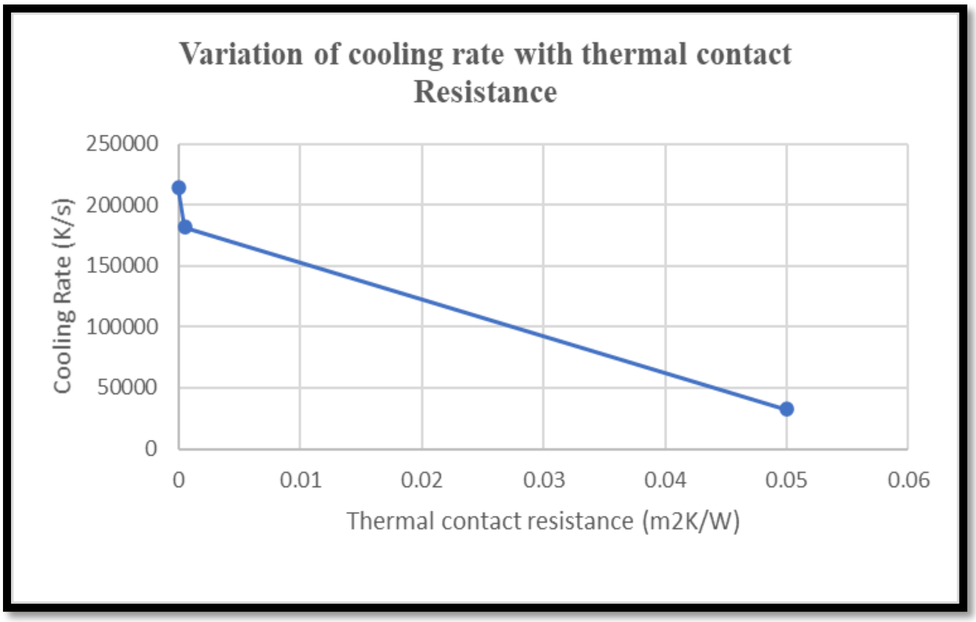


Figure 26: shows the decrease in cooling rate as thermal contact resistance is increased.

4.6 Simulation to study the effect of plate thickness to enhance the cooling rate and to analyse the peak temperature at different depths

The effect of plate thickness to enhance the cooling rate and to analyse the peak temperature at different depths was studied in this present work. Sample sizes of thickness 1.5 mm and 3mm were taken and the surface hardening was carried out. It was noticed that the cooling rate is more in case of 3 mm thickness sheet. **Fig 27-28** shows the temperature variation on top surface of sheet for different thickness. From **Fig 29**, it is concluded that the up to 0.4mm from top surface of specimen there will not be any effect of thickness of sheet on temperature but as depth increases the cooling is more in case of 3 mm thickness sheet. Time history of temperature at the top surface was also studied and its effect with sheet thickness was investigated, that there was increase in cooling rate with increase in sheet thickness, although the peak temperature remaining same as shown in **Fig 30**.

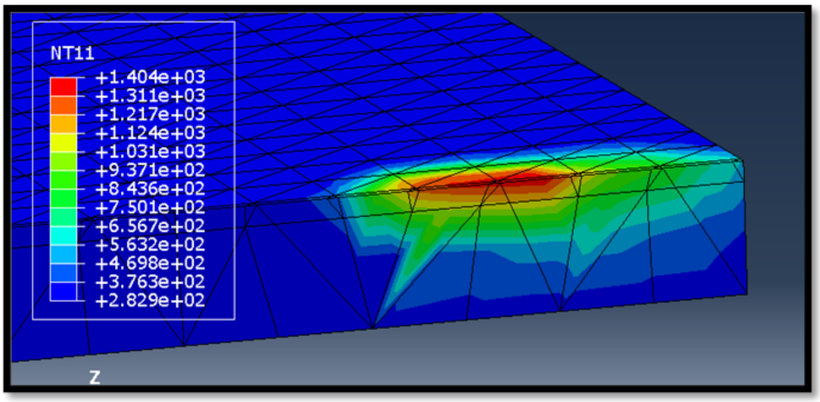


Figure 27: Temperature distribution for 3.0 mm sheet

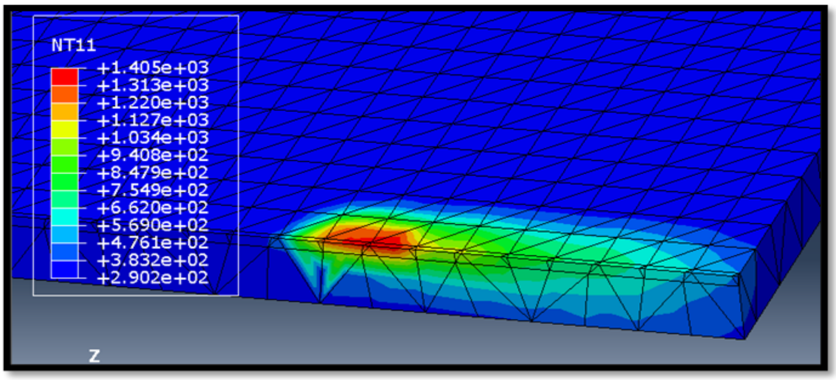


Figure 28 Temperature distribution for 1.5 mm sheet

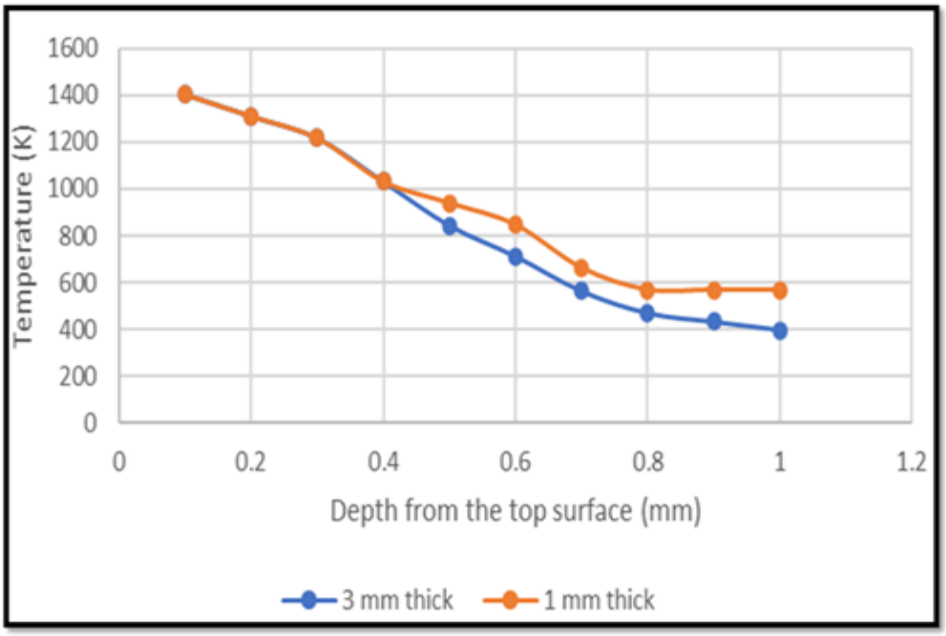


Figure 29: Temperature at different depths from top surface

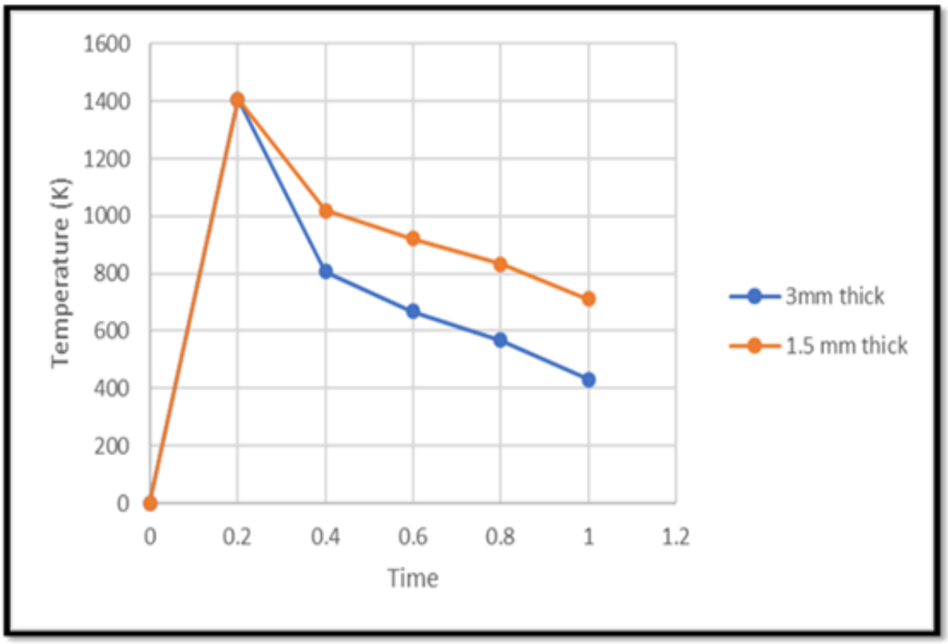


Figure 30: Time history of temperature at the top surface and its effect with sheet thickness.

4.6 Simulation of *continuous and repetitive* laser pulse heating

- **Process Parameters**

1. Heat flux: **Case I:** 2000W for 60sec

   Case II: 2000W for 40sec (ON/OFF mode).

2. Beam spot Diameter: 20mm

- **Material Properties:** Temperature dependent.

- **Transient Analysis -** 200sec

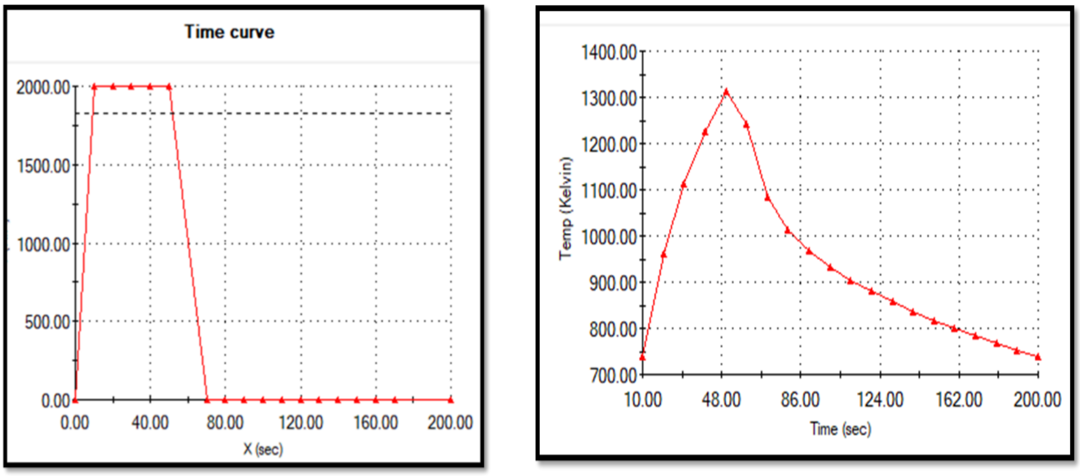


Figure 31: Shows the continuous laser pulse for 60sec and then cooling, corresponding to that temperature profile generated.

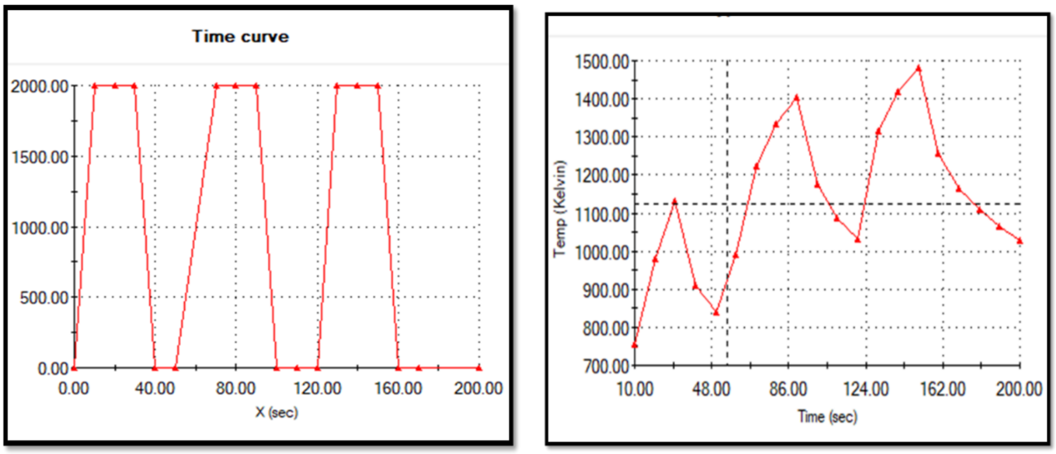


Figure 32: Shows the repetitive laser pulse for 60sec and then cooling for 20 sec and again same cycle repeats, corresponding to that temperature profile generate

4.7 Simulation of Moving heat source

1. **Sample dimensions (Ti-6AL-4V)**

Length- 100mm

Width- 100 mm

Thickness- 20mm

2. **DFLUX subroutine**: Surface heat flux is written in subroutine and compiled in FORTRAN compiler. Following is the code written in FORTRAN Compiler

```
DFLUX (FLUX, SOL, KSTEP, KINC, TIME, NOEL, NPT, COORDS,
    &            JLTYP, TEMP, PRESS, SNAME)
    C
     include 'ABA_PARAM.INC'
    C
    dimension FLUX (2), TIME (2), COORDS (3)
    CHARACTER*80 SNAME

    X=COORDS (1)
    Y=COORDS (2)
    Z=COORDS (3)

    Dist = 0.0
    Y_center = 0.0 - ((2/60.0) *(TIME (2)))
    X_center = 0.0
    YT=Y_center - Y
    XT=X_center - X

    Dist = SQRT((YT*YT) +(XT*XT))

            if (Dist .le. 0.0025) then
    FLUX (1) = 22918311.0
    else
    FLUX (1) = 0.0
    endif

    RETURN
    END
```

Fig: Shows the code in FORTRAN to move laser source

3. <u>Process Parameters</u>

Beam Spot diameter: 5 mm

Laser Power: 600W

Scanning Speed: 2000mm/min

Transient Analysis: 300sec

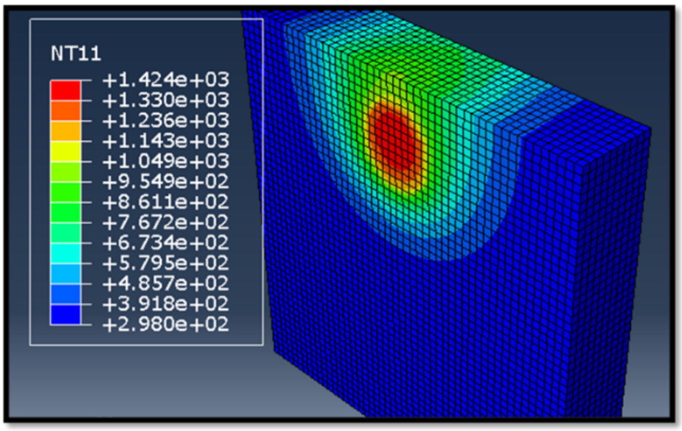


Fig. 33 Shows the laser beam moving along length of sample and temperature rise.

Chapter 5 Conclusions and future scope

5.1 Conclusion

From the simulation performed it is concluded that to achieve the maximum surface hardness on Ti6AL4V the parameters of laser should be selected in such a way that the ***peak temperature should lies between (1290 K-1340 K)***. The optimized parameters are laser power 600W, scanning speed 2000 mm/min and beam spot diameter as 5 mm. There was increase in surface hardness value from ***324 HV to 448 HV***. The case hardening depth is about 0.36 mm for a Ti6AL4V sheet of thickness 3 mm corresponding to these laser parameters. It is also investigated that ***the hardness value decreases along depth as well as distance from beam spot centre***. It was found that peak temperature remained same for different heat sink material. ***There was increase in cooling rate with increase in thermal conductivity of heat sink***. To enhance the cooling rate the thermal contact resistance should be as small as possible. The effect of plate thickness to enhance the cooling rate and to analyse the peak temperature at different depths were studied and it was found that the ***cooling rate was more in case of 3 mm sheet as compared to 1.5 mm sheet.***

Table below shows the summary of objectives with conclusions and the approach used in various objectives.

Serial No.	**Objective**	**Conclusions**	**Approach Used**
1.	Simulation and Comparison of Continuous and repetitive laser pulse heating and cooling,	Peak temperature is more in case of repetitive laser pulse.	Simulation in SolidWorks
2.	Selection of Laser parameters for achieving maximum surface hardness	***Optimised parameters*** Laser Power: 600W Scanning speed: 2000mm/min Beam spot: 5mm	1. Abaqus FORTRAN compiler 2. Transient Heat analysis 3. Fine mesh near beam spot region

3.	Simulation of Vickers Hardness Before laser Hardening	334 HV	1. Ludwick's Hardening law 2. Abaqus Simulation
4.	Simulation of Vickers Hardness after laser Hardening	450 HV	1. Johnson Cooks model- (not able to capture cooling rates) 2. Rosenthal Equation used. 3. Flow stress curve using JMatPro software
5.	Variation of hardness along depth	As depth increases the hardness value decreases.	Using objective 4
6.	Variation of hardness on moving away from centre of beam spot.	As distance from centre of beam spot increases the hardness value decreases.	Using objective 4
7.	To increase cooling rate by used of Heat sink.	Peak temperature remained same for different heat sink material. There was increase in cooling rate with increase in thermal conductivity of heat sink.	1. Heat sink materials: Cu, MS, SS 2. Assumption: Without any thermal contact resistance 3. Simulation in Abaqus
8.	Peak temperature variation due to different thickness of sheet.	The cooling rate is more in case of 3 mm sheet.	Compared sheet thickness of 1.5 mm and 3 mm.
9.	Effect of sheet thickness on cooling rate.	shows increase in cooling rate with increase in sheet thickness Although the peak temperature remaining same	Compared sheet thickness of 1.5 mm and 3 mm.
10.	Effect of contact resistance between Ti6AL4V sheet and sink material.	To enhance the cooling rate the thermal contact resistance should be as small as possible.	Modelling of two sheets having contact resistance at the interface. Using Rosenthal equation to find cooling rate

5.2 Future Scope

1. All simulated resulted were validated from past research, people are trying to investigate.
2. In this present study to find the Hardness value, ***we have assumed the 2D axis symmetry analysis. In future 3D analysis*** can be done so as to get more accurate results.
3. The main aim was to increase the hardness of top surface of specimen. To achieve this the cooling rate has to be enhanced. In this present study Heat sink of different materials were used to increase the cooling rate. In future ***we can use the concept of PELTIER EFFECT***, by placing it on bottom surface of specimen and try to achieve lower temperature on this surface.
4. All results were simulated using ABAQUS based FEA software. In ***future these results can be validated experimentally.***

References

1. Borowski et.al. (2010) Investigation of the influence of laser treatment parameters on the properties of the surface layer of aluminium alloys.
2. Ming-der J, Yih-fong T (2004) Optimisation of electron-beam surface hardening of cast iron for high wear resistance using the Taguchi method. Int J Adv Manufacturing Technology 24:190–198.
3. Badkar DS, Pandey KS, Buvanashekaran G (2011) Parameter optimization of laser transformation hardening by using Taguchi method and utility concept.
4. Low Temperature Thermal Conductivity of Ti6Al4V Alloy L. Risegari · M. Barucci · L. Lolli · G. Ventura ©Springer Science+Business Media, LLC 2008
5. Kubra Karayagiz, Alaa Elwany, Gustavo Tapia, Brian Franco, Luke Johnson, Ji Ma, Ibrahim Karaman & Raymundo Arroyave (2018): Numerical and Experimental Analysis of Heat Distribution in the Laser Powder Bed Fusion of Ti-6 Al-4 V, IISE Transactions, DOI: 10.1080/24725854.2018.1461964
6. Theoretical and experimental study on laser surface hardening by repetitive laser pulses Ashish Kumar Nath, Aniruddha Gupta, Frederick Benny Department of Mechanical Engineering, Indian Institute of Technology Kharagpur, Khargapur-721302, India
7. Flow Stress Equations of Ti-6Al-4V Titanium Alloy Sheet at Elevated Temperatures Duc-Toan Nguyen1,#, Young-Suk Kim2 and Dong-Won Jung3 1 School of Mechanical Engineering, Hanoi University of Science and Technology, 1A-Dai Co Viet Street, Hai Ba Trung District, Hanoi City, Vietnam, 10000
8. Laser transformation hardening of Ti6Al4V in solid state with accompanying kinetic model J. D. Hahn et.al.
9. Experimental determination of cooling rates in selectively laser-melted eutectic Al-33Cu Simon Pauly⁎, Pei Wang, Uta Kühn, Konrad Kosiba
10. Micro structural and mechanical characterization of Ti6Al4V refurbished parts obtained by laser metal deposition Ramesh Raju

Muthu kannan Duraiselvama,n, VijayPetley b, ShwetaVerma b, R.Rajendran b

11. . Dao, M.; Chollacoop, N.; Van Vliet, K.J.; Venkatesh, T.A.; Suresh, S. Computational modelling of the forward reverse problems in instrumented sharp indentation. Acta Mater. 2001, 49, 3899–3918. [CrossRef]
12. Zhai, J.G.;Wang, Y.Q.; Kim, T.G.; Song, J.I. Finite element and experimental analysis of Vickers indentation testing on Al2O3 with diamond-like carbon coating. J. Cent. South Univ. 2012, 19, 1175–1181. [CrossRef]
13. Laser transformation hardening of carbon steel sheets using a heat sink Hyungson Ki, Sangwoo So, Sanseo KimS chool of Mechanical and Nuclear Engineering, Ulsan National Institute of Science and Technology (UNIST), 50 UNIST-gil, Ulju-gun, Ulsan 689-798, Sou
14. A test-validated prediction model of thermal contact resistance for Ti-6Al-4V alloy Yan-Jun Daia, Jian-Jun Goub, Xing-Jie Rena, Fan Baia, Wen-Zhen Fanga, Wen-Quan Taoa,
15. https://nptel.ac.in/courses/112/107/112107248/
16. https://www.researchgate.net/
17. https://www.google.co.in/books/edition/Design_and_Modeling_of_Mechanical_System/iktADwAAQBAJ?hl=en&gbpv=1&dq=ludwick+hardening+law&pg=PA951&printsec=frontcover
18. https://abaqusdocs.mit.edu/2017/English/SIMACAEMATRefMap/simamat-c-johnsoncook.htm
19. https://www.sentesoftware.co.uk/videos
20. https://www.simuleon.com/abaqus-tutorials/