Formability Studies of NiTi Shape Memory Alloy Using Laser forming Technique

M.Tech Thesis

by

Abhinav Sharma

(1602181001)

Department of Metallurgy Engineering and Material Science

Indian Institute of Technology Indore

JUNE 2018

Formability Studies of NiTi Shape Memory Alloy Using Laser forming Technique

A THESIS

Submitted in partial fulfillment of the requirements for the award of the degree ***of***

Master of Technology

by

Abhinav Sharma

Department of Metallurgy Engineering and Material Science

Indian Institute of Technology Indore

JUNE 2018

Indian Institute of Technology Indore

Candidate's Declaration

I here by certify that work which is being presented in the thesis entitled **Formability studies of NiTi shape memory alloy using laser forming technique** in the partial fulfillment of the requirements for the award of the degree of **MASTER OF TECHNOLOGY** and submitted in the **DISCIPLINE OF METALLURGY ENGINEERING AND MATERIAL SCIENCE, Indian Institute of Technology Indore,** is an authentic record of my own work carried out during the time period July 2016 to May 2018 under the supervision of **Dr. I.A. Palani** and **Dr. Santosh Hosmani** of Discipline of Mechanical and Electrical Engineering respectively.

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

Abhinav Sharma

(1602181001)

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

(Dr. I.A. Palani) (**Dr. Santosh Hosmani)**

Abhinav Sharmahas successfully completed his M.Tech Oral Examination held on…………

Signature of the Thesis Supervisors **Signature of Convener, DPGC**
Date: **Date:**

Signature of the PSPC Member 1 **Signature of the PSPC Member2**
Date: **Date:**

Acknowledgement

I take this opportunity to express my deep sense of respect and gratitude for, Dr. I.A. Palani, for believing in me to carry out this work under his supervision. His constant encouragement, friendly interactions, and constructive support have enabled this work to achieve its present form. His innovative perspective towards things and his continuous pursuit for perfection has had a profound effect on me and has transformed me majorly. I feel greatly privileged to be one of his students.

I am immensely grateful to Dr. Santosh Hosmani, for his every-ready support and personal attention even in the busiest of his schedule. Discussions with him have been extremely knowledgeable and have significantly shaped this thesis.

I am thankful to IIT Indore for giving me an opportunity to carry out the research work and providing all the facilities. Very special thanks to Prof. Pradeep Mathur, Director, IIT Indore, for supporting and providing us facilities to perform my work smoothly here.

I am extremely thankful to Mr. S.S. Mani Prabu, Mrs. Nandini Patra for guiding and helping me out from the very first day I joined this project. I would also like to express my thanks to R.Mithun and all members of Opto-Mechatronics group for their moral support and the friendly nature we have created in our lab.

Lastly, but undoubtedly the most valued, gratitude is expressed for my parents, for letting me choose my dreams and supporting me endlessly. Your un-matched support made this work possible.

Abhinav Sharma

Dedicated to my Guide –

my mother,

my father,

my brother,

my grandparents,

my teacher,

and my friends

Abstract

Laser forming is an advanced manufacturing which is widely used in automotive and manufacturing industry by deforming metallic and non-metallic sheets. In this process, a continuous fiber laser is irradiated over Ni-Ti sheet. As the laser beam imbibed over the sheet, a step temperature thermal gradient got induced across the thickness of the sheet. The bending moments due to uneven thermal stresses leads to the deformation of the sheet without using any external forces.

Shape memory alloy (SMA) is a class of smart material which is known for two distinct properties such as superelasticity (SE) and thermal shape memory effect (SME). SMAs have the ability to achieve high deformation and return to a certain predefined shape upon unloading or after heating above a certain temperature. SME refers to the phenomena where the SMA will automatically come to its original position after heating and SE is the effect where SMAs may undergo huge non-linear deformation and comes back to its original shape upon unloading. Due to these amusing properties SMAs have found various applications in the region of industrial sector such as for making fasteners, coupling, actuators, etc.

This paper shows the experiments performed on Ni-Ti sheets of dimension 60mm×50mm with a maximum power of 50W. The process parameters which were varied are number of passes (10 to 30), power (30W to 50W) to get the maximum bending angle with a uniform spot diameter of 2mm.

The study between variations of the bending angle with process parameters is done. After this the characterization of the samples was done using differential scanning calorimeter (DSC) and the changes in phase transformationof Ni-Ti SMA with respect to change in power and number of passes is studied.

LIST OF PUBLICATIONS

Papers in Conference Proceedings

- Abhinav Sharma,S.S. Mani Prabu, I.A.Palani, S.S.Hosmani, Rohit Patil, “Formability studies on NiTi Shape memory alloy using laser forming technology”, International Conference on Emerging trends on Materials & Manufacturing Engineering(ICMME-2018), Sri Chandrasekharendra Saraswathi Viswa Mahavidyalaya, Kancheepuram, Tamil Nadu India,, 8^{th}-9^{th} March, 2017.

- Best paper presentation award in material processing session in ICMME-2018.

Contents

LIST OF FIGURES

LIST OF TABLES

Abbreviations Used

SMA	Shape memory alloy
SME	Shape memory effect
MSMA	Magnetic shape memory alloy
A_s	Austenite start
A_f	Austenite finish
M_s	Martensite start
M_f	Martensite finish
OWSME	One way shape memory effect
TWSME	Two way shape memory effect
DSC	Differential scanning calorimeter
OCP	Open circuit poten

Chapter1: Introduction

1.1 Background

SMAs are a group of metallic alloys that can return to their original form (shape or size) when subjected to a memorisation process between two transformation phases, which is temperature or magnetic field dependent. This transformation phenomenon is known as the shape memory effect (SME). The basic application of these materials is quite simple, where the material can be readily deformed by applying an external force, and will contract or recover to its original form when heated beyond a certain temperature either by external or internal heating (Joule heating); or other relevant stimuli such as a magnetic field for MSMAs.

Practically, SMAs can exist in two different phases with three different crystal structures (i.e. twinned martensite, detwinned martensite and austenite) and six possible transformations [1,2] (see Figure1). The austenite structure is stable at high temperature, and the martensite structure is stable at lower temperatures. When a SMA is heated, it begins to transform from martensite into the austenite phase. The austenite-start-temperature (A_s) is the temperature where this transformation starts and the austenite-finish-temperature (A_f) is the temperature where this transformation is complete. Once a SMA is heated beyond A_s it begins to contract and transform into the austenite structure, i.e. to recover into its original form. This transformation is possible even under high applied loads, and therefore, results in high actuation energy densities [3]. During the cooling process, the transformation starts to revert to the martensite at martensitestart-temperature (M_s) and is complete when it reaches the martensite-finish-temperature (M_f). The highest temperature at which martensite can no longer be stress induced is called M_d, and above this temperature the SMA is permanently deformed like any ordinary metallic material [4]. These shape change effects, which are known as the SME and pseudoelasticity (or superelasticity), can be categorized into three shape memory characteristics as follows:

(1) One-way shape memory effect (OWSME):

The one-way SMA (OWSMA) retains a deformed state after the removal of an external force, and then recovers to its original shape upon heating.

(2) Two-way shape memory effect (TWSME) or reversible SME:

In addition to the one-way effect, a two-way SMA (TWSMA) can remember its shape at both high and low temperatures. However, TWSMA is less applied commercially due to the 'training' requirements and to the fact that it usually produces about half of the recovery strain provided by OWSMA for the same material [5–7] and it strain tends to deteriorate quickly, especially at high temperatures [8]. Therefore, OWSMA provides more reliable and economical solution

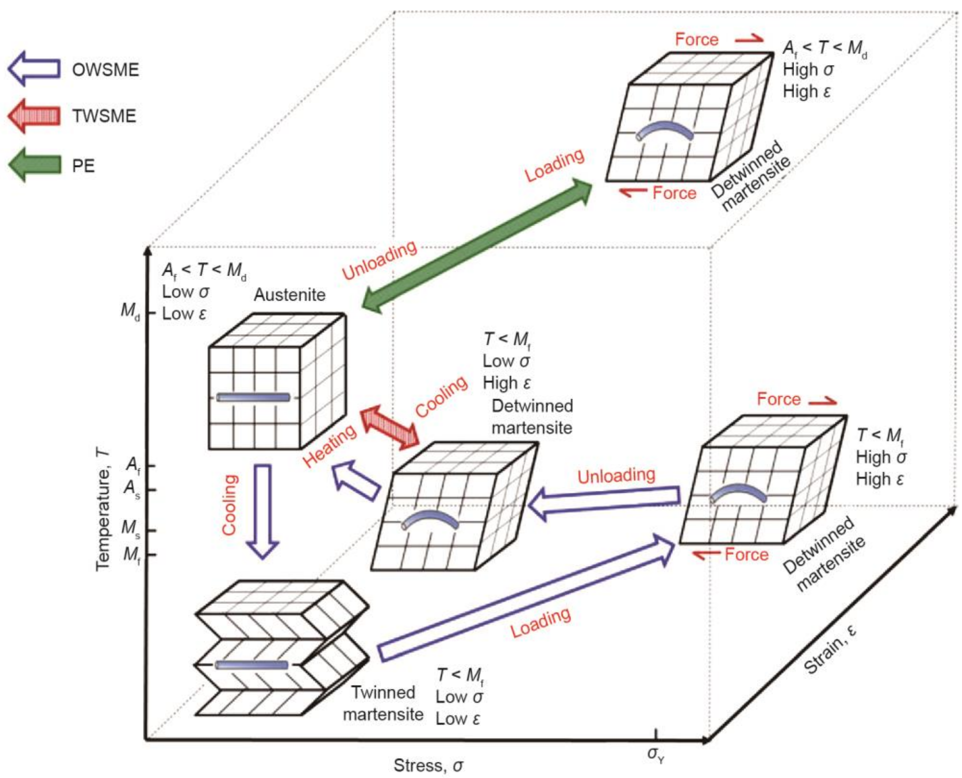

Figure 1:- SMA phases and crystal structures

Laser, an acronym for **L**ight **A**mplification by **S**timulated **E**mission of **R**adiation has the capability to produce a beam of electromagnetic radiation with wavelength ranging from ultraviolet to infrared which is highly coherent, convergent and monochromatic in nature. Lasers are capable of delivering power from a few milliwatts (mW) to hundreds of kilowatts with accurate spot dimensions. Due to these unique properties lasers have found applications in fields like communication and broadcasting, metrology, military, chemical and medical, material processing, micro fabrication and maskless lithography.

The use of a laser beam in forming processes was introduced at the end of 20th century and is still under development. The laser beam makes forming technology applicable for industrial use, which formerly had to be done manually due to the lack of reproducibility or flexibility of the heat source used (e.g. straightening of distortion by heating with a gas torch). The main advantages of thermal forming processes are the fact that there's no spring-back effect and that tool and work piece are not in contact during the process. The latter fact also increases the flexibility of the processes, because no special tool is needed. Different geometries, therefore, can be produced by using the same set-up and changing only the process parameters.

Laser forming has become a viable process for the shaping of metallic components, as a means of rapid prototyping and of adjusting and aligning. The laser forming process is of significant value to industries that previously relied on expensive stamping dies and presses for prototype evaluations, relevant industry sectors include aerospace, automotive, and microelectronics. In contrast with conventional forming techniques this method requires no mechanical contact and hence offers many of the advantages of process flexibility associated with other laser manufacturing techniques such as laser cutting and marking. Laser forming can produce metallic, predetermined shapes with minimal distortion. The process is similar to the well established torch flame bending used on large sheet material in the ship building industry but a great deal more control of the final product can be achieved.

1.2 Process:-

Figure2 illustrates the schematic diagram of a straight-line irradiation process which produces a bend angle from a flat sheet metal piece. The sheet metal is clamped at one side of the machine. The heating on the material surface by a laser beam occurs on one side along a selected line. The surface melting of the material is avoided by adjusting the laser parameters such as laser power, feed rate and beam diameter. The sheet metal expands in the heated zone and thermal stresses are produced by the restriction of the surrounding material. The thermal stresses lead to a bend angle in the sheet metal. The principle of the thermal deformation is described in detail in the following section. The focal lengthof the laser is 320mm. Industrial lasers are used as a beam source, including excimer, carbon dioxide (CO_2), ytterbium, erbium and neodymium. The choice of the laser depends on the task. The excimer laser can be used for the production of parts with length and width dimensions in the range of 10 µm due to its extremely short pulse duration [20, 21].

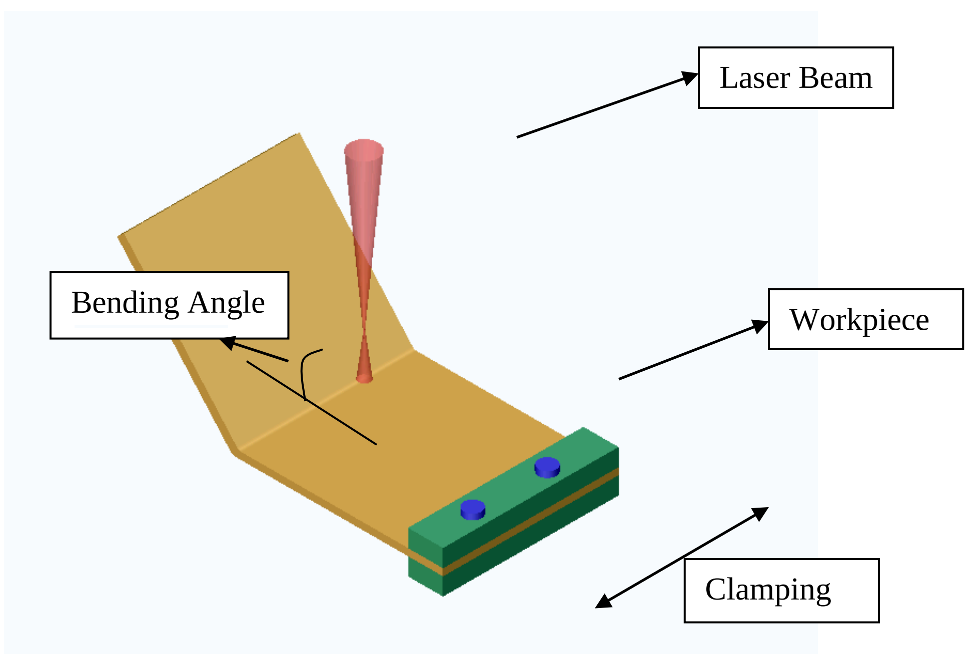

Figure 2:-Schematic view of a straight-line irradiation by a defocused laser beam to produce a bend angle from a flat sheet metal

Although laser forming uses active energy from a laser beam instead of external forces, small gravitational forces are induced in the region of the bend edge by part of plate weight. The influence of the gravitational forces can be neglected unless the operation is associated with precision bending involving a large part

[10]. Generally, coatings (for example, graphite or phosphate) are used in order to improve the absorption of the laser beam energy into the surface. Without any coating, the absorption rate can be enhanced by using polarized light or using fiber laser. In general, one or two degrees of bend angle are achieved per irradiation. The bend angles may increase up to 180° with repetition of irradiations i.e. number of passes. The path of the laser is dependent on the desired shape. In the simplest case, the path may be a point, in other cases the path may be a straight line across the whole part and, for spatially formed parts and extrusions the path would be very sophisticated radial and tangential lines.

1.3 Principle:-

In the traditional metal forming processes such as bending, drawing, stamping and pressing, a sheet of metal is plastically deformed when it is subjected to stress that is greater than the yield point. In the laser forming process, the plastic deformation occurs by the thermal stresses introduced into the surface of a metal sheet during the laser heating and subsequent cooling. The principle of thermal deformation is qualitatively described in this section using a laser forming mechanism (i.e., temperature gradient mechanism).

Figure 1.3 shows the temperature gradient mechanism involved in the laser forming process. When a laser beam of high power density is rapidly guided across the surface of a metal sheet, the material absorbs a part of the laser energy on the surface and the thermal energy is conducted into the material in lower rate than that of the absorption on the surface, resulting in a steep temperature gradient through the thickness direction as shown in Figure 1.3(a). As a result, a differential thermal expansion occurs through the thickness direction. Initially, the material expands in the heated zone so that the whole shape of the material bends away from the beam as shown in Figure 1.3(b). This is called 'counter-bending'. This thermal expansion is converted into elastic tensile strain and compressive stress because free expansion of the heated material is restricted by surrounding material. Once the stress reaches the temperature-gradient flow stress, any additional thermal expansion is converted into a plastic strain. To achieve higher efficiency in the process, the thermal expansion has to be converted into more plastic than elastic strain. The amount of elastic strain may be minimized by using high temperatures.

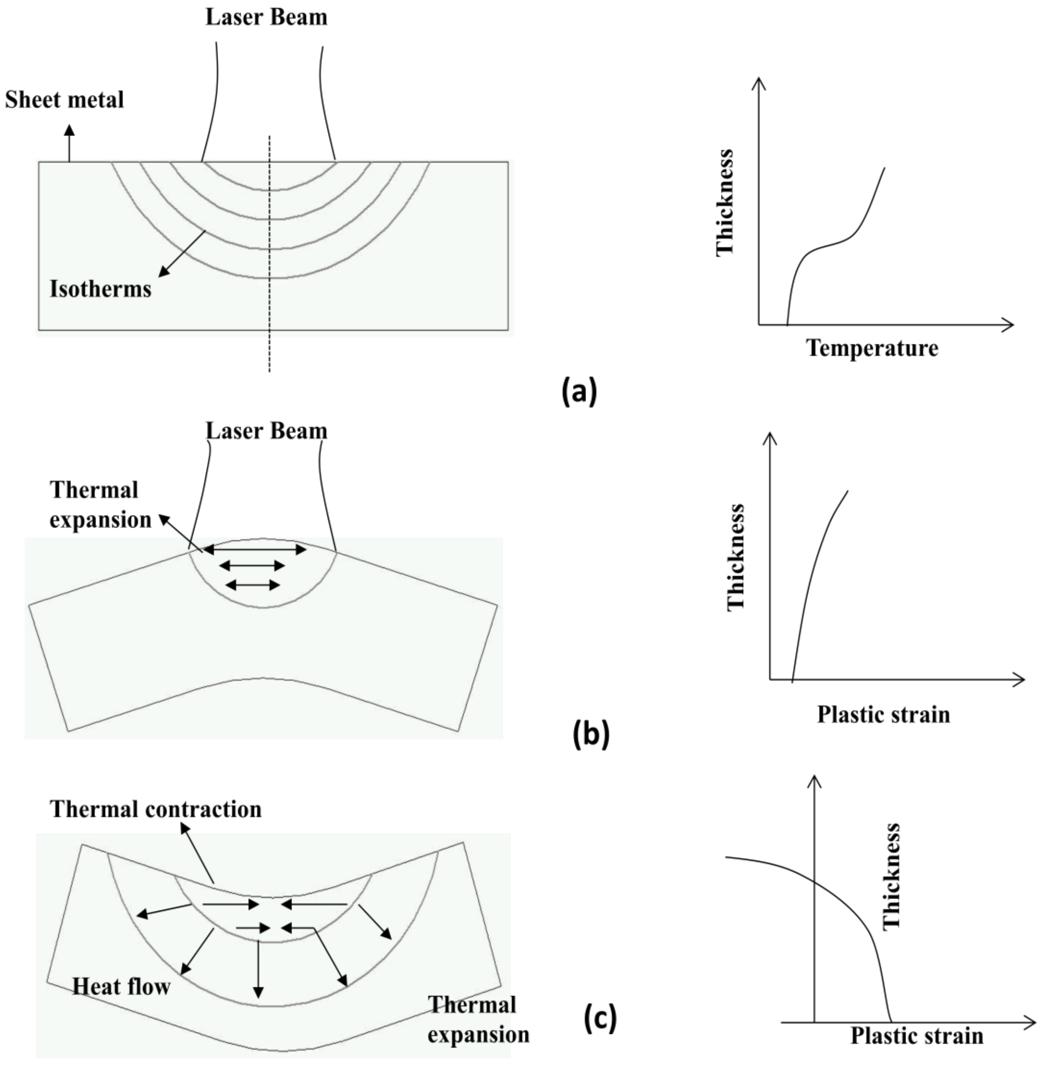

Figure3:-Temperature gradient mechanism involved in the laser forming process: (a) temperature gradient; (b) during heating; and (c) during cooling.

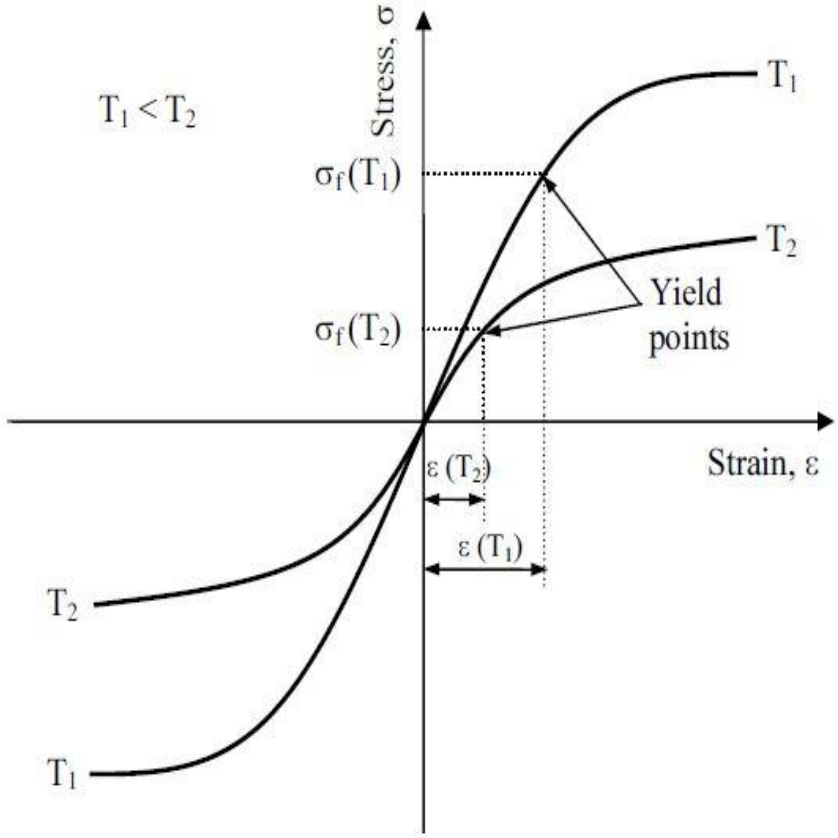

Figure4:-Stress-Strain relationships of material as a function of temperature.

As shown in Figure 1.4, the elastic strain as a function of temperature, ε(T), is determined by the elastic modulus *E* and the flow stress $\sigma_f(T)$, $\varepsilon(T) = \sigma_f(T)/E$. During cooling mainly by the heat conduction into the material, the material contracts in the upper layer of the sheet so that the higher tensile stress occurs in the upper region. Therefore, the sheet metal is plastically bent toward the cooling laser path to relax the higher tensile stress as shown in Figure 1.3(c). A flow chart of this forming process is shown in Figure 1.5.

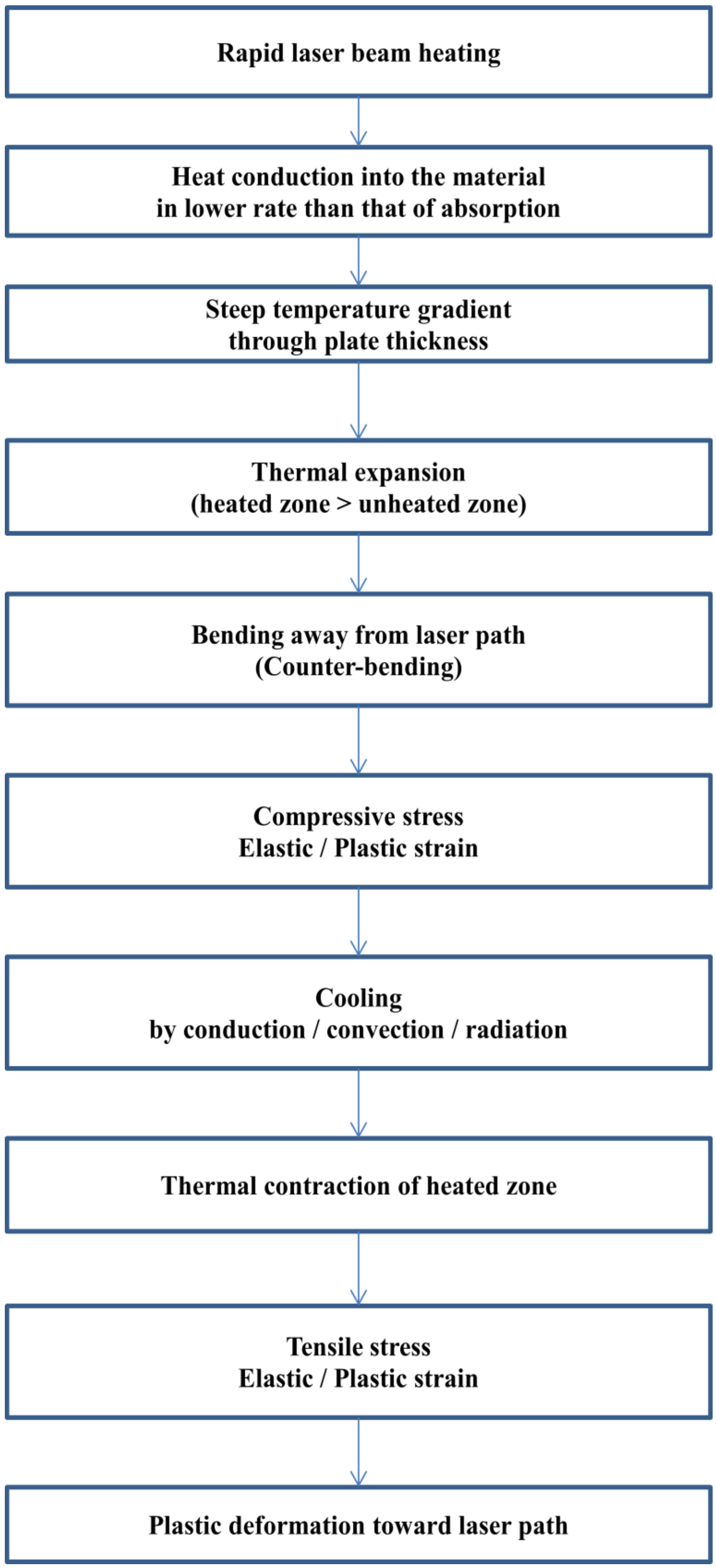

Figure5:-A flow chart of laser forming process.

1.4Advantages and Disadvantages:

Due to the fact that the laser forming process involves thermal stressesintroduced into a metal sheet by irradiation rather than external forces, which is employed in the conventional forming methods, the laser forming technique has the following advantages compared to the conventional forming operations.

• Flexible forming processes and the elimination of lead timeassociated with producing component for specific tooling can berealized because special hard tools are not required in this process.
• Precise deformation can be achieved because spring-back behavioris not involved which is related to the quality of product.
• Forming is available in inaccessible areas because this process is anon-contact forming process.
• Brittle, hard and thick material can be processed.
• A wide variety of complex shaped parts can be obtained through thedevelopment of new irradiation patterns.

Despite its potential advantages, the laser forming technique is not entirelyfree of drawbacks which may not yet be eliminated at the present developmentstage. Some limitations are addressed as follows:

• The forming process is somewhat slow. For some types of formingit is slower by a factor of 5, for others it may be a factor of 20 whencompared to traditional methods of stamp and die.
• The process is energy consuming because of the low energyconversion factor of laser sources.
• The process requires safety protection equipment for the personnel because of multidirectional reflection of the laser beam from the metal.

1.5 Motivation:-

Laser forming has become a viable process for the shaping of metallic components. The laser forming process is of much importance to industries that previously relied on expensive stamping dies and presses for prototype evaluations on a large scale, relevant industry sectors include aerospace, automotive, and microelectronics. In contrast with conventional bending techniques this method requires no mechanical contact and hence offers many of the advantages of process flexibility and lower cycle time associated with other laser manufacturing techniques such as laser cutting and marking. Laser bending can produce metallic, predetermined shapes with minimal distortion. The process is similar to the well established torch flame bending used on large sheet material in the ship building industry but no doubt a great deal of more control of the final product can be achieved. One of the main characteristics of a laser-bending process is that it does not require use of hard tooling or external forces. Hence, a laser forming process has many advantages such as no spring-back, high process flexibility, and the capability of production of complex shapes, structures and the formation of very small parts.

Accordingly, over the years, many researchers have investigated not only the phenomena of the process, but also the realistic product applications in order to realize better achievements with the laser-bending process. Very rapid strides have been made on all fronts of science, processing, control, modeling, application developments etc. and this has made it an invaluable tool that is now being increasingly considered to be an integral part of component design. The laser beam techniques are eminently suited to modify a wide range of engineering properties. The properties that can be modified by adopting the laser technique include mechanical,thermo-mechanical, electrochemical, optical, electrical and magnetic/acoustic properties.

NiTi shape memory alloy has been widely employed in various medical fields because of its special mechanical properties, good corrosion resistance and excellent biocompatibility. Owing to the need for reliable fabrication of micro medical devices, laser forming of NiTi has drawn some attention.In recent days, NiTinol's contribution in the manufacture of bio-implants is getting increased. Bio implants such asorthopedic implants, orthodontic wires, bone substitution material and stent are fabricated using NiTinol

1.6 Research Objectives

The various research objectives of this research are as follows:-

1. Reliability:

Establish an assessment strategy of the reliability of the laser forming process, as well as evaluating the process robustness with regard to uncertainties of the input variables (e.g., laser power, feed rate, plate thickness and coefficient of thermal expansion). It is assumed that the variations of the input variables follow the Gaussian distribution.

2. Property Sensitivity:

Identify which material properties significantly affect the angular change in the straight-line process. The material properties to be investigated are confined to coefficient of thermal expansion, thermal conductivity, specific heat and modulus elasticity.

3. Characterization:

The characterizations of the Niti sheets were done so as to analysis the variation or change comes in the properties of the material after the irradiation of the laser.

Chapter 2: Literature Review

This section provides an insight to the current technology available in the field of laser forming. It also highlights various methods used by researchers on this topic. Laser forming is a complex transient process that involves thermodynamics, elastic-plastic mechanics, metallography etc. To control the deformation of metal sheet, research of mechanics plays the major role. Forming mechanisms are governed by the temperature field which in turn is influenced by geometry of workpiece, laser power, laser spot diameter, laser pulse duration, scanning velocity, scanning path and so on.

Here we get the feel of the topic by getting to know about various mechanisms governing laser forming, influence of various parameters on the laser forming operation.

Shichun and Jinsong [9] did the experimental study to find out the changes in the bending angle with process parameters. Process parameters consist of laser energy parameters, material parameters and sheet geometry parameters. The laser energy parameters include laser power, path feed-rate, beam spot diameter and feed number. Material parameters include coefficient of thermal expansion, density and specific heat at constant pressure. Sheet geometry parameters include sheet length, width and thickness. The experiments were performed on a type of LCM408 laser machine, with a CO2 laser source of 2 kW. Steel 08 (corresponding to AISI 1008), aluminium L3M (corresponding to ASTM 1050, annealed) and duralumin LY12CZ (corresponding to ASTM 2024, quenched and naturally aged) sheets were chosen as the working materials for the tests of laser bending. The sheet surfaces were coated with carbon black before testing in order to increase the absorption of laser power. The sheet metals after irradiation were cooled naturally. The conclusions drawn from the tests were that the bending angle varied in direct proportion to the laser power and feed number, and in inverse proportion to the path feed-rate and beam spot diameter.There was no significant influence of the strength at room temperature on the bending angle. Among the sheet geometric parameters only sheet thickness had remarkable effect on the bending angle, which decreases sharply with increase in the sheet thickness.

Shen and Yao [10] did the experimental study of mechanical properties of sheet metal after laser irradiation. Many sheet metal components formed by mechanical pressing are subjected to cyclic loading during their service life. The investigations indicated that the fatigue performance of the pressed components decreased significantly compared to the stock plate specimens of the same material. This decrease in life is attributed not only to the increase in tensile residual stress but more importantly also to the degradation of the material gains resulting from the mechanical forming process. The observed decrease in fatigue life has led to a search for an alternative manufacturing process for enhancing the fatigue performance. Laser forming is a flexible manufacturing process that forms a metal sheet by means of thermal stresses induced by external heat instead of external force.The objectives of this study are to characterize the mechanical properties of laser formed samples. The tensile properties and the low-cycle fatigue life under different laser processing parameters were investigated.

Monotonic tensile behaviour of low carbon steel specimens with different laser processing parameters was investigated. The tensile properties of specimens after laser forming changed slightly compared to the unprocessed ones. Low-cycle fatigue damage and life of the specimens were compared with that of the unscanned ones. The enhancement in fatigue life as indicated by the laser-formed specimens was encouraging. SEM analysis also revealed the reason why laser-formed low carbon steel has a longer fatigue life than before laser forming. The compressive residual strain is the most important reason why the fatigue life of low carbon steel after laser forming improves.

Shen et al. [11] proposed a new mechanism of laser forming. Laser forming is a complex thermal–mechanical process. To reveal the mechanisms dominating the forming process is essential to control accurately the deformation of metal plate. Numerous efforts had been made to understand the mechanisms of laser forming. Proposed mechanisms mainly included temperature gradient mechanism, buckling mechanism and upsetting mechanism. However, in the investigation of laser forming, it is found that the above three mechanisms cannot explain fully the process of deformation. Based on the study of thermal transfer and elastic–plastic deformation, the above three mechanisms are further explained. In addition, a new mechanism, coupling mechanism, is proposed. To verify the validity of the mechanisms proposed, numerical simulations are carried out, and simulation results are consistent with analysis of mechanisms.

Ueda et al.[12] used temperature distribution for determining the bending angle. Laser forming is a thermal process for the deformation of sheet metal by inducing localized thermal stress. Temperature distribution is the most important factor for determining the bending angle of the sheet metal. In the present study, the combined effect of the temperature of the workpiece, the temperature gradient between the two surfaces of the sheet, the size of the area irradiated with laser beam, and the thickness of the workpiece is investigated both theoretically and experimentally. The temperature at the surface irradiated with CO_2 laser and at the opposite surface are simultaneously measured using two-color pyrometers with an optical fiber. The bending angle has been found to increase with the spot diameter and workpiece surface temperature and decrease with workpiece thickness.

Thomson and Pridham [13] discussed the development of a basic process monitoring and control system. Laser forming is a process that uses the energy of relatively high powered lasers to cause permanent deformation to components by inducing localized thermal stresses. This paper briefly discusses laser forming and the development of a basic process monitoring and control system used to overcome various problems due to the complex nature of the lasers and the manner in which they interact with material.

Guan et al. [14] established a three-dimensional coupled thermo-mechanical finite element model. The laser-forming process is a new flexible forming process without rigid tools and external force. The sheet metal is formed by internal localized thermal stress induced by laser. Material properties play an important role in laser forming. A three-dimensional coupled thermo-mechanical finite element model is established in this paper. The laser-bending process of a sheet blank is simulated numerically using the model. The relationship between the bending angle and material property parameters, such as Young's modulus, yield strength, coefficient of thermal expansion, specific heat, and thermal conductivity, are studied extensively by FEM simulation. The simulations show that the material with lower Young's modulus and yield strength can produce a larger bending angle. The thermal expansion coefficient is nearly in direct proportion to the bending angle. The bending angle decreases with the increase of the heat conductivity.

Hsieh and Lin [15] investigated numerically and experimentally the buckling mechanism of a thin metal tube during laser forming in this study. Metal tubes made of 304 stainless steel were heated by a CO_2 Gaussian laser beam, which induced the buckling phenomenon on the tube surface due to elastic–plastic deformation. This uncoupled thermal–mechanical problem was solved using a three-dimensional finite element method and was subsequently satisfactorily verified with displacement measurements. The transient bending angle and residual stress of the thin metal tube under specific operation conditions were also studied.

Chapter3: Experimental Setup

3.1 Laser Setup

The laser setup consists of a fiber laser (Scantech laser Pvt. Ltd) doped with rare earth elements like erbium, ytterbium, neodymium, etc. It has a rated capacity of 50 W with a galvo scanner which deflects the beam in X and Y direction with afocal length of 160mm as shown in figure below.

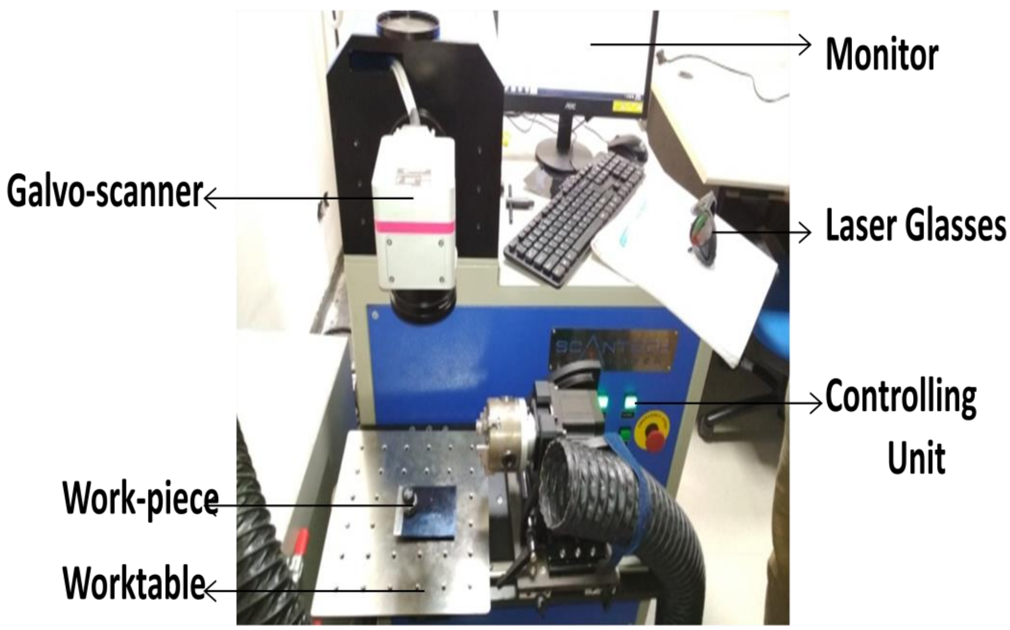

Figure6: - Experimental setup used for laser forming

Controlling unit:

It consists of a controlling unit which consists of the following switches to control the laser:

a. Galvo On/Off
b. Laser On/Off

c. PC On
d. PC reset
e. Laser enable
f. Rotary enable
g. Z-axis Up
h. Z-axis Down

Figure7:- Controlling unit of the fiber laser

Firstly the PC is turned on, after that the galvo and laser will be turned on to enable them. We can see the red spot on the surface of the worktable which indicates that the laser is properly functioning.

The Z-axis Up and Down switches are used to control the movement of the worktable in the Z direction in order to adjust the focal length of the laser. The rotary enable switch is used in case of a circular workpiece.

3.2 Workpiece Details:

Test setup is developed to perform experiments based on the medium used. It comprises of a laser source, controlling unit, workpiece holder and laser beam design software. The Scanmark software is used to form a laser beam according to our design requirement like line, circular or ellipse, etc. Ni-Ti SMA is used here for the study. Following are the specifications of Ni-Ti material.

Table 1 Specifications of NiTi material

Thermal conductivity(W/cm-^{o}C)	0.18
	0.086
Density(g/cm^{3})	6.45
Specific heat capacity(cal/g- ^{o}C)	0.20
Young's modulus(GPa)	83
	41
Poisson's ratio	0.33

Workpiece: NiTi (Nitinol) Sheet

Dimensions of the specimen: Length: 60mm Width: 50mm Thickness: 0.25mm

Laser machine used: Fiber laser (doped with rare earth elements like erbium, ytterbium, neodymium, etc)

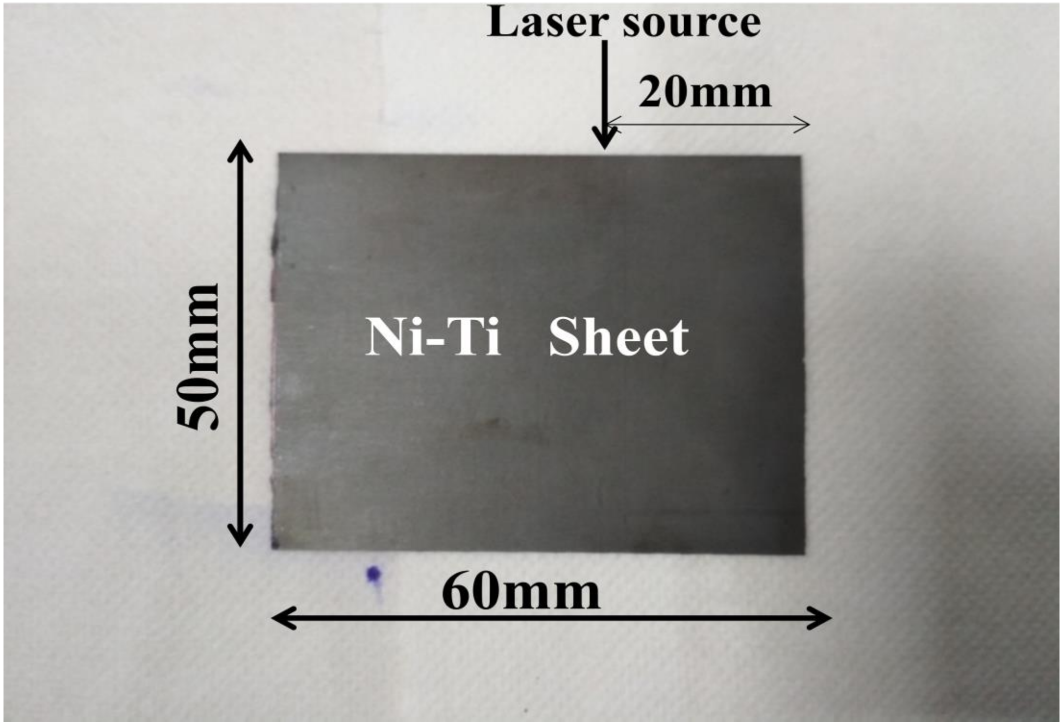

Figure8:- NiTi sample used for experiment.

Ranges of various laser parameters:-

- Laser power: 30 to 50 W
- Spot diameter: 0.2 mm
- Pulse duration: 0.5 to 20 ms
- Number of passes: 10 to 30
- Marking speed: 50 Bits/sec

Input parameters:

- Laser power
- Spot diameter
- Number of passes
- Marking speed

Output parameter:

- Bending angle

3.3 Experimental procedure:

Firstly the workpiece is fixed over the worktable at the focal length of the laser. Then with the help of scanmark software we will make a laser line beam which will be at a distance of 20mm from the extreme end of the sheet. Now the parameters of laser such as power,spot diameter, mark speedand number of passes were fixed.The laser line beam is then irradiated on the surface of the Ni-Ti sheet by turning on the laser enable switch.

The forward and the backward stroke are considered as one single pass. After the completion of process the workpiece is allowed to cool for 3 to 5 minutes and then its further analysis is done. The sheets were scanned for different number of passes in order to get the maximum bending of sheets. The differentlaser and process parameters affect the bending angle. The parameters which were varied are: Power (30W to 50W), Number of passes (10 to 30).

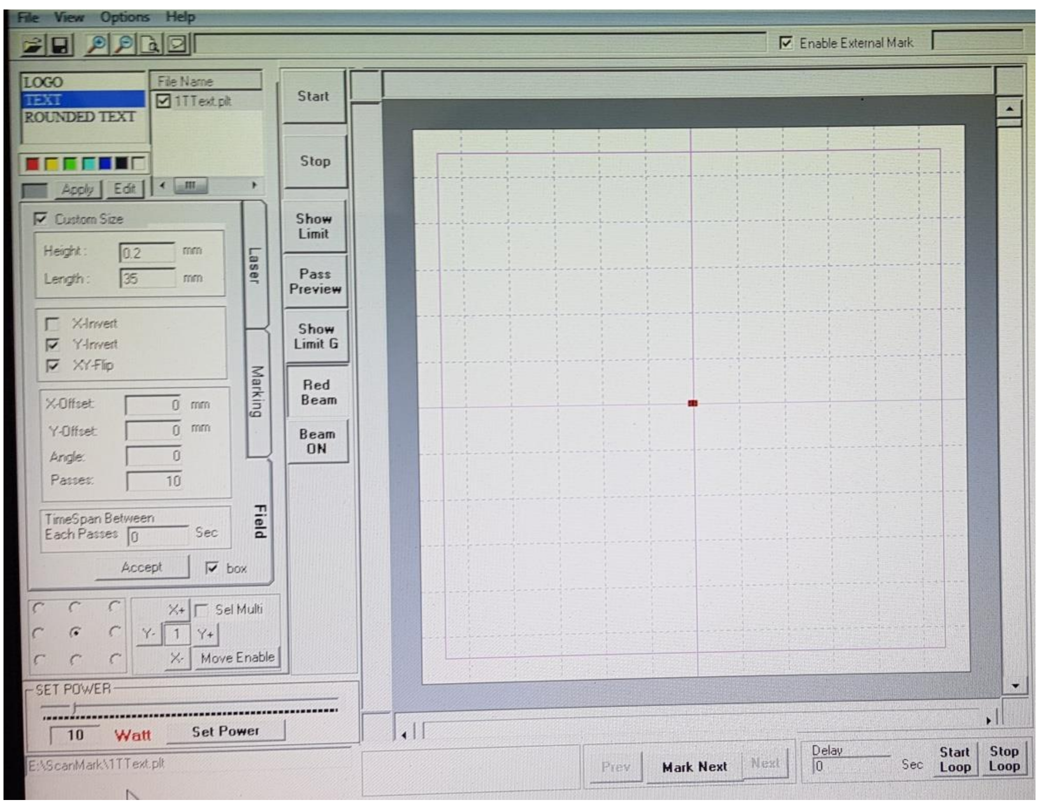

Figure9 – Forming line beam using scanmark software

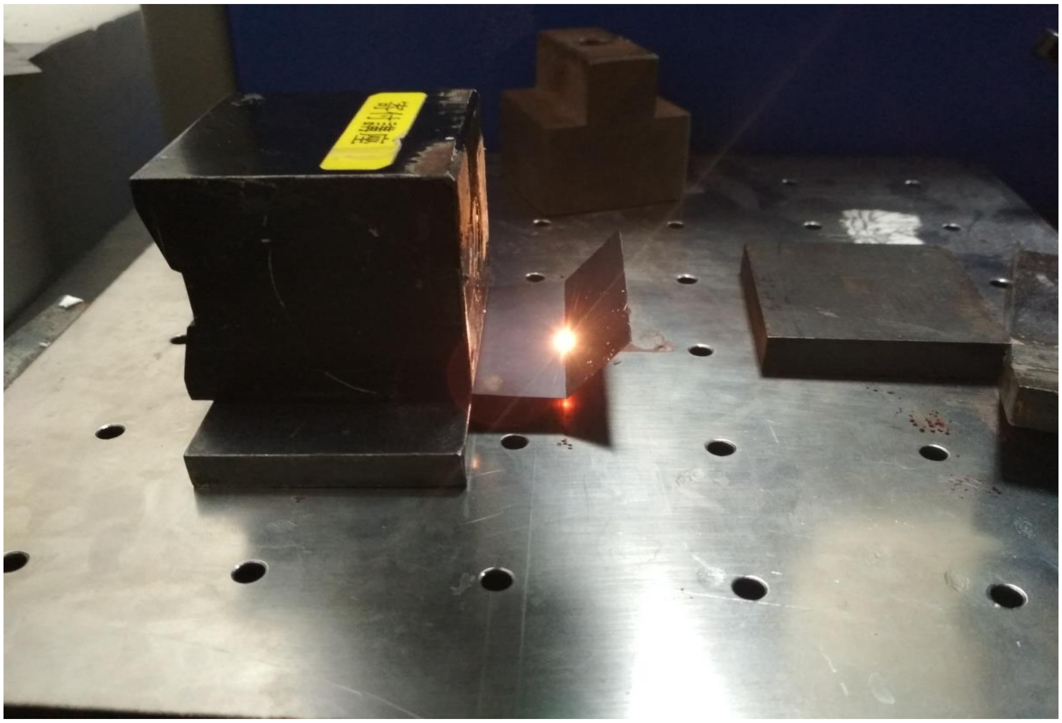

Figure10 - Irradiation of laser on the Ni-Ti sheet.

Figure11 – Bended Ni-Ti samples after laser irradiation

There is no time lapse given between each passes. A total of 6 Ni-Ti samples were bent having a thickness of 0.25mm as shown in figure3. Here the spot diameter is kept 2mm for all the samples

Chapter 4: Results and Discussion

4.1 Temperature Analysis

The temperature analysis of the NiTi sheet with respect to the power and the number of passes was done.

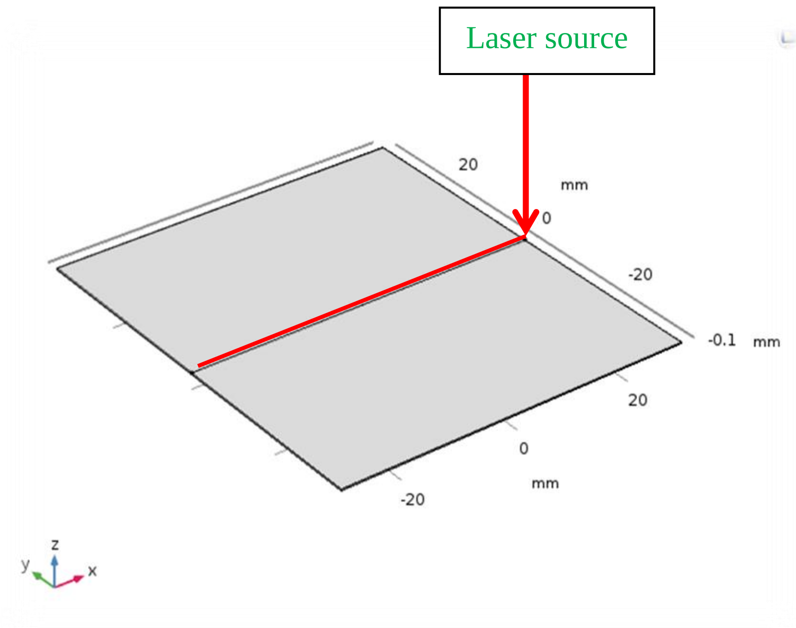

Figure12- Model of the NiTi sample

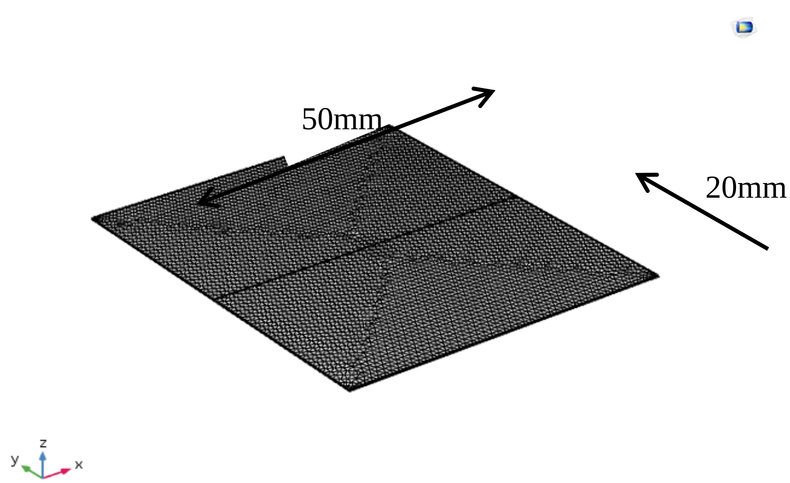

Figure13: Mesh diagram of the sample

1. Power - 30W

No. of Passes - 10

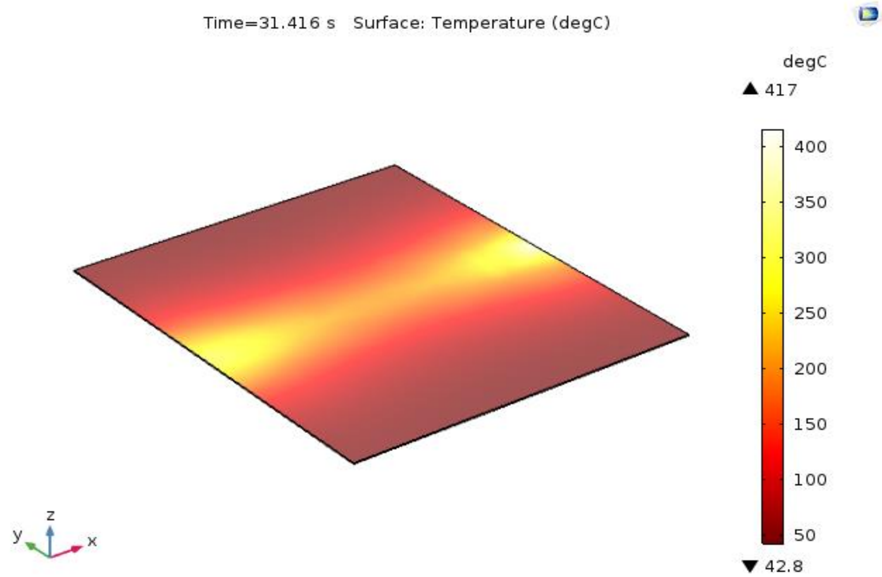

Figure14- Infrared image at 30P and 10P

No. of Passes - 20

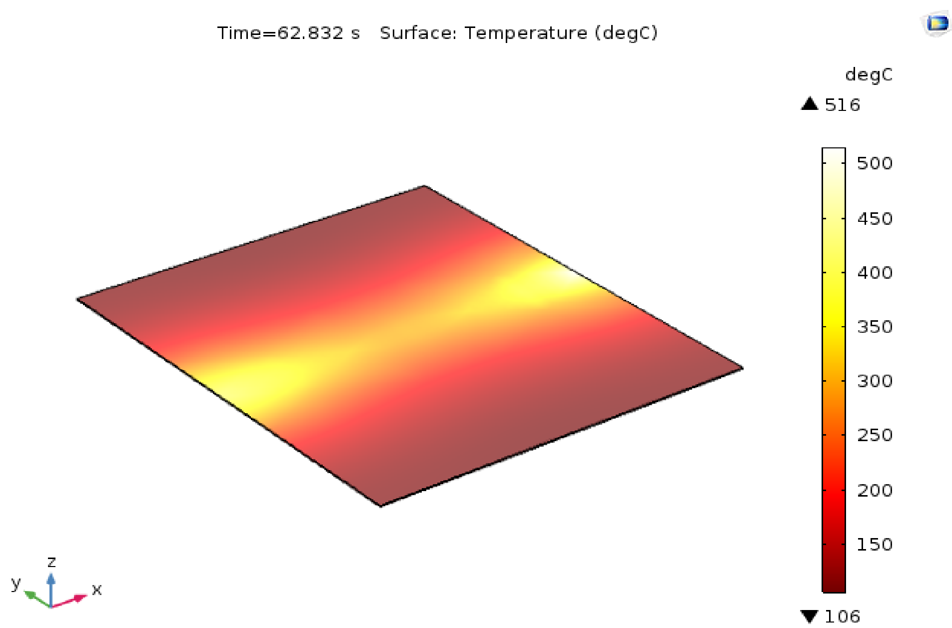

Figure15- Infrared image at 30P and 20P

No. of Passes - 30

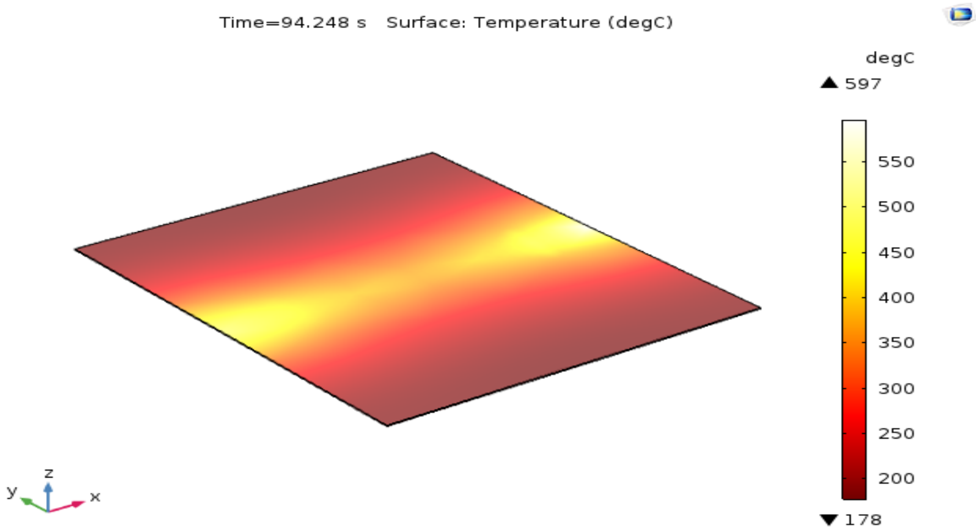

Figure16- Infrared image at 30P and 30P

2. Power - 40W

No. of Passes - 10

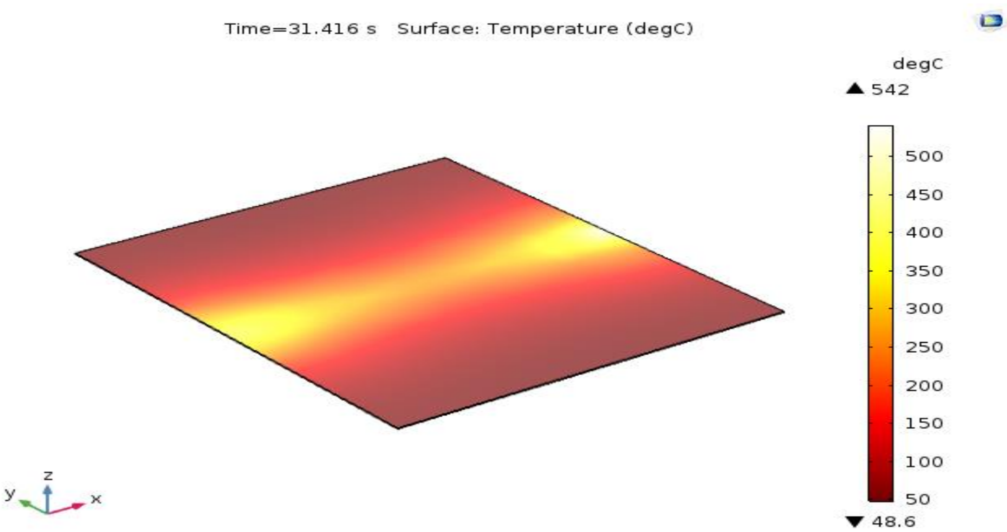

Figure17- Infrared image at 40P and 10P

No. of Passes - 20

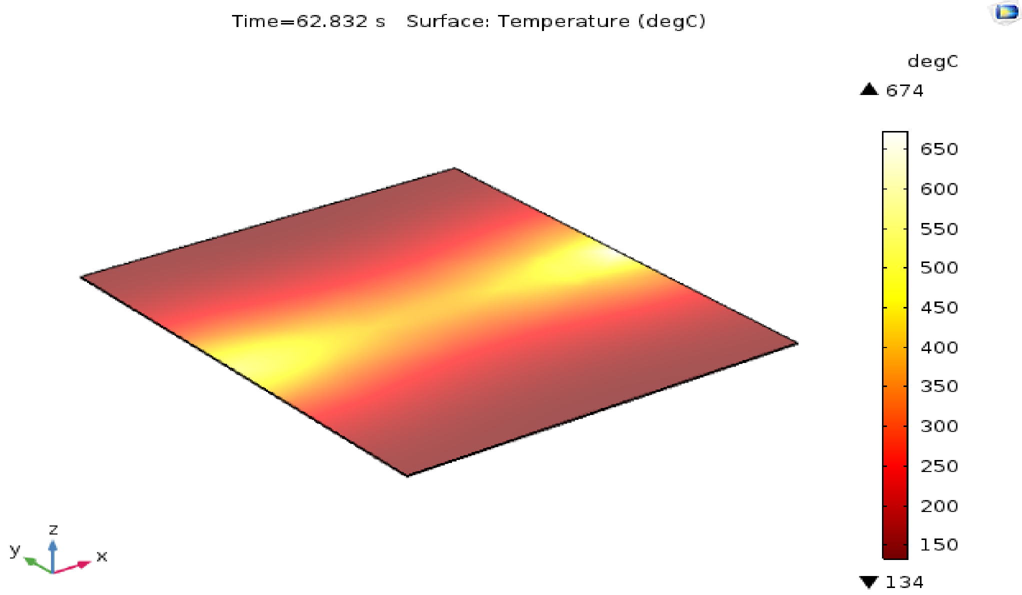

Figure18- Infrared image at 40P and 20P

No. of Passes - 30

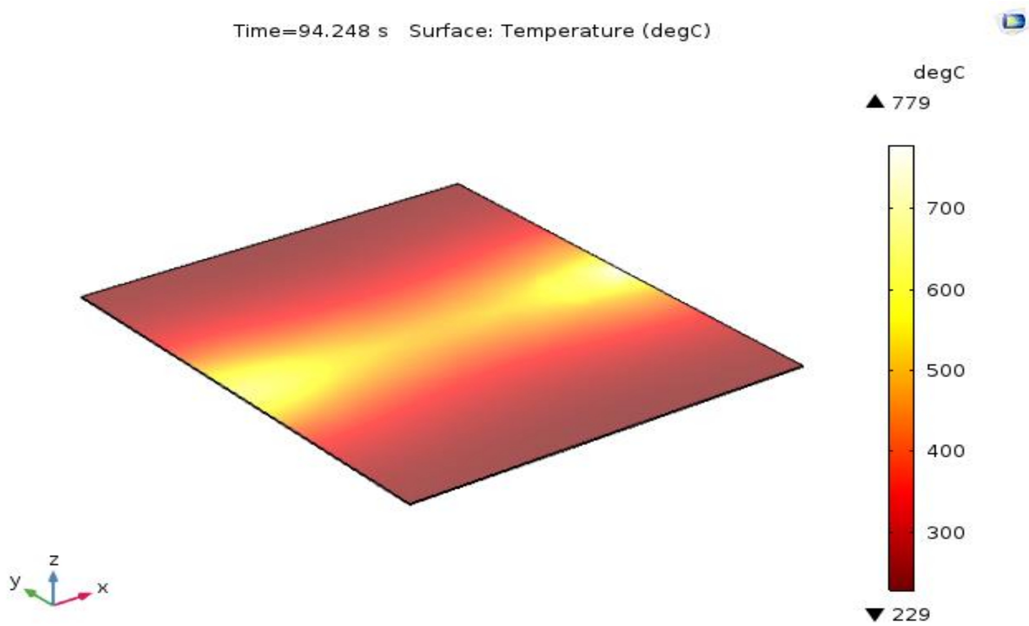

Figure19- Infrared image at 40P and 30P

3. Power - 50W

No. of Passes - 10

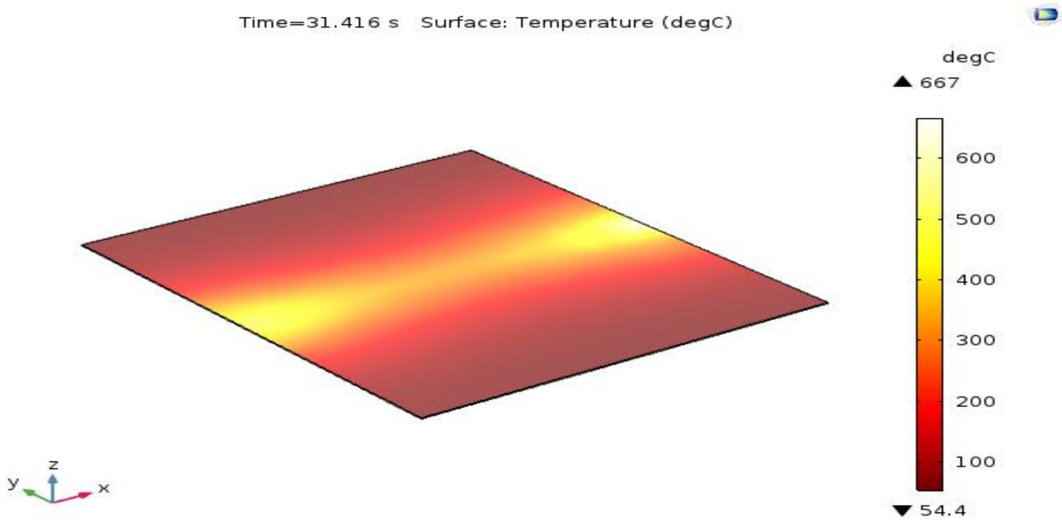

Figure20- Infrared image at 50P and 10P

No. of Passes - 20

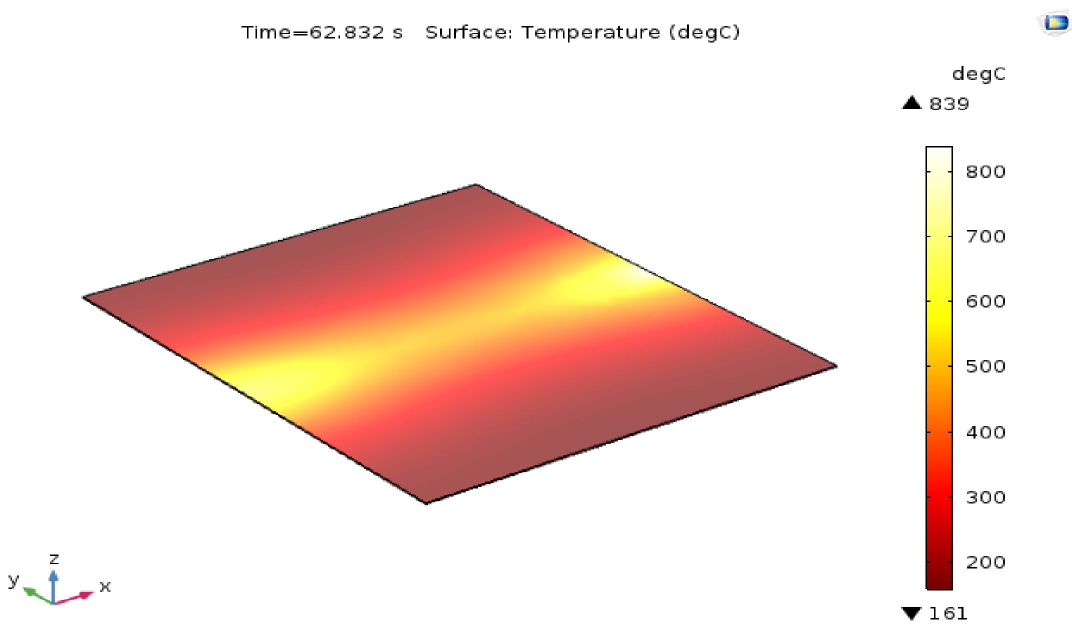

Figure21- Infrared image at 50P and 20P

No. of Passes - 30

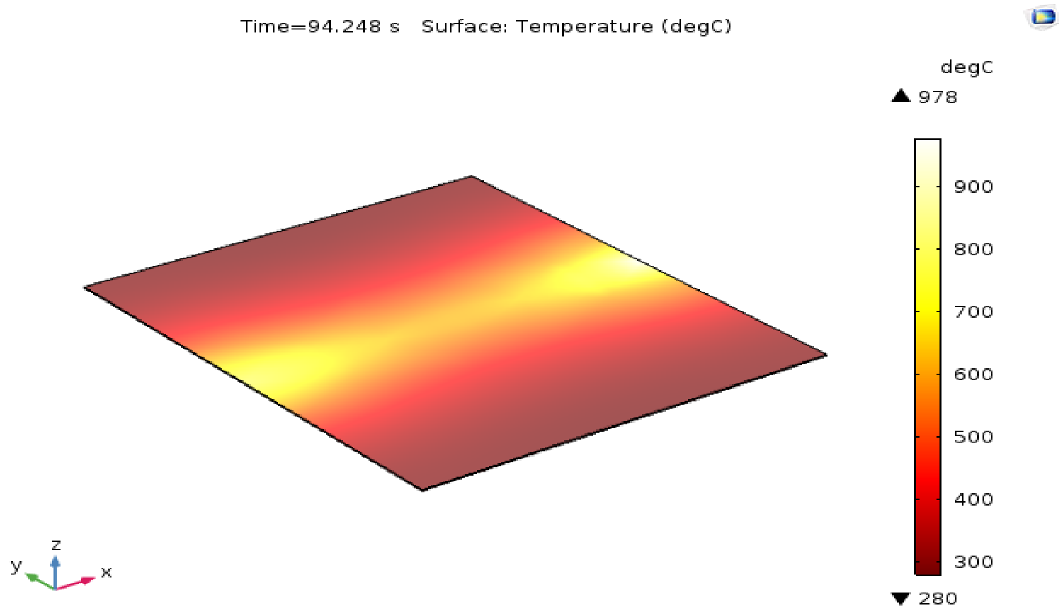

Figure22- Infrared image at 50P and 30P

Temperature Graph

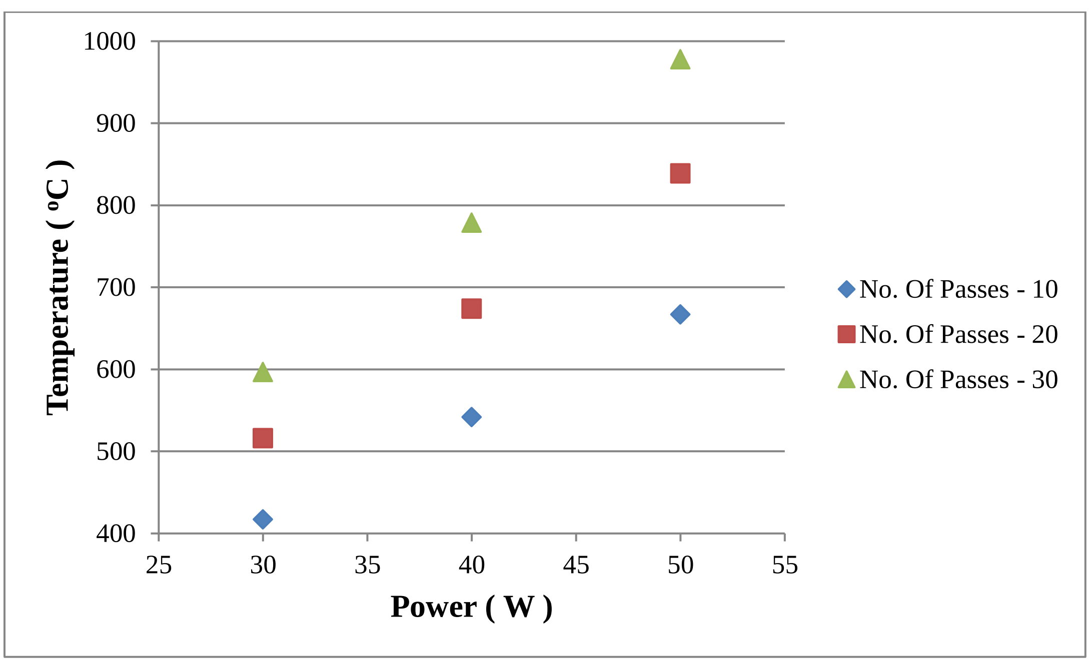

Figure23- Temperature graph

4.2 Bending angle Vs Power

The deviation of bending angle with respect to power and number of passes are discussed in this chapter. Also the phase transformationalbehavior as well as the optical microstructure and the hardness of the Ni-Ti samples with respect to the change in process parameters were analyzed and studied.

Laser is applied at three different powers i.e. 30W, 40W and 50W on the NiTi samples.A non-linear relationship can be seen between the bending angle and power. As the power is increased, the bending angle also gets increased due to generation of more thermal compressive stresses on the irradiated area.

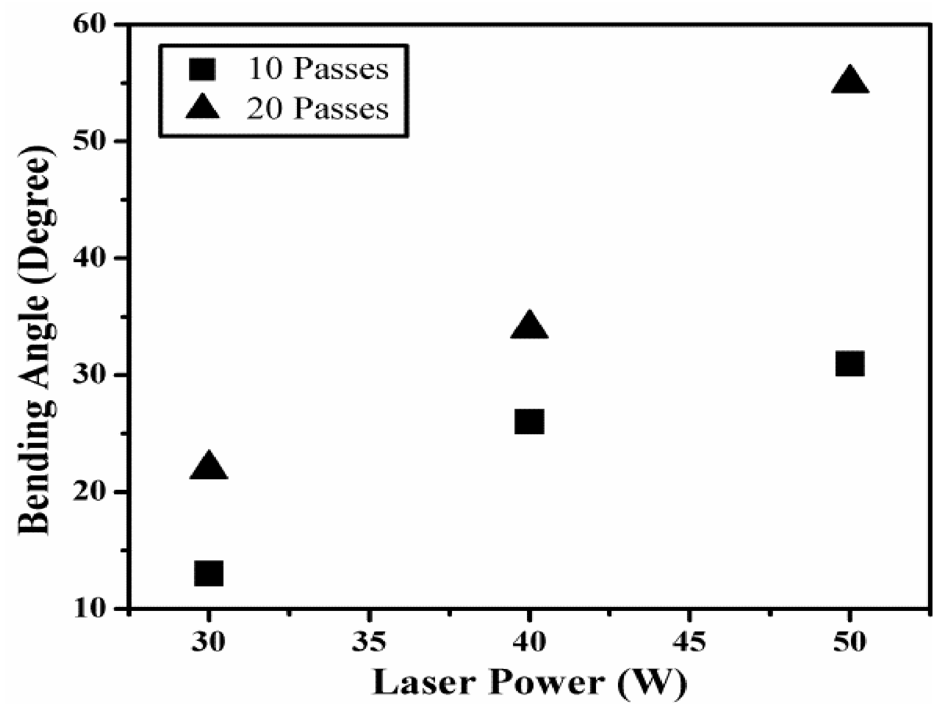

Figure24- Bending angle variations with power

But after a certain time the increment in the angle is not so steeper because of the decrement of the thermal extension and plastic deformation of the irradiated surface. It indicates that there is an optimal temperature after which there is no such large variation in the increment of the bending angle.

Table 2Variation of bending angle with changing power

PARAMETER / S.No.	POWER(W)	Bending Angle (Degree)
1	30	13
2	30	22
3	40	26
4	40	34
5	50	31
6	50	55

4.3Bending angle Vs Number of passes

Figure5 shows the variations in the bending angle with reference to number of passes for three different laser powers 30W, 40W and 50W.Whereas figure6 shows the change in the bending angle with reference to power at two different number of passes i.e. 10 and 20 passes. It can be noticed that power and number of passes are the two important parameters which are affecting the bending angle of sheet.

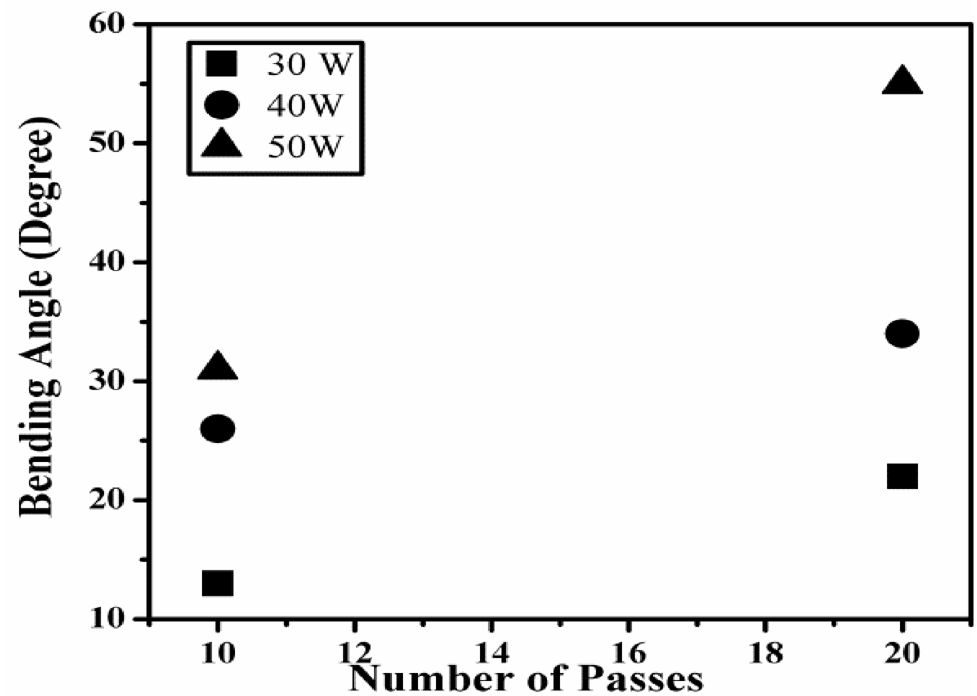

Figure25- Bending angle variations with number of passes.

With the increase of laser power and number of passes the thermal compressive stresses will increase and leads to thermo-mechanical effects over the sheets due to which the bending angle increases.

Table 3Variation of bending angle with changing passes

PARAMETER / S.No.	Number of passes	Bending Angle (Degree)
1	10	13
2	20	22
3	10	26
4	20	34
5	10	31
6	20	55

The increase in the compressive stresses leads to more plastification of the irradiated surface and thermal expansion to the opposite side of the sheet leading to more forming of the desired sheet.

4.4 DSC analysis

Differential secondary caliometry basically tells whenever there is some change in the phase of the material with change in temperature.

Figure7 shows the differential scanning caliometry curves of Ni-Ti sheet for 30W power at two different passes i.e. 10 and 20. It can be clearly seen from the DSC curves that there is a significant single stage transformation seen in both the heating and cooling curves.

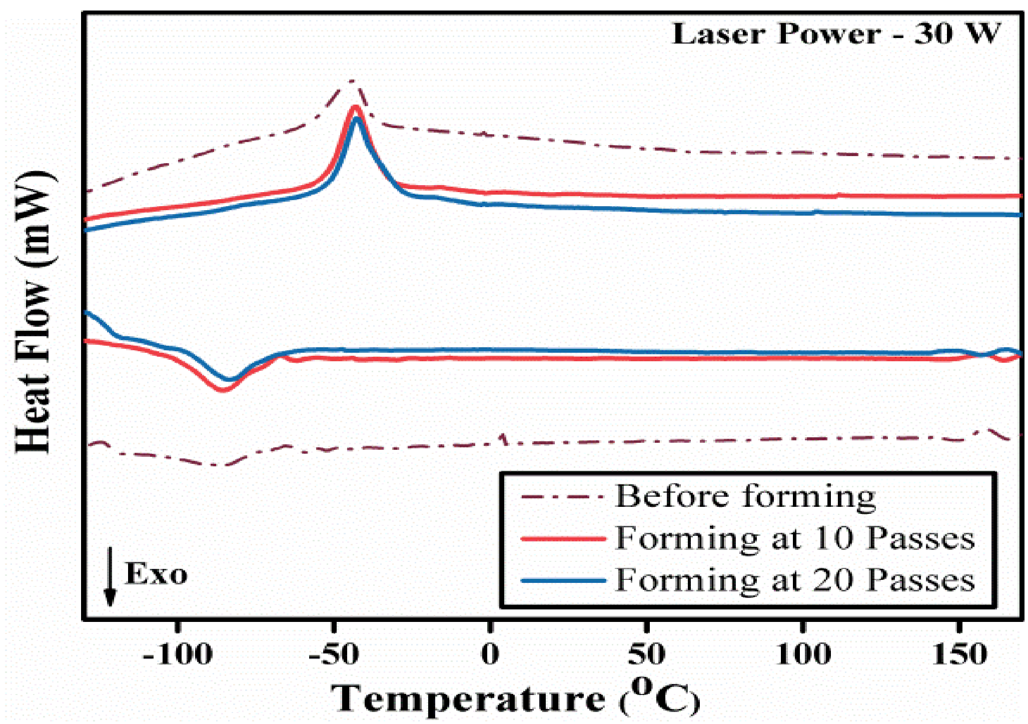

Figure26- DSC curves at 30 W power.

The Austenite start temperatures are (A_s) = -52.5°C and -50.9°C whereas the austenite finish temperatures are (A_f) = -32.6°C and -33.2°C. Also in the cooling curve the martensite start are (M_s) = -71°C and -70.7°C whereas the martensite finish temperatures are (M_f) = -100.9°C and -94.4°C. During heating martensite will transform into austenite and while cooling austenite will transform into martensite.

Table 4:-Phase transformation temperature at 30W power

S.No.	**Phase**	**Temperature (°C)**	
		10 passes	20 passes
1	A_s	-52.5	-50.9
2	A_f	-32.6	-33.2
3	M_s	-71.0	-70.7
4	M_f	-100.9	-94.4

Figure8 shows the DSC curves of the Ni-Ti sheet at 40W for 10 and 20 numbers of passes. Here the Austenite start temperatures are (A_s) = -52°C and -52.1°C whereas the austenite finish temperatures are (A_f) = -35.8°C and -19.4°C. Also in the cooling curve the martensite start are (M_s) = -74.8°C and -50.2°C whereas the martensite finish temperatures are (M_f) = -97.8°C and -101.1°C.

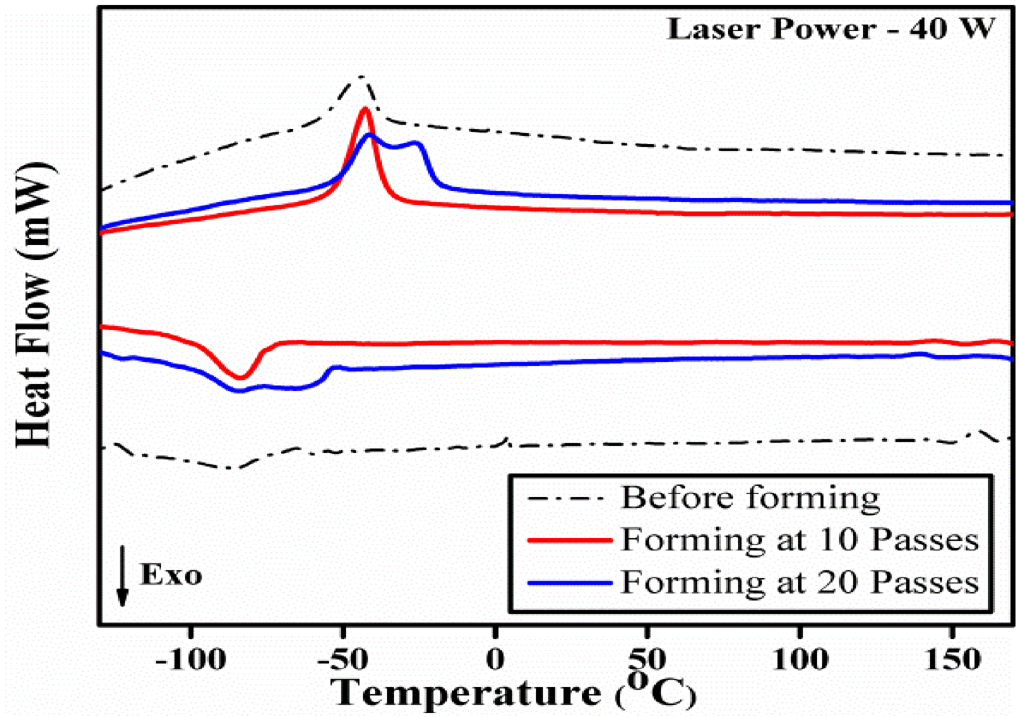

Figure27- DSC curves at 40 W power

The curves in both the heating and cooling curves are clearly noticeable. Here, there is a single stage transformation in the Ni-Ti SMA only for 10 passes while for 20 passes there is a two-stage transformation in the Ni-Ti due to the generation of R-phase in the material [7].

Table 5:-Phase transformation temperature at 40W power

S.No.	**Phase**	**Temperature(°C)**	
		10 passes	20 passes
1	A_s	-52	-52.1
2	A_f	-35.8	-19.4
3	M_s	-74.8	-50.2
4	M_f	-97.8	-101.1

Figure9 shows the DSC curves of Ni-Ti sheet for 50W power at two different passes i.e. 10 and 20. The austenite start (A_s) temperatures for 10 and 20 passes are -53.7^{o}C and 0.4^{o}C whereas austenite finish (A_f)temperatures are -28.9^{o}C and 47^{o}C, likewise martensite start (Ms) temperatures are -65.3^{o}C and -58.7^{o}C and martensite finish (M_f) temperatures are -103^{o}C and -103.9^{o}C.

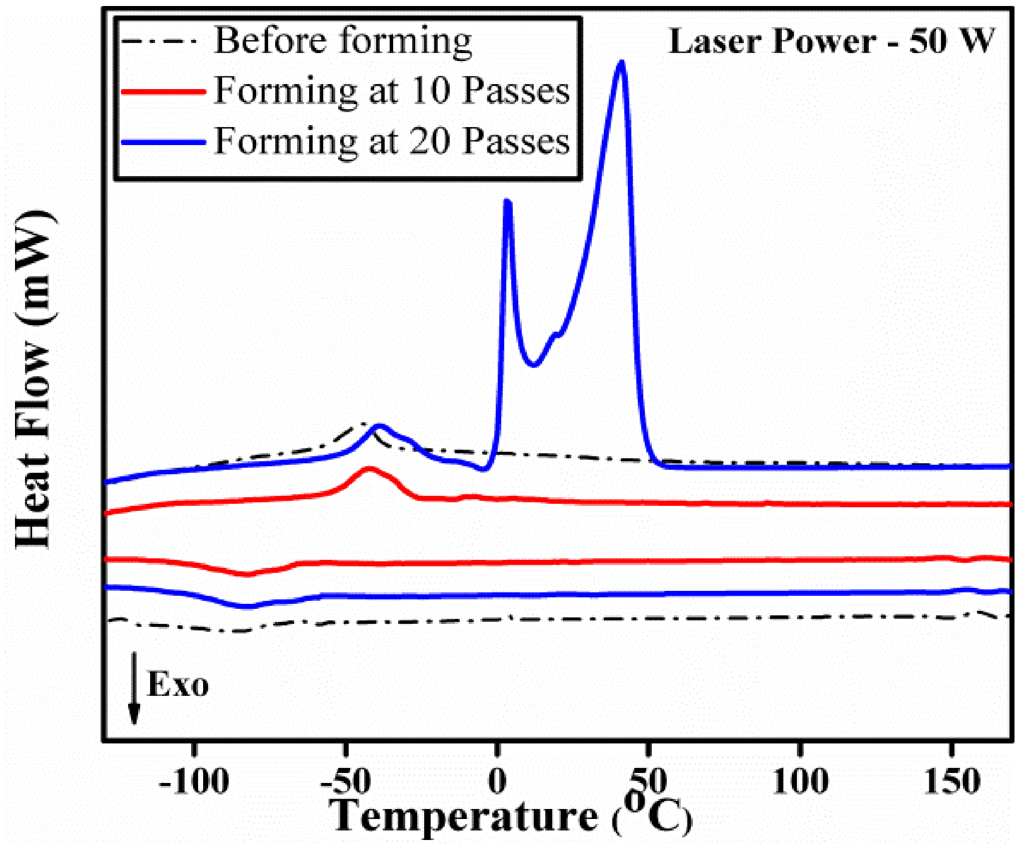

Figure28- DSC curves at 50 W power

Table 6:-Phase transformation temperature at 50W power

S.No	Phase	Temperature(ºC)	
		10 passes	20 passes
1	A_s	-53.7	0.4
2	A_f	-28.9	47
3	M_s	-65.3	-58.7
4	M_f	-103.0	-103.9

Here also we see can that for 10 number of passes there is only a single stage transformation in the Ni-Ti SMA while for 20 number of passes there is a two-stage transformation due to the generation of R-phase which entail that with the increase in laser power and number of passes, the forward transformation has changed from one stage to two stage.

4.5 Hardness analysis

The laser is applied at different power which leads to change in the hardness of the material. Since the thickness of the sheet was very less i.e. 0.25mm. Thus, Vickers micro-hardness test was done for all the samples.

4.3.1Hardness at different powers with 10 passes

Hardness is one of the most important parameter for a material which helps us in determining its life. From the below table we can see that with the increase in power, the hardness of the material is getting decreased for the three different sections i.e. Irradiated, heat affected and unaffected zones.

Table 7:- Micro-hardness at different power with 10 passes

POWER (W)	PASSES	HARDNESS(HV)		
		Irradiated zone	**Heat affected zone**	**Unaffected zone**
30W	10	650	583	330
40W	10	610	497	346
50W	10	550	450	362

Based on the above values a graph is plotted between the hardness and the different powers. This decrease in the hardness of the NiTi sheet occurs because of the wear of the material from the surface of the workpiece.

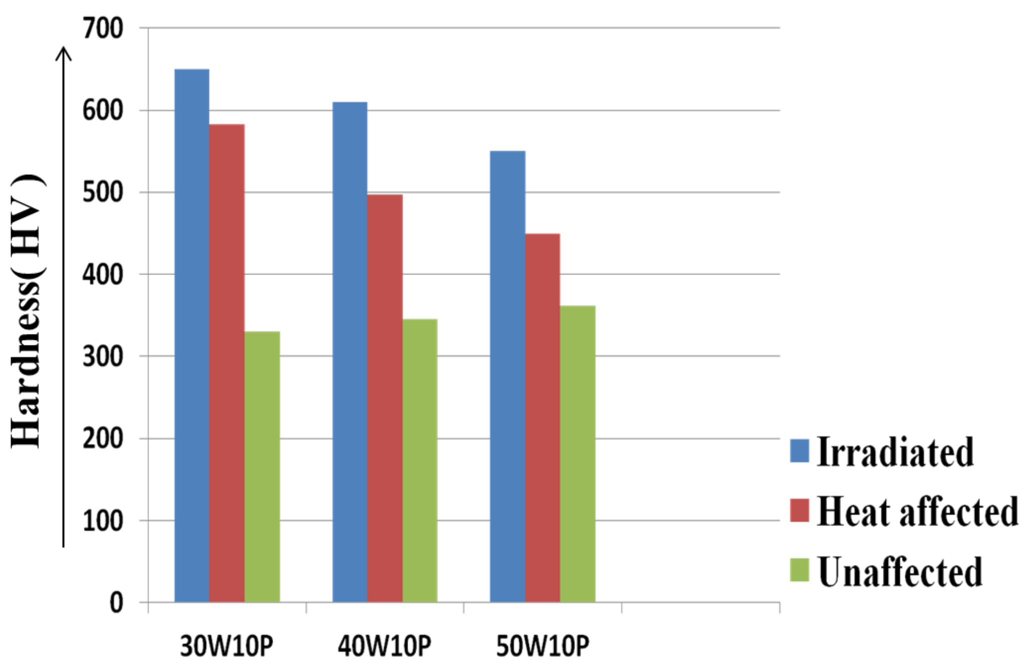

Figure29- Hardness variations at 10 passes

4.3.2Hardness at different powers with 20 passes

The numbers of passes were increased from 10 to 20 in this case and we have seen a further slight decrease in the hardness of the material from the values calculated and given below in the Table8.

After plotting the graph we can simply conclude from these results that with the increase of the number of passes there is more wear in the material which leads to the decrease in its hardness.

Table 8:- Micro-hardness at different power with 20 passes

POWER (W)	PASSES	HARDNESS(HV)		
		Irradiated zone	**Heat affected zone**	**Unaffected zone**
30W	20	625	553	310
40W	20	579	483	316
50W	20	480	425	322

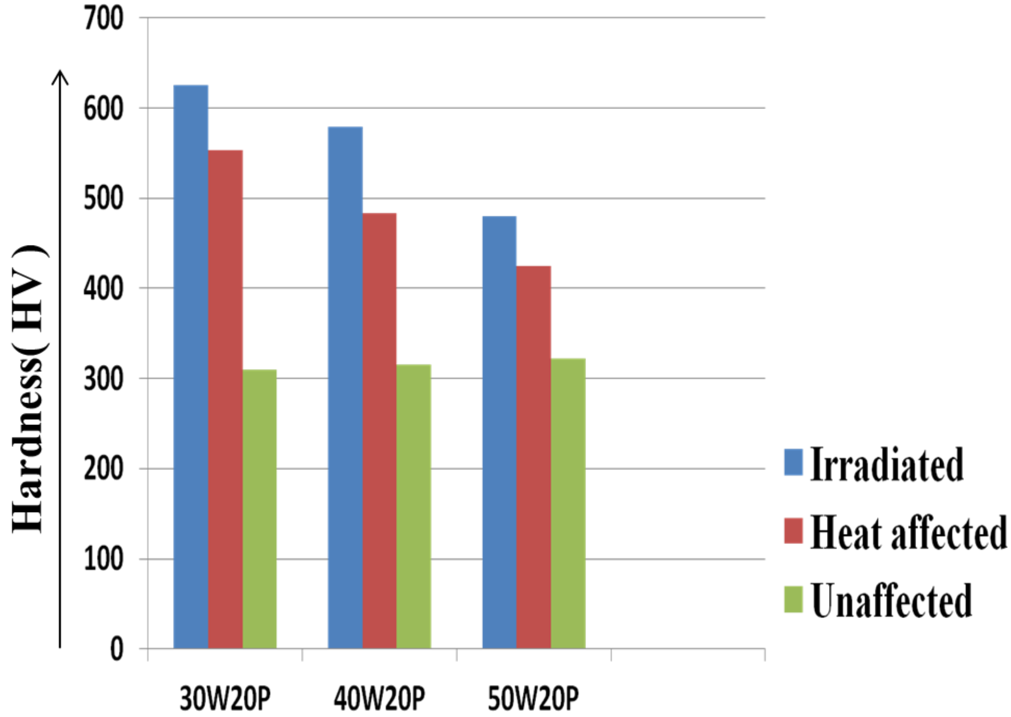

Figure30- Hardness variations at 20 passes

4.3.3Hardness at different powers with 30 passes

As for higher number of passes there will be more wear in the material which leads to further its decrement in its hardness. Since lesser the hardness more will be the ductility. Hence when we further increases the passes from 20 to 30 and the values were obtained as shown in Table9. From the coming results we can see there is a further decrement in the hardness of the material and increase in its ductility.

Table 9:- Micro-hardness at different power with 30 passes

POWER (W)	PASSES	HARDNESS(HV)		
		Irradiated zone	**Heat affected zone**	**Unaffected zone**
30W	30	585	485	324
40W	30	525	455	326
50W	30	495	410	332

There may be the generation of soft phase in the material due to the shift from the martensite phase to unstable Rhombohedral(R) phase which leads to decrement in the hardness values and increase in its ductility.

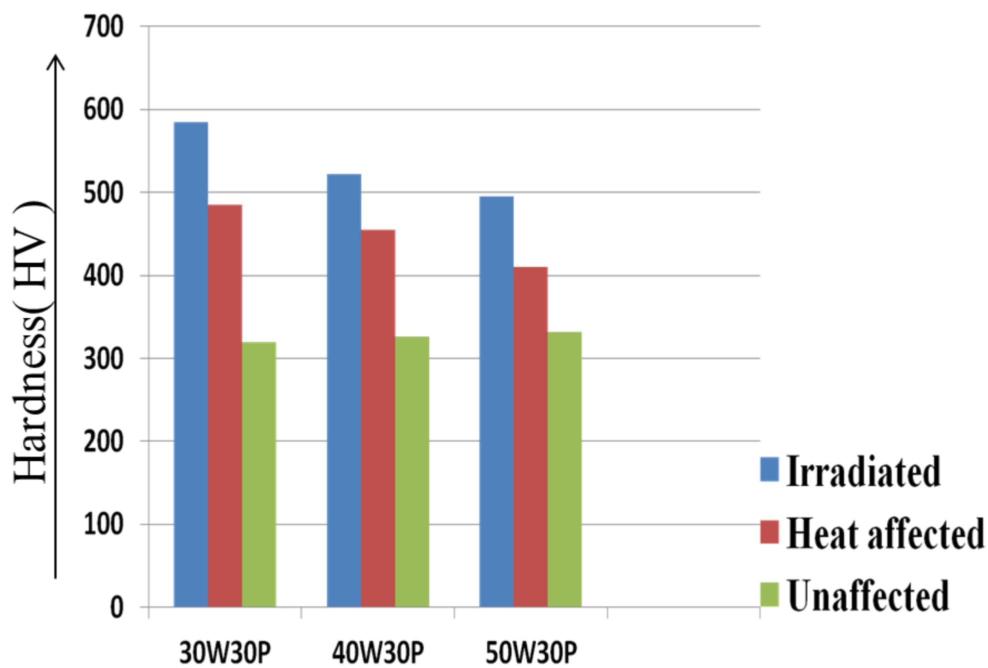

Figure31- Hardness variations at 30 passes

From all of the results we could come to the conclusion that in case of NiTi alloy, the hardness of the material will decrease with increase in power and number of passes while its ductility gets improved with it.

4.6 Corrosion test

NiTi shape memory alloy has been widely employed in various medical fields because of its special mechanical properties, good corrosion resistance and excellent biocompatibility. Owing to the need for reliable fabrication of micro medical devices, laser forming of NiTi has drawn some attention.In recent days, NiTinol's contribution in the manufacture of bio-implants is getting increased. Bio implants such asorthopedic implants, orthodontic wires, bone substitution material and stent are fabricated using NiTinol

Corrosion behaviors of the laser-welded NiTi shape memory alloy and base metal in 3.5% NaCl solution were investigated by means of electrochemical techniques.

1. **Open circuit potential test**

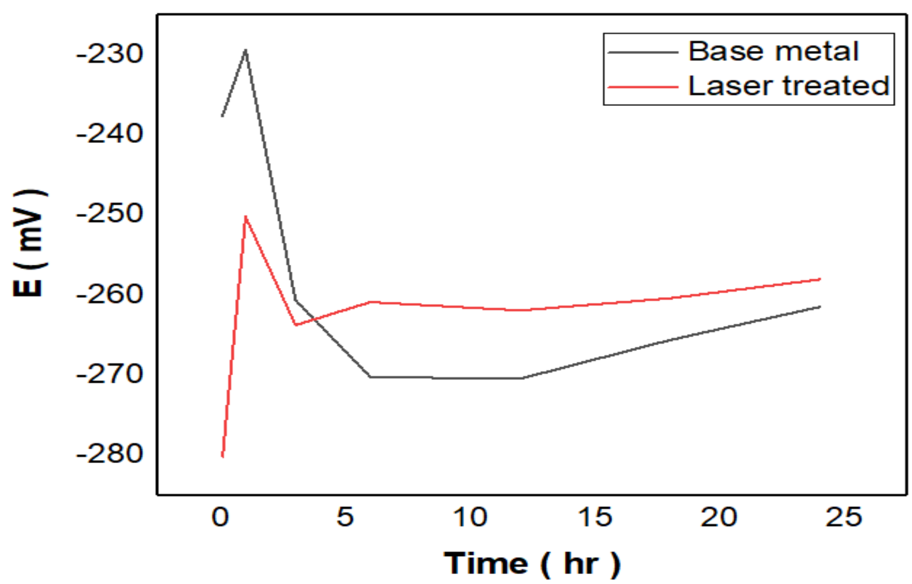

Figure32- Evolution of open cicuit potential with timefor base and laser treated sample

The open circuit potential (OCP) or E_{corr} of dense and porous NiTi alloys in 3.5% NaCl solution were measured over a period of 24 h. Above figure presents the evolution of the OCP as a function of time, where it is obvious the OCP of base NiTi alloy experienced a sharper rate of change compared to the laser treated NiTi alloys.

As E_{corr} indicates the ionization tendency of a material in a specific solution. It varies for different solutions for the same sample. Higher the OCP, higher will be the corrosion resistance. This is basically due to the build-up of a corrosive passive layer on the surface.

Most of the literature surveys have revealed this passive layer film contains TiO_2. This film is present on the surface and it prevents the material from corrosion. The corrosion resistance completely depends on the stability of this passive film

2. **Potentiodynamic Polarization test**

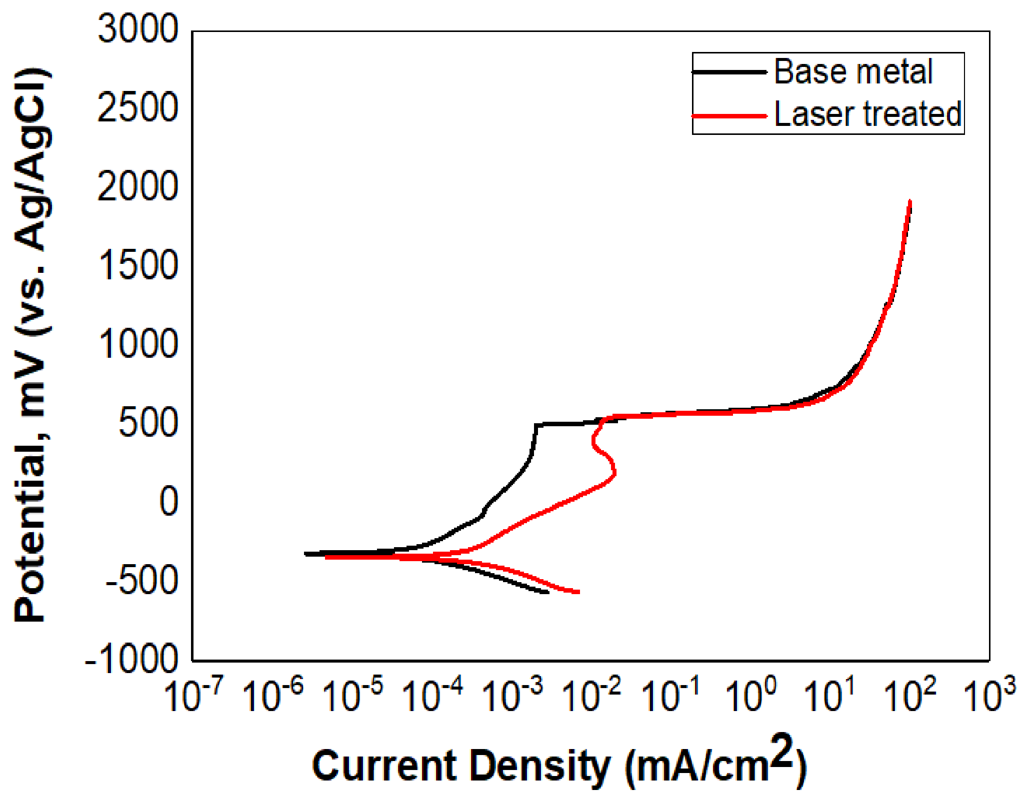

Figure33- Polarization curves of base and laser treated sample after immersionfor 24 hours

The corresponding variations in the potentiodynamic polarization for the base metal and laser treated NiTi samples were measured. The values suggested that the current density (I_{corr}) for laser treated NiTi is higher than that of base sample. I_{corr} indicates the flow of current at open circuit potential due to oxidation and reduction reactions. As from the results, the current density for the treated sample is higher which indicates lower corrosion resistance because more the current flow more will be rate of oxidation. Hence, more will be the corrosion.
The laser forming has the strong tendency to form some intermetallic compounds like Ti_2Ni, Ni_4Ti_3 which leads to the change in the corrosion resistance
Thus, from the results we could analyze that the corrosion of the material increases with the increase in power and number of passes due to the decrease in the resistance due to the formation of some intermetallic compounds.

Chapter 5: Biomedical application

Shape memory alloys (SMA) are materials that have the ability to return to a former shape when subjected to an appropriate thermo mechanical procedure. Pseudoelastic and shape memory effects are some of the behaviors presented by these alloys. The unique properties concerning these alloys have encouraged many investigators to look for applications of SMA in different fields of human knowledge. The purpose of this chapter is to present a brief discussion of the thermo mechanical behavior of SMA and to describe their most promising applications in the biomedical area. These include cardiovascular and orthopedic uses, and surgical instruments.

Biomedical applications of SMA have been extremely successful because of the functional properties of these alloys, increasing both the possibility and the performance of minimally invasive surgeries. The biocompatibility of these alloys is one of the important points related to their biomedical applications as orthopedic implants, cardiovascular devices, and surgical instruments, as well as orthodontic devices and endodontic files.

Figure34- Different kind of lower leg fractures

Biocompatibility is the ability of a material to remain biologically innocuous during its functional period inside a living creature. This is a crucial factor for the use of SMA devices in the human body. A biocompatible material does not produce allergic reactions inside the host, and also does not release ions into the bloodstream. The period during which a biomaterial remains inside the human body is an important aspect to be considered concerning its use.

Generally, the biocompatibility of a material is strongly related to allergic reactions between the material surface and the inflammatory response of the host. Several aspects can contribute to these reactions such as patient's characteristics (health, age, immunological state, and so on), and material characteristics.

Nickel, although necessary to life, is a highly poisonous element. Studies have shown that persons having systematic contact with nickel present problems such as pneumonia, chronic sinusitis and rhinitis, nostril and lung cancer, as well as dermatitis caused by physical contact.

Unlike nickel, titanium and its compounds are highly biocompatible; moreover, due to their mechanical properties, they are usually employed in orthodontic and orthopedic implants. The oxidation reaction of titanium produces an innocuous layer of TiO_2 which surrounds the sample. This layer is responsible for the high resistance to corrosion of titanium alloys, and the fact that they are harmless to the human body.

Medical staples

Medical staples play an important role to the healing process of broken and fractured bones. The shape memory orthopedic staples are placed directly into the region of the break to compress the two parts of the bone. These staples, in their opened shape, are implanted to the fractured site of the bone, while through heating the staples tend to close, compressing the separated part of fracture. In this application, the heating is performed by an external device, and not due to the body temperature.

Figure35- NiTi staples used for joining fractured bones

<u>Plates for fractured bones</u>

Shape memory plates also have been used to heal and recover the fractured bones, in the injured area where it is not possible to apply cast such as facial areas, nose, jaw, and eye socket. They are inserted to the fracture and fixed with intermediate. This maintains the original alignment of the bone and enables cellular regeneration. NiTi alloys combine high strength, unique fatigue resistance, and good ductility.

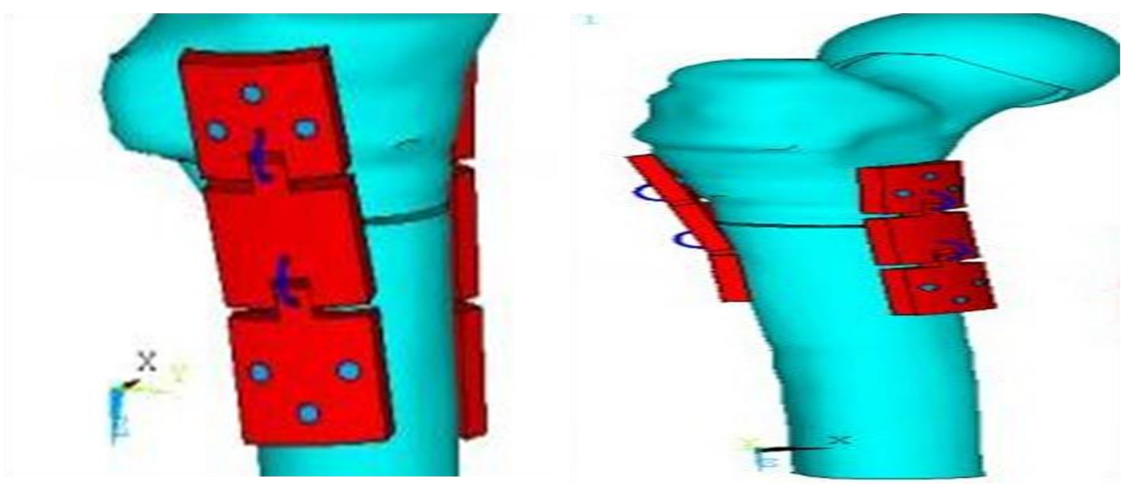

Figure36- NiTi plates used for shoulder fracture

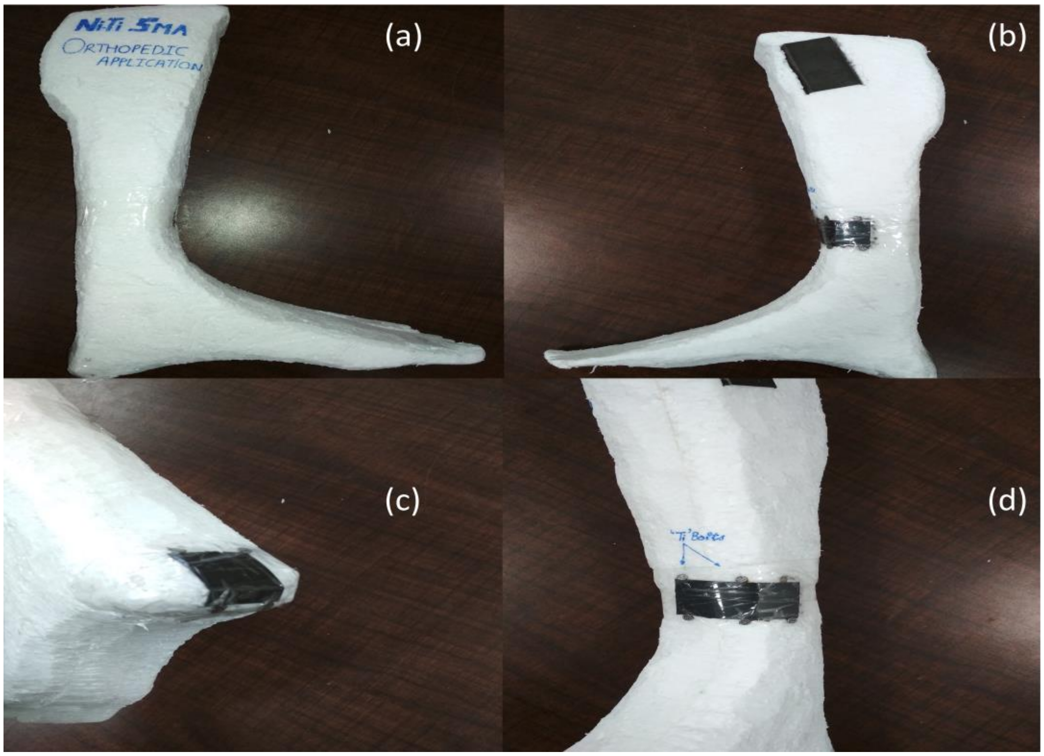

Figure37- (a)Prototype of a leg(b)NiTi sheets used in fracture of tibia and fibula(c)NiTi sheet used in ankle fracture (d)'Ti' bolts used for fixing the sheet.

The above figure shows the laser formed NiTi sheets used for different fractures on different locations on the leg. The main advantage behind using these sheets is they are very lighter in weight as well as they have more lifespan as compare to any other material.

Laser forming plays a very important role in this aspect as we could be able to form the sheet for complex parts of the body which could not be possible by any other conventional method. There is no springback effect in laser forming which is one of the biggest advantage with this method.

From, the hardness and the corrosion test we have seen that the corrosion resistance of the material gets improved. Whereas, the ductility of the material also gets improved after laser forming which act as major advantages for our biomedical applications

Chapter 6: Conclusion and Future Recommendation

The main aim of this thesis was to investigate the effect of laser forming on shape memory alloy so as to make them suitable for the various suitable applications such as in biomedical sector.

The laser is applied at a focal length of 280mm on all the NiTi samples with a spot diameter of 0.2mm at different number of passes and different powers.

In current work laser forming on Ni-Ti sheets of 0.25 mm were performed. The variation in the bending angles with respect to the process parameters were calculated and it is found that there is a certain non-linear increment in the bending angle with an increment of power and number of passes. The DSC analysis done for the samples also gives the idea that there is only a single stage transformation in the Ni-Ti SMA for 30W laser power in 10 and 20 passes while for 40W and 50W laser power there is a two stage phase transformation occurs due to the generation of R-phase.

Also the micro-hardness test of the different samples shows that there is a decrement in the hardness of the sample with the increase in number of passes and power. This decrement is due to the generation of soft phase inside the material because of the R-phase and also when there is more number of passes the material removal is more and there will be more wear in the material which leads to decrease in the strength and hardness of the material but increase in the ductility of the material.

So, finally the experimental investigations on the laser bending parameters have led to the following specific conclusions:

- Laser power is the most significant factor followed by the number of passes.

- There is a non-linear increment in the bending angle with increase in power and number of passes.
- There is two stage transformation in the NiTi due to the generation of R-phase.
- The hardness of the sheet decreases with increase in power and the number of passes due to the generation of soft phase because of the wear of the material.
- The ductility of the material is improved with power and passes as the hardness is decreased.

Future recommendations

The research can be extended to achieve the better hardness of the material by changing the spot diameter or number of passes of the laser. The power of the laser can be reduced in order to achieve more hardness in the material.

The problem coming in the proper variation of the bending angle with the power and the number of passes which can be optimized. It can be used to make several other shapes according to the shape of the body for the biofluidic applications.

The heat input rate and the temperature range can be further controlled so that we would be able to know the exact heat input required to deform a sheet a certain angle. Thermocouple can play a vital role in this regard.

Moreover, the underwater laser study could be done by keeping the sheet in the water at different distances from the water surface in order to control the heat rate and temperature range.

Different kind of pastes such as charcoal, lime, etc could be applied so that there could be more absorption of the laser on the sheet which will be helpful in controlling the bending of sheet.

Orthopedic treatment also exploits the properties of SMA in the physiotherapy of semi-standstill muscles The NiTi wires reproduce the activity of hand muscles, promoting the original hand motion. The two-way shape memory effect is exploited in this situation. When the glove is heated, the length of the wires is shortened. On the other hand, when the glove is cooled, the wires return to their former shape, opening the hand. As a result, semi-standstill muscles are exercised.

Chapter 7: Bibliography

[1]. Sun L, Huang WM. Nature of the multistage transformation in shape memory alloys upon heating. Met Sci Heat Treat 2009;51:573–8.

[2]. Mihálcz I. Fundamental characteristics and design method for nickeltitanium shape memory alloy. Periodica Polytechnica Ser Mech Eng 2001;45:75–86.

[3]. Lagoudas DC. Shape memory alloys: modeling and engineering applications. 1st ed. New York: Springer; 2010.

[4]. Duerig TW, Pelton AR. Ti–Ni shape memory alloys. Materials Properties Handbook, Titanium Alloys, Materials Park, OH: American Society for Metals; 1994. p. 1035–48.

[5]. Huang W, Toh W. Training two-way shape memory alloy by reheattreatment. Mater Sci Lett 2000;19:1549–50.

[6]. Perkins J, Hodgson D. The two-way shape memory effect. Butterworth-Heinemann, Engineering Aspects of Shape, Memory Alloys(UK), 1990; 1990. p. 195–206.

[7]. Schroeder TA, Wayman CM. The two-way shape memory effect and other ‘‘training’’ phenomena in Cu–Zn single crystals. Scr Metall 1977;11:225–30.

[8]. Ma J, Karaman I, Noebe RD. High temperature shape memory alloys. Int MaterRev 2010;55:257–315.

[9]. Shichun W. and Jinsong Z., An experimental study of laser bending for sheet metals, Journal of Materials Processing Technology, Volume 110, Issue 2, 19 March 2001, pp 160-163.

[10]. Shen H. and Yao Z., study on mechanical properties after laser forming, Optics and Lasers in Engineering, Volume 47, Issue 1, January 2009, pp 111-117.

[11]. Shi Y., Yao Z., Shen H. and Hu J., Research on the mechanisms of laser forming for the metal plate, International Journal of Machine Tools and Manufacture, Volume 46, Issues 12-13, October 2006, pp 1689-1697.

[12]. Ueda T., Sentoku E., Yamada K. and Hosokawa A., Temperature Measurement in Laser Forming of Sheet Metal, CIRP Annals - Manufacturing Technology, Volume 54, Issue 1, 2005, pp 179-182.

[13]. Thomson G. and Pridham M., Improvements to laser forming through process control refinements, Optics & Laser Technology, Volume 30, Issue 2, March 1998, pp 141-146.

[14]. Guan Y., Sun S., Zhao G. and Luan Y., Influence of material properties on the laser-forming process of sheet metals, Journal of Materials Processing Technology, Volume 167, Issue 1, 25 August 2005, pp 124-131.

[15]. Hsieh H. and Lin J., Study of the buckling mechanism in laser tube forming, Optics & Laser Technology, Volume 37, Issue 5, July 2005, pp 402-409.

[16]. Kim J. and Na S.J., 3D laser-forming strategies for sheet metal by geometrical information, Optics & Laser Technology, Volume 41, Issue 6, September 2009, pp 843-852.

[17]. Magee J., Sidhu J. and Cooke R. L., A Prototype laser forming system, Optics and Lasers in Engineering, Volume 34, Issues 4-6, October 2000, pp 339-353.

[18]. Vollertsen, F., 1998, Forming and Rapid Prototyping, in Handbook of the EuroLaser Academy, Schuocker, D. Editor, Chapman & Hall: Vienna, Austria.

[19]. Geiger, M. and Meyer-Pittroff, F., 2002, ‘Laser beam bending of metallic foils’, In: Proceedings of SPIE, 4426, pp. 187-190.

[20]. Behler, K., Beyer, E. and Herziger, G., 1988, ‘Using the beam polarization to enhance the energy coupling in laser beam welding’, Laser Materials Processing, pp. 98-105.

[21]. Widlaszewski, J., 2001, ‘Thermal deformation of multilevel spatial structures induced by laser pulses’, In: Proceedings of the LANE, pp.569-574.

[22]. Magee, J., et al. 1997, ‘Laser forming of aerospace alloys’, In: ICALEO, pp. 156-165.

[23]. Edwardson, S. P., et al., 2001, ‘3D laser forming of saddle shapes’, In: Proceedings of the LANE, pp. 559-568.

[24]. Hennige, T., 1997, ‘Laser forming of spatially curved parts’, In: Proceedings of the LANE, pp. 409-420.

[25]. Magee, J., Watkins, K. G. and Hennige. T., 1999, ‘Symmetrical laserforming’, In: Proceedings of ICALEO, pp. 77-86.

[26]. Masubuchi, K., 1992, ‘Studies at M. I. T. related to applications of laser technologies to metal fabrication’, In: Proceedings of LAMP, Nagaoka,pp. 939-946.

[27]. Vollertsen, F. and Rodle, M., 1994, ‘Model for the temperature gradientmechanism of laser bending’, In: Proceedings of the LANE, pp. 371-378.

[29].X.J. Yan, D.Z. Yang, X.P. Liu,2007, ‘Corrosion behavior of a laser-welded NiTi shape memory alloy, pp. 623-628.

[30]. Deepan Bharathi Kannan T., Sathiya P., Ramesh T., 1997, ‘Experimental investigation and characterization of laser welded NiTinol shape memory alloys’, 2017, pp. 253-261.

[31].X.T. Sun, Z.X. Kang, X.L. Zhang, H.J. Jiang, R.F. Guan, X.P. Zhang,2011A comparative study on the corrosion behavior of porous and dense NiTi shape memory alloys in NaCl solution, pp. 6389-6396