Investigations on Formability of NiTi Complicated Shape Memory alloy Structures using Laser Forming Techniques

M.Tech Thesis

by

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Indian Institute of Technology Indore

JUNE 2020

Investigations on Formability of NiTi Complicated Shape Memory alloy Structures using Laser Forming Techniques

A THESIS

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

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by

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Candidate's Declaration

I hereby certify that work which is being presented in the thesis entitled **Investigations on Formability of NiTi Complicated Shape Memory alloy Structures using Laser Forming Techniques** in the partial fulfillment of the requirements for the award of the degree of **MASTER OF TECHNOLOGY** and submitted in the **DISCIPLINE OF MECHANICAL ENGINEERING, Indian Institute of Technology Indore,** is an authentic record of my own work carried out during the time period July 2018 to May 2020 under the supervision of **Dr. I.A. Palani** and **Dr. Santosh Hosmani**of Discipline of Mechanical and Metallurgy Engineeringrespectively.

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

Shivam Gupta (1802103007)

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 S Hosmani)

Shivam Gupta has successfully completed his M.Tech Oral Examination held on 23/07/2020.

Signature of the Thesis Supervisors | Signature of Convener, DPGC

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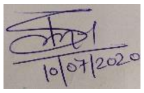

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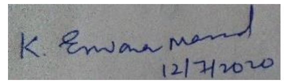

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Shivam Gupta

Dedicated to my Guide – my mother,

my father, mybrother,

mygrandparents, 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 super elasticity (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 Thesis shows the experiments performed on Ni-Ti sheets of dimension 50mm×200mm with a maximum power of 35W. The process parameters which were varied are Power (25W to 35W), Scan Speed (40 to 75) to get the required profile 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), XRD, SEM for the changes in phase transformation of Ni-Ti SMA with respect to change in power and Scan Speed isstudied.

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Abbreviations Used

SMA	Shape memory alloy
SME	Shape memory effect
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
XRD	X-Ray Diffraction

INTRODUCTION

Shape Memory Alloys(SMAs) are a distinct class of shape memory materials with the potential to regain their shape and size when it is exposed to the raise in the temperature also known as memorization property of the SMA. An increase temperature can result in shape recovery even under high applied loads. Cu- Al-Ni, In-Ti, Ni-Al, Au-Cd, Cu-Sn, Cu-Zn-(X), Ni-Ti, Fe-Pt, Mn-Cu, and Fe-Mn-Si are some examples of these alloys.

1.1 SMA Background:

Among all the SMA the Ni-Ti Alloy have been found most useful because of good mechanical properties, stability, practicality and superior thermo-mechanical performance as compared to the other SMA material include copper-aluminum-nickel, copper-zinc-aluminum and iron- manganese-silicon alloys. The Ni-Ti alloys family also known as Nitinol. In 1961, Ni-Ti alloys unique property of shape memory was discovered in the Naval Ordnance Laboratory (NOL) after this Ni-Ti alloys also known as Nitinol.

William J. Buehler, a researcher at the Naval Ordnance Laboratory in White Oak, Maryland, was the one to discover this shape memory alloy. The actual discovery of the shape memory property of Nitinol came about by accident. At a laboratory management meeting, a strip of Nitinol was presented that was bent out of shape many times. One of the people present, Dr. David S. Muzzey, heated it with his pipe lighter, and surprisingly, the strip stretched back to its original form. In1965, the researcher added the third material like Co or Fe in the existing Ni-Ti which result in the drastic change in the SMA Transformation Temperature.

Smart materials have received increased demand in recent years because of their huge potential in revolutionizing engineering applications. Among smart materials SMA is currently the predominant topic for research because of its compatibility in various applications and also its property of memorization i.e. large recoverable strains occur within it due to crystallographic transformation. These unique properties are achieved through a solid-state phase change (molecular rearrangement) that occurs in an SMA.

SMA exist in two phase each one has a different crystal structure thus different properties three different crystal structures (i.e. twinned martensite,detwinned martensite and austenite and six possible transformations. Stability of phase depends on the temperature. Parent Phase having high temperature phase is known as austenite and the phase having low temperature is called martensite. Phase transformation is occur by the shear lattice distortion such kind of transformation is called martensitic transformation. Austenite generally exists in the simple cubic crystal structure and martensite generally exists in the orthorhombic, tetragonal or monoclinic.

1.2 Phenomenon in SMA:

The material in the room temperature without any loading the structure of the material is twinned martensite, as we applied the load and the material start deformation the structure of the material changed to the detwinned or deformed martensite, now if SMA is heated, it begins to transform from martensite into the austenite phase. The temperature at which the martensite start transforming austenite is known as austenite starts Temperature (As). At this temperature the materials start regaining their initial shape. The temperature at which the martensite is fully transform into the austenite is known as austenite finish temperature (A_f). At this temperature material is fully recovered its initial shape. The transformation of martensite into the austenite is called the forward transformation. This effect of the SMAs is known as the shape memory effect

(SME). While cooling the austenite to the room temperature material starts transforming from austenite to the martensite. The temperature at which the austenite start transforming to the martensite is known as martensite start temperature (Ms) and the temperature at which the austenite fully transform into the martensite that temperature is known as 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.

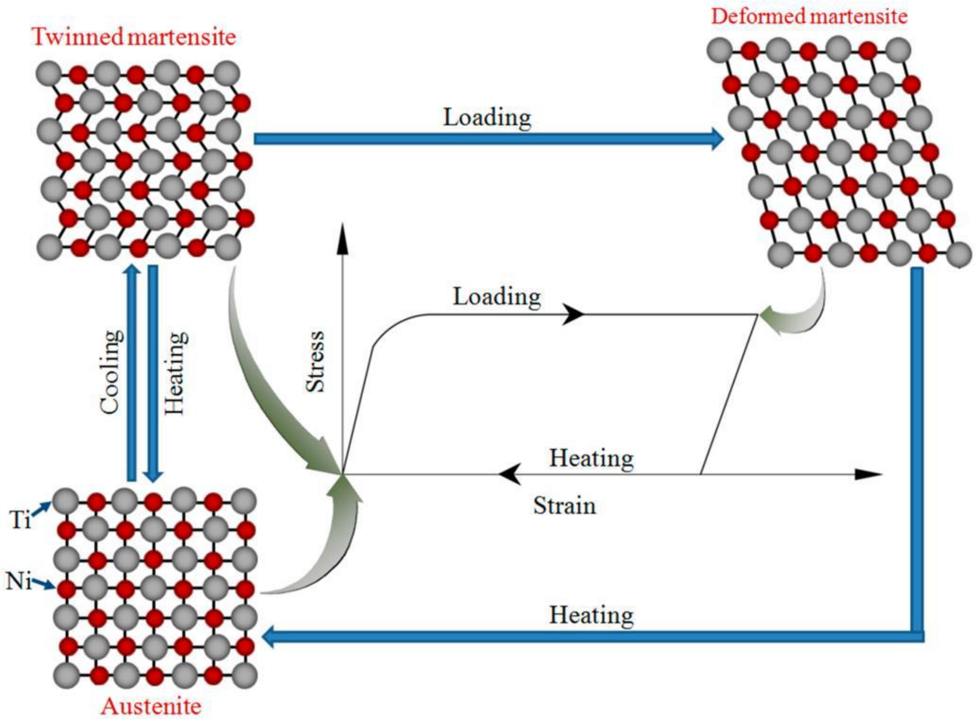


Fig 1.1 Deformation Mechanisms of NiTi Shape Memory Alloy

When the SMA is heated from the room temperature it starts transforming to the austenite phase. When we applied load to the SMA material in the austenite state it transform to the martensite after this of we unload it again there is the change in the phase i.e. SMA will again transform to the austenite phase without change in temperature it regain its initial shape this phenomena is called the pseudoelasticity.

One-way shape memory effect (OWSME):

One way shape memory effect means initial shape can only be recovers in one way, in case of One Way SMA the deformed shape is retains after removing the external load, and then regain to its initial shape upon heating.

Two-way shape memory effect (TWSME):

TWSME is similar to the OWSMEA only the extra feature which the two-way SMA (TWSMA) has its capability to remember its shape at both high and low temperatures. However, TWSMA has its limited usages because of the ‘training’ requirements and to the fact that it usually produces approximately half of the recovery strain provided by one way SMA for the same material and it strain tends to deteriorate quickly, especially at high temperatures. Therefore, OWSMA provides more reliable and economical solution.

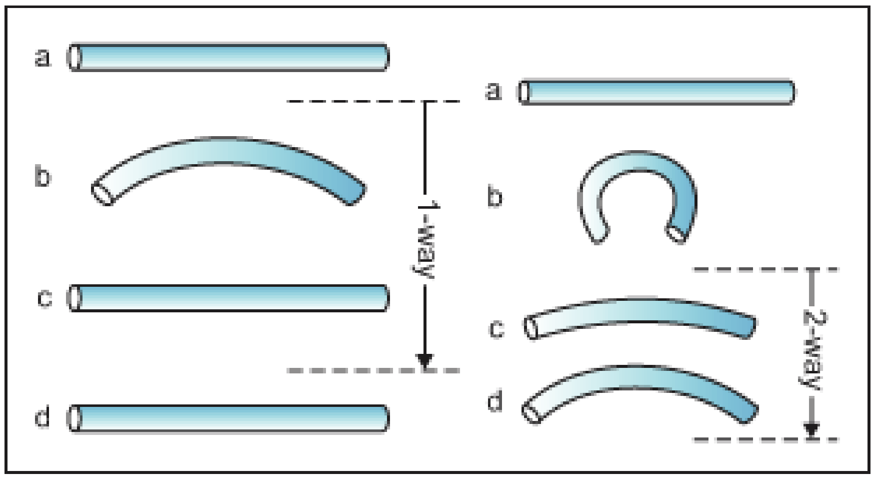


Fig 1.2 Schematic of the OWSME and TWSME

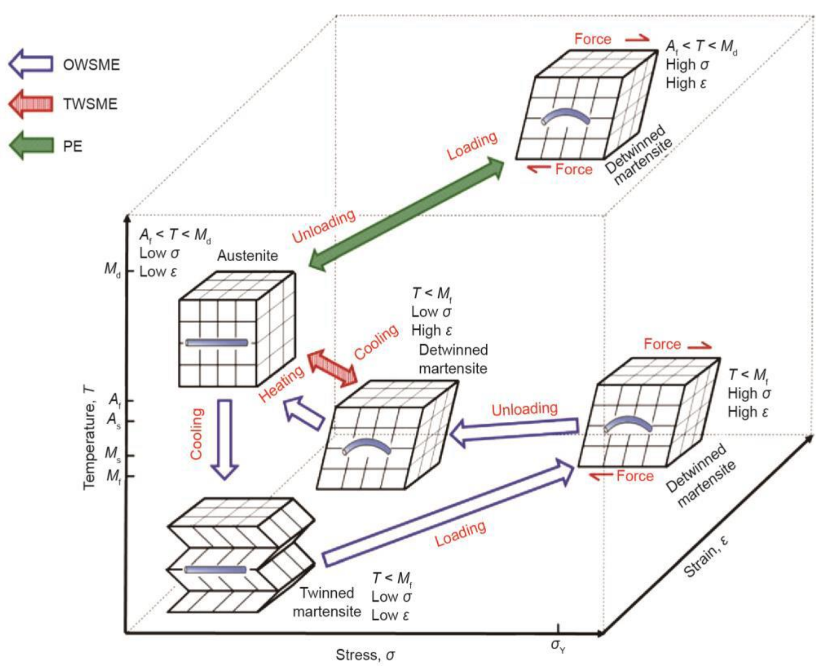


Figure 1.3:- SMA phases and crystal structures

1.3 Laser Introduction:

Laser stands for **L**ight **A**mplification by **S**timulated **E**mission of **R**adiation. Laser is a beam of electromagnetic radiation of single wavelength ranging from ultraviolet to infrared as the wavelength is varying the output from the laser in the form of heat energy which the laser gives also varies from milliwatts to hundreds of kilowatts. Laser beam is highly coherent, convergent and monochromatic in nature. Because of small spot diameter it can be accurately used for the precise manufacturing. Because of these unique properties laser find its many application such as micro fabrication, mask less lithography, metrology, military, communication and broadcasting and medical, material processing.

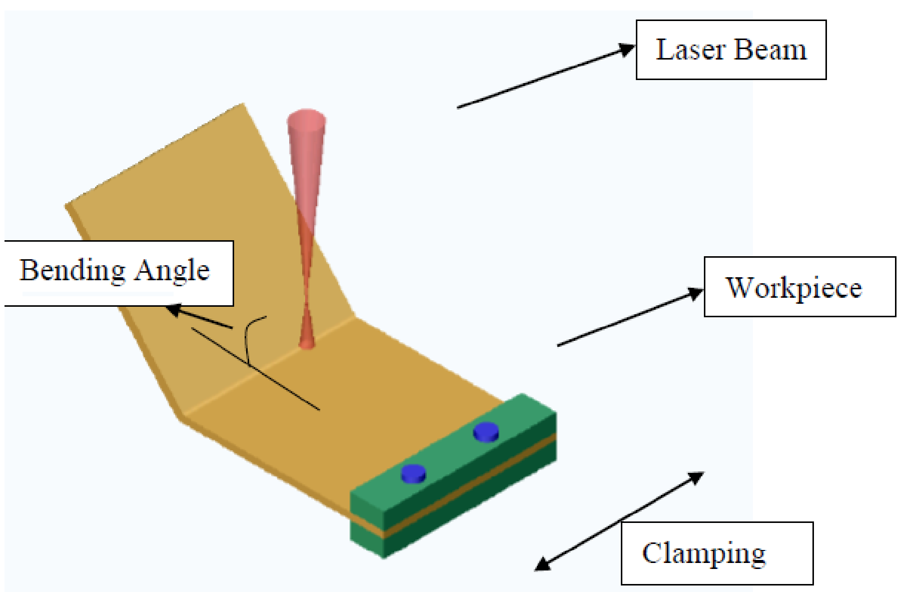


Fig 1.4 Schematic view of a straight-line irradiation by a defocused laser beam

The laser beam is used from the end of the 20th century in the metal forming process and still laser forming is the hot topic among the researcher. Laser forming bring the revolution in the field of forming industries by making the system automated which was earlier the manual process and eliminate the various problem such as the lack of reproducibility or flexibility of the heat source used. The advantage of the laser forming is the production of the customize product very fast, because no special tool is needed. Different geometries, therefore, can be produced by using the same set-up and changing only the process parameters. There is no spring back effect while the material is cooled and it is a non contact type process as there is no contact between the laser and work piece hence there is no tool wear. Laser forming has become a commercial process for the shaping of the metal or alloys sheets because it is easy to aligning and adjust and its fast making component or rapid prototyping without any human intervention. Laser forming do not required the expensive stamping dies and presses for the forming process which is earlier used in the conventional forming result in the cost saving and allows the flexibility in the forming process. Laser forming can produce metallic, predetermined shapes with minimal distortion. Laser forming process is similar to the torch flame bending used in the ship building industry but in laser forming care has to taken by controlling the beam so that the final product is achieved with great accuracy.

1.4 PROCESS: -

In the process of laser forming the beam of laser coming from the source are allowed to strike on the metallic sheet which induce the thermal stress in the sheet and when this thermal stress is greater than plastic stress result in the forming of the sheet. Metallic sheet is clamped from one side and allowed to deform from other side to obtain the desired shape. The sheet is position in such a way that the laser beam strikes it in the defocused position. If we put sheet in the focus point of the laser the depth of penetration is more which result in the melting of the sheet which is not desirable in the forming process. The surface melting of the material is avoided by adjusting the laser parameters such as laser power, feed rate and beam diameter. In forming the deformation is a plastic deformation not a melting. There are many Industrial lasers are available as a beam source, including excimer, carbon dioxide (CO2), ytterbium, erbium and neodymium etc. the selection of laser depends upon the task to be performed. In this experiment the continuous laser of focal length 320 mm is used. The excimer laser can be used for the production of parts with length and width of micron level dimensions because of its extremely short pulse duration Figure 1.4 shows the schematic diagram of a straight-line irradiation process which produces a bend angle from a flat sheet metal piece. The forces which the metalic sheet expeiance majaoly is the force due to the thermal stree and also the small magnitude of the gravitational force which is generally neglected and only consider 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. the absorption of the laser on the surface is less in order to increase the laser beam energy absorption Generally, coatings of graphite or phosphate are used in order to increase the absorption of the laser beam energy into the surface. There is another way also to increase the laser beam absorption without any coating, by using the polarized light or using fiber laser. In general, per pass one or two degrees of bend angle are achieved. 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 the “C” shape forming process the laser is traced in a curve profile and more complex profile is design by using a combination of the these straight and curve profile.

1.5 PRINCIPLE:-

In the conventional metal forming processes such as pressing, bending, stamping drawing, when a load is applied on the metallic sheet and stress induce in it greater than the yield stress a metallic sheet is plastically deformed. In the laser forming process, the thermal stress is induce by the heating of plate with the help of laser which cause the plastic deformation. In the laser forming There are three important mechanism which explain the thermo-mechanical behavior of the laser forming, each mechanism is depend on the combination of various laser parameters and component geometry. These three mechanisms are temperature gradient mechanism (TGM), the buckling mechanism (BM) and the upsetting mechanism (UM).

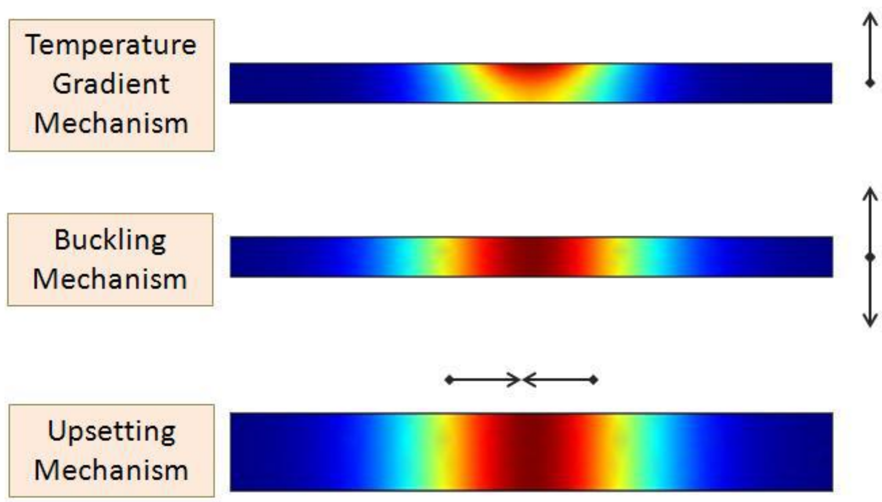


Fig. 1.5 Temperature distributions among all the mechanism

Temperature Gradient mechanism (TGM):

The mechanism employed in this work is Temperature gradient mechanism (TGM). This mechanism causes the bend of the metallic sheet in out of the plane towards the laser beam direction. In order to establish the required for thermal gradient mechanism required the depth of heating is small as compared to the sheet thickness, this requirement is fulfilled by suitable combination of spot size, laser power and transverse speed.

When a laser beam of high power interact with the sheet for small time period, the time period is so small that the heat flow in the thickness direction is very less and the top surface absorb the most of the heat so top surface become hot and bottom surface is cooler compared to the top surface due to this there is huge or steep temperature gradient along the direction of the thickness. On heating the top surface expand and the sheet will move away from the laser beam this is known as counter bending. The magnitude of this counter bend is negligible as compared to the final bend angle.

Initially while laser heating process on the top surface of the sheet purely elastic strains are generated in the laser exposed area. These elastic strains change themselves as differential thermal expansion throughout the sheet thickness. On further addition of heat from laser beam when the stress induce due to thermal strain exceeds the yield strength of the material, which has decreased with increasing temperature. Further thermal expansion is restricted by the cold surrounding material, resulting in plastic deformation in the heated area. The cooling is taken place by all the modes, convection, radiation and conduction but mainly through the heat conduction into the material because of large temperature gradient, the material contraction taking place in the top layer of the sheet hence the higher tensile stress occurs in the upper region. Therefore, the sheet metal is plastically bent toward the laser beam to relax the higher tensile stress as shown in Figure 1.6(c). A flow chart of this forming process is shown in Figure 1.7.material properties such as the thermal diffusivity of the metallic sheet are important parameter while selecting the optimize laser parameters.

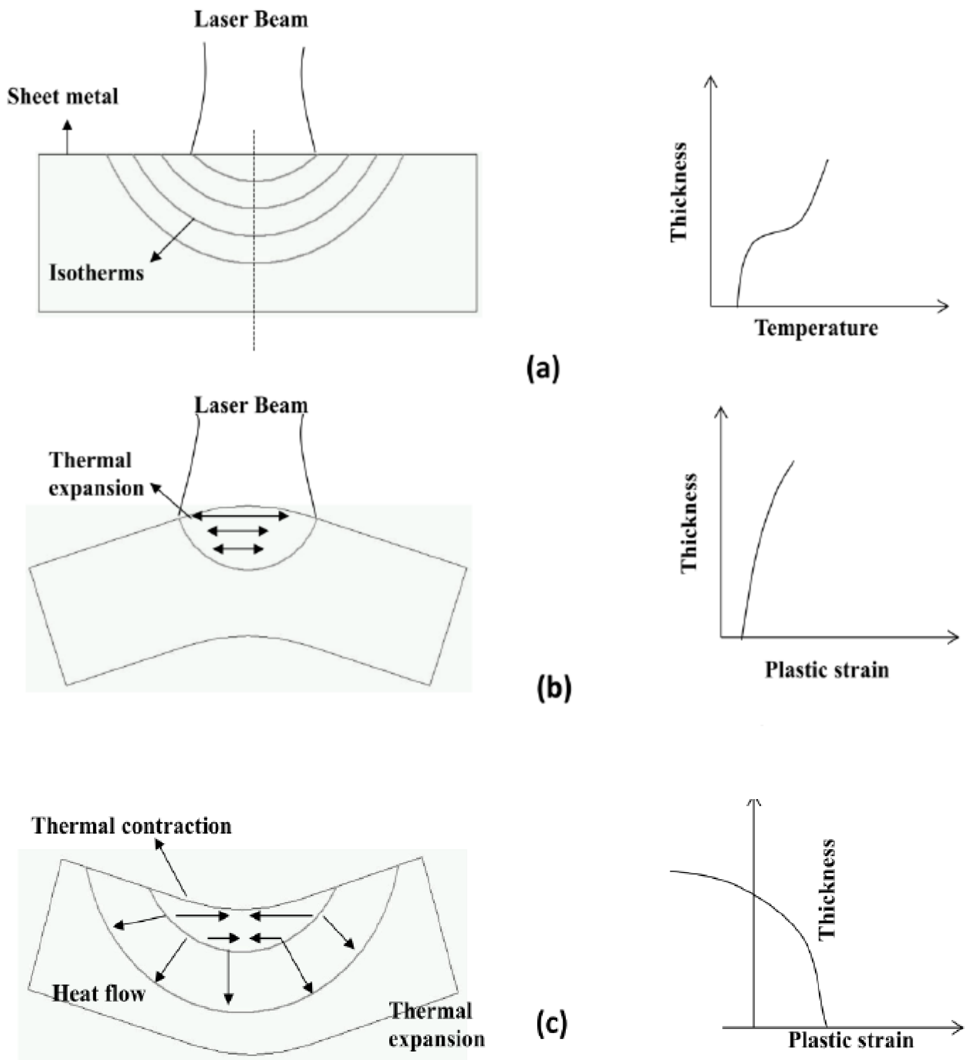


Fig1.6 Steps in TGM

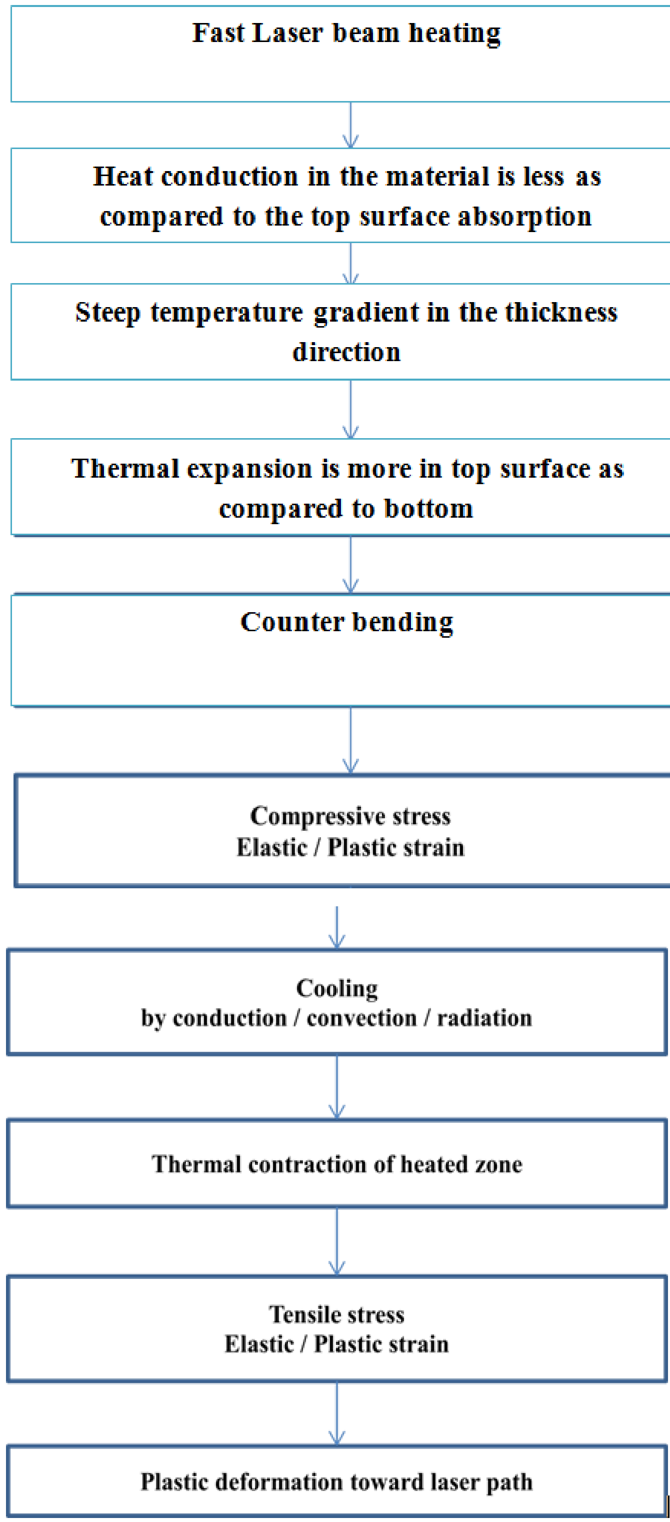


Fig.1.7 the flow chart of the laser forming

Buckling mechanism (BM)

In the buckling mechanism the sheet can be form either in or out of the plane depend on the requirement by pre bending of the sheet in the desired direction, and second way is to apply some mechanical load or gas pressure to bend the sheet after the heating from the laser. In the Buckling mechanism (BM) the laser beam of large diameters compared to metallic sheet thicknesses combined with low traverse speeds thus result in buckling in either side.

Due to selection of such parameter i.e. low speed and large beam diameter the amount of heat generated is more and the time to dissipate the heat is also more so heat get dissipated in the material and material is heated uniformly and no temperature gradient is generated. Because of uniform heating the buckling take place in the longitudinal direction.

Upsetting mechanism (UM):

The UM is a mechanism of shortening of work piece in the longitudinal direction by the uniform heating of the work piece with suitable parameters such as larger beam diameter as compared to thickness and less speed of laser scanning. Due to homogeneous heating of the workpiece throughout the thickness Thermal expansion in the irradiated area occurs which reduce the flow stress of the material. As this expansion is restricted by surrounded bulk material which induce sufficiently high thermal strain causes compressive stresses to develop, result in shortening of the work piece in the longitudinal direction.

1.6 Advantages and Disadvantages:

Laser forming is non conventional forming process and it has many advantages over the traditional forming process. The laser utilize induce thermal stress to form the shapes rather than to use external force as used in the traditional forming process.

- As it is a non contact process it does not require the expansive dies for the forming which ensure that the process is economical.
- In laser forming it is easy to change the process parameters which allow the flexibility in the production process and also it is fast as the set up time is not required.
- Accurate and precise forming is archived because of the small beam diameter and no spring back effect.
- With the help of laser, forming can be done to the area where it is difficult to reach in the traditional forming process.
- According to kaung-jau FANN and jhe-yung SU As a result, both experiment and analysis show that cold forming might not be practical for Ni-Ti shape memory alloy sheet, because the springback is still too high for a maximum achievable deformation under bi-axial tensile stress state.
- If forming temperatures are too high, the mentioned oxidation takes place and with increasing temperature the degradation of the material increases as well. The consequence of these processes is formation of very stable oxide layers which are often a part of the surface and cause destruction of the material due to the formation of cracks.

- With the increasing content of Ni, rolling is more difficult and when the limit of 51 % of Ni is exceed, any rolling of NiTi alloys is more difficult.

Beside its many advantages, the lasers forming also have some drawback which is not rectify yet. Some limitations are as follows:

- It required the skilled worker for operate who understand and operate the laser in a effective manner.
- The efficiency of the laser conversion is very small that why it is energy consuming.
- The laser forming is generally used for making the prototype not used for mass production because it is too much slow as compared to the conventional forming.

- Laser is harmful for our skin as well as for our eyes. Safety protection equipment is required because of the reflection of the laser beam from the workpiece in all direction.

1.7 Motivation:

Now a day's most of the customers desire things according to their comfort zone or according to their desire. As the view or desire may vary from one person to another. To meet their desire a fast responsive system is required. In the manufacturing field to meet the desired of the customer required fast change in the manufacturing setup. In the forming process conventionally expansive die and press are used for the particular forming which is suitable for the mass production not for the customize production. For customize production laser emerge as a viable tool which allow the fast and customize production in the various industry sectors such as aerospace, automotive and microelectronics .Laser forming has become a feasible process for the shaping of metallic sheets. As laser forming does not required mechanical contact which offers the process flexibility and lower cycle time. Idea of laser forming came from the torch flame bending used on large sheet material in the ship building industry. In laser forming the parameter is more control as compared to the laser bending process in order to get the desired formed product. Laser forming requires no external forces, so the spring back may be negligible, allow process flexibility and it can shape complex curved surface and the formation of very small parts. Many hard and brittle materials, such as titanium alloy, nickel alloy, ceramics, etc, can be processed.

- In the past the researcher has not only investigating the process of laser but also works on the practical application in order to make the optimum control parameter while manufacturing. Very rapid work in the field of laser has been done such as controlling, processing, modeling, and some practical application etc. this make the laser easy to control and predict the change in properties of the sheets without performing any laser processing. There are many properties that can modified through laser technique such as thermo- mechanical, optical, mechanical, electrical etc.

- Ni-Ti shape memory alloy find its application in many field scuh as aerospace,medical etc. because of its shape memory effect, good mechanical properties, excellent corrosion resistance, excellent biocompatibility.

- NiTi shape memory alloy has been widely employed in various medical fields because of its special mechanical properties, good corrosion resistance and excellent biocompatibility.

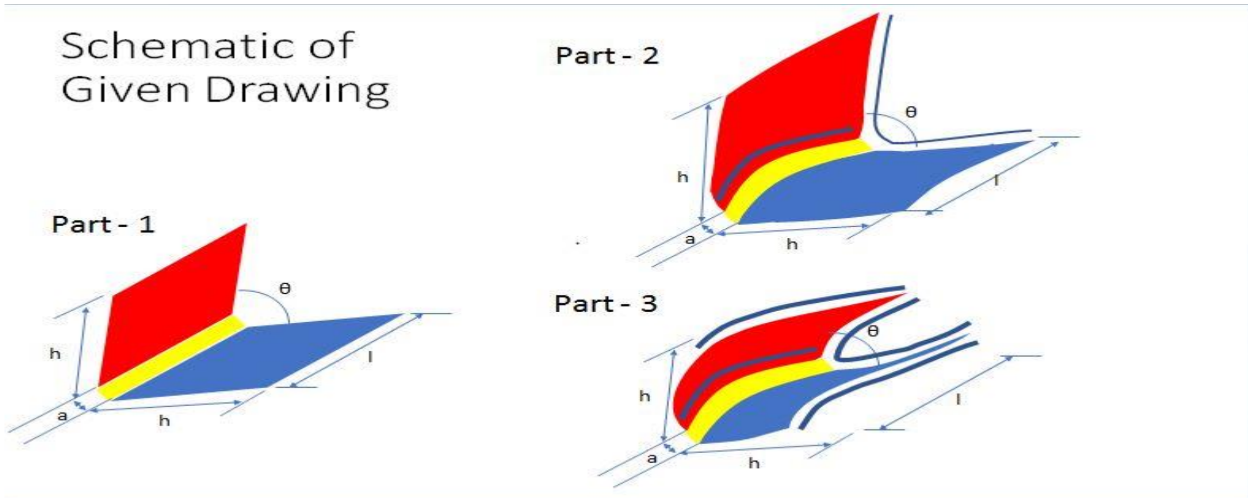
- Laser forming of the Nitinol is emerging in recent days. In the bio medical implants or in the biomedical clamp as they both require the good flexibility in the process which the laser offer because different people require the different implants whewre as the Ni-Ti offer the excellent biocompatibility. Hence laser forming of Nitinol become the topic of current discussion.

1.8 Research Objectives:

The various research objectives of this research are as follows:

Required profile:

Figure shows the profile which we have to replicate in the SMA sheet from laser forming.



Reliability and repeatability:

The primary objective of this project is to develop a given profile and optimize parameter so that the repeatability can be achieved in term of power, scan speed, number of passes.

Characterization:

The characterization of the Ni-Ti Sheet so that to analyze the material properties after the irradiation of the laser.

Chapter 2: Literature Review

This section provides a brief introduction about the present technology available in the field of laser forming. It also highlights the other methods used by researchers on this topic. Laser forming is a tedious transient process that involves elastic-plastic mechanics, thermodynamics, metallography etc. research of mechanics plays the major role in controlling the deformation of metal sheet. Temperature field governed the Forming mechanism which is influenced by Workpiece geometry, laser spot diameter, laser power, 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 did the experimental study to investigate the changes in the bending angle with process parameters. Process parameters consist of sheet geometry parameters, laser energy parameters, material parameters and. The laser energy parameters include laser scan speed, laser power, beam spot diameter, and feed number. Material parameters include various parameters such as density and specific heat at constant pressure coefficient of thermal expansion,. Sheet geometry parameters include sheet length, width and thickness. The experiments use a laser with a CO_2 laser source of 2 KW has a machine type of LCM40. Steel 08 (corresponding to AISI 1008), aluminum 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. For increase of the laser absorption the sheet top surface is coated with the carbon black before testing. The sheet metals were cooled naturally after irradiation. The conclusions drawn from the tests were that the bending angle varied in inverse proportion to the Scan Speed and beam spot diameter and direct proportion to the laser power and feed number. There was no significant change in 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 Performed the experiments to investigate the mechanical properties of sheet metal after laser irradiation. Many sheet metal components formed by mechanical pressing are subjected to fatigue loading during their service life. The investigations indicated that the cyclic loading of the performance of the pressed components decreased significantly compared to the base 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 result to the 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. 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. 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 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. 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 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.

Chapter 3: Experimental Setup

3.1 Laser Setup

The laser used in the experiment is the continuous fiber laser machine of Scantech laser Pvt. Ltd. The laser is doped with element such as ytterbium (YB), neodymium, erbium etc. the wavelength of the continuous laser is 1064 nm and the focal length is 300 mm. The laser has the maximum power of 50W. Laser consists of the galvo scanner which position the beam in X and Y direction there is also provision to control the work piece in the Z direction in the controlling unit of the laser machine. The picture of the laser machine is shown below:

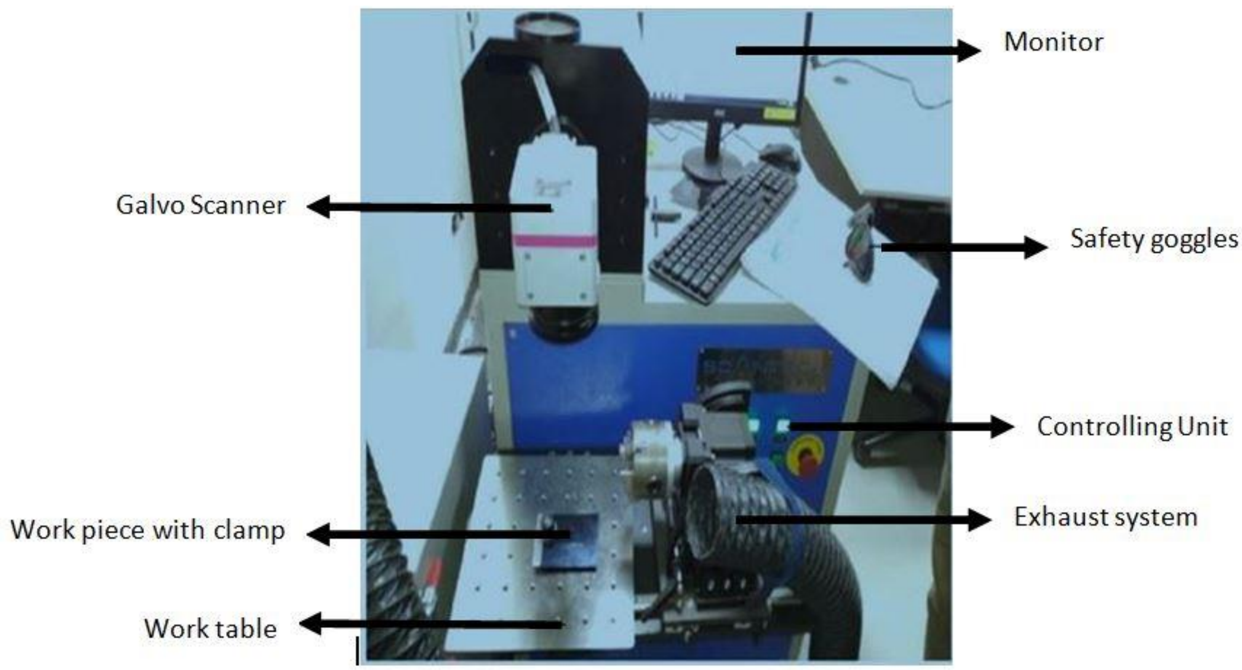


Fig 3.1 **Experimental laser setup used in laser forming**

Controlling unit:

There are some controlling units in the laser machine which control the Z position of the work table and ON /OFF of the laser machine and laser beam, when we used circular work piece we used the rotary enable switch. Number of switch which controlling unit contains are as follows:

1. PC on
2. PC Reset
3. Z axis up
4. Z axis down
5. GalvoOn/Off
6. Laser On/Off
7. Laser Enable

8. Rotary Enable

Fig 3.2 Controlling Unit of Laser Machine

To start the set up of continuous fiber laser initially the PC is turned on, after that the galvo and laser will be turned on. After starting all these the red spot on the surface of work table will come from the galvo scanner which indicates that the laser is functioning properly.

3.2 Workpiece Details:

Initial iteration is done on the Stainless Steel so that we get the idea how we can get the desired profile.

Final shape is replicate on the Ni-Ti shape memory alloy. In Ni-Ti alloy Ni and Ti both have the equal elemental content in the alloy. The Scan mark software is used for making the profile to form the sheet in the desired shape.. Ni-Ti SMA is used for the study. Following are the specifications of Ni-Ti material.

Table 1 Properties of the NiTi Material:

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

Workpiece: NiTi (Nitinol) Sheet

Dimensions of the specimen: Length: 50mm Width: 20mm Thickness: 0.40mm

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

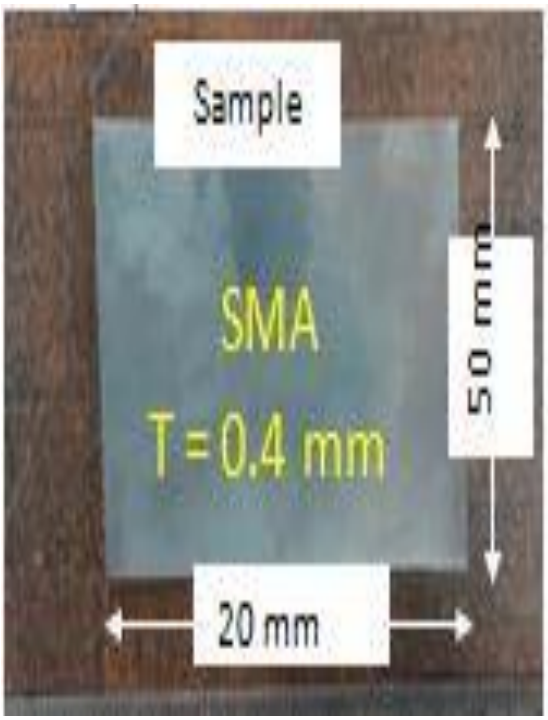


Figure 3.3 NiTi sample used for experiment.

Fig 3.4 Sample preparation at Wire EDM

Input Parameters:

- Number of passess
- Scan Speed
- Laser Power
- Spot diameter

Output Parameters:

- Bend angle

Variations in various laser parameters are:

Scan Speed: 40-70 mm/sec.

Number of passes: 5

Spot diameter: 0.2 mm

Laser power: 25-35 W

Pulse duration: 0.5-20ms

3.3 Experimental procedure:

For performing the experiment first the Workpiece is cut from the Wire EDM in the required dimension. After this the Workpiece is clamped in the worktable at the defocus point below the focus point. For making the "C" profile arc is first make in the AutoCAD software and then with the help of some external source we insert that arc profile in the scanmark software which is install in the laser setup Monitor. Laser Parameters such as the laser power, scan speed, beam diameters are fixed for some number of passes. The laser beam is then irradiated on the surface of the workpiece by making the laser switch enable. Now with the controlling unit the laser beam is on and the galvo scanner complete the profile in the X and Y direction. For making the C shape clamped structure the worktable is shift in the negative Z direction after a given set of passes. Forward and the backward stroke are counted as a single pass. When the process is complete the workpiece is allowed to cool for 3-5 Minutes and then further analysis is done.

The sheets were scanned for different number of speeds in order to get the desired shapes of sheets. The different laser and process parameters affect the bending angle. The parameters which were varied are: Power (25W to 35W), Scan speed (40 to 70 mm/sec.). There is no time gap between each passes. A total of 9 Ni-Ti samples were bent having a thickness of 0.40mm. The spot diameter is kept 2mm for all the samples.

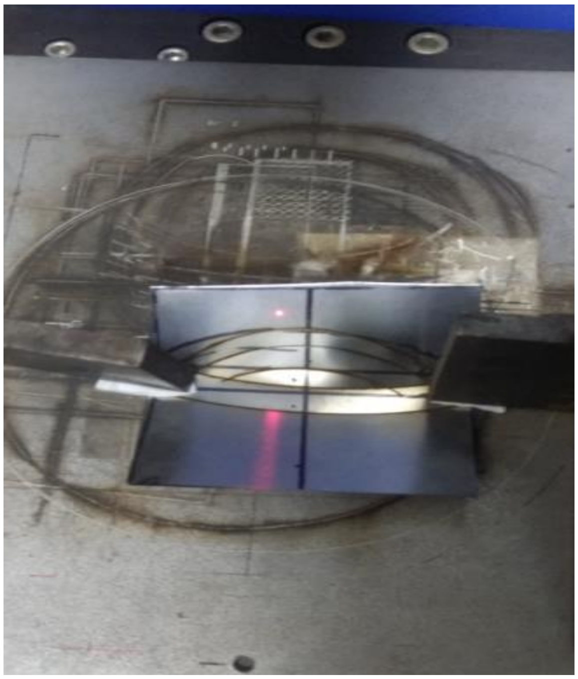


Fig. 3.5 Irradiation of laser on the Ni-Ti sheet

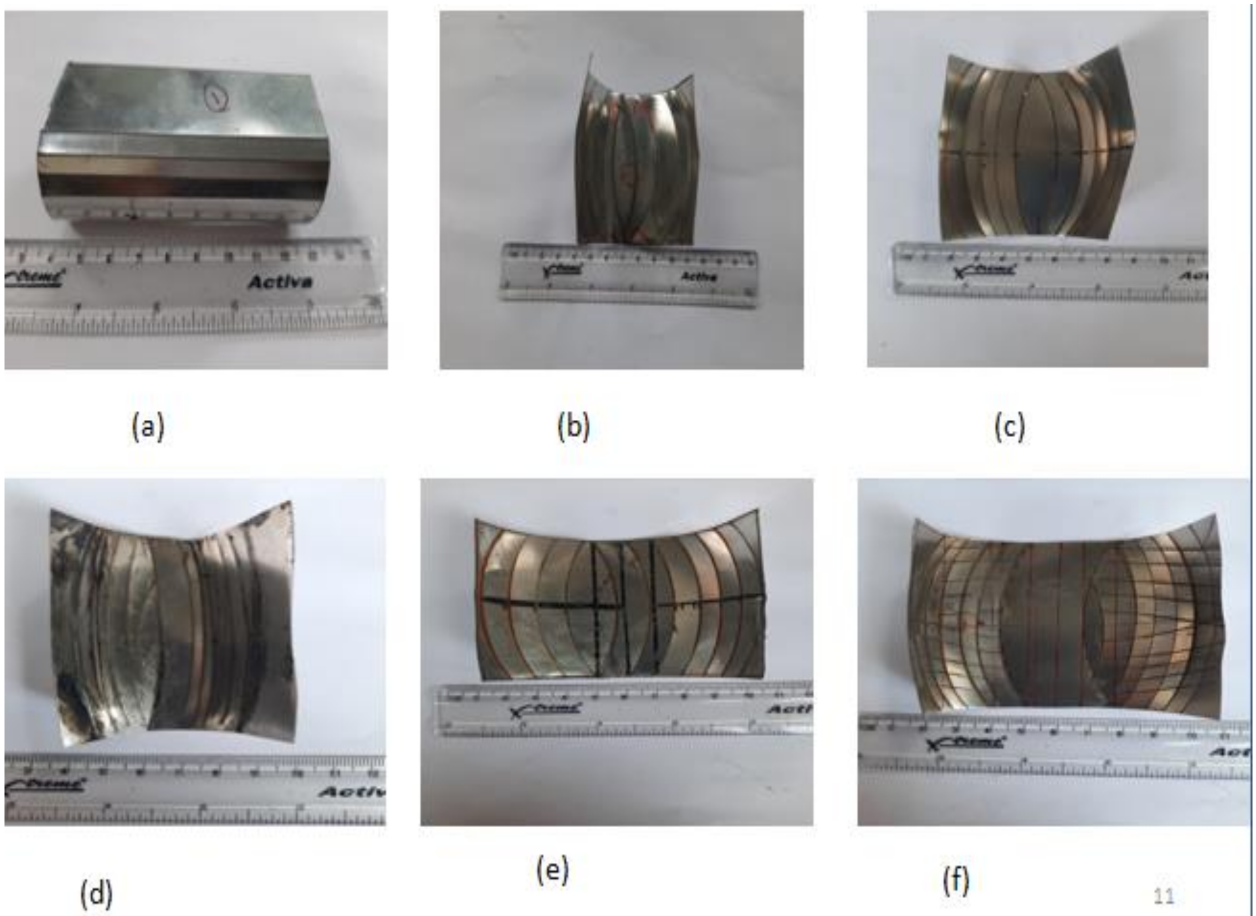


Fig. 3.6 Initial iteration on steel for making the correct profile

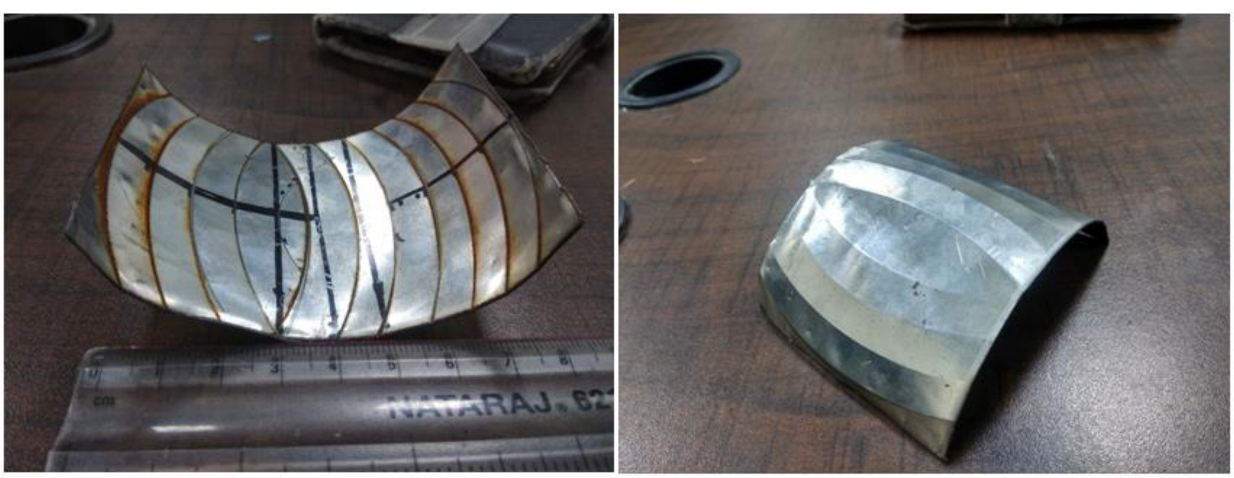


Fig 3.7: final required profile on the SS profile

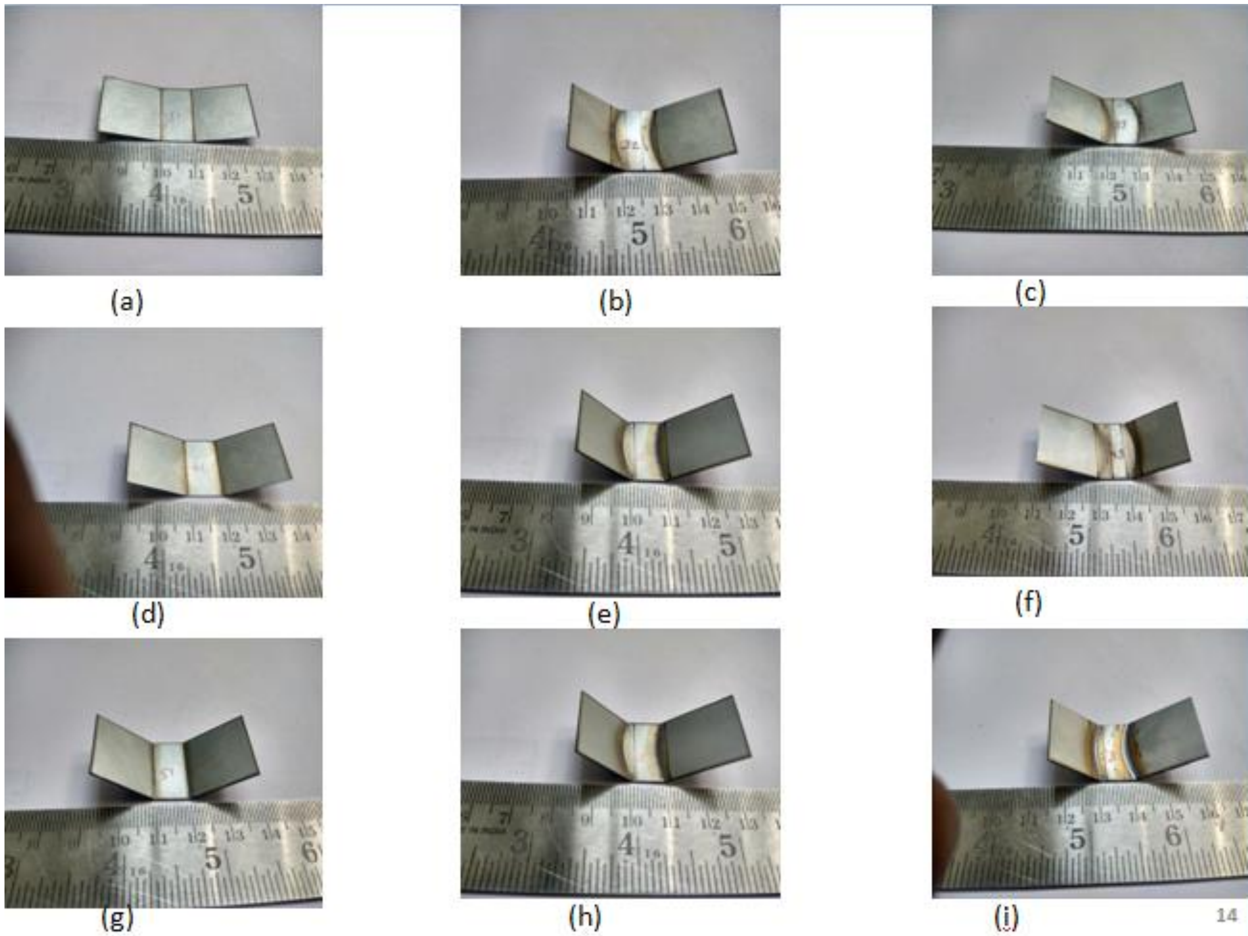


Fig 3.8 Sample of SMA laser forming

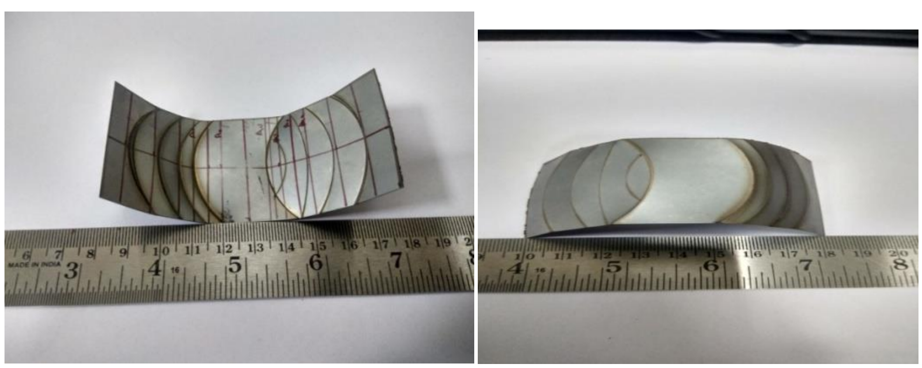


Fig 3.8: Desired profile

3.4 Methodology:

Below chart show the methodology:

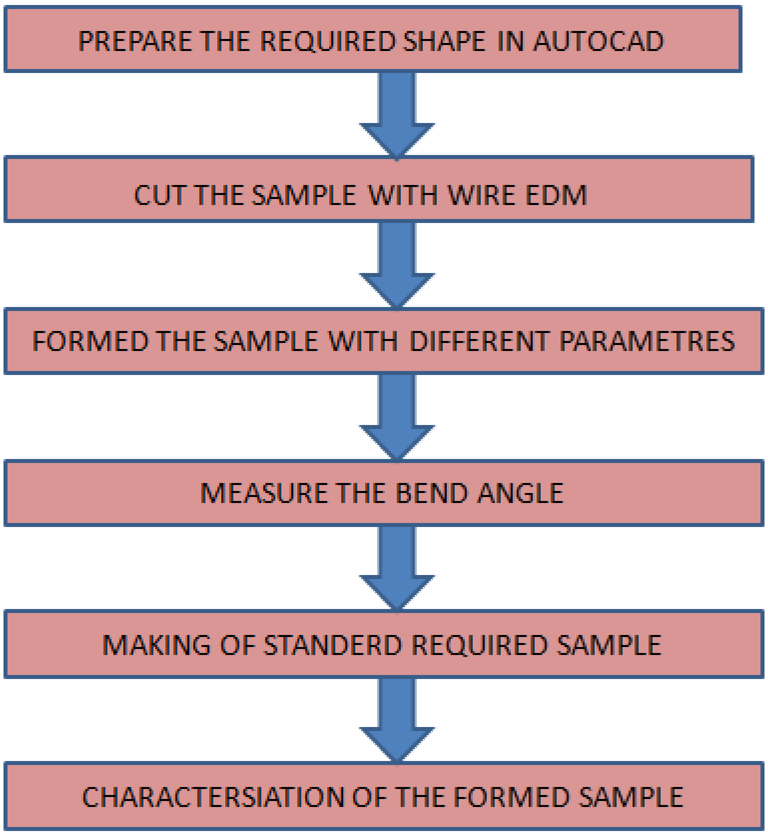


Fig. 3.9 methodology flow chart

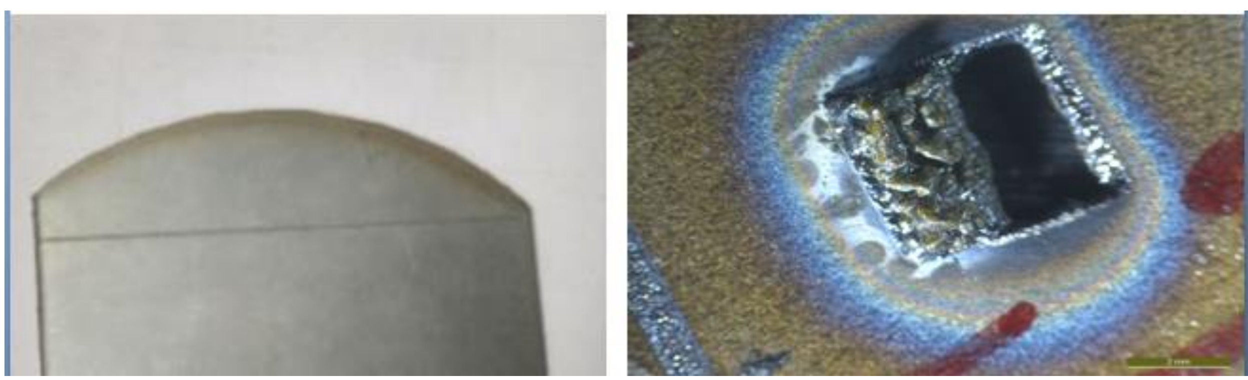
Chapter 4: Results and Discussion:

Laser power selection, the variation of bending angle with respect to power and scan speed is discussed in this chapter. Also the SEM images and microstructure image of the irradiated area are shown in this chapter. The change in the phase transformation temperature, anisotropy of the SMA Sheet, XRD analysis was done.

4.1 Laser Power selection:

For laser power Selection in the experiment we passes the laser on the workpiece from minimum power to the power where the forming start to the power where the cracks start in the metallic sheets.

The laser power selection for experiment is 25, 30 and 35 W because below 25 W there is no Forming in the SMA Sheets and above 35 W melting of sheet take place for the same no. of passes. Image of which are as follows:



(a) (b)

Fig: 4.1 (a) laser irradiated with power 20W; (b) Laser irradiated with power 40W

4.2 Bending angle Vs Power:

Variation of the bending angle with respect to the laser beam power is discussed here When Ni-Ti sample Sheet is subjected to the laser beam at three different powers i.e. 25, 30,35W. As the power is increased the bend angle is increase due to the thermal compressive stress induce in the irradiated area of the sample. As the time of irradiation increase the increment in the bend angle is not so fast as it was earlier because of the decrement of the thermal extension and plastic deformation of the irradiated surface. It shows that there is an maximum temperature corresponding to the maximum bending angle after which there is negligible change in the bend angle while increasing the time duration for which the laser is irradiated on the Ni-Ti sheet. This shows a nonlinear relationship between the bending angle and power.

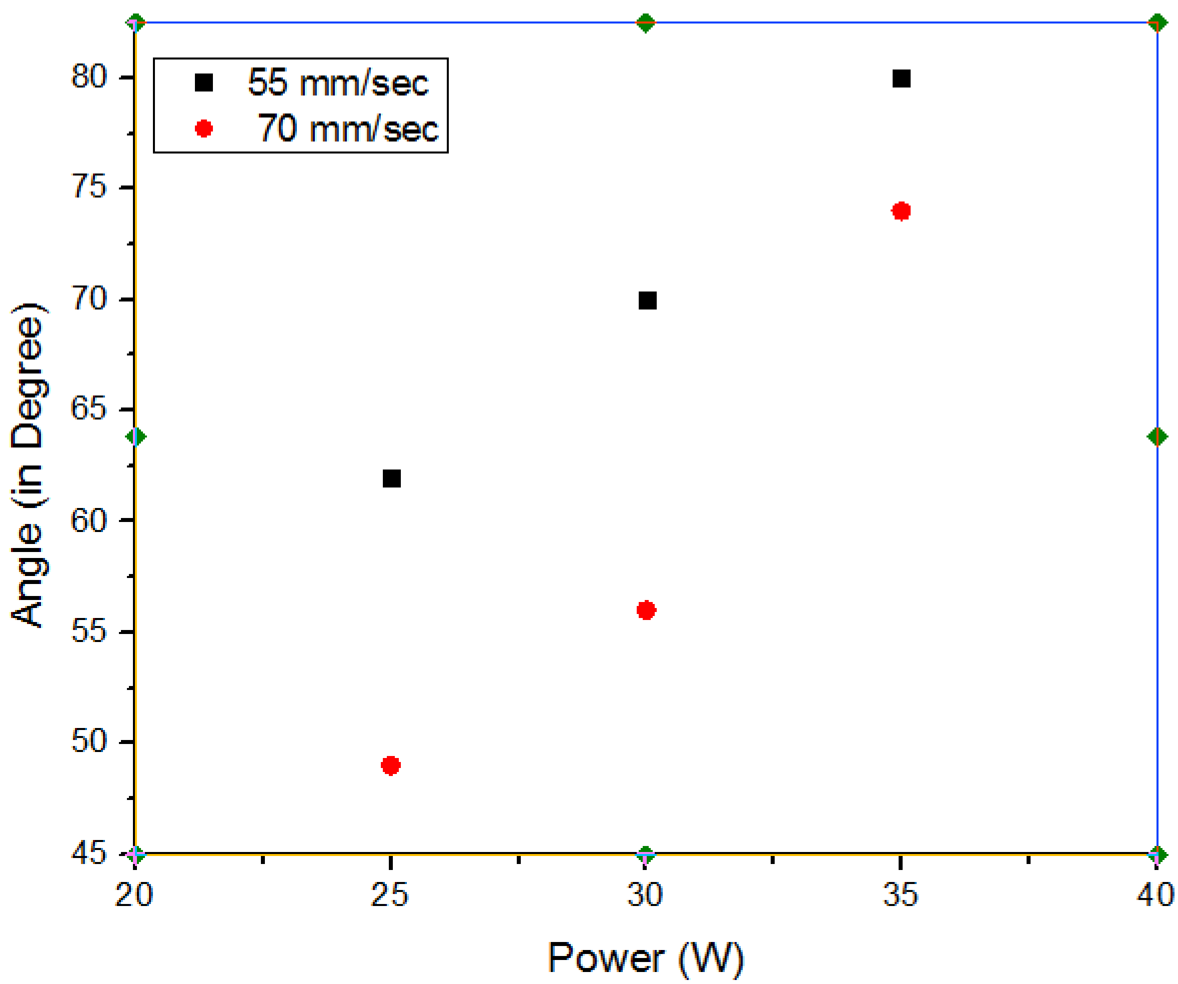


Figure 4.2 Bending angle variations with power.

Table 2 Variation of bending angle with power

Power (W)	**Bend angle (in Degree)**
25	62
25	49
30	70
30	56
35	80
35	74

4.3Bending angle Vs Scan speed:

Variation of bending angle with respect to the laser scan speed are discussed here when Ni-Ti sheet is subjected to the different scan speed i.e.40,55,70 mm/sec..Figure shows the change in the bending angle with reference to the scan speed. It shows that the power and scan speed are two important parameters which are affecting the bending angle of sheet. As the scan speed of the beam increase the bending angle is decrease as the time interaction of laser and workpiece is reduce which induce less thermal compressive stress and result in less plastification of the irradiated zone in the SMA Sheet and less thermal expansion to the opposite side of the sheet leading to less forming of the desired sheet hence less bending angle. Scan speed and the bending angle shows the inversely relationship between them.

Table 3 Variation of bending angle with Scan speed:

Scan Speed (mm/sec)	**Bend angle (in Degree)**
55	62
55	70

55	80
70	49
70	56
70	74

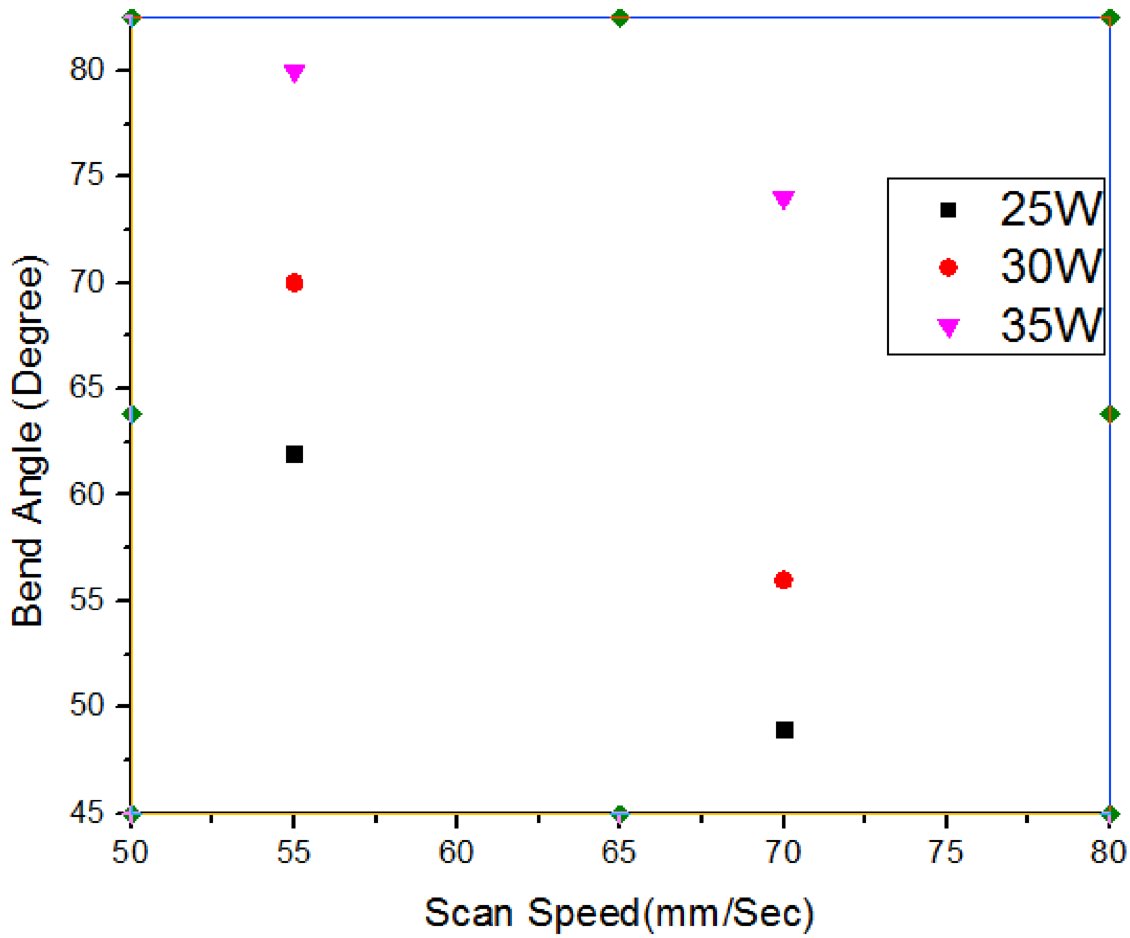
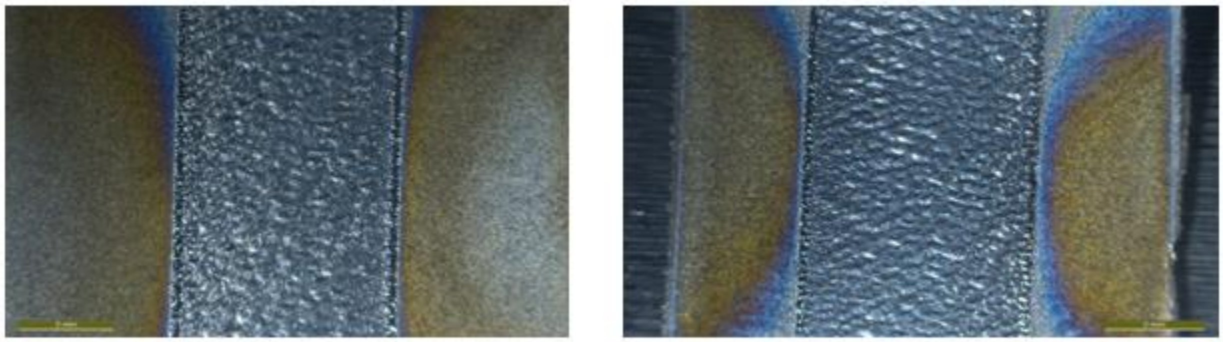


Figure 4.3: Bending angle variations with scan speed.

4.4 Microscopic Image:

The microscopic image of the irradiated sample are shown in the fig. the figure shows that as the laser power increases the heat affected zone is also increases which is shown in the diagram by the change in the colour near the irradiated region. In figure the sample is irradiated with the power 25W and 35W.



Power = 25 W　　　　Power = 35 W

Fig. 4.4 Microscopic image at different power

4.5 SEM Images:

SEM (Scanning electron microscopy) gives the information about the samples external morphology (texture). Below figure shows the SEM and EDX image of the Base material. The EDX image of the base material shows that there is equal composition of both Ni and Ti in the NiTi alloys thus Ni is 50% and Ti is 50%.

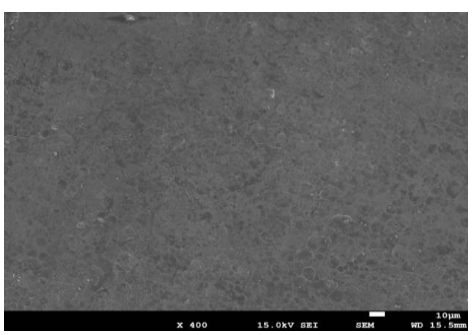


Fig 4.5: SEM image of the base Sample

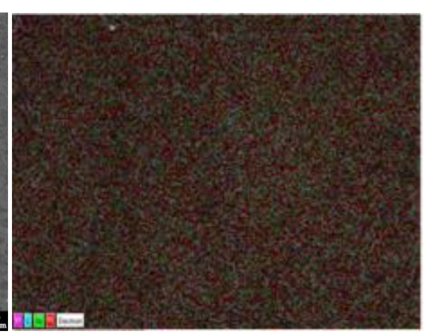


Fig 4.6: EDX of the base Sample

SEM IMAGE AT POWER 25W:

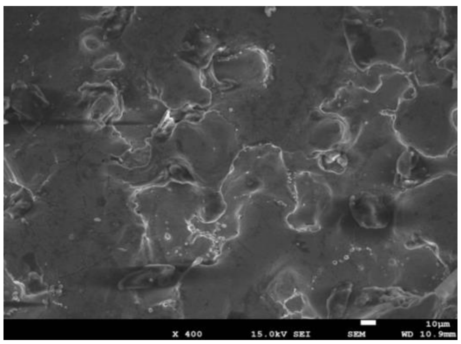


Fig 4.7: SEM image of the laser irradiated zone

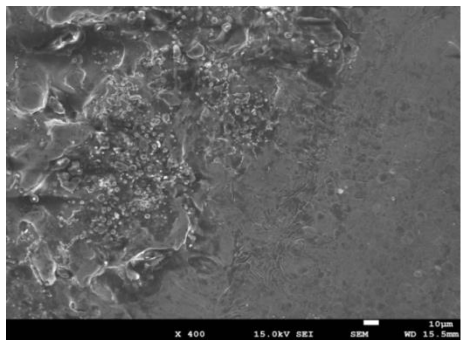


Fig 4.8: SEM image of the transition zone

SEM IMAGE AT POWER 30W:

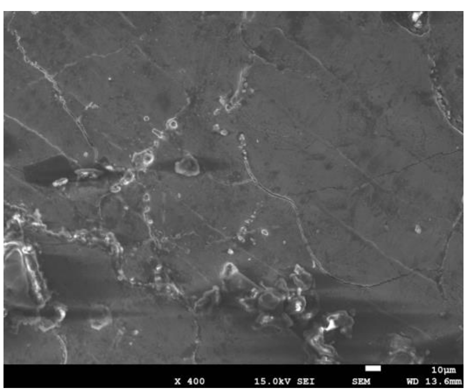


Fig 4.9 : SEM image of the laser irradiated zone

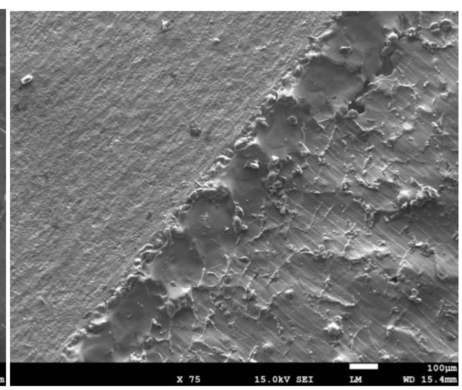


Fig 4.10: SEM image of the transition zone

SEM IMAGE AT POWER 35W:

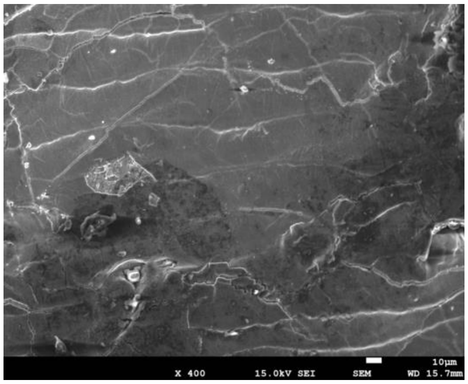


Fig 4.11: SEM image of the laser irradiated zone

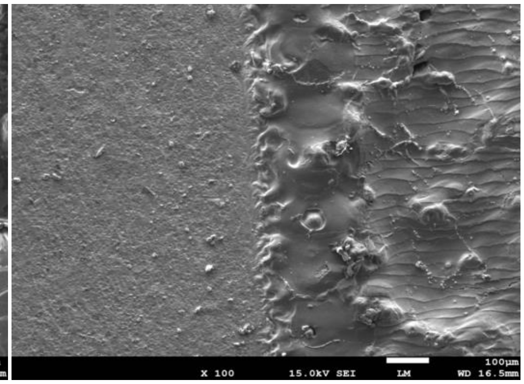


Fig 4.12: SEM image of the transition zone

4.6 X- ray Diffraction (XRD) analysis:

The X-ray diffraction (XRD) analysis was carried out to analyze the effect of laser on the phases of Ni-Ti. Figure shows the comparative plot of the Diffraction pattern of the Ni-Ti sheet of base material and the sheet irradiated with the laser. The indexed pattern of the Ni-Ti sheet base material and the sheet with laser irradiation shows the same pattern which consist of the B2 cubic austenite phase. It is to be noted that there is no intermediate phase.

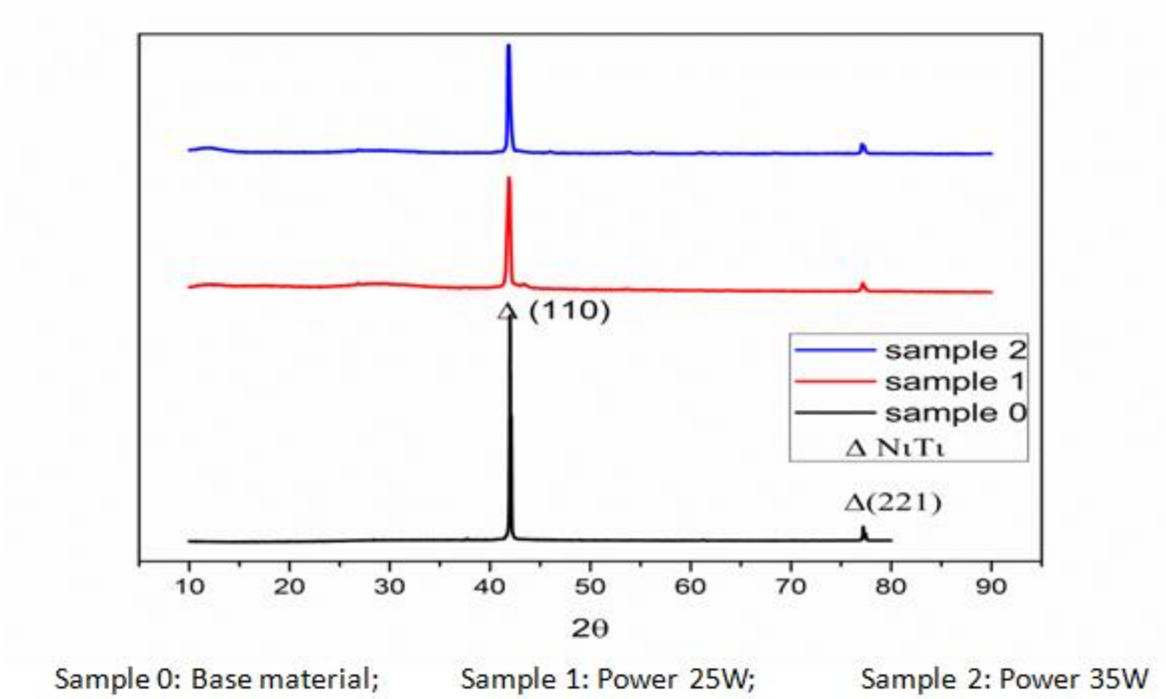


Fig 4.13 XRD plot at different power

4.7 DSC analysis:

Differential scanning caliometry is used to identify the change in phase temperature when the material is subjected to some processing. In DSC we require the small sample of approx 5mg which is put in the ceramic crucible and heated from -50 degree C to 150 degree C. all the sample is heated one by one and the change in the phase transformation temperature is observed in base sample and in the formed sample. Figure below shows the differential scanning caliometry curves of Ni-Ti sheet for base material and the sample at 25W and 35 W. It is seen from the DSC curves that there is a significant single stage transformation in both heating and cooling curve. The reversible transformation start and finish temperatures of austenite are denoted as As, A_f and for martensite as Ms, M_f . As seen from the Differential Scanning Calorimetry (DSC) plots, forward and reverse transformations showed a slight shift in transformational temperatures after laser Forming. The transformational temperatures are affected by the presence of precipitates, dislocations, grain size, thermal stress and detwinning. During Laser forming of NiTi, the refinement of grains and detwinning in the irradiated region could be the cause of the shift in the transformational temperatures

.

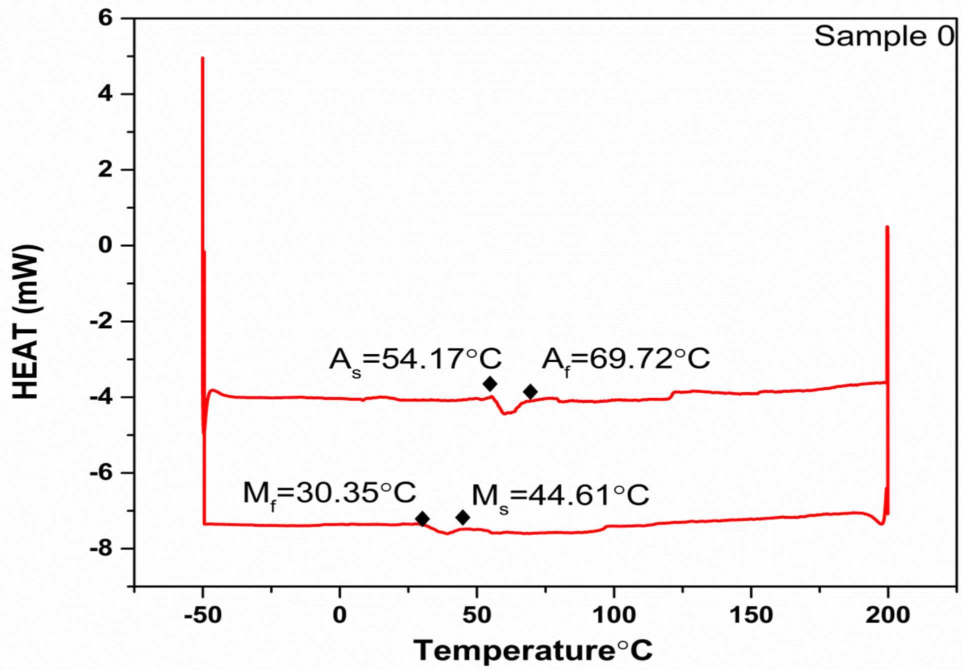


Fig 14: DSC of base

The Austenite start temperatures are (As) = 54.17^{0}C and the austenite finish temperatures are (A_f) = 69.72^{0}C. Also in the cooling curve the martensite start are (Ms) = 44.61^{0}C and the martensite finish temperatures are (M_f) = 30.35^{0}C. During heating martensite will transform into austenite and while cooling austenite will transform into martensite.

TABLE 4 FOR BASE MATERIAL

S.No.	Phase	Temperature(^{0}C)
1	A_s	54.17
2	A_f	69.72
3	M_s	44.61
4	M_f	30.35

DSC OF THE SAMPLE IRRADIATED WITH 25W:

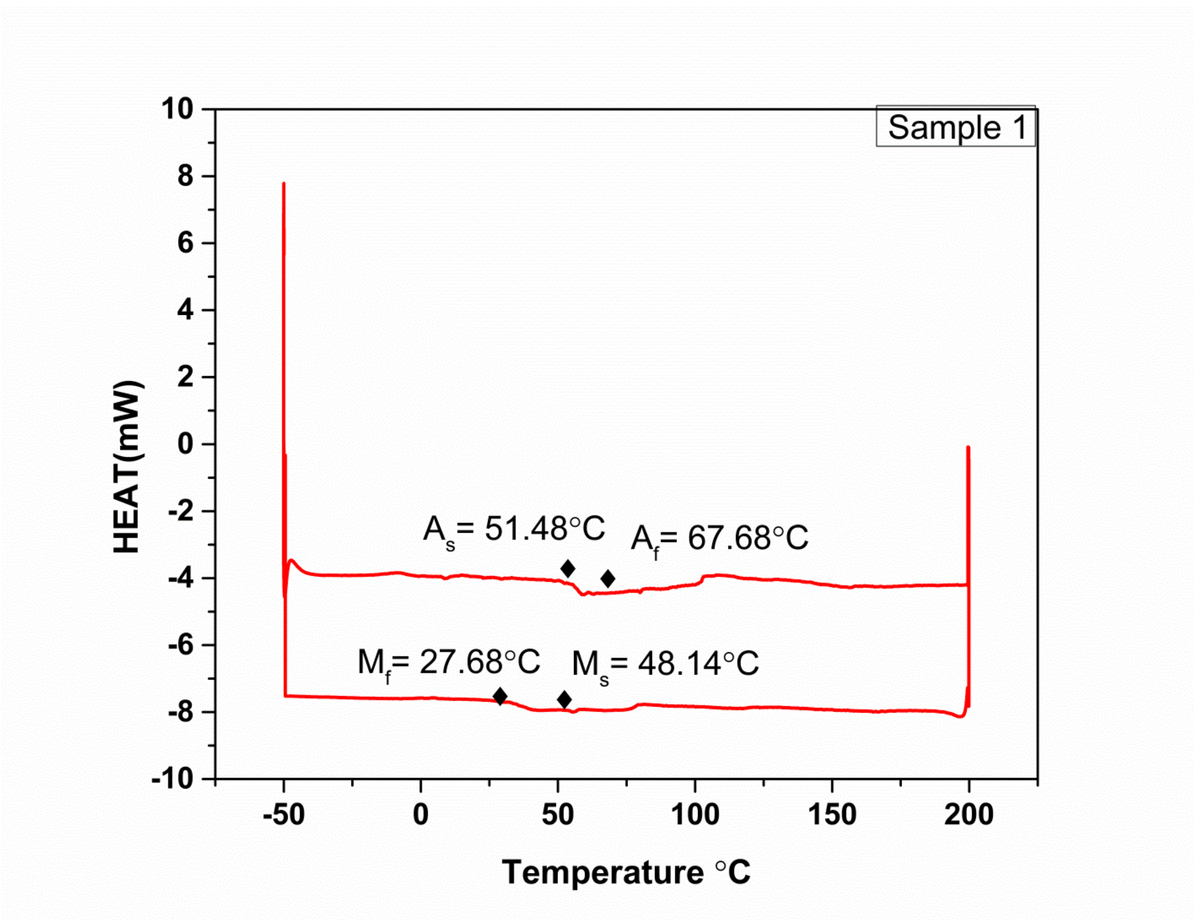


Fig 4.15: DSC of the Sample irradiated with 25W

Table 4.4 for phase Transformation Temperature at 25W:

S.No.	Phase	Temperature(^{0}C)
1	A_s	51.48
2	A_f	67.68
3	M_s	48.14
4	M_f	27.68

DSC FOR SAMPLE IRRADIATED WITH 35W POWER

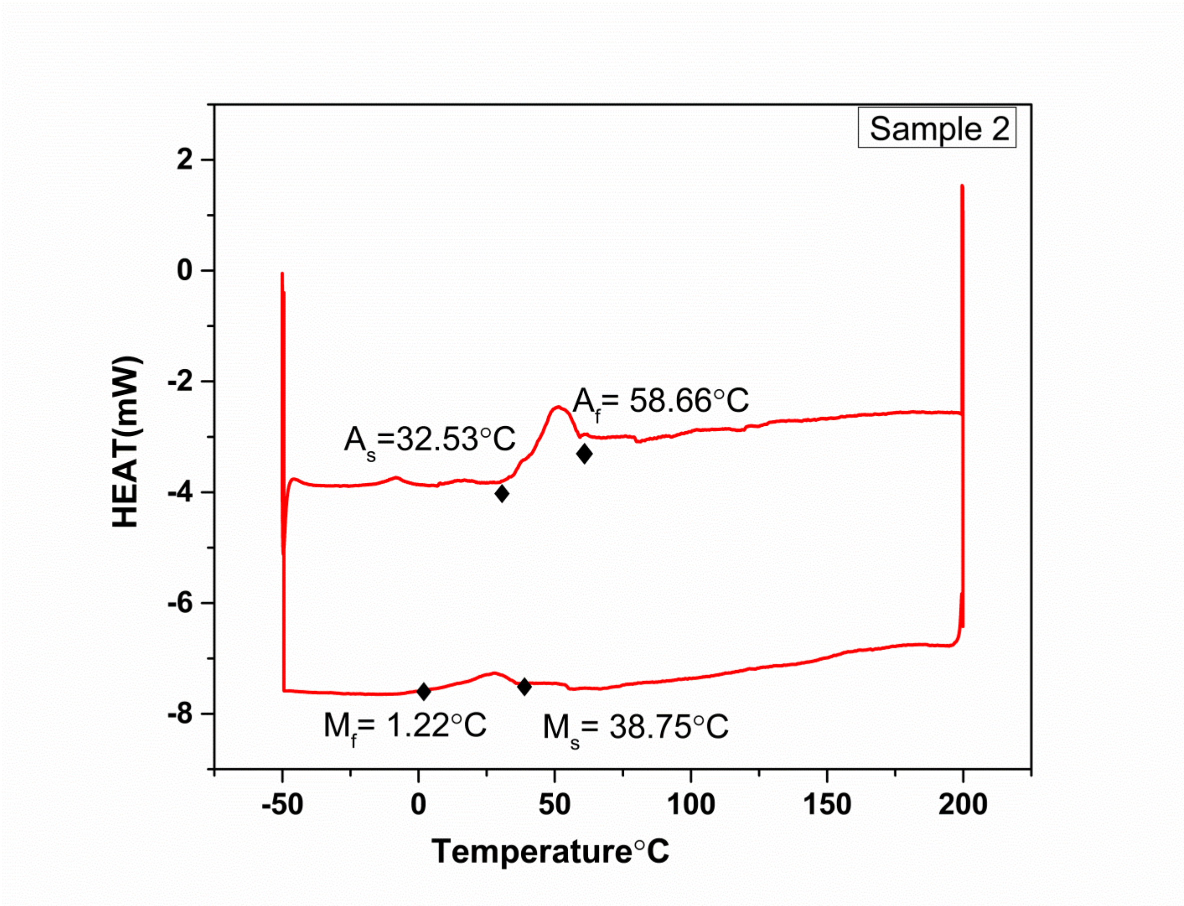


Fig 4.16: DSC of the Sample irradiated with 35W

Table 5 for phase Transformation Temperature at 35W:

S.No.	Phase	Temperature(^{0}C)
1	A_s	32.53
2	A_f	58.66
3	M_s	38.75
4	M_f	1.22

4.8 Anisotropy of the Ni-Ti Sheet:

For checking anisotropy the load of 50 gram are applied. Fig shows the sample preparation for the microstructure Image i.e. Hot Mountingand the images of indentation.

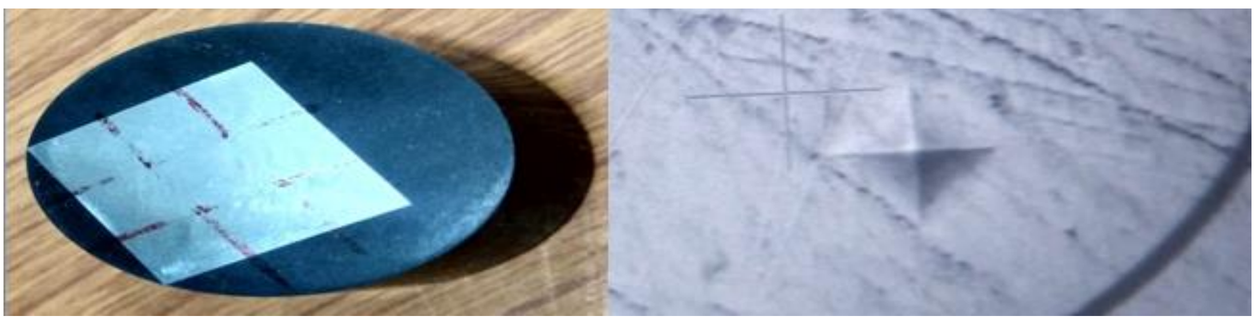


Fig4.17: Hot mounted SMA Sheet and microstructure Image of indentation

The pattern of the Hardness checking point is shown in the below figure:

7		5
6	4	
1	2	3

Fig4.18 arrangement of points in sample for hardness test

The hardness value are Tabulated as:

Table 4.5 Hardness value

Point number	**Hardness value(HV)**
1	260
2	279
3	273
4	299
5	270
6	279
7	291

The given Hardness value shows that the hardness is of uniform nature in the SMA Sheet.

Chapter 5: Conclusion and Future Recommendation

The main aim of this thesis was to make a Desire profile and investigate the change in the properties after the 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 320mm on all the NiTi samples with a spot diameter of 0.2 mm at different Scan Speed and at differentpowers.

In current work laser forming on Ni-Ti sheets of 0.40 mm were performed. The variation in the bending angles with respect to the process parameters was calculated and it is found that there is a certain non-linear increment in the bending angle with an increment of power and Scan speed. 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 25W and 35W and Scan Speed at 40, 70mm/sec. XRD analysis was also done where result shows that there is no extra phase generation in the Laser irradiated area while laser forming. The SEM image and EDX of the base material shows that the composition of NiTi in the base material is equal i.e. 50% Ni and 50% Ti. SEM image of the laser irradiated region shows that there is small cracks on 35W power. The microstructure image Shows that as the power increases the heat affected area also increase. The base material is isotropic in the nature.

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 Scan speed.

- There is a non-linear increment in the bending angle with increase in power and Scan Speed.
- There is Single stage transformation in the NiTi.
- There is No extra phase is generated in the irradiated region.
- There are small cracks in the material at 35W.
- The Base material is isotropic in the Hardness

Future recommendations:

The research can be extended to achieve the better heat control on the surface of the material by changing the spot diameter or Scan Speed of the laser.

The problem coming in the proper variation of the bending angle with the power and the Scan Speed which can be optimized. It can be used to make several other shapes according to the shape of the body for the other applications where the precise control in the forming is required.

The thermo couple can be employ to the surface of the Sheet while laser processing so that 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.

Different kind of the coating can be applied on the surface of the Workpiece such as charcoal, lime etc. so that the absorption can be increase and help in the bending of the Sheet.

Moreover, the underwater laser forming can also be done in order to control the heat rate and temperature range.

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