Finite Element Simulation ForThermal Analysis In Laser Forming Of D36 Ship Building Steel

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Abstract: ***The laser bending process is one of the advanced bending processes which can be achieved by elasto-plastic deformation through the local introduction of thermal stresses. It is a thermo-mechanical process in which a laser heat source of suitable power is used for bending the material rather than any external force. In this work, sequential thermal analysis is carried out for SOLID70 element by using ANSYS. The deformation of a sheet, subjected to an irradiation, has been studied through a sequentially coupled thermo-mechanical elasto-plastic simulation by using the finite element model (FEM). D36 shipbuilding steel sheet has been taken as the work-piece material for the analysis. The thermal effects due to heat input into the work-piece are analyzed which includes temperature distribution, thermal flux distribution, thermal gradient distribution and variation of thermal properties with time.***

Keywords: Laser beam forming, Gaussian distribution, FEM.

1. Introduction and Literature Review

Laser beam forming (LBF) is a non-contact process of forming the sheet by localized heating with the help of a laser beam which induces thermal stress gradients throughout the thickness of the sheet, causing localized plastic deformation of the sheet without use of any external force. A laser bending process has many advantages such as no mechanical spring-back effect, precise incremental adjustment, high level of process flexibility, easiness to control, eliminated need for tooling, excellent energy efficiency, variety of applications, possibility to form hard-to-formed materials and the capability of production of complex shapes due to which it has shown a great promise and so has lately been the subject of considerable interest. LBF mechanisms mainly include Temperature gradient mechanism (TGM), Buckling mechanism (BM) and upsetting mechanism (UM). Potential applications of laser manufacturing include cutting of complex shapes, drilling on curved surfaces, surface treatment, welding of dissimilar metals etc. With increasing knowledge, the process offers significant potential value to industry such as, shipbuilding, microelectronics, aerospace etc.

In laser bending of sheet metals, the temperature gradient developed in the direction of the thickness plays an important role controlling the bending angle. In the process of laser bending, sheet metal is heated above the melting temperature due to which a shallow melt pool is developed in the heated region. As a result temperature gradients are formed in the vicinity of the melt pool which causes the development of thermal stress field in this region during the solidification. Because of the complexity faced in the physical process involved with laser bending process, model studies have been carried out which can provide useful information on the physical process taking place during the heating and cooling cycles of laser processing. Moreover, model study reduces the experimental cost and time. In addition, the investigation of laser bending of sheet metal becomes essential day by day as per the increasing demand. In the present work ANSYS has been used for model study.

Jibin*et al.* [1], in their work carried out a three-dimensional FEM simulation which includes a non-linear transient coupled thermal-structural analysis accounting for the temperature dependency of the thermal and mechanical properties of the material. The time-dependent temperature distribution, stress, strain and bending angle were obtained from the simulations and the results are in agreement with the experimental results. Cheng and Lin [2] established an analytical model to describe the three dimensional temperature field for a finite plate with a Gaussian heat source moving at a constant velocity. They also studied the effects of the laser forming parameters on the temperature distributions using the established model. In their study, the temperature-dependent thermal conductivity of the material is considered. Based on their study, it can be concluded that the distance between the center of the laser spot and the location where the peak temperature occurs increases slightly as the beam diameter and the scan velocity increases. Also the temperature decreases with increase in thickness. Simulation of the transient deformation of thin grade 304 stainless steel metal sheets heated by a single pulse of a CO_2 laser beam were analyzed by Hsieh and Lin [3]. In their work, the laser beam was assumed to be Gaussian mode and the coupled thermo-elasto-plastic problem was treated as three-dimensional. They numerically calculated the temperature field, deformation pattern, stress–strain states, and the residual stress distribution of the specimen and the transient response of the bending angle was validated by experiments. The results obtained from their numerical study revealed that a high temperature gradient exists for a positive bending angle and a low one for a negative bending angle. Guan *et al.* [4] established a three dimensional coupled thermo-mechanical finite element model. They studied 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 by FEM simulation. The simulations showed that the thermal expansion coefficient is nearly in direct proportion to the bending angle and the bending angle decreases as the heat conductivity increases. Ueda *et al.* [5] used temperature distribution for determining the bending angle. In their study, the combined effect of the temperature of the work-piece, the temperature gradient between the two surfaces of the sheet, the size of the area irradiated with laser beam, and the thickness of the work-piece were investigated both theoretically and experimentally. They measured the temperature at the surface irradiated with CO_2 laser. The bending angle was found to increase with the increase in spot diameter and work-piece surface temperature and decrease with work-piece thickness. Marya and Edwards [6] analyzed the laser bending of Ti–6Al–2Sn–4Zr–2Mo sheets using a well-known conduction model of a traveling Gaussian heat source, which can relate process variables to physical events known to occur at particular temperatures.

In this work, a detailed thermal analysis has been carried out by using FEM, where the work-piece is modeled as like a cantilever beam by fixing one end and keeping other end free. Laser beam of different powers are made to pass with different velocities along the centerline, parallel to the fixed end.

Attempts are going on to carry out curvilinear laser bending and producing various forms on the sheets. The mathematical modeling of the process, inverse modeling, optimization, and control are hot research areas along with experimental research. It is envisaged that research and applications in the area of laser bending will be strengthened in the near future.

2. Finite Element Model For Thermal Analysis

The element used for thermal analysis in ANSYS is SOLID70, which is an eight-noded thermal mass, solid brick element. SOLID70 has a three dimensional thermal conduction and convection capability with a single degree of freedom, temperature at each node. The element is applicable to a three dimensional, steady state or transient thermal analysis with or without material nonlinearities. The dimension of the work-piece is taken as 40mm (length) × 40mm (width) × 2mm (thickness).The work-piece is divided into 40 elements along each side and 2 elements along the direction of the thickness. The total elements are 3200 i.e. 40 elements along the X-direction (width), 40 elements along the Y-direction (length) and 2 elements along the Z-direction (thickness). X-Y-Z represents the global cartesian co-ordinate system and local cylindrical co-ordinate systems are defined at each node through the centreline along the X-direction.

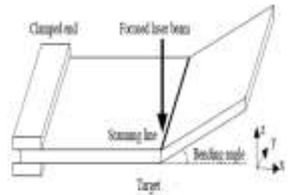

Figure1: Arrangement of work-piece.

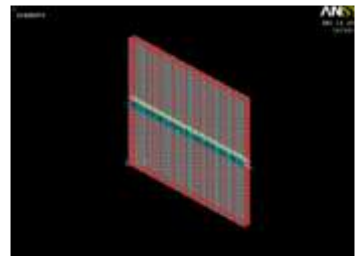

Figure2: Meshed model of the work-piece.

2.1 Heat Input Model

Laser beam is scanned along the centerline of the work-piece. The heat input is modeled as moving heat source over the top surface of the work-piece parallel to the fixed end i.e. along X-direction. The heat flux is applied at the local co-ordinate system and is shifted from one local co-ordinate system to the next local co-ordinate system at each load step to assume moving heat flux. The heat flux generated by the laser beam can be assumed to have Gaussian distribution which can be expressed as

$$I(r) = \frac{2AP}{\pi R^2} e^{-\left(2r^2 / R^2\right)}$$

Where, I is the heat flux distribution, A is the absorption coefficient of the work-piece surface, P is the laser beam power, R is the laser beam radius and r is the distance from the center of the laser beam. Here the laser beam power P=0.75kW, absorption coefficient of the work-piece surface A=0.68 and the laser beam radius R=2mm.

Heat affected zone has not been analyzed in this work. This study investigates the laser forming processes using the finite element analysis with respect to material responses during the processes, including complex processes, process optimization, process reliability and the effects of thermal and mechanical material properties. Bending angle formed during laser forming process is due to the thermal stress developed along the thickness of the work piece material. A detailed study of thermal effects on the work piece during laser forming process has been carried out in this work by using finite element modeling, which includes distribution of temperature, thermal flux and thermal gradient. The developed model considers temperature-dependent thermal properties and a Gaussian moving heat flux source applied on the external surface of the work piece.

2.2 Material Model

Material properties which are temperature dependent are important for the accurate calculation of temperature field distribution. The temperature dependent material property includes thermal conductivity, specific heat and density. Different values of these properties for different temperatures are taken from linear interpolation data provided by the table listed below.

I. TABLE 1. THERMALPROPERTIES OF D36 SHIPBUILDING STEEL [7]

Temperature [°C]	*Thermal Conductivity [W/m°C]*	*Specific Heat[J/kg°C]*	*Density* $[Kg/m^3]$
20	35.1	427	7860
200	36.8	502	7795
400	36.2	602	7725
600	32.0	741	7654
800	25.8	686	7609
1000	27.2	653	7604

2.3 Boundary Conditions

The room temperature is considered to be 20°C and the work-piece is assumed to be surrounded by air at room temperature. The heat flux generated by the laser beam is applied on the top surface of the work-piece which is given by equation (1). On the other hand, the heat flux at the bottom surface is assumed to be only due to convection with convective heat transfer co-efficient h=10 W/m^2°C.The conduction of heat between the work-piece and the support to hold the work-piece is not considered during the analysis. Material may undergo phase transformation at elevated temperature during laser assisted bending. The maximum temperature attained by the work-piece is kept below the melting point of steel which is around 1400°C. So it is assumed that the surface of the work-piece will not melt, and hence the effect of phase change and latent heat is not considered during the analysis. The analysis was performed up to the time point when the work-piece was cooled to room temperature. It is also assumed that the cooling of laser beam irradiated material occurs due to free convection of heat to the air.

2.4 Results Of The Simulation

The ANSYS-APDL code is used to study the effects of laser heating of the work-piece. The results presented in this section include temperature distribution, thermal flux distribution, thermal gradient distribution and a parametric study to investigate the thermal effects of two most influential operating parameters, viz. laser power and scanning velocity. The dimension of the work-piece is kept constant throughout the analysis, i.e 40mm × 40mm × 2mm.

Power(Watt), Scan Speed(mm/s), Thickness(mm) of the plate, Absorptivity of the plate material. In this case we fix the dimension of the work piece as 40mm(length)×40mm(breadth)×2mm(thickness).

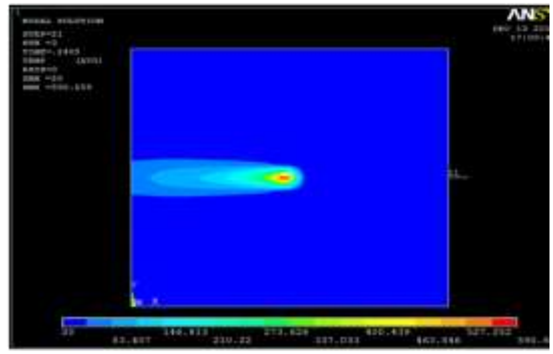

Figure 3: Temperature distribution at 0.2405 sec along X-direction on the top surface of the work-piece.

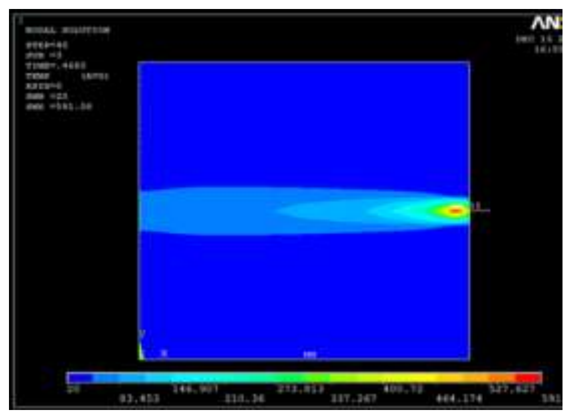

Figure 4: Temperature distribution at 0.4685 sec along X-direction on the top surface of the work-piece.

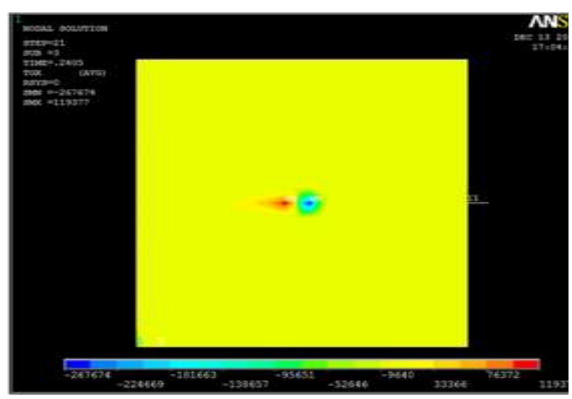

Figure 5: Thermal gradient distribution at 0.2405 sec along X-direction on the top surface of the work-piece.

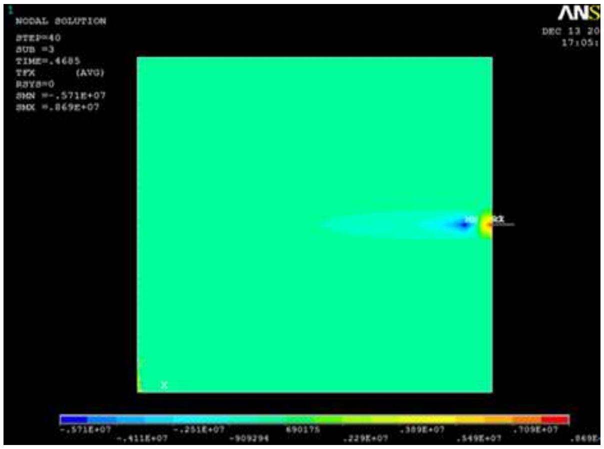

Figure 6: Thermal flux distribution at 0.4685 ec along X-direction on the top surface of the work-piece.

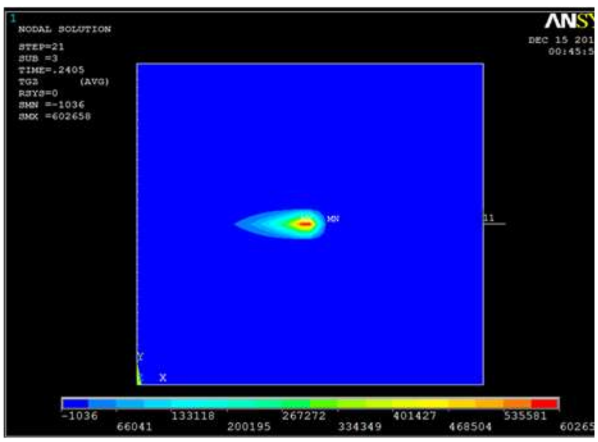

Figure 7: Variation of thermal gradient with time at 1200W along Z-direction.

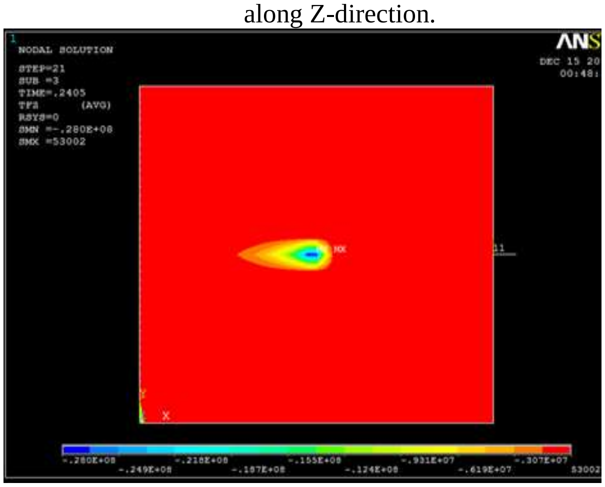

Figure 8: Variation of thermal flux with time at 1200W along Z-direction.

Figure 3 and 4 shows the distribution of temperature on the top surface of the work-piece along the laser irradiated path. Maximum thermal stress occurs at the region shown by the red colour which increases with the number of passes of the laser beam. From the figure it is observed that the maximum temperature attained by the work-piece is 591.08°C. Figure 5 and 6 shows the distribution of thermal gradient and thermal flux respectively along X-direction at different time levels. The maximum value of thermal flux distribution is found to be 0.869×10^{7} J/m^{2} and the maximum value of thermal gradient distribution is found to be 119586 °C/

3. Effects of laser power

Scanning speed of the laser beam is kept constant at 80mm/s during the investigation of the effects of laser power. As the laser power increases, the amount of heat input increases and hence the thermal properties of the material like temperature gradient along the direction of the thickness, maximum temperature attained by the work-piece increases.

Variations of thermal gradient as well as thermal flux at different time levels are analyzed for different values of laser power. Figure 7 shows the variation of thermal gradient with time and Figure 8 shows the variation of thermal flux with time along the direction of thickness of the work-piece. In both cases, the value of laser power has been taken as 1200W. The maximum value of thermal gradient is found to be 602658 °C/m and the maximum value of thermal flux is found to be 53002 J/m2. Different values will be obtained for different laser powers.

4. Effects of velocity

Laser power is kept constant at 0.75kW during the investigation of the effects of velocity. The time of contact between the laser beam and work-piece decreases with increase in scanning velocity and hence the amount of heat input to the work-piece decreases. As a result, small temperature gradient is developed along the thickness of the work-piece which in turn reduces the amount of bending.

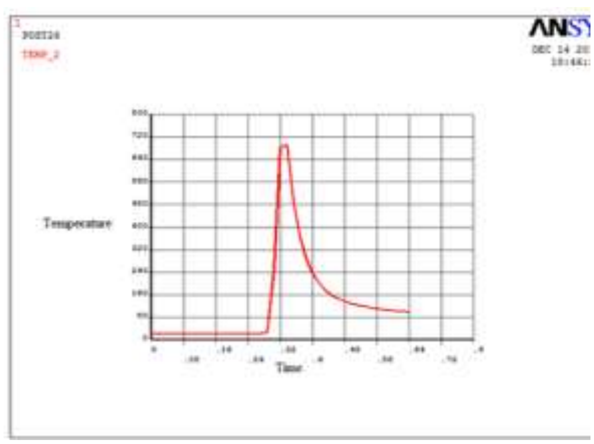

Figure 9: Variation of temperature(°C) with time(sec) at 60mm/s velocity.

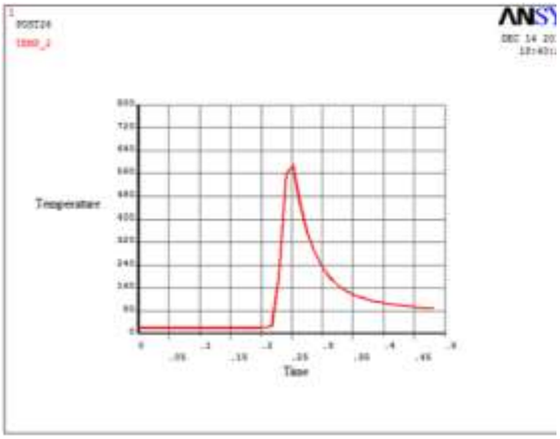

Figure 10: Variation of temperature(°C) with time(sec) at 80mm/s velocity.

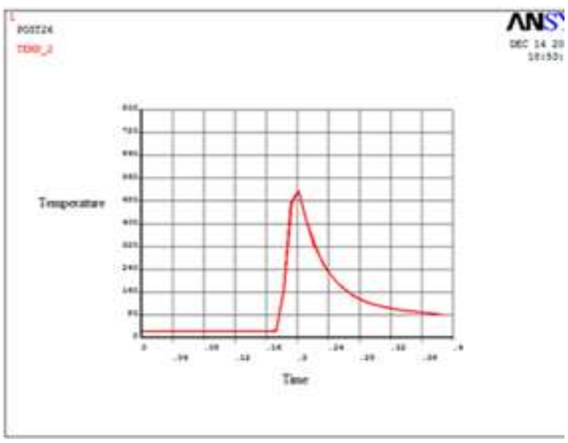

Figure 11: Variation of temperature(°C) with time(sec) at 100mm/s velocity.

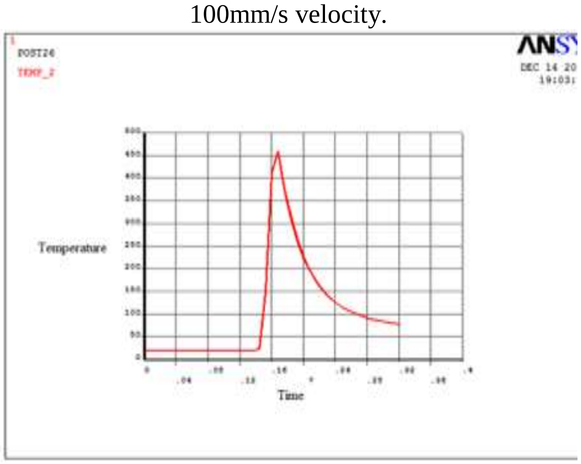

Figure 12: Variation of temperature(°C) with time(sec) at 120mm/s velocity.

Figure 9, 10, 11 and 12 shows the variation of temperature with time at different values of velocity. Gaussian distribution has been followed for the distribution of temperature. From these figures it has been observed that as the scanning velocity of the laser beam increases, temperature distribution on the surface of the work-piece decreases. From figure 9, the maximum temperature attained by the work piece at 60 mm/s velocity is found to be 690°C and from figure 12, it is found to be 460°C when the scanning velocity is 120 mm/s.

- The bending angle increases with increasing laser power.
- The time of contact between the laser beam and work piece decreases with increase in scanning speed and hence the amount of heat input into the work piece decreases. Therefore bending angle is found to be reduced for increasing rate of scanning speed.
- Maximum temperature attained by the work piece decreases with increase in sheet thickness. In this case, bending angle is found to be reduced when sheet thickness increases.

All these are process variables that can be changed or adjusted through electronic control. However, it is not possible to consider all these operating parameters affecting the desired results. Among these operating parameters laser power, scanning speed and sheet thickness are considered for the analysis in this work.

5. CONCLUSIONS

Perfect modelling and simulation of laser forming process is a complicated task. The work presented here is a humble attempt to simulate a finite element model in ANSYS and obtain the thermal effects of laser forming process for D36 shipbuilding steel. The developed model considers temperature-dependent thermal properties and a Gaussian moving heat flux source applied on the external surface of the work-piece. The two most influential operating parameters; laser power and scanning velocity are considered for the analysis. From the analysis it has been observed that the development of thermal gradient throughout the thickness of the work-piece is directly proportional to the laser power and laser power increases with increase in beam spot diameter. The effect of laser power decreases with increase in scanning velocity. Temperature distribution, thermal flux distribution and thermal gradient distribution on the surface of the work-piece are analyzed at different time levels. Variation of thermal gradient and thermal flux with time are also analyzed for different laser powers at constant scanning velocity. Also the variation of temperature with time for different scanning velocities is plotted by keeping the laser power constant.

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References

[1] P. Jibin, Z. Liwen, W. Cunshan, D. Chuang, "Numerical simulation and experimental investigation of laser bending of steel plate,"International Symposium of Research Students on Materials Science and Engineering, Department of Metallurgical and Materials Engineering, Indian Institute of Technology, Madras (2004).

[2] P.J. Cheng, S.C. Lin,"An analytical model for the temperature field in the laser forming of sheet metal,"

Journal of Materials Processing Technology, Vol. 101 (2000), p. 260-267.

[3] H.S. Hsieh, J. Lin,“ Thermal–mechanical analysis on the transient deformation during pulsed laser forming,” International Journal of Machine Tools & Manufacture, Vol. 44 (2004), p. 191–199.

[4] Y. Guan, S. Sun, G. Zhao, Y. Luan,“ Influence of material properties on the laser-forming process of sheet metals, ” Journal of Materials Processing Technology, Vol. 167 (2005), p. 124-131.

[5] T. Ueda, E. Sentoku, K. Yamada, A. Hosokawa,“Temperature Measurement in Laser Forming of Sheet Metal, ” CIRP Annals-Manufacturing Technology, Vol. 54 (2005), p. 179-182.

[6] M. Marya and G. R. Edwards,“ An analytical model for the optimization of the laser bending of titanium Ti–6Al–2Sn–4Zr–2Mo,” Journal of Materials Processing Technology, Vol. 124 (2002), p. 337-344.

[7] L. Zhang, E.W. Reutzel, P. Michaleris,“ Finite element modelling discretization requirements for the laser forming process, ” International Journal of Mechanical Sciences, Vol. 46 (2004), p. 623-637.

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