Laser Damage Effect Studies with Hollow Metallic Targets

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Abstract: Present paper deals with the investigations of the effects of interaction of laser beam with mild steel hollow cylinderical surface for different boundary condition. The design of such type of target has been shown in the analysis. The outer and inner surface temperature profile under different environment conditions is analysed through simulation software. The effect of environment conditions on the temperature profile of the target heavily depends on the convectinal heat transfer coefficient (h), which depends on the wind velocoty. It also depends on various parameters like ambient temperature, power density, target thickness and other thermo-physical properties. The power on the target was 1.5 kW out of 2 kW is equally divided into two circles. It is assumed that incident power at target is equally distributed in the inner circle and annulus of the beam i.e. the power absorbed by the target material is 300 W in inner circle and 300W in the annulas. For thicker target, heat diffuses through it slowly with respect to time. The temperature of the target increases rapidly with time and reaches more than its melting temperature in some cases depending on the heat coefficient and power density and absorption conditions. The temperature distribution along radial and depths have been studied theoretically by simulating the environment conditions through ANSYS software.

Index Terms: Ablation, Damage, Laser, Laser effects, Laser material interaction, LMI

1 INTRODUCTION

When a laser beam interacts with material such as metals, some of its energy is lost due to specular reflections and scattering from the surface and the rest is absorbed at the metal surface. The interaction [1] depends markedly on the laser beam parameters, environmental conditions and characteristics of the material. At the non transmitting material interface the absorbed fraction of incident laser radiation penetrates into the bulk of material at skin depth. Subsequent absorption of this radiation by free carriers within the metal raises the temperature of its surface. As the temperature rises, absorption coefficient of metal for incident radiation increases resulting in stress and distortion of the surface. In the limit, catastrophic damage [3, 4] may occur due to mechanical failure by melting of the surface. When upper surface layer temperature rises up to vaporization temperature, significant mass gets ablated from the surface.

The temperature rise of at a depth z below the surface at a time t after the beam is incident on metal sheet and the heat flow starts is given by:

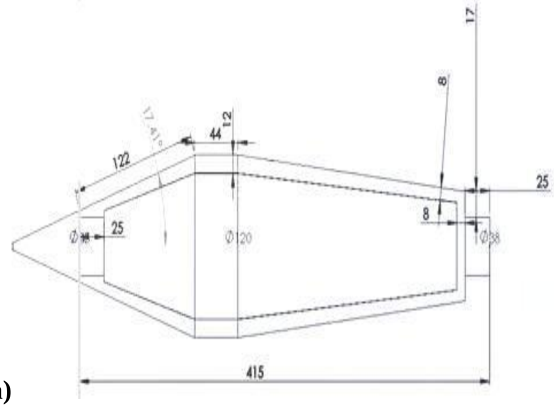
$$T(z,t) = \frac{2H}{K}\sqrt[2]{(\chi t)}\,ierfc\left[\frac{z}{2(\chi t)^{\frac{1}{2}}}\right]$$

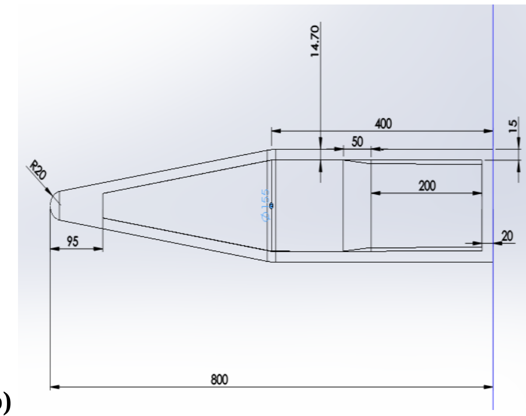
The energy Q required to ablate the mass, Δm of a thin plate is given by:

$$Q = \Delta m * s(T_m - T_0) + \Delta m * s(T_v - T_m) + \Delta m * L_m + \Delta m * L_v$$

Where, T_0 is ambient temperature, Δm is ablated mass from target, s is specific heat, T_m is the melting temperature, T_v is vaporising temperature, L_m is latent heat of melting and L_v is latent heat of vaporisation of target material.

Fiber laser beam of 19.6 mm diameter and divergence of 0.39 mrad created a spot of 10 mm diameter on to the target with the help of suitable optics. The geometries of two types of shell structured target are given in fig 1(a) and 1(b).

(a)


(b)


(a) Diameter: 120 mm, Length : 415 mm, Wall Thickness at laser interaction point: 12 mm
(b) Diameter: 155 mm, Length : 800 mm Wall Thickness at laser interaction point: 14.7mm

Fig-1 Schematic of Cylindical shell Targets

2 TARGET MATERIAL PARAMETERS:

Physical property	***value***
Material	*MS*
Specific heat (s)	*0.435 J/gm^{0}K at 300K (varies with temperature)*
Melting point (T_m)	*17000 K*
Vaporizing Temperature (T_v)	*3100 K*
Latent heat of melting (L_m)	*275 J/gm*
Latent heat of vaporization (L_v)	*6362 J/gm*
Density of mild steel	7861kg/m^3
Absorption Coefficient	40% (average)
Emissivity	0.4
Convective heat transfer Coefficient	5 W/m^{2}K
Thermal conductivity	48.8 W/m K (varies with temperature)

Table 1: Thermophysical properties of target

3 EXPERIMENTAL SCHEME AND SIMULATION STUDIES BY SOFTWARE

It is assumed that the incident power at target is equally distributed in the inner circle and annulus of the beam (Fig.2a). The power is 300 W in inner circle and 300W in the annulas. It means the power is divided 50% in inner part of 5 mm and 50% in outer part of 10 mm beam. These assumptions have been made to simulate the analysis. Simulation studies for thermal analysis of laser irradiated hollow cylindrical targets of diameter 120 and 155 mm (Fig 1a, 1b) respectively. A laser power of required intensity when pointed on the surface of the target causes its rapid heating leading to its localized structural failure. The heat gets conducted inside also and causes simultaneous heating of inner surface of the hollow structure. The temperature rises with respect to time increase rapidly and than rises slowly. The temperature profile of the hollow target was obtained with respect to time and other variable parameters such as ambient temperature and the convective heat transient coefficient. The objective of this study is to predict the temperature rise along the wall thickness at the localized hot spot where the Laser beam is pointed.

Three dimensional heat transfer analysis was carried out on *Ansys Mechanical 2015* software. The *Ansys* solves the problem by iterative process of Finite Element Methods (FEM). The shell geometry was created in *Ansys* itself. The meshing was done by selecting the Auto Mesh option in the software. Total 7181 numbers of Tetrahedral Elements (TET 10) were generated along with 13847 nodes. The boundary conditions and loading conditions were then applied considering all three viz. conduction, convection and radiation modes of heat transfer into account. Different combinations of ambient temperatures and convective heat transfer coefficients were included in the problem. Variation of thermal conductivity and heat capacity with respect to temperature was also taken into account. The results were obtained in the form of graphs of temperature w.r.t. time. The experimental schme is shown in Fig 3.

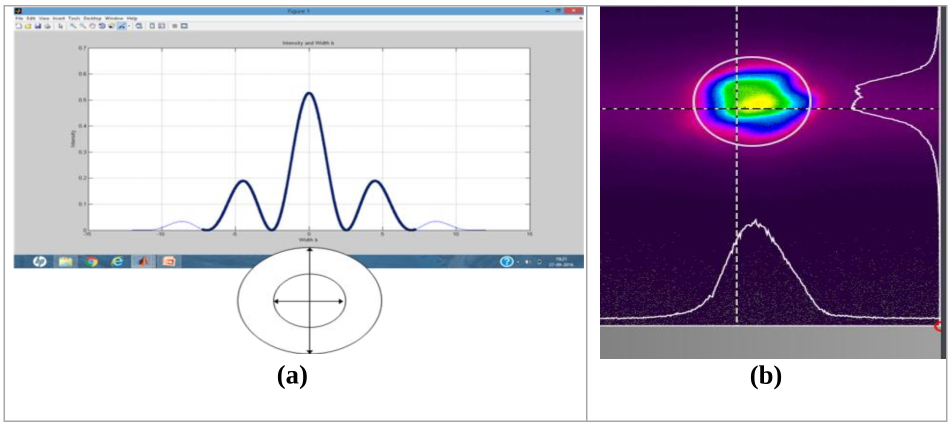


Fig. 2 Beam Power Distribution

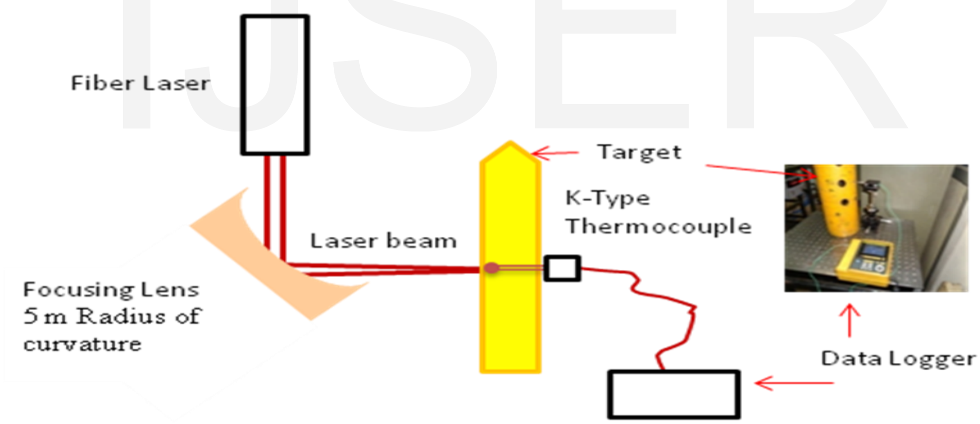


Fig.-3 Experimental setup for measurement of temperature rise

4 RESULTS AND DISCUSSIONS:

Laboratory experiments were carried out for validation of the above simulated data results. The required laser spot diameter of 10 mm was achieved by focusing the laser beam from laser collimator by a concave lens of 5 m radius of curvature. The temperature was measured by data logger using the standard K-Type themocouple. Different cases were considered for experiments as follows:

I. HOLLOW CYLINDERICAL TARGET OF DIAMETER 120 MM

The experiment was done in the lab at room temperature. The reslult are shown in Fig.4. Theoretical results are fairly matched with the experimental results.

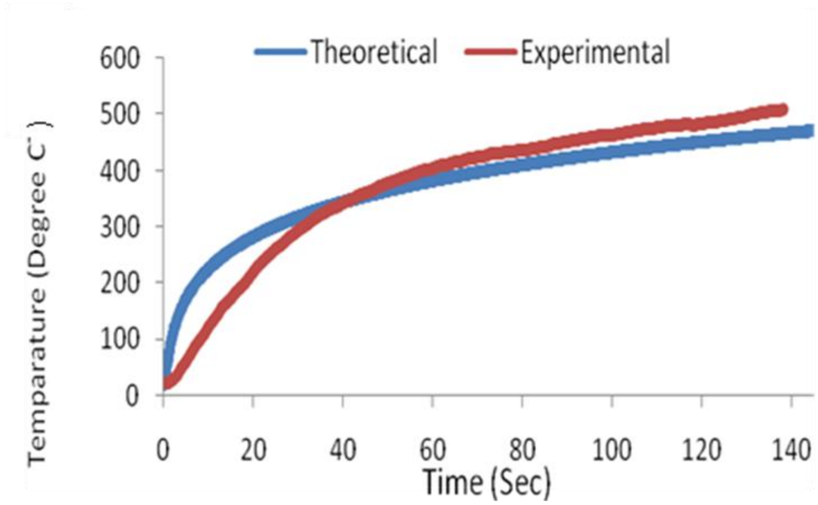


Fig.-4: Comparison of Theoretical & Experimental results of temperature rise

II. HOLLOW CYLINDERICAL TARGET OF DIAMETER 155 MM

The experiment was done in laboratory at normal room temperature. The results are shown in Fig.- 5. The results shows that no deviation with theoretical and experimental data.

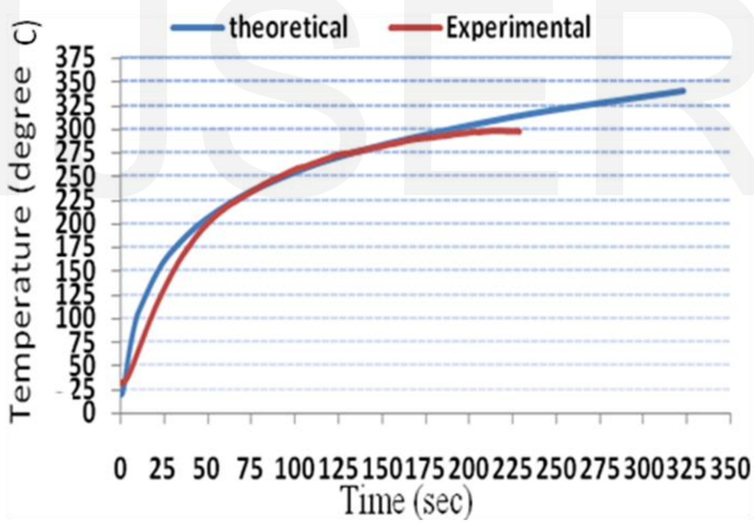
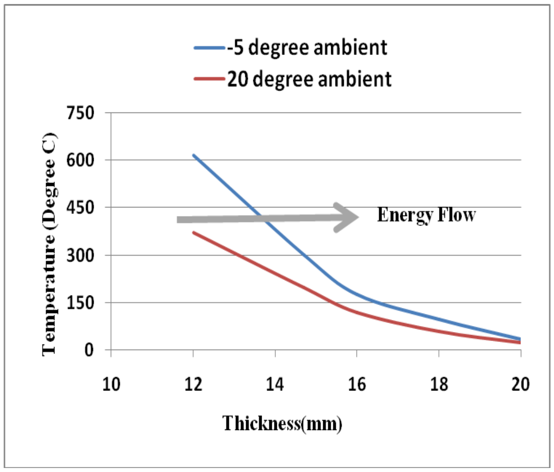


Fig.-5: Comparison of Theoretical & Experimental results of temperature rise

At such incident high power, the surface temperature of target rises above boiling point in few sec. Mass is ablated from front surface of the target and it gets damaged due to penetration of beam. Focused beam on target produces high temperature. At this temperature the material starts melting rapidly. The radiation loss due to surface temperature is therefore omitted from calculations. The inner surface temperature results are verified by experiments in lab using K-type thermocouple which is a direct method to measure the temperature with respect to time.

The variation of temperature with respect to thickness of wall of the shell structure and convective heat transfer coefficient is given in Fig.6 (a) and 6(b) respectively. The inner wall temperature decreases with increase in thickness. The heat transfer coefficient also affects the rise of temperature.

(a) 

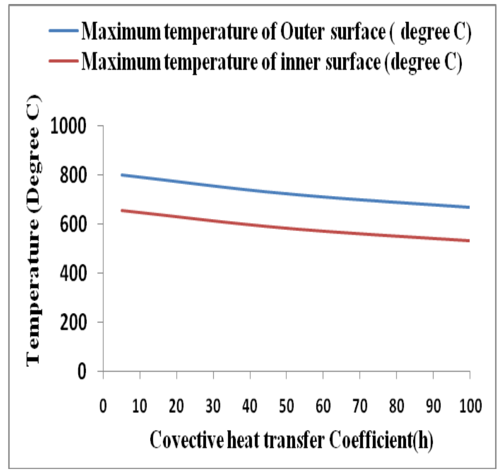
(b) 

Fig. 6 Temperature dependency with respect to thickness and Convestive heat transfer coeff.

5 CONCLUSION:

The results of experiments were compared with those of simulation studies. Simulation results are comparable with the experimental results. The inner wall temperature reaches a value greater than 240 ^{0}C in time less than 40 s for 120 mm shell target and less than 150 s for 155 mm shell target. High power laser beam deposit energy at the target rapidly, and the time to achieve damage is short. However, various factors are affecting propagation. So to avoid instabilities or bore through the atmosphere it is required that energy be delivered to a target for a longer time period. This increases the average rate of energy delivery and time required for the beam to engage its target. To achieve our aim of destroying a target, it may be achieved by firing laser for a longer time duration.

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