3D FEM Simulation to Predict the Heat Affected Zone during Laser Machining on Stainless Steel 304

A M Sifullah, Y Nukman, and M A Hassan

***Abstract*—** The minimization of Heat Affected Zone (HAZ) is important in the field of laser machining. The heating of stainless steel-304 with high power laser (CO2) changes the microstructure of material and creates identical HAZ, which needs to identify. In this study a 3D transient finite element model was developed and employed to predict the volume of heat affected zone in stainless steel-304, during laser machining. The 3D transient finite element model was simulated by using ANSYS. The temperature dependent material properties of stainless steel-304 and average absorbtivity were considered in simulation. The outcomes of the model were validated with the experimental results. In this study the average relative error of width of HAZ in 3D transient finite element model was found 2.72%. The model showed a good agreement with the experimental result. Moreover, it was observed that HAZ increase with laser power increase and laser scan speed decrease. The proposed model will be useful in the field of laser assisted mashing, laser cutting and laser welding to optimise the laser power and speed.

***Index Terms*—** FEA, Heat Affected Zone, Stainless steel-304**.**

I. Introduction

In the field of material processing and manufacturing use of high power lasers are in common and all most all kinds of metals, non- metals, alloys, composites can be processed by laser [1]. During laser interaction with work piece a variety of thermo-chemical processes such as heating, melting and vaporization happens, which initiates complicated changes in micro structure and grain refinement in the material and cause HAZ formation. Kou et al. formulated a 3D heat flow model by using the Fourier differential equation and validated with experiment on stainless steel-1018 [2]. Bokota and Iskierka, formulated another model for thermal heat distribution by using Fourier-Kirchhoff equation [3]. Later Finite Element Method (FEM) became popular to formulate the steady or transient 2D/3D heat flow model development due to it's simplicity and accuracy and scope to consider different laser parameters. Khan and Yilbas, presented an analytical model for thermal stress by using finite element method (FEM) to cut sheet metal [4]. Sheng et al. proposed a 2-D FEM model to identify the width of HAZ and validated with experiment [5]. Recently Petru et al. (2013), analyzed the volume of HAZ in Haynes 188 alloy by using CO2 laser at different laser power and speed. The study reviled that the width of HAZ depends not only on laser parameters but also other factors such as assist gas pressure, material properties of work piece[6]. In this study a 3-D transient FEM model is proposed to measure the width of HAZ in stainless steel-304. The model is evaluated by experimental result of Sheng et al. (1995) [5].

Manuscript received March 10, 2015. This work was supported by Financial and technical supports from the University of Malaya under the Grant RP010C-13AET (UMRG).

A M Sifullah is with Department of Mechanical Engineering, Faculty of Engineering, University of Malaya, 50603 Kuala Lumpur, Malaysia (e-mail:sifullah@siswa.um.edu.my).

Y Nukman is with Department of Mechanical Engineering, Faculty of Engineering, University of Malaya, 50603 Kuala Lumpur, Malaysia (e-mail: nukman@um.edu.my).

M A Hassan is with Department of Mechanical Engineering, Faculty of Engineering, University of Malaya, 50603 Kuala Lumpur, Malaysia (e-mail: mohsenegypt@um.edu.my).

II. Experimental Investigation

A. Experimental Setup

Sheng et al. (1995) did an experiment to measure the width of heat affected zone [5]. The laser was CW type CO_2 and work piece was stainless steel 304 with 3.2 mm thickness. During experiment the laser powers were varying from 550 W to 750 W and velocities of work piece were varying from 0.25 mm/s to 2.5 mm/s. The focal length of lens was 127mm and the beam radius was 0.27mm.

B. Heat Affected Zone Estimation

Laser heating is a thermo-chemical process, combined with heating, melting, material removal and sharp solidification or quenching. During this process when the temperature of work piece reached the melting point, a molten layer was created and material removal was taken place. After heating, when the laser moved further the process of solidification initiated grain refinement near the kerf area. For austenitic stainless steel chromium carbide might be formed at the grain boundary during quenching process. Due to presence of sulfur and phosphorus the formation of sulfide and phosphide may also takes place. For this reason a distinct band of HAZ was created, where the internal properties of material had been changed. Sheng et al. (1995) measured the volume of HAZ by SEM and the corresponding temperature range was found 400 ^{o}C - 800 ^{o}C [5, 7]. Similarly, from the contour plot of nodal temperature of 3D transient FEM model the maximum range of width of HAZ was measured from the centreline perpendicularly, where the temperature was about 400^{o}C.

III. Thermal Modelling

A. Physical Description of Model

During experiment the laser beam was fixed in a co-ordinate system X-Y-Z and the work piece was moving at velocity *v*. The striking point of laser on the surface of work piece was considered as origin of co-ordinate system X-Y-Z. As the work piece was moving (–) X direction, the width of HAZ was formed on X-Z plane. The sample work piece of stainless steel-304 was 20 mm long and 10 mm wide having

http://dx.doi.org/10.15242/IAE.IAE0415201

3.2mm thickness.

During estimation of heat flow in laser heating following assumptions were considered:

- The laser beam was pointed on the surface of the work piece perpendicularly.
- The work piece was fixed and the beam was moving at a constant velocity.
- The nature of laser beam was Gaussian and absorbed heat flux was expressed by

$$q(x,z)=\frac{2PA}{\pi r^2}\exp\left(-\frac{2(x^2+z^2)}{r^2}\right) \qquad (1)$$

where, P was laser power, A was abroptivity, r was beam radius.

- The temperature dependent thermo-physical properties of work piece (stainless steel- 304) as shown in Table 1.
- The average value of absorptivity was considered 0.22.
- The material of stainless steel was homogeneous.
- The ambient temperature was considered 22^{0}C.
- The natural convection co-efficient was assumed 50 W/m^2 K
- In the simulation the node remained in the mesh after exceeding the melting temperature (1460^{0}C).
- The effect of radiation heat loss was negligible compare to conduction and convection heat transfer. Hence radiation heat transfer was not considered.
- Phase change was considered.
- The effect of assist gas pressure and internal heat generation were ignored.

TABLE I: THERMO-MECHANICAL PROPERTIES OF STAINLESS STEEL-304.[8]

Temperature (^{o}C)	Density (g cm^{-3})	Thermal Conductivity (W m^{-1} K^{-1})	Specific Heat (J g^{-1}K^{-1})
20	7931	15.5	435
100	7896	16.2	452
200	7849	17.5	479
300	7801	18.9	499
400	7753	20.3	517
500	7704	21.8	534
600	7655	23.4	551
800	7555	26.6	585
1000	7453	29.8	622
1200	7346	33.1	663
1450	7249	36.3	865

B. Mathematical description of the model

Using the Fourier's law, the time dependent 3D transient heat conduction in the space beneath the irradiated surface by ignoring viscous heating and pressure work can be expressed by the following Eq.(2) as[9]:

$$\rho c_p\left(\frac{\partial T}{\partial t}+v\frac{\partial T}{\partial x}\right)=\frac{\partial}{\partial x}\left(k\frac{\partial T}{\partial x}\right)+\frac{\partial}{\partial y}\left(k\frac{\partial T}{\partial y}\right)+\frac{\partial}{\partial z}\left(k\frac{\partial T}{\partial z}\right)+Q \qquad (2)$$

where, k,Q,c_p,v,ρ were thermal conductivity, heat generation per unit volume, specific heat, velocity and density of work piece respectively.

At time $t = 0$

$$T(x,y,z,0) = T_a \qquad (3)$$

At the bottom, top and lateral surface of the work piece the boundary condition of heat flux was expressed by Eq.(4) as

$$-n.\left[-k\left(\frac{\partial T}{\partial x}+\frac{\partial T}{\partial y}+\frac{\partial T}{\partial z}\right)+\rho c_p vT\right]=q+h(T_a-T) \qquad (4)$$

where, n, q, T, T_a were normal vector of the boundary surface, the thermal load, absolute temperature and ambient temperature respectively.

During phase change the relative values of enthalpy in the corresponding states with respect to temperature were described by Equation (5-8) [10]

$$H_S=\rho c_{p(s)}(T_S-T_0) \qquad (5)$$

$$H_m=H_s+\rho c_{p(*)}(T_l-T_s) \qquad (6)$$

$$H_l=H_m+\rho c_{p(l)}(T_+-T_l) \qquad (7)$$

$$c_{p(*)}=c_{p(m)}+\frac{H_l}{T_l-T_s} \qquad (8)$$

where, T_S, T_0, T_l, T_+ were solidus temperature, lower limit reference temperature, liquidus temperature and upper limit reference temperature respectively. H_S, H_m, H_l were enthalpy of solid, mushy and liquid states.

C. Simulation of 3D FEM Model

On the basis of above assumptions 3D transient FEM model was simulated in ANSYS Mechanical (version 13). A very finely mapped mesh (Fig. 1) was used where the incident heat flux was Gaussian in nature. The mesh was built with eight-nodded 3-D thermal element (Solid 70). The model contained 80,000 elements and 86,346 nodes. The length, width and thickness of the work piece were 10 mm x 3.2 mm x 10 mm. The phase change was considered by using temperature varying enthalpy Eq.7-10. The moving heat flux was formulated by using load steps.

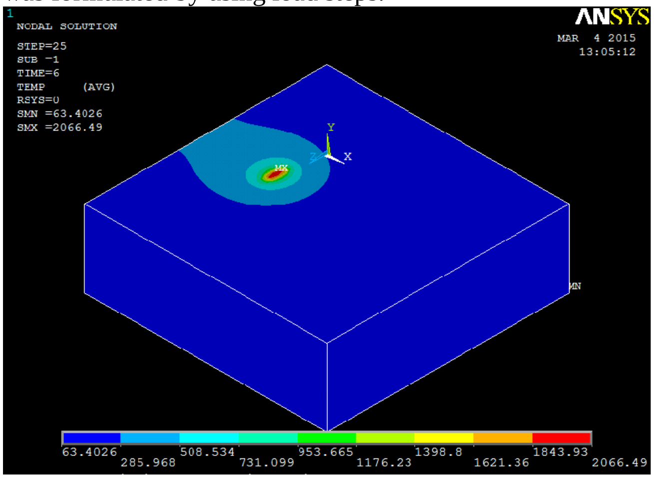

Fig. 1. 3-D FEM temperature profile of Stainless Steel-304, Power 550W, velocity 1.5 mm/s, time at 6 sec

IV. MODEL VALIDATION

At different laser power and speed the width of HAZ in 3d FEM model is shown in table 2. The average relative error of width of HAZ in 3D transient FEM was found 2.72% and all the individual relative errors were within ±10%. Hence, the proposed model is acceptable.

TABLE II: THERMO-MECHANICAL PROPERTIES OF STAINLESS STEEL-304.[8]

Test No	Power (W)	Speed (mm/s)	Width of HAZ (mm)		
			Experiment	3D FEM	Relative Error (%)
1	550	0.625	5.00	4.50	10.00
2	600	0.625	5.50	5.00	9.09
3	700	0.625	7.00	6.80	2.86
4	750	0.625	7.50	7.20	4.00
5	600	1	5.50	4.60	16.36
6	750	1	7.25	7.20	0.69
7	550	1.25	2.43	2.50	-4.00
8	600	1.25	3.50	3.60	-2.86
9	700	1.25	4.50	4.90	-8.89
10	750	1.25	6.00	6.00	0.00

V. RESULT AND DISCUSSION

A. *Thermal profile of 3D transient FEM model*

The melting temperature of stainless steel-304 was 1460^0C. Hence, after exceeding the melting temperature the metal started to melt. In simulation the element was remain in the mash after exceeding the melting point, thus the maximum nodal temperature in the contour plot was found around 2060^0C at 6 second. When the laser power was 550W and scanning speed was 1.25 mm/s. The maximum width of HAZ was measured considering 400^0C as critical temperature as shown in Fig 2. Here the maximum width of HAZ was 2.5 mm as shown in figure. The contour plot of nodal temperature distribution on X-Y surface was wider than the X-Z surface, due to heat loss by convection. Thus the rate of heat propagation inside the material was larger than at the surface.

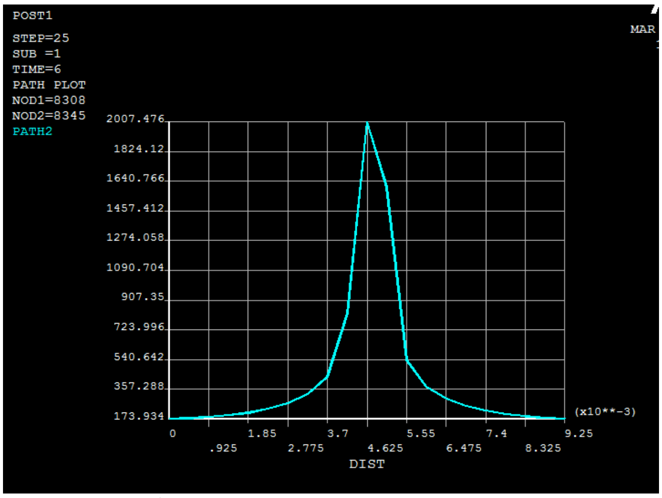

Fig 2. Width of HAZ at laser power 550W, Speed 1.5mm/s, at time at 6 sec

B. *Comparison between 2D FEM model and 3D transient FEM model*

The result of maximum width of HAZ at different laser power and speed in proposed 3D transient FEM model was compared with result of 2D FEM model proposed by Sheng et al. (1995).The experimental result was considered as benchmark [5] as shown in Fig. 3. At 0.625 mm/s laser speed the average relative error from experiment was about 13.74% in 2D FEM analysis. On the other hand in 3D transient FEM model it was 6.48%. Similarly at 1.25 mm/s laser speed the average relative error of 2D FEM from experiment was about 24.06%. In 3D transient FEM model it was 3.93%. It indicates the proposed 3D transient FEM model was more accurate than the 2D FEM model. Because, in 3D FEM transient model the major heat transfer (conduction, convection) was considered along all axis and phase change was taken into count.

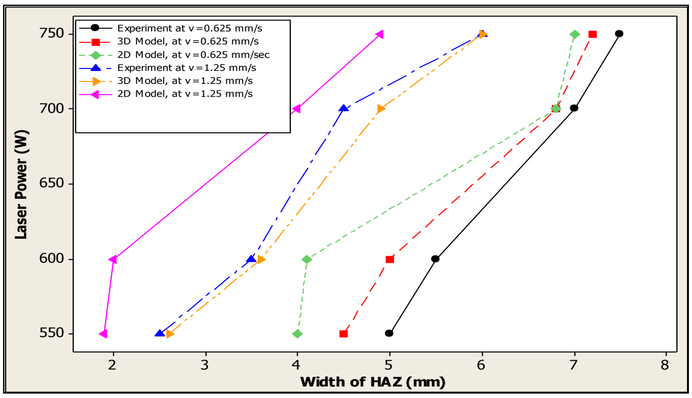

Fig 3. Comparison of width of HAZ among 2D FEM, 3D transient FEM and experiment result at different laser power and speed.

VI. CONCLUSION

From the above study it was found 3D transient model can predict the volume of HAZ likely as experiment. The accuracy of 3D transient FEM model was found 93.17%.

VII. ACKNOWLEDGEMENT

Financial and technical supports from the University of Malaya under the Grant RP010C-13AET (UMRG) are gratefully acknowledged.

REFERENCES

[1] H. Eltawahni, A.-G. Olabi, K. Benyounis, Investigating the CO_2 laser cutting parameters of MDF wood composite material, Optics & Laser Technology, 43 (2011) 648-659. http://dx.doi.org/10.1016/j.optlastec.2010.09.006

[2] S. Kou, D. Sun, Y. Le, A fundamental study of laser transformation hardening, Metallurgical Transactions A, 14 (1983) 643-653. http://dx.doi.org/10.1007/BF02643780

[3] A. Bokota, S. Iskierka, Numerical prediction of the hardened zone in laser treatment of carbon steel, Acta Materialia, 44 (1996) 445-450. http://dx.doi.org/10.1016/1359-6454(95)00225-1

[4] O.U. Khan, B. Yilbas, Laser heating of sheet metal and thermal stress development, Journal of materials processing technology, 155 (2004) 2045-2050. http://dx.doi.org/10.1016/j.jmatprotec.2004.04.229

[5] P.S. Sheng, V.S. Joshi, Analysis of Heat-Affected Zone Formation for Laser Cutting of Stainless-Steel, Journal of Materials Processing Technology, 53 (1995) 879-892 http://dx.doi.org/10.1016/0924-0136(94)01761-O

[6] J. Petru, T. Zlamal, R. Cep, K. Monkova, P. Monka, Influence of cutting parameters on heat-affected zone after laser cutting, Tehnički vjesnik, 20 (2013) 225-230

[7] I. Masumoto, T. Shinoda, T. Hirate, Weld Decay Recovery by Laser Beam Surfacing of Austenitic Stainless Steel Welded Joints, Transactions of the Japan Welding Society, 21 (1990) 11-17.

[8] H.T. Lee, C.T. Chen, Numerical and Experimental Investigation into Effect of Temperature Field on Sensitization of AISI 304 in Butt Welds Fabricated by Gas Tungsten Arc Welding, Materials transactions, 52 (2011) 1506-1514.
http://dx.doi.org/10.2320/matertrans.M2011071

[9] J. Yang, S. Sun, M. Brandt, W. Yan, Experimental investigation and 3D finite element prediction of the heat affected zone during laser assisted machining of Ti6Al4V alloy, Journal of Materials Processing Technology, 210 (2010) 2215-2222.
http://dx.doi.org/10.1016/j.jmatprotec.2010.08.007

[10] L. Chen, P. Wang, P. Song, J. Zhang, Finite Element Numerical Simulation of Temperature Field in Metal Pattern Casting System and "Reverse Method" of Defining the Thermal Physical, Acta Metallurgica Sinica (English Letters), 20 (2009) 217-224.
http://dx.doi.org/10.1016/S1006-7191(07)60029-5

Abu Mohammed Sifullah
Country: Bangladesh
MSc. Engineering Student, Department of Mechanical Engineering, University of Malaya, 50603 Kuala Lumpur, Malaysia
Research Area: Laser machining & optimization.

Dr. Nukman Bin Yusoff
Country: Malaysia
Associate Professor
Department of Mechanical Engineering, University of Malaya, 50603 Kuala Lumpur, Malaysia
Area of expertise:
Control Technology (Mechatronics), Material Processing Technology (Laser Materials Processing), Cad/Cam And Cnc (CAD/CAM).

Associate Prof. Dr. Mohsen Abdel Naeim Hassan Mohamed
Country: Egypt
Associate Professor
Department of Mechanical Engineering, University of Malaya, 50603 Kuala Lumpur, Malaysia
Area of expertise:
Micro Forming, Sheet Metal Forming, Biomaterials And Elastomers, Finite Element Analysis, (Deep drawing, rolling of metal foils, Finite element analysis of metal forming processes, Mechanics of Deformable bodies).
Biomaterials Engineering (Heart Mechanics, Heart Tissues, Mechanical behaviour of heart Tissues, Piezoelecletric Polymeres For Artificial Heart)
Medical Electronics (Bios MEMS, Micro sensor, electro-mechanical properties, heart cell)
Mechanical Control (Control of Flying objects, Sliding Mode control, PID-Fuzzy control)