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Numerical Analysis of Laser Heating for Laser Assisted Micro Milling Application

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Abstract: The promising processing techniques of micro scale parts are very important in products miniaturization and functions enhancement. Combination of two or more processing techniques gives better processing performance especially when dealing with difficult-to-cut materials. For that reason, the combination of laser beam and micro milling process has been widely studied and proven efficient in reducing cutting force and tool life extension. However, this process needs a precise temperature control in order to eliminate heat effect generated by laser beam irradiation. In this study, temperature distributions are determined numerically to characterize the melted zone and heat affected zone geometry. From the results, the estimation of tool and micro milling cutter distance together with the allowable depth of cut are determined.

Introduction

The temperature distribution need to be clearly known in laser assisted micro milling due to the higher cooling rate. In addition, small different of tool position will cause a significant changes on the tool engagement temperature. Consequently machining performance will be also largely affected the cutting force deviation. Hence, it is crucially important to study the temperature distribution in order to determine machine setup and machining parameters in obtaining the optimum machining performance

A lot of numerical studies on temperature distribution generated by laser beam have been reported. The study was firstly reported by Goldak et al. (1984), where the heat flux was expressed in double ellipsoid shape [1]. The simplified of Gaussian equations for beam heat flux distribution were then studied and reported. For deep penetration welding, the keyhole mechanism brings significant effect in determining the laser absorption rate. For shallow heating, the keyhole effect can be neglected. The heat flux distribution can be expressed by

$$q(x,y) = \frac{AKP}{S} \exp\left[\frac{x^2+y^2}{b^2}\right] \quad (1)$$

A is absorption rate (%), K is intensity distribution constant, S is irradiated surface area (mm^2) and b is laser beam radius (mm). In most cases, the value of K is equal to 2 [2, 3]. However this value could be differed due to laser delivery system characteristics. Meanwhile, the value of A might be changed due to material surface conditions. From previous studies, the value of A for Ti6Al4V work-piece was ranging from 0.35 to 0.60 [2, 4, 5]. In lieu of the aforementioned drawbacks, further study need to be carried out to determine the appropriate range of values and validate these numbers with the numerical analysis model.

In this study, a simulation model of heating process using middle power Nd:YAG laser was developed, compared and validated through numerical and experimental results. The values of A and K were defined through numerical analysis. The validated model was used to estimate the acceptable depth of cut for laser assisted micro milling process.

Methodology

Laser irradiation experiment. A pulsed wave Nd:YAG laser with maximum average laser power 300 W was used in this study. Laser head with focusing length 160 mm and laser beam focusing diameter 0.7 mm is mounted on Z axis of three axis CNC table system. A wrought titanium alloy, Ti6Al4V with 1.8 mm thickness was irradiated linearly in a distance of 25 mm. The scanning was started from 5 mm away from the work-piece edge to ensure that the laser irradiates with constant power.

For metallurgical analysis, the work-pieces were sectioned and polished perpendicular to irradiation travel direction at 15 mm from the irradiation stating edge. The melted zones (MZ) and heat affected zones (HAZ) were observed using high magnification microscope.

Table 1 shows the scanning parameters used in experimental as well as in numerical analysis. Thermal properties of titanium alloy were referred from [4]. Since the scanning process only generates heat on the top of the surface, therefore the keyhole effect can be neglected.

Table 1: Processing parameters used for numerical analysis

Parameters	Values
Pulse width, t_p (ms)	1.0
Pulse repetition rate, f_p (Hz)	100
Scanning speed, v (mm/min)	210
Peak power, P_{peak} (W)	85, 115, 140

Numerical analysis. Fig. 1 shows the schematic diagram of the developed numerical analysis model in this study. The model of laser irradiation was made with circular heat source moves along a 10 mm length of center line. The value of absorption rate A was considered as constant to simplify the model. To reduce the element number, the model was made with half size as the heat source and the actual specimens are symmetric. The value of A was varied between 40 to 60 % by referring to [5]. Total size of the model is 6 mm x 10.08 mm x 1.0 mm. The laser heating area was meshed with size of 0.035 mm/side. Heat convection was applied from the starting edge of side, top and end surface. The value of Gaussian distribution constant K was taken as 3, based from the preliminary results.

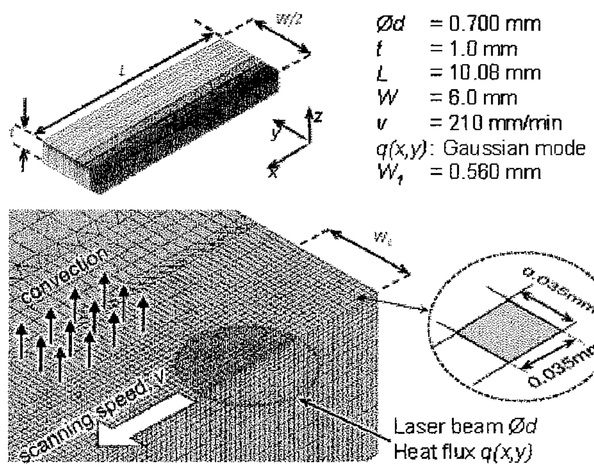


Fig. 1: Finite element model for laser heating thermal analysis

Results and Discussions

Fig. 2 shows the numerical result of temperature changes at the distance of 1 mm form the starting edge (x = 1.0 mm). Three shifted point was taken as sample to show the differences of maximum temperature achieved. The red line is for the temperature changes at the center of irradiation line (y

= O mm). The blue line is when the point is shifted to 0.350 mm from irradiation center line in y axis direction. Green line is when y is 0.560 mm. Heating process using pulse wave laser with f_p 100 Hz and t_p 1 ms creates enormous fluctuated temperature. The cooling time between pulses was sufficient for the specimens to chill down from approximately 2300 °C to less than 500 °C.

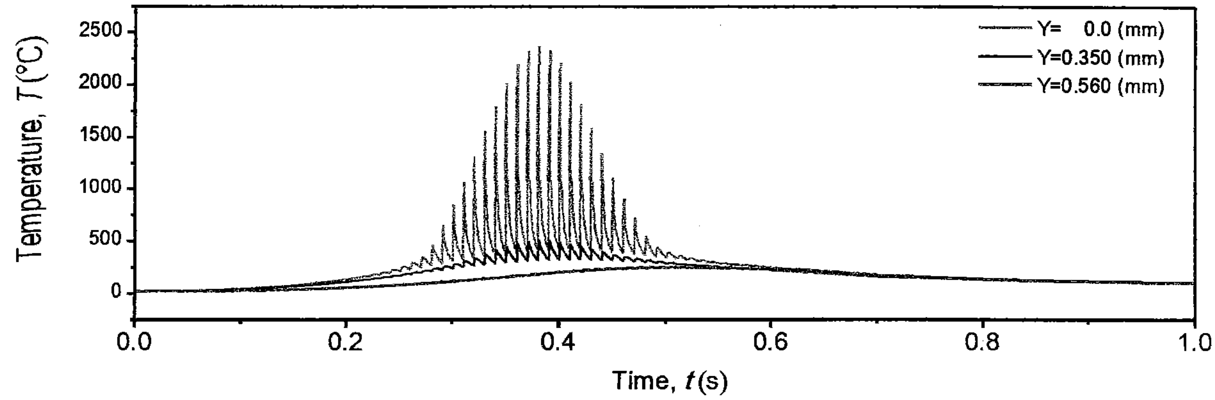
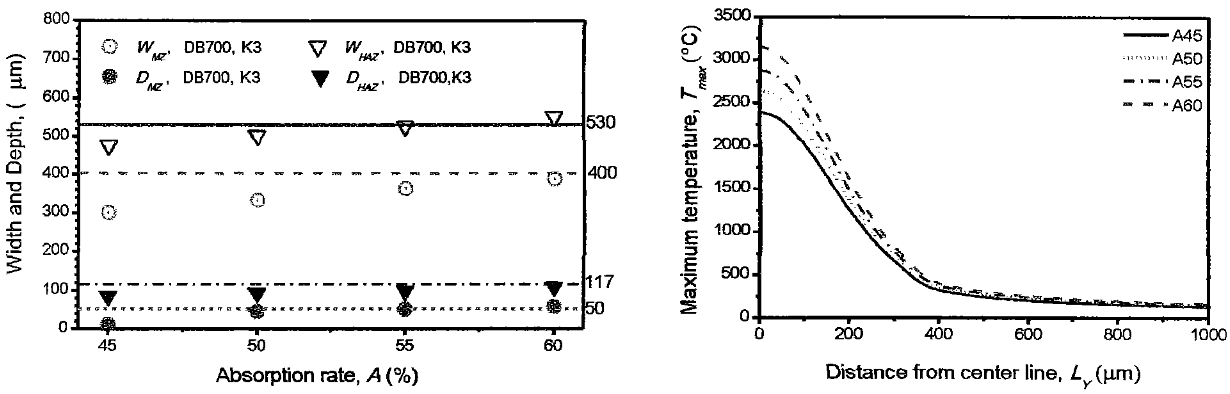


Fig. 2 : Temperature changes at difference offset distance from scanning center line (calculated using A=45% and P_{peak}=140W)

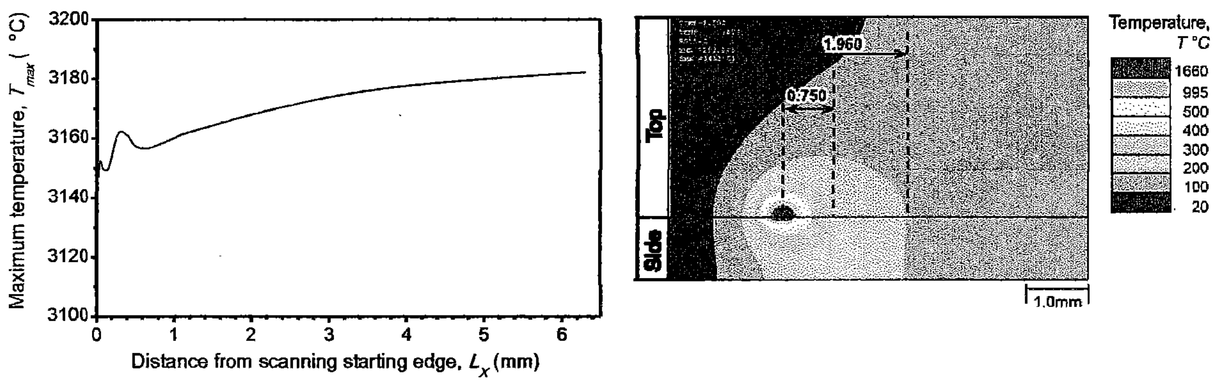


(a) (b)

Fig. 3 : Result analysis of (a) melting zone and heat affected zone measurement, (b) top surface maximum temperature using different absorption rate (calculated using A=45% and P_{peak}=140W)

Fig. 3 (a) shows the MZ and HAZ measurement obtain from analysis. The values were taken at the cross sectional region at the distance of 2 mm from scanning start edge The horizontal lines indicate the targeted values for MZ and HAZ which were obtained from the experiment. It was found in the analysis that the depth (D_{HAZ}) and width (W_{HAZ}) of HAZ significantly increased due to an increase the value of A. The simulated value of MZ depth (D_{MZ}) was comparable with the experiment when the value of A increases to 55 %. However, the width of MZ (W_{MZ}) from the analysis recorded 10 % smaller than experimental measurement. In analysis, increasing the value of A up to 60 % has significantly increased the W_{HAZ} but the value of D_{HAZ}, D_{MZ} and W_{MZ} exceeded the targeted experimental values. This shows that the actual laser beam energy intensity is distributed in Gaussian mode but with minor differences compared to analysis model. The absorption rate became difficult to be defined. It is because the errors are impossible to be perfectly eliminated due to some assumption made in order to simplify the analysis of the model. The model can be assumed reliable for temperature distribution characterization with error is less than 10%. From Fig. 3 (b), severe variation of the temperature distribution in y axis can be seen in area within 0.350 mm from center line. This area is the area that was directly heated up by the laser beam. The temperature of the external area increases to less than 500 °C. This means that there is no possibility of serious oxidation at the non-irradiated area. Applying different A values (45 to 60 %) does not bring obvious temperature dereference on the non-irradiated area.

The maximum temperature distribution along the scanning line is shown in Fig. 4 (a). As the scanning path began, the temperature increases from 3142 °C to 3162 °C at 0.35 mm from the starting edge. However, as the distance increases to 0.7 mm, the temperature drastically decreases to 3157 °C. Then, the temperature gradually ascended with approximately 8° C/mm incremental rate until it reaches the distance of 4 mm. Furthermore, it can be observed that the maximum temperature become almost constant when the distance beyond 6 mm with approximately 1° C/mm incremental rate. Obvious temperature fluctuation at the beginning of the scanning path was due to the limited heat conduction direction. The heat energy was accumulated in the edge and it can only be conducted in forward and side direction.



(a) Top surface temperature distribution at center scanning line

(b) Temperature distribution from top and side surface

Fig. 4 : Temperature distribution using A = 60 %, P_{peak}=140 W, v = 210 mm/min, f_p = 100 Hz and t_p = 1 ms)

Fig. 4 (b) shows the temperature distribution when the laser beam moves to the distance of 4.9 mm from the starting edge. By considering that the micro end mill tool need to be located at the area with temperature between 200 °C to 300 °C, the distance between the laser beam spot to the center point of micro end milling tool need to be located in range of 0.8 mm to 1.9 mm. However, under this scanning parameter there will be a balance of MZ and HAZ remaining uncut. Comparatively small diameter of micro end milling tool requires thin HAZ layer without any MZ created by the laser heating process. Thus, it is important to determine the appropriate scanning parameters which can generate less temperature fluctuation without any MZ.

Conclusions

From the work carried out, the following conclusions can be drawn:

1) The HAZ and MZ size are well agreed with the experiment result if the value of absorption rate, A is between 50 % to 60 % and heat density distribution constant, K is 3.
2) Heating process using pulsed wave laser creates large temperature fluctuation in the irradiated area. Further study need to be done to obtain scanning parameters which can generate less fluctuated heat with no MZ created on the top surface.
3) In the case of cross sectional direction, no significant temperature differences can be seen at the non-irradiated area.
4) The distance between the laser beam spot to the micro end milling tool should be located between 0.8 mm to 1.9 mm.
5) The allowable cutting depth is between 0.050 to 0.117 mm when the P_{peak} is 140 W, t_p is 1 ms and f_p is 100 Hz.

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References

[1] J. Goldak, A. Chakravarti and M. Bibby, A New Finite Element Model for Welding Heat Sources, Metallurgical Transactions B. 15B (1984) 299-30.

[2] J. Yang, S. Sun, M. Brandt and 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.

[3] M. Labudovic and Kovacevic, Modelling of the laser surface nitriding of Ti-6Al-4V alloy-analysis of heat transfer and residual stresses, Proc. Instn. Mech. Engrs. 215 no. C (2001) 315-340.

[4] R. Wiedenmann, M. Langshorst and M. F. Zeah, Computerised optimization of the process parameters in laser assisted milling, Physics procedia. 12 (2011) 607-616.

[5] M. F. Zaeh, R. Wiedenmann and R. Daub, A Thermal Simulation Model for Laser-Assisted Milling, Physics Procedia. 5 (2010) 353–362.