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Determination of Heat Flux Intensity Distribution and Laser Absorption Rate of AISI D2 Tool Steel

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Abstract. The prediction of fluctuated temperature distribution generated by pulsed wave laser in laser assisted micro milling (LAMM) is crucial. The selection of processing parameter by minimize the effect on the processing characteristic is decisive to ensure the machining quality is high. Determining the effect of heat generated in underneath surface is important to make sure that the cutting tools are able to cut the material with maximum depth of cut and minimum defects in term of tool wear and tool life. In this study the simulation was carried by using Ansys APDL. In order to confirm the actual and distribution irradiation of temperature from simulation, an experimental was done to validate the results. The experiment was conducted by using Nd:YAG laser with wavelength 1064 nm.

Introduction

The demands on miniaturization product increase significantly and require improvement on processing method. The new method was introduced to enhance and improve the machinability by considering the tool wear, tool life and surface integrity. Hybrid machining process is a combination between two machining method that capable to address the issue. By applying preheating method via laser induce thermal softening well known as laser assisted machining (LAM) can be used to reduce the materials strength during machining process. Integration of laser beam heating and milling process has been widely reported with many researchers to reduce the cutting forces, material strength and extended the tool life effectively. Anderson et al. [1] showed the reduction in cutting force is 25% and increment of tool life between 200 to 300%. It also successfully reduced the total machining cost by applying LAM in machining of Inconel 718. Otherwise, Shi et al. [2] reported the plastic deformation of Inconel 718 materials was reduced due to the reduction of cutting force when the preheat temperature rise between 700 to 800 °C.

However the fluctuated temperature distribution on the pulsed laser must be clarify to identify the appropriate distance between tool and laser point. Navas el al. [3] shows that the optimum distance of 45 mm between laser spot and cutting tool in turning process has achieved the maximum reduction of cutting force and minimum tool degradation by applied overheating. Furthermore, Dumitrescu et al. [4] revealed that the appropriate distance for AISI D2 material is 85 mm in laser assisted turning process.

Thus, it is important to determine the possible distance between micro milling tool and laser beam with minimum effect on tool life and tool wear. Besides that, laser irradiation plays a significant role on determining tool location. Therefore, accurate temperature changes prediction is important in laser assisted micro milling. In this study, computational simulation is performed to predict the temperature distribution. The model was validated by comparing numerical and microscopic analysis result. The influencing factors of laser heating on AISI D2 materials was also identify.

Methodology

Numerical Analysis. A model was developed to predict the thermal distribution on surface materials of AISI D2 during laser pre-heating process. The workpiece size is 8 mm x 1.8 mm x 1.0 mm in width, length and thickness, respectively. To simplify the analysis, several assumptions were considered namely material homogenous, the process in transient condition and laser irradiation condition is conduction mode without keyhole formation. The material properties such as thermal conductivity, specific heat and density is based on the temperature dependent as shown in Table 1.

Table 1: Thermo-physic properties of AISI D2 [5]

Temperature, T (K)	Thermal Conductivity, k x 10^{-6}(W/μm.K)	Specific Heat, c (J/kg.K)	Density, ρ x 10^{-15} (kg/μm^3)
298	29.0	412.21	7700
673	29.5	418.36	7650
1100	30.7	421.83	7600
1990	32.3	431.00	7560

To reduce the total number of element, the model was created with half size of the actual width from the center of scanning line and heat source. The Gaussian distribution theory on laser energy was used as a heat source on the top surface. It can be expresses as shown in Equation 1.

$$Q_{x,y} = \frac{K.P.A}{\pi r^2} exp\left(\frac{-K(x^2+y^2)}{r^2}\right) \quad (1)$$

Where:

K : Constant

P : Laser power

A : Absorption rate

r : Efficient beam radius

x,y : Distance from laser beam center

In this study, the laser beam diameter size and distribution were measured and confirmed by using laser beam profiler and power meter. These parameters were became an input value for the numerical simulation. The diameter and power of the laser beam is 700μm and 136 W, respectively. In addition, the scanning speed was set at 210 mm/min. The meshing shape and size at the laser scanning line region was designed in triangular shape with 35 μm width and length. Various K value will be applied according to the higher intensity produce small diameter beam in simulation [6].

Microscope Observation and Model Validation. The specimens were cross-sectioned perpendicularly to the scanning line with the distance of 15 to 20 mm from the starting point of laser irradiation. The distance is confirmed by considering the stability of irradiation along the scanning process and emitted laser power consistency. Cross sectional view of melting and heat effected zone region were used and compared with the numerical simulation validation.

The model is validated when the melting and heat affected zone (HAZ) shape and size are similar from the actual experiment. The acceptable error should be less than 10%. The border line of melting zone is defined as the melting temperature point of the material in range between 1713 to 1850 K. It can be assumed that the HAZ border line start from the phase transformation temperature of 1033K [7].

Result and Discussion

Laser irradiation was done by using Nd:YAG laser source with the wave length of 1064 nm. The laser power, pulse width and pulse repetitionrate were set at 10W, 1 ms and 100 Hz respectively. In order to confirm the actual power output value, the power meter was used to read the measurement. It was observed that the actual power output is not similar with the machine setting. For the machine setting of 10 W, the actual output power was measured at 13.9 W. This value was used as an input in the simulation. Fig. 1 shows the cross sectional view of melted zone created using various laser power (P), 100 Hz pulse repetition rate (f_p), 1 ms pulse width (t_p) and 210 mm/min scanning speed. It shows that the keyhole was formed by applying laser power exceed than 18.2 W. This indicated that the keyhole formation in the gaussian beam distribution for simulation process can be neglected when applying laser power less than 18.2 W.

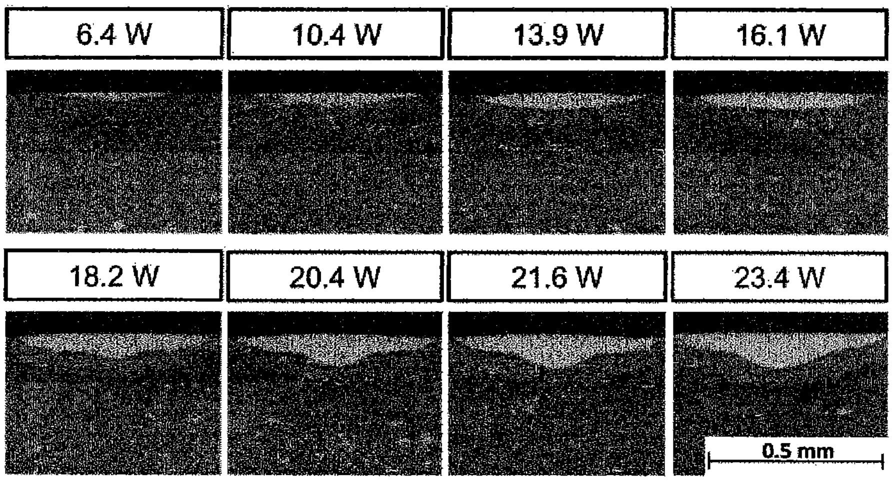


Fig. 1: The melted zone and keyhole formation in the cross sectional irradiation line

In the simulation, Gaussian distribution (Equation 1) was used to generated heat flux in the scanning process. However, in the initial stage, the constant value of K can be assumed is equal to 3 [8]. The K values translate the effect on intensity regarding beam density and power of irradiation. Fig. 2 shows the simulation result using average power 13.9 W and various absorption rates on surface material. Crater was observed when the absorption rate, A is set at 0.8 compare to 0.7. Furthermore, as the melted zone width decreases as the absorptivity value decrease.

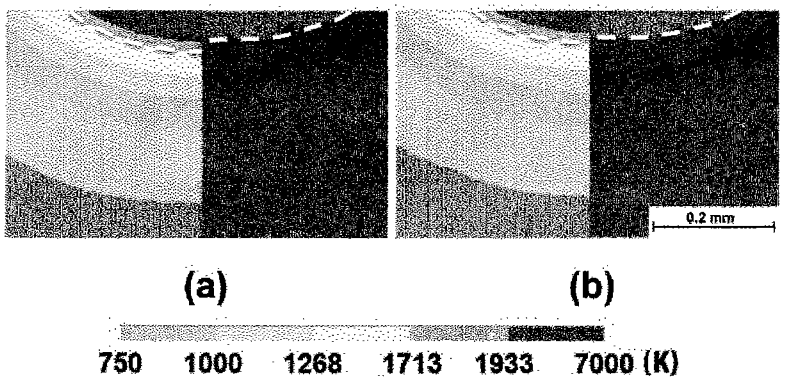


Fig. 2: The effect of asorptivity in the melting zone shape and size (a) A=0.8 (b) A=0.7

According to the previous reported on AISI D2, the absorption rate is 80% on the workpiece surface [9]. By applying the same absorption rate value, the shape and size in the simulation process was not similar. It may due to the inappropriate value of K, which contributes to the higher intensity and beam density, subsequently creates a crater in the simulation compare to actual experiment. Furthermore, the fluctuated temperature distribution and cooling time need to be considered to minimize the calculation error.

Under similar laser power and absorptivity, but with the different value of *K* ranging from 3 to 2.5, the melting shape, size and HAZ region is more identical (Fig. 3). The melting depth in the simulation is in range of melting temperature point. However, the actual melting width via experimental much more wider than simulation, with the error less than 10%. This is probably due to the laser irradiation angle in actual machine is not exactly 90°. In this situation, the beam shape is not circular but more to ellipse shape. This, in turn, wider melted zone can be formed compare to the simulation.

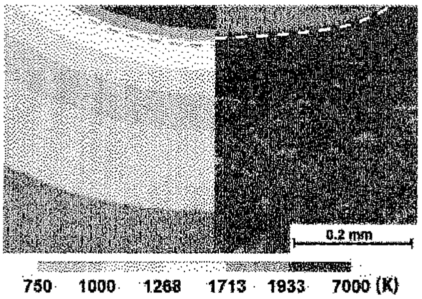
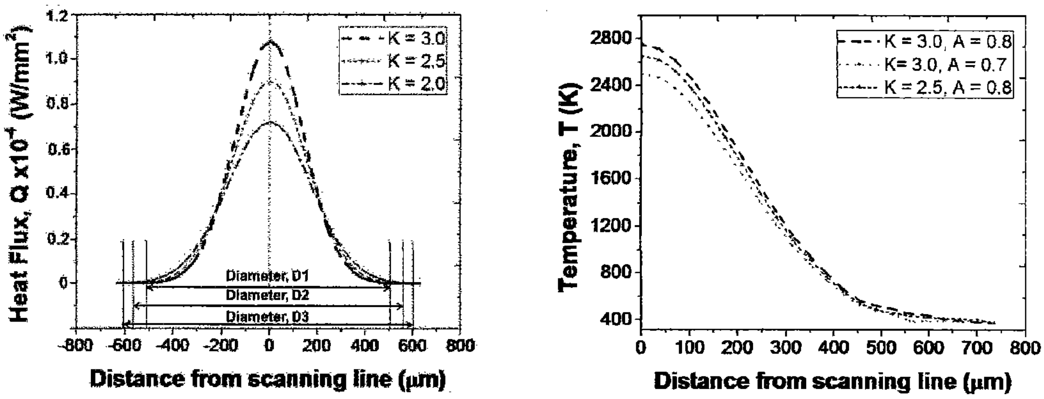


Fig. 3: Melted zone and HAZ size comparison (P=13.6 W, A=0.8 and K=2.5)



(a) (b)

Fig. 4: Result analysis (a) heat flux distribution with using different *K* value on theoretical (b) temperature distribution with using different absorption rate and *K* value in simulation

Figure 4 (a) shows the significance to change the *K* value in the heat flux distribution on the simulation result. The distance of D1, D2 and D3 represent the diameter beam changes using various *K* value. Generally, *K* value shows the interrelationship between laser beam intensity and diameter. Analysis was revealed that intensity rate for every *K* values is different and when using K=3 the higher beam density will produce to increase the penetration depth. While for K=2.5 the melting width is wider due to the low beam density produced and preheating process occur on the surface. From the Fig. 4 (b), it can be seen that the influence of *K* value and absorption rate in temperature distribution. Higher *K* value and absorption rate produce maximum temperature in the simulation. It is clearly shows that the increment of beam density was influenced by the *K* value and the absorption rate which allows producing higher temperature. This phenomenon will effect on the shape and size of the melting and the HAZ region.

Conclusions

The main conclusions drawn from this research can be summarized as follows:

i. The model of the simulation was validated when the absorption rate, A is 80% and heat density distribution constant, K is 2.5. Therefore, the Gaussian beam distribution of pulsed wave Nd:YAG laser on AISI D2 tool steel materials can be written as:

$$Q_{x,y} = \frac{2.5P.A}{\pi r^2} exp\left(\frac{-2.5(x^2+y^2)}{r^2}\right)$$

ii. The keyhole formation in the simulation can be ignoring by applying the average laser power below than 18.2 W and it can happen in conduction mode.

iii. The K value and the absorption rate are the significance parameters that influenced the melting zone and HAZ size.

iv. In the simulation, the beam shape must be assumed as ellipse shape to produce more accurate calculation. Further study is needed to modify the APDL program in ellipse beam shape.

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