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Analysis of a Laser Assisted Milling Process with Inclination Angles

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LAM (Laser Assisted Machining) is an effective machining method that can achieve a machining process for materials, which are difficult to cut, and a significant reduction in machining costs. Recently many researches on micromachining of plates or cylinders in connection with LAM have been conducted. However, in laser assisted milling processes the heat sources of laser are irregularly varied according to shapes of workpieces. Also, there are few researches of laser assisted milling processes with inclination angles. In this study, a thermal analysis of the laser assisted milling process for inclination planes is performed as a basic research in milling researches. Regarding the workpiece with various inclination angles, a temperature profile analysis is performed using a moving heat source. In addition, the effects of preheating are verified through the thermal analysis and experiment performed in this study. By analyzing the obtained temperature profile, a proper laser power control method is proposed according to inclination angles. The results of this analysis can be used to estimate thermal deformations on workpieces and tools and to apply as a heat source analysis method in laser assisted milling processes.

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1. Introduction

LAM with laser preheating can reduce a machining cost of about 60 ~ 80% as it is used to processes for materials, which are difficult to cut, such as ceramic, Ni, and etc.[1] Also, due to the characteristics of high strength coherence, monochromaticity, and flexibility in its machining, applications in LAM have been largely extended to various machining fields.[2,3]

Recently a lot of research on micromachining of plate or cylinder in connection with LAM has been conducted.[4,5]

Gupta et al. demonstrated an experimental method for fatigue crack initiation using a laser micromachining technique. Also they provided study results on hydraulic pressure induced stress and strain at laser micromachined notches in titanium tubes and a comparison with EDM method.[6]

Liang et al. presented a new micromachining method by generating circular interference patterns with femtosecond laser pulses. The pattern was then focussed and impinged on a solid copper substrate.[7]

Although LAM has several advantages, it shows difficulties in estimating precise machining and heat treatment results. The reason is that there are sudden changes in temperature due to very small heat input areas, large energy densities, and movements of heat sources.[8,9]

Recently milling process products are required more than that of turning in some manufacturing sites, such as mold, automobile, aircraft, and so on, and advanced industries, such as aerospace, biomedical, optical component, and etc.[8] Therefore, it is necessary to conduct a research on laser assisted milling processes.[10] However, the heat sources of laser in laser assisted milling processes are irregularly varied according to shapes of workpieces. Also, there are almost no researches on laser assisted milling processes with inclination angles.

In this study, a thermal analysis of the laser assisted milling process for inclination planes is performed as a basic research in milling researches. The analysis is performed for the process that heats workpieces, which have various inclination angles, using a moving heat source. In addition, by investigating temperature profiles varied with inclination angles, a power control method for various inclination angles is proposed. In the results of this analysis, it can be used to estimate the thermal deformation on workpieces and tools and to apply as a heat source analysis method in laser assisted milling processes.

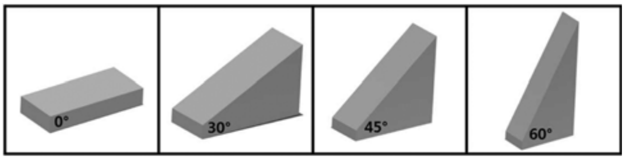

Fig. 1 Models with different angles used in the analysis

Table 1 Conditions of the analysis

Block size (0°)	25 mm × 15 mm × 5 mm
Laser power	220 W
Laser feed rate	10 mm/s
Convection heat	5 W/m^2°C
Analysis time	1.9s

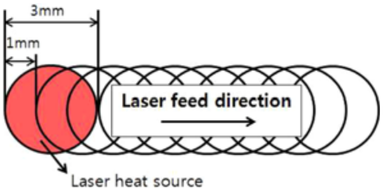

Fig. 2 Sequential moving method of heat sources

2. Finite element method

2.1 Analysis model

The size of planar plate (0°) is a 25 mm × 15 mm × 5 mm. The others are given inclination angles on the planar plate. It uses hex dominant as a method of mesh division. Fig. 1 illustrates the models with inclination angles of 0°, 30°, 45°, and 60° for a planar plate used in this analysis. Also, the laser heat source shape used in the analysis is a circle beam that has a top-hat energy distribution. Table 1 represents the conditions used in this analysis.

The absorptance for AISI1045 by the diode laser is used to as 40%.[8] The reason that uses AISI1045 as a workpiece is to compare the results with the existing studies and experiments at an inclination angle of 0°.

2.2 Analysis method

Fig. 2 represents a method for the movement of the heat source used in the analysis. It shows a sequential movement by overlapping the heat input area of the circle beam as much as 2/3. Because the diameter of the laser heat source is configured by 3 mm, the distance for the movement of a single block is 1 mm. The beam size in an inclination plane is used as an input by calculating the laser heat source area according to the inclination angles.

3. Result of the analysis

3.1 Results of the analysis with angles

The A_1 transformation temperature of AISI1045 is 730°C and the melting temperature is about 1450°C. The phase change is presented at the transformation temperature during the heating of AISI1045. In this study, a method that controls the laser power for maintaining a temperature of about 1350°C, which is lower than the melting point of about 100°C, is proposed for maximizing the efficiency of the softening effect and for using the basis of experimental data for the ceramic experiments.

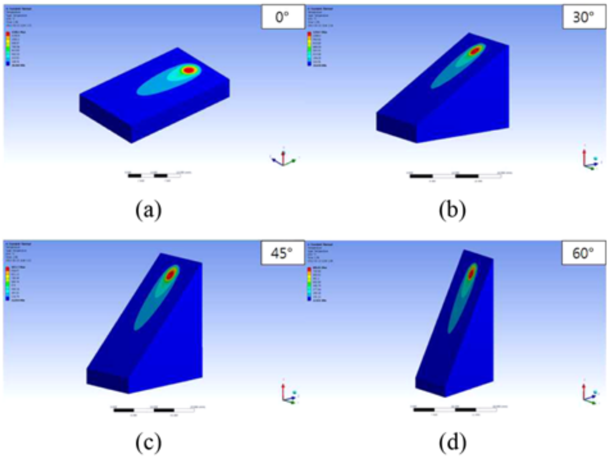

Fig. 3 Results of the analysis by inclination angles (a) 0° (b) 30° (c) 45° (d) 60°

Table 2 Laser spot diameter and maximum temperature according to inclination angles

Angle [°]	0	30	45	60
Laser spot dia. [mm]	3	3.46	4.24	6
Temperature [°C]	1348.1	1219.7	1052.7	806.9

Table 3 Temperature measured by power control

Angle [°C]	Power [W]	Temperature [°C]
0	220	1348.1
30	249	1350.2
45	297	1350.8
60	407	1349.8

Fig. 3(a) represents the maximum temperature, 1348.1°C, as the laser power 550 W is reduced to 220 W at the inclination angle of 0°.

The temperature analysis of the workpieces according to inclination angles is performed using the same power of 220 W.

Fig. 3(b) shows the results of the analysis at the angle of 30°. In the results of this analysis, the maximum temperature is 1219.7°C. Fig. 3(c) shows the results of the analysis at the angle of 45°. In the results of this analysis, the maximum temperature is 1052.7°C. Fig. 3(d) shows the results of the analysis at the angle of 60°. In the results of this analysis, the maximum temperature was 806.9°C.

Table 2 represents the maximum temperature according to inclination angles. It is decreased with increases in inclination angles because the thermal energy per unit area is decreased with the increase in inclination angles.

3.2 Results of the analysis by power control

In the results of the maximum temperature, it is recognized that a power control process is required in machining and heat treatment processes according to inclination angles. The power that can obtain a similar value to the maximum temperature at the angle of 0° is calculated through trials and errors. Table 3 represents the results of this calculation by power control. It is verified that the larger the inclination

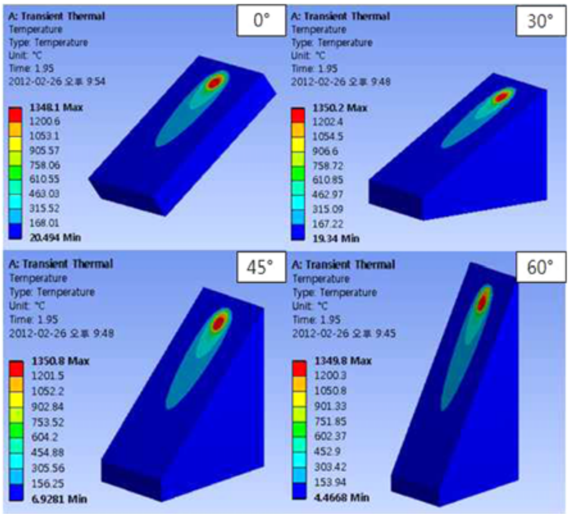

Fig. 4 Result of the analysis by power control

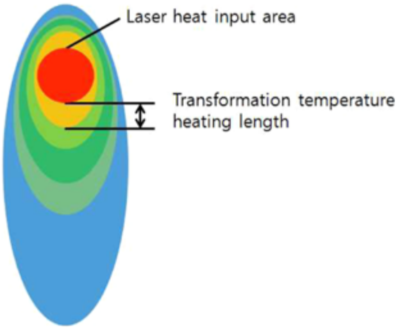

Fig. 5 Transformation temperature heating length

Table 4 Transformation temperature heating length with inclination angles

Angle (°)	Transformation temperature heating length (mm)	
	Before power control	After power control
0	0.33	0.33
30	0.13	0.33
45	0.02	0.33
60	-	0.33

angles are presented, the higher power is required.

Fig. 4 illustrates the results of the analysis after the power is controlled for the inclination angles of 30°, 45°, and 60°.

Fig. 5 shows the transformation temperature heating length. The transformation temperature heating length is a distance to a position, which is heated by more than a 830°C of transformation temperature from a laser heat input area, and that can be used to estimate heat treatment effects.

Table 4 represents the transformation temperature heating length with inclination angles.

Based on its length, it is disappeared at more than 60° because the maximum temperature is smaller than the transformation temperature. After the power control, the transformation temperature heating length is maintained about 0.33 mm because the maximum temperature is kept about 1350°C with inclination angles.

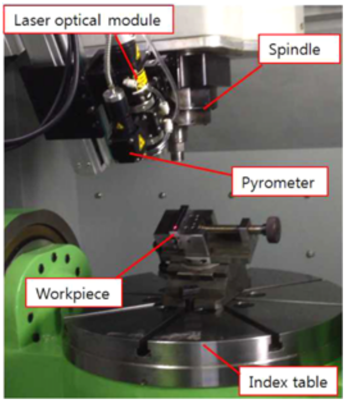

Fig. 6 Experimental set-up for LAM

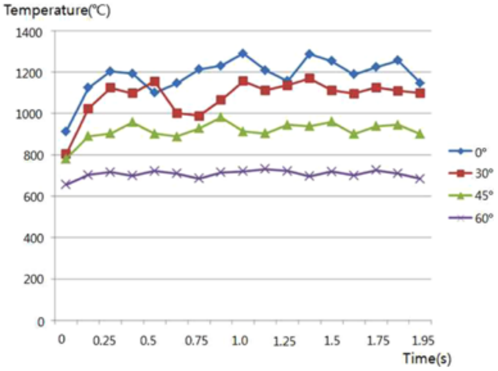

Fig. 7 Surface temperature with inclination angles

4. Experiment on LAM

4.1 Configuration of the experiment system

Fig. 6 shows a fabricated LAM system for implementing the experiment. The wavelength of the laser optical module was 808 ~ 980 nm. Also, a high power diode laser (HPDL) with the maximum power of 1 kW was used. A pyrometer was used to measure the surface temperature of the workpiece, so that the temperature of the laser heating zone was measured in real-time. As mentioned above section 2.1, experiment was performed by the laser power of 550 W. For comparing with the analysis results, feed rate was used the same value of the analysis, 10 mm/s.

4.2 Experiment on LAM

The shapes of the laser heat source were changed according to inclination angles of the workpieces. Thus, the temperature distribution of the surface was changed. Fig. 7 shows the results of temperature distributions in the wokpieces according to the inclination angles. In the laser assisted milling process, a preheating process with a proper temperature level is required. Thus, a temperature range above annealing temperature, which improves the machinability and removes residual stresses through softening the specimen and belows the A_1 Temperature that represents a phase transition, was proposed. As shown in the graph, it showed the maximum temperature as 1290.3°C at the inclination angle of 0° that is higher than the A_1 temperature of 730°C and 159.7°C lower than the melting temperature, 1450°C.

It showed the maximum temperature as 1170.5°C at the inclination

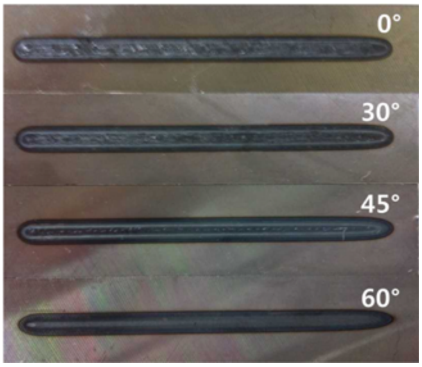

Fig. 8 Surface of workpiece according to inclination angles after preheating

Table 5 Comparison of the results of the thermal analysis and experiment with inclination angles

Angle [°]	Analysis [°C]	Experiment [°C]	Error [%]
0	1348.1	1290.3	4.3
30	1219.7	1170.5	4.0
45	1052.7	980.9	6.8
60	806.9	730.7	9.4

angle of 30° and that exhibits 279.5°C lower than the melting temperature. Also, the maximum temperatures of the inclination angles of 45° and 60° were recorded as 980.9°C and 730.7°C respectively.

It is verified that the preheating temperature of workpiece is changed by inclination angles in a practical experiment.

The preheating temperature change has an effect on the surface of materials. Fig. 8 represents the surface of materials according to the preheating temperature. It shows that transformation of surface was most affected by the laser source at the angle of 0°. It can find that increases in inclination angles represent decreases in preheating effect.

4.3 Comparison of the thermal analysis and experiment

Table 5 represents the comparison of the results of the thermal analysis and experiment with inclination angles. The error represents the smallest value as 4.0% at 30° and the biggest value 9.4% at 60°. Overall, the errors are increased according to the inclination angles. Also, it agrees with the thermal analysis within the error range of 9.4%.

5. Conclusion

In this study, a thermal analysis of the laser assisted milling process for inclination planes is performed. Regarding the workpiece with various inclination angles, a temperature profile analysis is performed using a moving heat source. Based on the analyzed temperature profile, a proper laser power control method according to inclination angles was proposed.

(1) It is verified that increases in inclination angles represent increases in heat source areas and that decreases the thermal energy per unit area and leads to decrease the temperature.
(2) A power control method according to inclination angles is proposed. It is recognized that the laser power is increased as a second order function according to the increase in inclination angles.
(3) It is possible to estimate the heat treatment effects by analyzing a specific temperature heating length according to inclination angles.
(4) In the comparison of the results of the thermal analysis and the experiment, the error rate between the final temperature and the mean temperature is below 9.4%. In the comparison of the tendency in distributing the overall temperature in both the thermal analysis and the experiment, it shows a nice agreement in the results.

Based on the results obtained by using the method proposed in this study, it is possible to estimate a temperature profile of moving heat sources in laser assisted milling processes. In addition, it is expected that the results of this analysis can be used in various fields including the estimation of thermal deformations and stresses in workpieces and tools.

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