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# A Study on the Optimum Machining Conditions for Laser-Assisted Turn-Mill

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*Laser-assisted turning (LAT) is an effective machining method for difficult-to-cut materials, such as nickel and ceramics. Many researchers have studied the machining characteristics and the effectiveness of LAT. However, LAT is in the early stage of application, and has only been used in a limited fashion for round workpieces. Therefore, in this paper, laser-assisted turn-mill (LATM) processing is proposed to complement LAT. LATM is able to machine various section shapes than LAT by using turning and milling processes at the same time. Additionally, the influence of parameters such as laser power, cutting speed, feed rate, and depth of cut is studied to decrease the cutting force and surface roughness. Also, the optimum machining conditions of LATM of AISI 1045 steel are determined through design of experiment.*

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## 1. Introduction

In recent years, research on laser machining has increased worldwide. Above all, studies on laser-assisted machining (LAM) have mainly been conducted to maximize the efficiency and productivity in thermally assisted machining processes.[1-3]

LAM is a method that applies a machining process after softening a workpiece in which the preheating process is applied to its machining section using a high-energy laser beam. This processing can reduce the shear strength of materials so that material removal occurs through plastic deformation rather than brittle fracture. LAM also leads to decreases not only in processing costs by about 60~80%, but also in cutting force and tool wear by about 30~50% and 20~30%, respectively.[4-7] LAM, however, is in the early stage of application, and has only been used in limited fields throughout the world, including turning and micro end-milling.

For laser-assisted turning (LAT) operations, it is relatively simple to integrate a laser beam with the lathe. The laser beam position, incident angle, spot size, and tool-to-beam distance are selected as process variables for LAT.[8] The advantage of LAT is that it is easy and it does not result in heating of the machined surface. In many cases, the preheating lowers the shear strength in metals and allows plastic deformation.[9]

Studies on LAM have been carried out to obtain the optimized machining conditions. For example, Kim et al.[10] performed a study on the machining parameters of nickel-based alloys using a high-power diode laser in order to improve the surface roughness. Sim et al.[11] studied the laser preheating effect of workpiece with rotated angle with respect to 2-axis through thermal analysis. Lee et al.[12] studied the material changes of silicon nitride workpiece according to the temperature in order to select the machining condition in LAT. Chang and Kuo[13,14] performed studies on the surface roughness and tool life through LAT experiments. The machining conditions influence the surface roughness in workpieces and these were analyzed using the Taguchi method. Tian Y. et al.[15,16] implemented to assume temperature of chip according to changes in the depth of cut in a LAM process applied for complex shapes using a 3D heat transfer simulation and verified its results. Kim et al.[17] performed a study estimating deformation shapes and temperature distributions in a laser heat source through LAT. Attia et al.[18] compared the material removal rate between laser-assisted finish turning and conventional machining. The surface finish of LAT was improved by more than 25% and the material removal rate was increased by approximately 800%.

However, there was a limitation, as the LAT process was only applied to round-shaped workpieces. Due to an increase in the customized production of special-purpose complex parts, research on laser-assisted

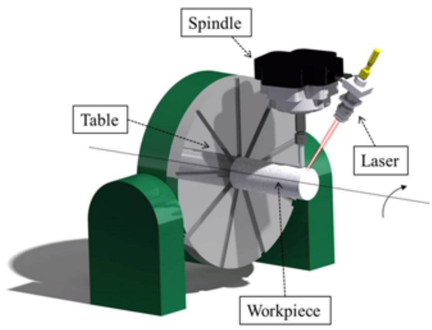


Fig. 1 Laser-assisted turn-mill

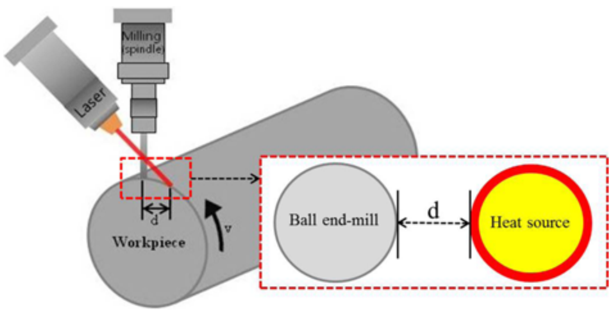


Fig. 2 Schematic of a laser-assisted turn-mill system

turn-mill (LATM) is necessary. Thus, the authors[17,19,20,21] proposed a LATM system by combining LAM to turn-mill. Fig. 1 shows the LATM system.

In this study, machining processes were performed to machine from a round-shaped workpiece to a square-shaped product using the LATM process. In addition, the Taguchi method was applied to obtain the optimum machining conditions of the LATM process. In addition, LATM machining has been applied to machine AISI 1045 steel material, which is used throughout the industry.

## 2. Thermal Analysis

### 2.1 LATM process

Fig. 2 shows the schematic of the LATM system that applies LAM to a turn-mill process, which was proposed by the present authors.[17] In Fig. 2, the round-shaped workpiece is rotated counterclockwise and the cutting is implemented after local softening using a laser heat source.[21,21] v and d are the rotation speed of the workpiece and the horizontal distance between the end of the tool and the laser heat source, respectively. In the LATM process in this study, the values of v and d were chosen to be 5 rpm and 2 mm, respectively.

Fig. 3 shows the shape of the workpiece to be machined in this study.[20,21]

### 2.2 Finite element model

To perform a thermal analysis of the laser heat sources, a finite element model (FEM) is modeled using the FEA package ANSYS Workbench. In the analysis, a laser heat source projection method that can predict the laser heat source accurately and efficiently was used as shown in Fig. 4.[17,20,21] The laser heat sources consist of 36 points, an interval is 10°, and it takes approximately 0.33 seconds for rotation of

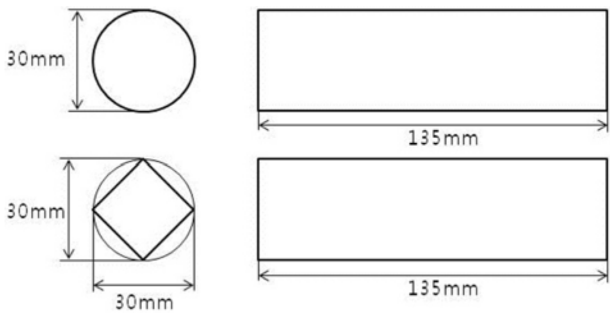


Fig. 3 Section shape and geometry information of the workpieces

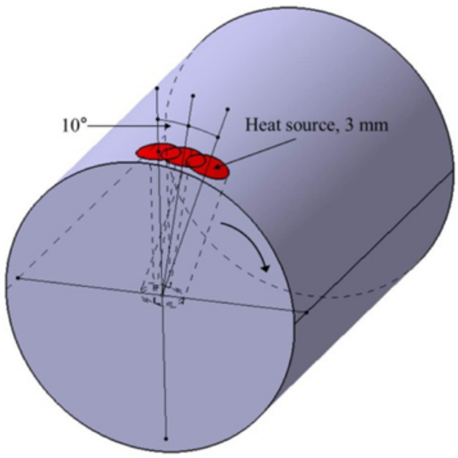


Fig. 4 The laser heat source projection method

Table 1 Conditions for the thermal analysis

| Material | AISI 1045 steel |
|---|---|
| Turning speed | 5 rpm |
| Laser beam diameter | 3 mm |
| Time | 12 s |
| Analysis range | 1 Revolution (0~360°) |

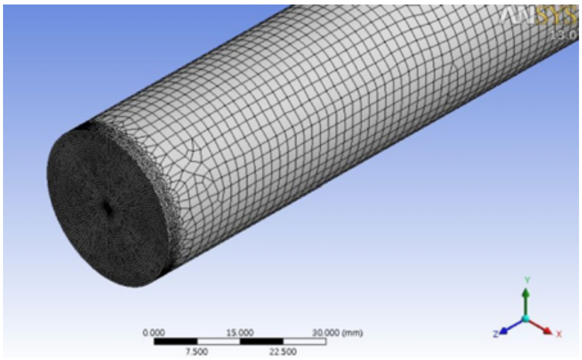

Fig. 5 Finite element model of the round-shaped workpiece

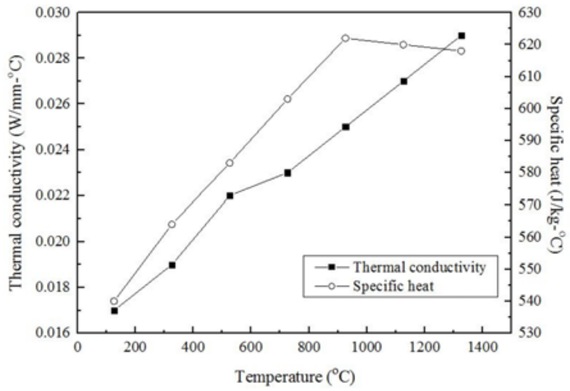


Fig. 6 Properties of AISI 1045 steel according to temperature

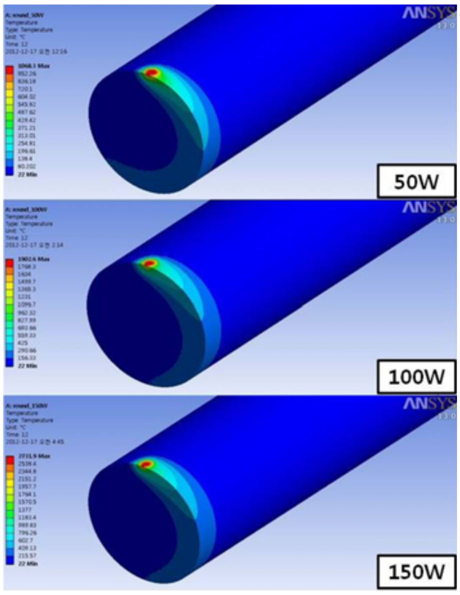


Fig. 7 Results of the thermal analysis of the round-shaped workpiece according to changes in laser power

the interval. Table 1 shows the conditions of a thermal analysis using a laser preheating process. Fig. 5 shows the FEM of the round-shaped workpiece. The meshes in the heat input zones were divided by 5 mm, and in the workpiece, by 2 mm, to increase the accuracy of the analysis. Fig. 6 shows the properties of AISI 1045 steel according to temperature.[22]

### 2.3 Results for the thermal analysis

Fig. 7 represents the results of the thermal analysis carried out by varying the applied laser power from 50 W, to 100 W, to 150 W. The maximum temperature of the workpiece for each laser power supply after completing its 360° rotation was recorded as 1068.3°C, 1902.6°C, and 2731.9°C, respectively.

Fig. 8 represents the cross-sectional temperature distribution in the workpiece from the thermal analysis. The result of the thermal analysis was used to determine the depth of cut in the LATM experiments. This depth of cut is able to fully softening the workpiece by obtaining an enough effect of preheating. The preheating depth and width for the

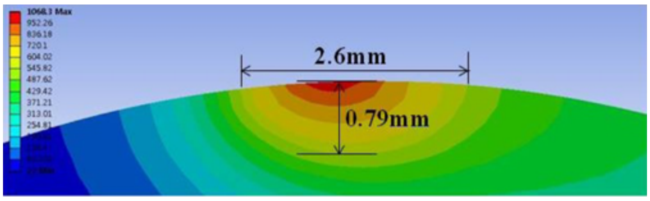


Fig. 8 Cross-sectional temperature distribution in the workpiece

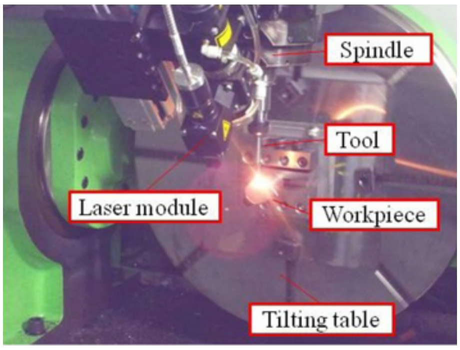


Fig. 9 Experimental set-up for LATM

round workpiece were 0.79 mm and 2.6 mm, respectively.

## 3. Experiment and Design of Experiment

### 3.1 The LATM system

In the experiment, the wavelength of the laser optical module was 940~980 nm and a high-power diode laser with the maximum power of 1 kW was used. In addition, a pyrometer was used to measure the surface temperature of the workpiece. The diameter of ball end-mill used in this study is 8 mm. Fig. 9 shows the established LATM system for conducting LATM experiments.

### 3.2 Taguchi method

One of the methods presented in this study is an experimental design process called the Taguchi design method. The Taguchi method is an efficient design of experiment methods, which can improve process performance with a minimum number of experiments. Additionally, Taguchi design allows for the examination of the variability caused by noise factors, which are usually ignored in the traditional experimental approaches.[23-25] Therefore, in this study, costs and time can be reduced through the Taguchi method. Fig. 10 illustrates the flow chart of the Taguchi method.

The purpose of this study is to determine the optimum machining conditions of the LATM process efficiently to achieve the smallest surface roughness value and cutting force value. The LATM parameters and their levels were determined through the thermal analysis data and the literature survey on LAM. The selected parameters were spindle speed, depth of cut, and laser power. The levels of the parameters were determined to be at three levels, as shown in Table 2. In addition, the standardized Taguchi method based on experimental design, an $L_9$ orthogonal array (OA), is used.

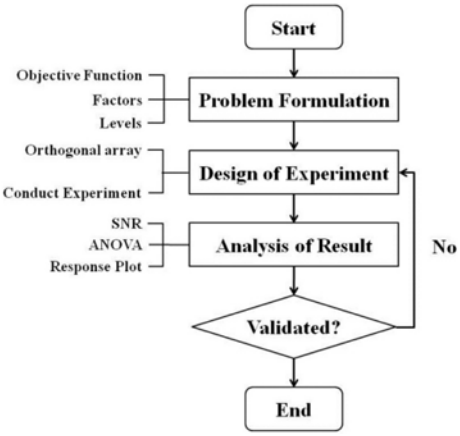


Fig. 10 Flow chart of the Taguchi method

Table 2 Machining conditions and their levels for the LATM process

| Control factor | Symbol | Unit | Level 1 | Level 2 | Level 3 |
|---|---|---|---|---|---|
| Spindle speed | A | rpm | 3000 | 5000 | 7000 |
| Depth of cut | B | mm | 0.25 | 0.5 | 0.75 |
| Laser power | C | W | 50 | 100 | 150 |

Table 3 Orthogonal array table for $L_9$ with an outer array of 2

| Run | A | B | C | Cutting force | Surface roughness |
|---|---|---|---|---|---|
| 1 | 1 | 1 | 1 | 70.8 | 2.14 |
| 2 | 1 | 2 | 2 | 71.9 | 1.83 |
| 3 | 1 | 3 | 3 | 75.73 | 3.60 |
| 4 | 2 | 1 | 2 | 65.51 | 1.68 |
| 5 | 2 | 2 | 3 | 67.42 | 2.08 |
| 6 | 2 | 3 | 1 | 81.98 | 2.99 |
| 7 | 3 | 1 | 3 | 63.9 | 1.01 |
| 8 | 3 | 2 | 1 | 77.8 | 3.75 |
| 9 | 3 | 3 | 2 | 77.45 | 2.14 |

## 4. Results and Discussion

### 4.1 Effect of parameters

Using the design parameter combinations in the specified OA table, nine different LATM experiments were performed. To ensure the accuracy of the results, the cutting force and surface roughness were fabricated for each of the parameter combinations, using the data presented in Table 3. According to the principles of the Taguchi method, the cutting force and surface roughness are defined by a minimum signal-to-noise (S/N) ratio.

The lowest cutting force was found when spindle speed A and level 2: A2, depth of cut B and level 1: B1, and laser power C and level 3: C3 were used, as shown in Fig. 11 and Table 4. The lowest surface roughness was found when spindle speed A and level 3: A3, depth of cut B and level 1: B1, and laser power C and level 3: C3 were used, as shown in Fig. 12 and Table 5.

### 4.2 Analysis of variance

ANOVA analysis was performed to verify the optimized machining conditions for the LATM process. Table 6 and Table 7 show the ANOVA results of the cutting force and roughness, respectively.

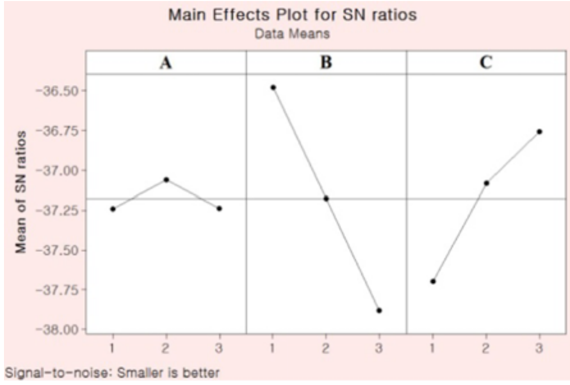


Fig. 11 Main effect plot of the S/N ratio of the cutting force

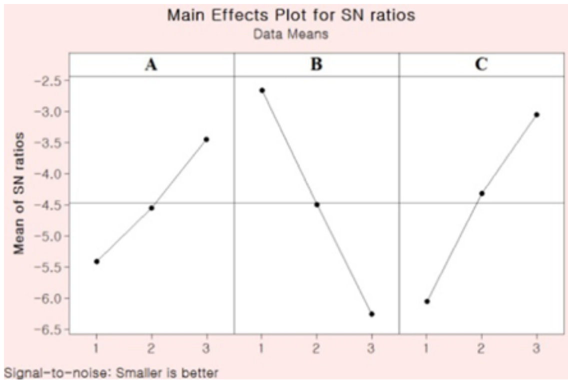


Fig. 12 Main effect plot of the S/N ratio of the surface roughness

Table 4 Response table mean S/N ratio for cutting force according to the machining conditions of the LATM process

| Level | A | B | C |
|---|---|---|---|
| 1 | -37.24 | -36.48 | -37.70 |
| 2 | -37.06 | -37.18 | -37.08 |
| 3 | -37.24 | -37.88 | -36.76 |
| Delta | 0.18 | 1.40 | 0.94 |
| Rank | 3 | 1 | 2 |

Table 5 Response table mean S/N ratio for the surface roughness according to the machining conditions of the LATM process

| Level | A | B | C |
|---|---|---|---|
| 1 | -5.409 | -2.652 | -6.045 |
| 2 | -4.543 | -4.494 | -4.308 |
| 3 | -3.447 | -6.252 | -3.045 |
| Delta | 1.962 | 3.601 | 3.000 |
| Rank | 3 | 1 | 2 |

Table 6 Analysis of variance for the cutting force

| Factors | Degree of freedom | Sum of squares | Mean of squares | F ratio |
|---|---|---|---|---|
| Spindle speed | 2 | 0.6495 | 0.0325 | 2.79 |
| Depth of cut | 2 | 2.9462 | 1.4731 | 126.39 |
| Laser power | 2 | 1.3721 | 0.6860 | 58.86 |
| Error | 2 | 0.0233 | 0.0117 | |
| Total | 8 | 1.4066 | | |

Table 7 Analysis of variance for the surface roughness

| Factors | Degree of freedom | Sum of squares | Mean of squares | F ratio |
|---|---|---|---|---|
| Spindle speed | 2 | 5.8002 | 2.9001 | 15.24 |
| Depth of cut | 2 | 19.4520 | 9.7260 | 51.11 |
| Laser power | 2 | 13.6136 | 6.8068 | 35.77 |
| Error | 2 | 0.3806 | 0.1903 | |
| Total | 8 | 39.2463 | | |

Table 8 Comparison of the predicted value and experimental value

| Factors | Optimal machining parameters | |
|---|---|---|
| | Prediction | Experiment |
| Level | A3B1C3 | A3B1C3 |
| Cutting force | 65.45 | 63.9 |
| Surface roughness | 1.12 | 1.01 |
| S/N ratio | -37.001/-0.103 | -36.110/-0.086 |

The degrees of freedom (DOF) are used when comparing the test statistic to statistical tables. The sum of squares (SS) is calculated using the sum of squares of the S/N ratio. The mean of squares (MS) is calculated using the mean of squares of the S/N ratio. In the results, the confidence (F ratio) of the spindle speed was lower than the confidence of the depth of cut and the laser power. Thus, the depth of cut and the laser power are more significant than the spindle speed. Therefore, the spindle speed (A) has a less significant influence than the depth of cut and the laser power of the LATM process. It can be confirmed that the depth of cut and the laser power are an important factors in LATM through the ANOVA analysis results. The depth of cut is determined by the laser power in LATM. When the laser power is constant, as the depth of cut deepens, the cutting force and surface roughness increase because the cutting tool is machining a less softened area than in case of the small depth of cut.

Table 8 shows a comparison of the predicted cutting force and surface roughness with the actual cutting force and surface roughness at the optimal machining parameter levels. The experimental results confirm the suitability of the Taguchi method for analyses and optimization of the response variable and machining parameters. Therefore, the errors between the prediction and experiment of the cutting force and the surface roughness are shown as 2.42% and 9.82%, respectively.

## 5. Conclusion

In this study, machining processes were performed to machine from a round-shaped workpiece to a square-shaped product using the LATM system, and the authors implemented thermal analyses through the laser heat-source projection method, which was also proposed by the present authors. In addition, the optimum machining conditions of the LATM process were obtained from the Taguchi method. The conclusions of this study may be summarized as follows:

1) The preheating depth and width for the round workpiece were computed through the thermal analysis. The preheating depth was used to determine the depth of cut in the LATM experiment.

2) The Taguchi method with an $L_9$ orthogonal array was used to determine the optimized machining conditions of the LATM process. The comparisons of the predicted cutting force and surface roughness with the actual cutting force and surface roughness at the optimal machining parameter levels have confirmed the suitability of the Taguchi method for the analyses and optimization.

3) Through ANOVA analysis, a spindle speed in the range of 3,000 ~7,000 rpm has a less significant influence than the cutting force and the surface roughness in the LATM process. It is thus found that the spindle rpm should be increased to obtain the effect of high-speed machining (HSM).

## ACKNOWLEDGEMENT

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