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A Study on the Machining Characteristics of Curved Workpiece using Laser Assisted Milling with Different Tool Paths in Inconel 718

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Abstract

Difficult-to-cut materials are being increasingly used in many industries because of their superior properties, including high corrosion resistance, heat resistance and specific strength. However, these same properties make the materials difficult to machine using conventional machining techniques. Laser-assisted milling (LAM) is one of the effective methods for machining difficult-to-cut materials. In laser-assisted milling machining occur after the workpiece is locally preheated using a laser heat source. Laser assisted machining has been studied by many researchers on flat workpiece or micro end-milling. However, there is no research on the curved shape using laser assisted milling. This study investigated the use of laser assisted milling to machine a three-dimensional curved shape workpiece based on NURBS. A machining experiment was performed on Inconel 718 using different tool paths (ramping, contouring) under various machining conditions. Finite elements analysis was conducted to determine the depth of cut. Cutting force, specific cutting energy and surface

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roughness characteristics were measured, analyzed and compared for conventional and LAM machining. LAM significantly improved these machining characteristics, compared to conventional machining. There results can be applied to the laser-assisted machining of various three-dimensional shapes.

Keywords: Laser-assisted milling; Curved workpiece; Difficult-to-cut material; Milling tool path; Nickel alloy

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1. Introduction

Nickel-based alloys and titanium alloy has high properties, so using increased many industrial fields such as precision machine, aerospace, engine, turbine blade, semiconductor. Difficult-to-cut materials are difficult to conventional machining because high-temperature strength , abrasion resistance, corrosion resistance are very higheris than general materials.[1-2]

For machining these materials, methods of machining are being widely research of cryogenic machining, thermally assisted machining. Cryogenic machining is used liquid nitrogen in manufacturing process. Cooling of cutting tool using liquid nitrogen for evaluation tool wear.[2] Thermally-assisted machining is used heat source in manufacturing process. Especially, laser-assisted machining (LAM) is one of the thermally enhanced machining method. It is soften the difficult-to-cut material using laser heat source.[3-5]

Ahn et al.[6] studied energy efficiency of specific cutting energy in laser-assisted machining. The specific cutting energy was represented by tangential force and material removal rate. Machining experiments conducted, compared to conventional process with laser assisted machining process. Kizaki et al.[7] studied laser-assisted machining of zirconia ceramics using a diamond bur. Grinding experiments were conducted to assess the effectiveness of the laser assisted machining. The results, revealed that the force and tool damage was reduced in the laser assisted machining. Bermingham et al.[8] studied the tool life and wear mechanisms with Ti-6Al-4V using laser assisted milling. Laser assisted milling process is compared against conventional machining (MQL, coolants) and LAM-MQL process. The results, LAM process are increased of adhesion, diffusion, attrition and notching wear. Woo and present author[9] studied the machining characteristics of AISI 1045 and Inconel 718 with cylindrical shape workpiece in LAM. Analysis were up-cut and down-cut milling. As a results, down-cut milling better than up-cut milling for the case of Inconel 718 in LAM. Bucciarelli et al.[10] studied micro milling experiments were dry, wet, and laser-

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assisted conditions. As a results, analysis are surface morphology, burr, part feature depth, cutting forces and tool wear. Hedberg et al.[11] studied laser assisted milling of Ti-6Al-4V with the consideration of surface integrity. Kong et al.[12] studied K24 nickel based super alloy for cutting performance and coated tool wear mechanisms using laser-assisted milling. Bermingham et al.[13] propose different tool path strategies for laser-assisted milling. Xi et al.[14] studied numerical modeling used SPH method with beta titanium alloy in laser assisted machining. Kang and present autor[15] studied constitutive equation of ceramic in laser-assisted milling process. Ravindra et al.[16] studied high-pressure phase transformation and ductile material removal with silicon nitride using micro-laser assisted machining. Kim and present author[17] studied spherical shape. Laser assisted machining has been studied by many researchers on flat workpiece or micro end-milling. However, there is no research on the curved shape using laser assisted milling.

The aim of this study is evaluation of machinability with NURBS(Non-uniform rational b-spline) based of curved workpiece for three dimension machining in laser assisted machining.

Thermally analysis was carried out to determine the optimum preheating temperature and effective depth of cut. Machining experiments of Inconel 718 with laser-assisted machining is used different tool path, different spindle speed and feed combinations. Contour milling analyze during up and down milling of tool path on both concave and convex surface. Ramp milling analyze during upward and downward milling of tool on both concave and convex surface. Experiment results are conventional machining compare with laser assisted machining such as cutting force and surface roughness. Fig. 1 shows a schematic diagram of curved shape machining using laser assisted machining

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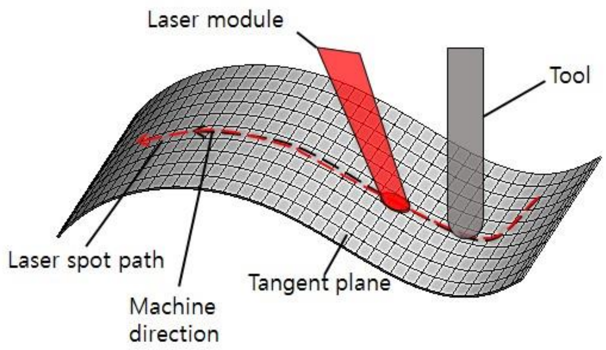

Fig. 1. Schematic diagram of the curved shape machining using laser assisted milling

2. Finite element analysis

2.1 Thermal analysis

A thermal analysis was conducted to determine the optimum preheating temperature and effective depth of cut prior to the experiments with laser-assisted machining.

A thermal analysis using temperature-dependent inputs is described by Eq. (1) as

$$\rho c_p \frac{\delta T}{\delta t} = \frac{\delta}{\delta x}\left(k\frac{\delta T}{\delta x}\right) + \frac{\delta}{\delta y}\left(k\frac{\delta T}{\delta y}\right) + \frac{\delta}{\delta z}\left(k\frac{\delta T}{\delta z}\right) + \dot{Q} \qquad (1)$$

where ρ, c_p, k and $\dot{Q}$ represent density, specific heat, thermal conductivity and power generation per unit volume, respectively.

The initial condition at time t = 0 are given by Eq. (2) as

$$T(x, y, z, 0) = T_0 \qquad (2)$$

The boundary condition can be defined by Eq. (3) as

$$-\mathrm{k}\frac{\delta T}{\delta z} = q(x, y) - h(T - T_0) \qquad (3)$$

where q,h,T, and T_0 represent heat flux, heat transfer coefficient, surface temperature and ambient temperature, respectively. A thermal analysis was carried out to determine the workpiece surface temperature. The thermal conductivity and specific heat of Inconel 718 based on the temperature are shown in Fig. 2.

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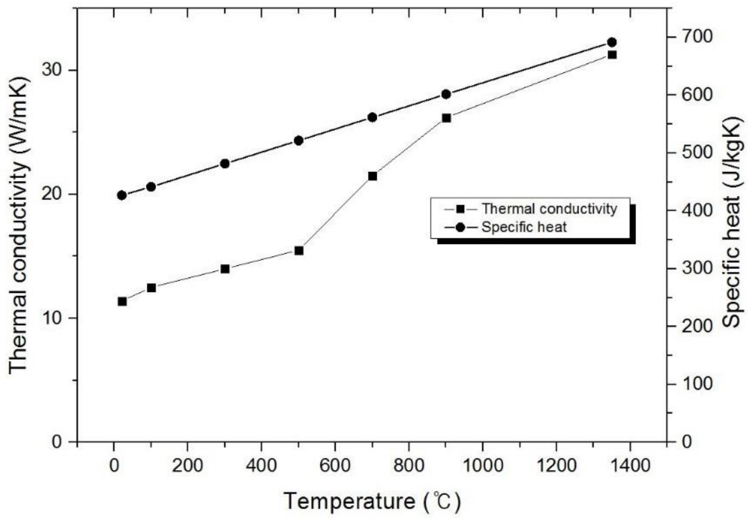

Fig. 2. Thermal conductivity and specific heat of Inconel 718 according to temperature

A finite element model was composed using the finite element analysis software ANSYS Workbench. A hexagonal dominant mesh was applied in the analysis model. The analysis model of contour milling for Inconel 718 included 99,941 nodes and 31,984 elements. The analysis model of ramp milling for Inconel 718 included 178,748 nodes and 56,789 elements. Fig. 3 shows the Finite analysis models. The laser heat source was assigned a mesh size of 0.5 mm for the contour milling and ramp milling, respectively.

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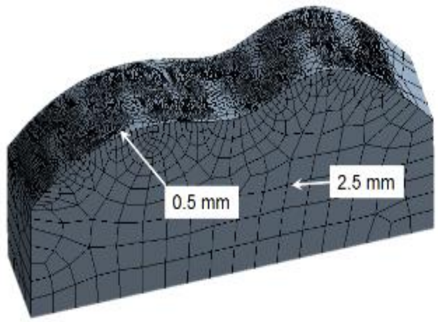
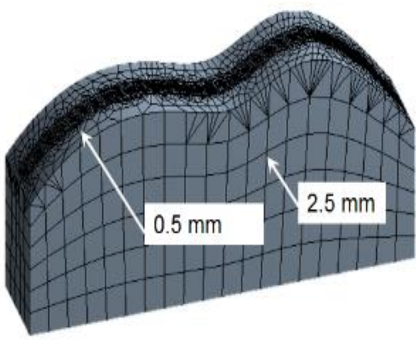


(a) Contour milling



(b) Ramp milling

Fig. 3. Finite elemenet analysis models

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2.2 Thermal analysis results

Using the FEM analysis, the results for preheating temperature and depth of cut of Inconel 718 were obtained. Fig. 4 shown was tensile strength of Inconel 718 according to temperature.18 Preheating temperature was estimated to be about 950 ℃. This is because a temperature of about 950 ℃ most suitable for reducing the residual stress caused by the heating of Inconel 718 as shown in Fig. 5. Consequently, in the contour milling, the preheating temperature was determined to be 938.87 ℃ and the effective depth of cut was determined to be 0.25 mm. In the ramp milling, the preheating temperature was determined to be 928.70 ℃ and the effective depth of cut was determined to be 0.25 mm.

The reason for selecting the depth of cut as 0.25 mm is that the residual stress rapidly decreased from 650 ℃ with Inconel 718, and the FEM analysis result was about 0.25 mm to obtain 650 ℃. Table 1 shows the maximum temperature of Inconel 718 for each laser power level both contour milling and ramp milling.

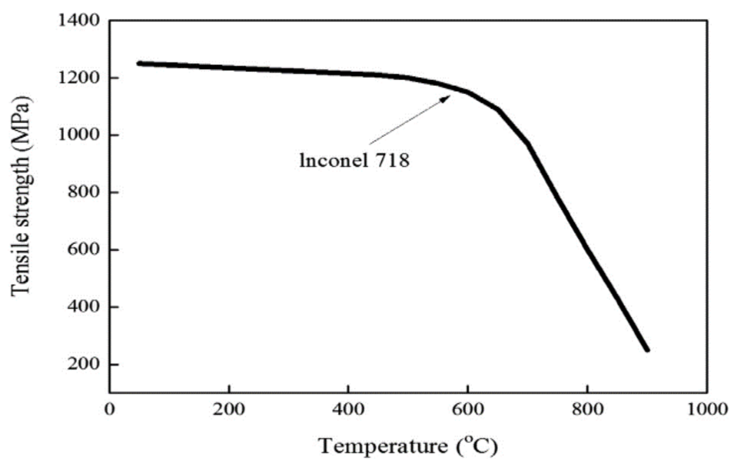

Fig. 4. Tensil strength of Inconel 718 according to temperature [18]

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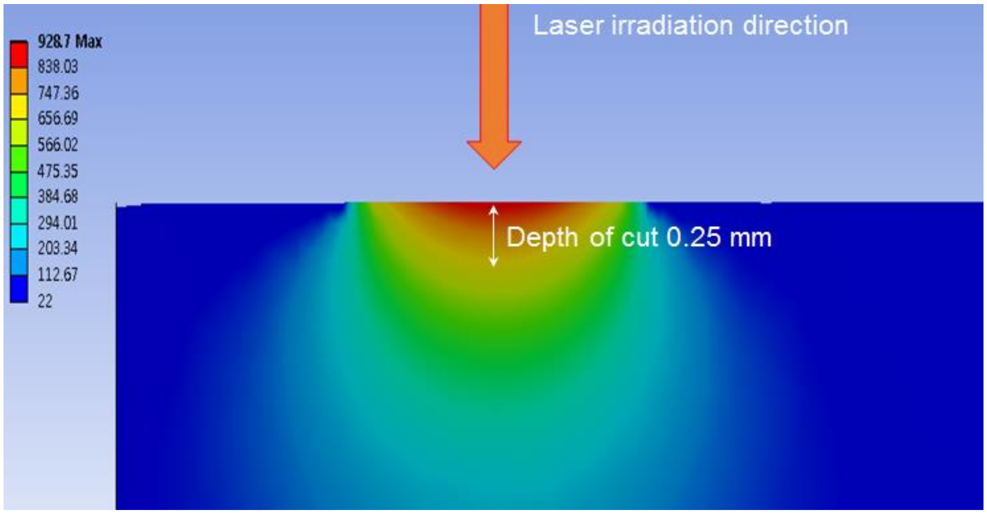
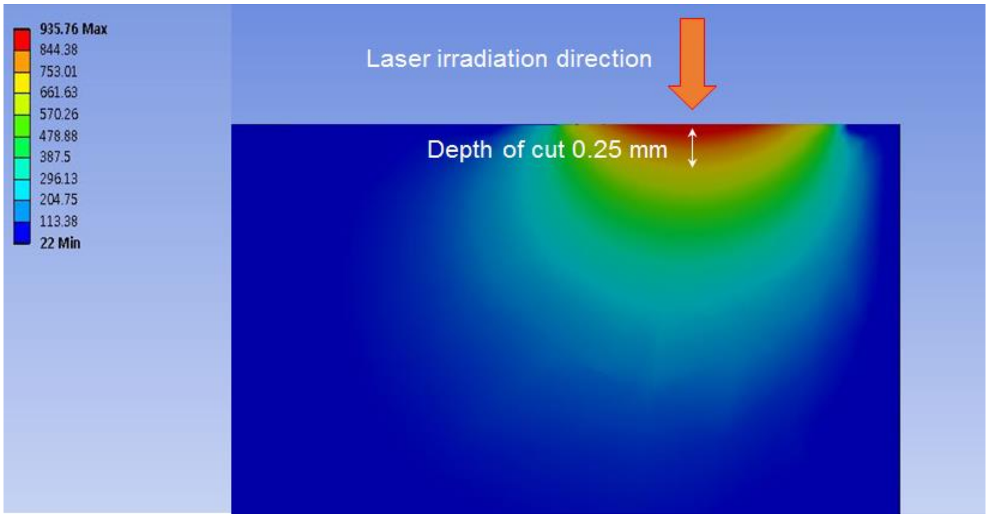


(a) Analysis result of ramp milling method



(b) Analysis result of contour milling method

Fig. 5. Analysis results of Inconel 718

Table 1 Maximum temperature of Inconel 718 each laser power

Laser power (W)	Contour (℃)	Ramp (℃)
80	814.35	803.93
90	877.06	869.43
100	938.87	928.70
110	997.60	986.98
120	1054.60	1044.00

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3. Experimental set-up

Experiments were performed on a 5-axis machining center, Hyundai-WIA Hi-V560M. For the experiment, different tool path techniques for ramp, and contour milling were conducted on a curved shape workpiece. Table 2 and Fig. 6 shows the experimental set-up.

In the curved shape, the laser heat source changes from an elliptical shape to a circular shape according to the curved surface. The shape of the laser heat source is changed to an elliptical shape the energy density is decreased, and the decreased energy density is used as input energy of the analysis.

There are two methods of controlling the temperature in laser assisted machining. One of them is the power control method, and the other one is the temperature control method. Both methods are control temperature using Pyrometer. The power control method is a method of maintain the laser power constant from any place, the temperature control method is a method of maintain the temperature of the surface constant from any place. In this study, the power control method was used. Fig. 7 shows change of laser heat source according to curved shape.

Table 2 Specifications of the experimental set-up

Instrument	Company	Specification
Machine	Hyundai-WIA	Hi-V560M
Laser optic	Laserline	LDM 1000-100
Pyrometer	Dr. Mergenthaler	LPC03
Dynamometer	Kistler	9257B
Amplifier	Kistler	5019

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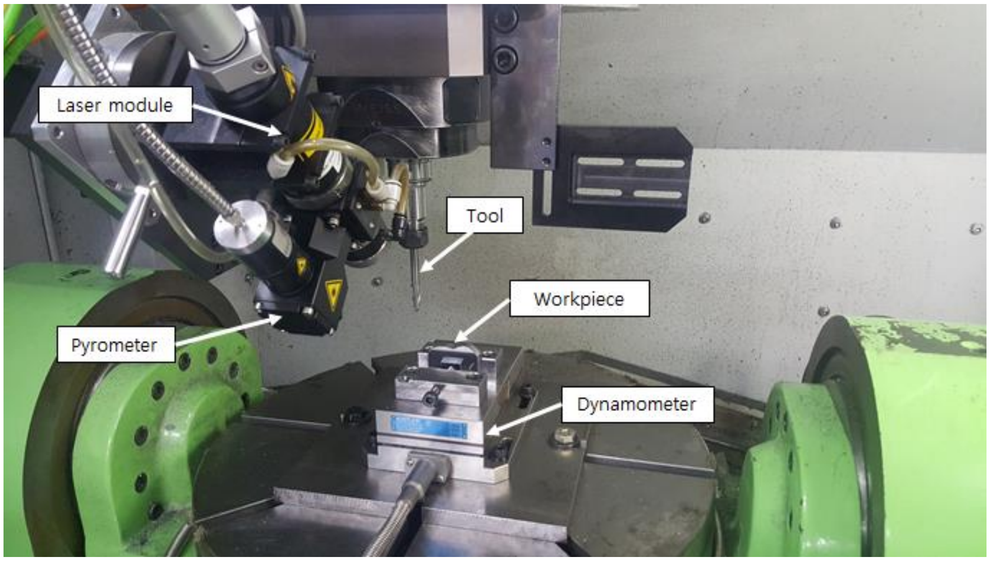

Fig. 6. Experimental set-up

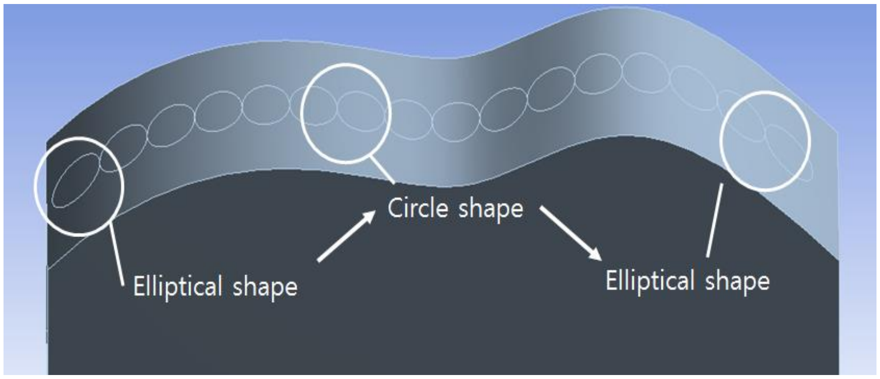

Fig. 7. Changes of laser heat source shape according to curved surface

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3.1 Contour milling method

During contour milling, the machining direction has to change in each region in order to maintain contact and continue milling. In the contour milling method, two types of milling operation are performed based on the orientation of the surface. These are designated up and down milling. These operation determine the relationship between the tool rotation direction and machining direction. In up milling, the tool rotates clockwise while the workpiece is moved from right to left. Down milling is the opposite of up milling. In the up milling process, the cutter rotates against the machining direction and the cutting chips are carried upward by the cutter. In the down milling process, the machining direction is the opposite, and the cutting chips are carried downward by the cutter. When machining a surface down milling is commonly used because down milling produces a better workpiece. Fig. 8 shows schematic diagram of contour milling method.

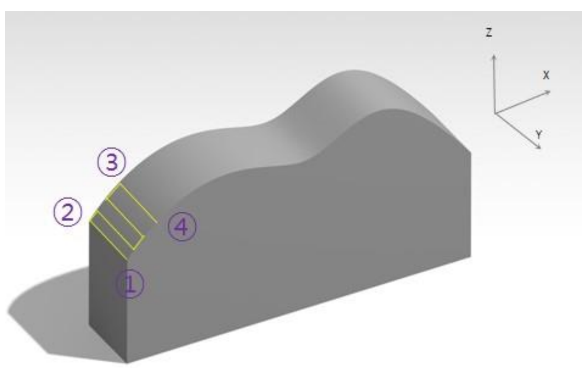

Fig. 8. Schematic diagram of contour milling method

3.2 Ramp milling method

In the ramp milling method, milling is also performed upward and downward based on the orientation of the surface. The important parameter that most affects the quality of the machining process during ramping down is the skidding of the tool on the surface. During

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the upward milling, only the front sides of the ball end mill are cutting the workpiece. And with down milling, only the back sides of the ball end mill contact the workpiece.

Fig. 9 shows schematic diagram of ramp milling method. Also, in ramp milling it is necessary to control the laser heat source because changing the machining direction from the +X direction to the –X direction requires that the laser heat source also be changed in the same direction. To resolve this issue, an additional axis module was equipped on the spindle. The additional axis is the U axis corresponding to the X axis and V axis corresponding to the Y axis. It can be controlled by NC code in conjunction with NC code. In this study, when the direction of the X axis was changed, the U axis was moved in advance to control the laser heat source. Fig. 10 Additional axes of on the laser module. Fig. 11 shows laser heat source moving method in ramp milling method. Table 3 shows experimental condition for LAM

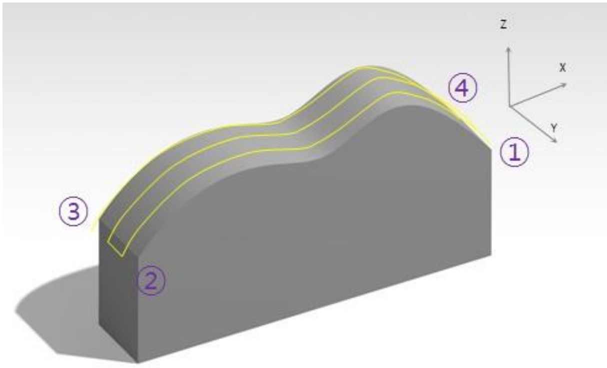

Fig. 9. Schematic diagram of ramp milling method

Table 3 Experimental conditions for LAM

Condition	Inconel 718
Tool path	ramp, contour

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Spindle speed (rpm)	6000, 8000, 10000
Feed rate (mm/min)	140, 200
Depth of cut (mm)	0.25
Tool	Ø 8 Ball end mill, 2F, 100L
Preheating temperature (℃)	950
Laser heat source size (mm)	3
Laser wavelength (nm)	800-980
Laser power (W)	100

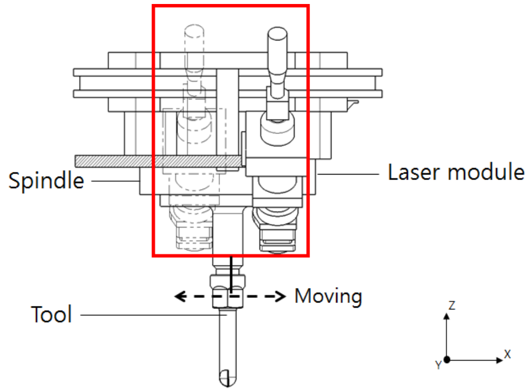

Fig. 10. Additional axes of laser module

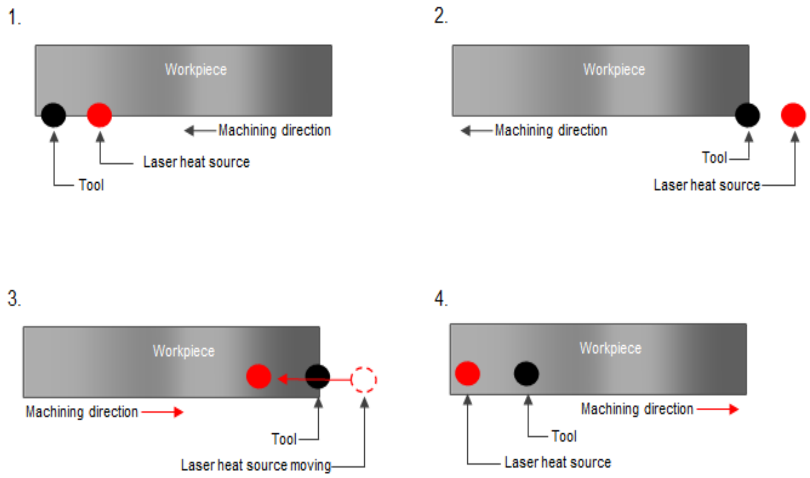

Fig. 11. Laser heat source moving method in ramp milling method

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4. Results

4.1 Cutting force

4.1.1 Contour milling method

The machining experiment was carried out by applying two methods, conventional machining and LAM. The contour milling method of experiment results are shown in Fig. 12 and Fig. 13. And as the inclination angle increased, the cutting force also increased. The results of the experiment showed that, using LAM, the cutting force was reduced by 25.1 %, 32.8 %, and 39.6 % when the spindle speed was 6,000 rpm, 8,000 rpm, 10,000 rpm, compared with conventional machining. Also, when the feed rate was 140 mm/min, 200 mm/min, the cutting force dropped by 15.5 %, 27.1 %, 32.2%.

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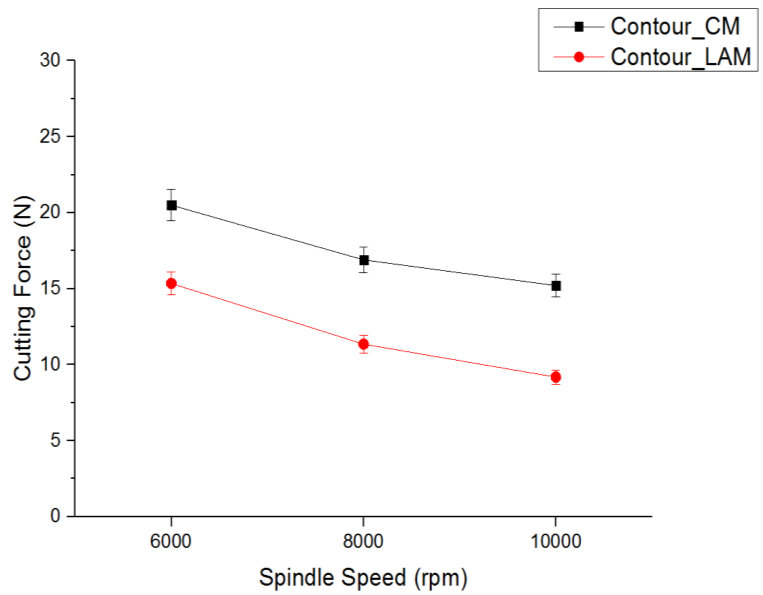

Fig. 12. Experiment results by the feed rate 140 mm/min in contour milling

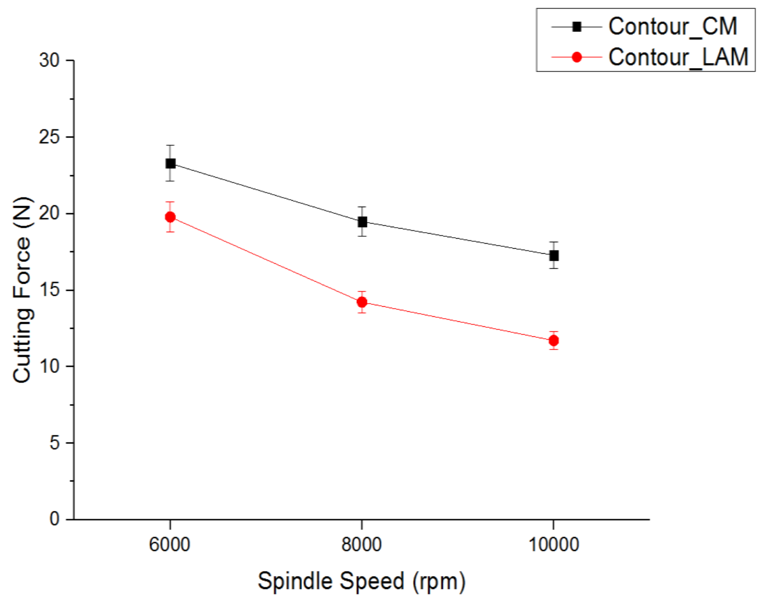

Fig. 13. Experiment results by the feed rate 200 mm/min in contour milling

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4.1.2 Ramp milling method

The ramp milling machining experiment was also conducted using the two methods, conventional machining and LAM, under various machining conditions. The ramp milling method of experiment results shown in Fig. 14 and 15. The cutting force was measured by dynamometer and amplifier. The experimental results showed that when the feed rate was 140 mm/min, depending on the spindle speed, the cutting force dropped by 2.1 ~ 15.6 % with LAM, compared with the conventional machining. When the feed rate was 200 mm/min, the cutting force dropped by 1.5 ~ 10.2 % with LAM. The cutting force was measured to the greatest at the concave section in LAM.

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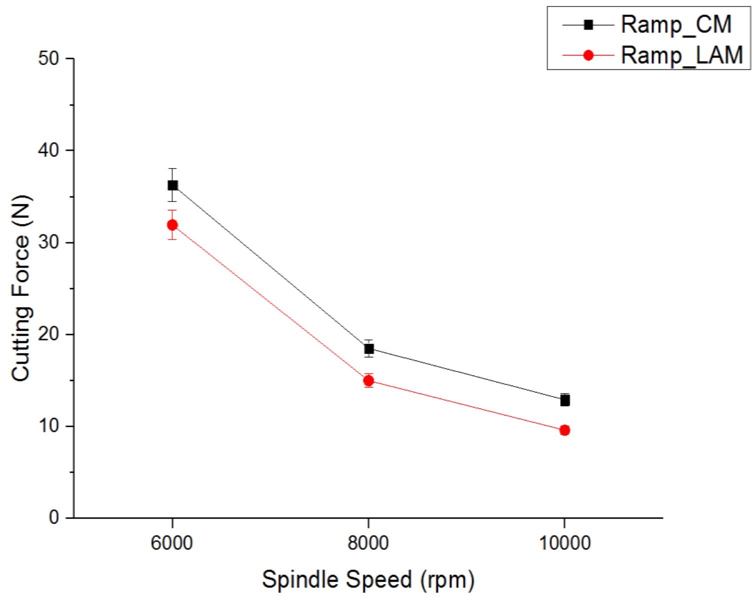

Fig. 14. Experiment results by the feed rate 140 mm/min in ramp milling

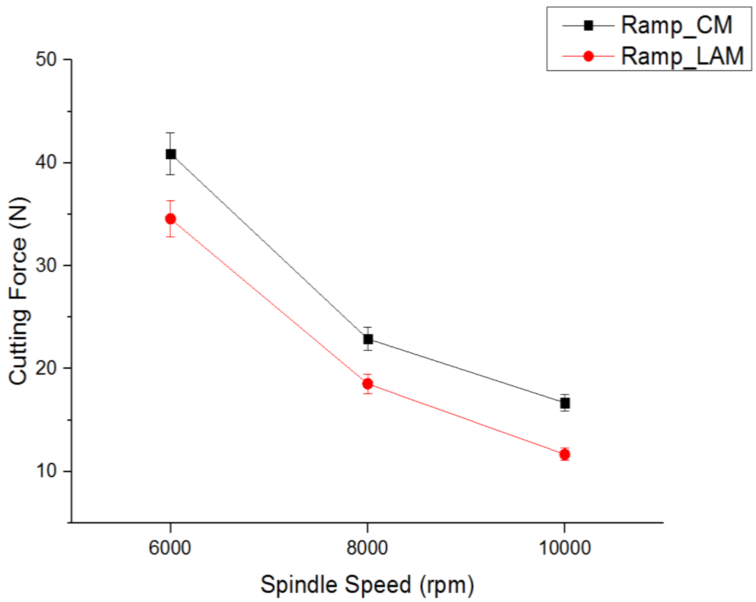

Fig. 15. Experiment results by the feed rate 200 mm/min in ramp milling

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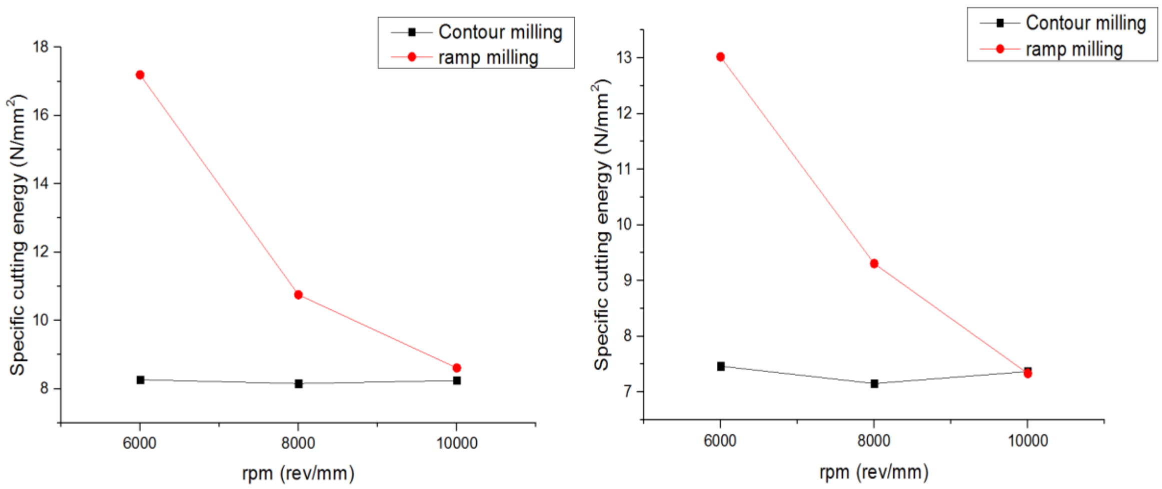
4.2 Specific cutting energy

The specific cutting energy (SCE) is an improtant parameter to evaluate the efficiency of a machining process. And it is the energy consumed in material removal rate per volume. In this study, was used to verify LAM efficiency with contouring and ramping. The SCE was expressed in terms of material removal rate (MRR), cutting force (F) and cutting speed (V). The equations used in the calculation is as follows, Eq. (1)

$$\text{Specific cutting energy} = \frac{F\times V}{MRR}\,[N/mm^2] \tag{1}$$

Fig. 16 shows the specific cutting energy of contour milling and ramp milling during various the spindle speed in the LAM. When compared were contour milling and ramp milling in the machining of inconel718, the spindle speed and feed rate was increased the SCE decreased rate was dropped. Totally, the SCE of contour milling was lower than ramp milling. When the spindle speed was increased in the ramp milling, the SCE rate was decreased by 49.91 % at the feed rate 140 mm/min.



(a) Feed rate at 140 mm/min (b) Feed rate at 200 mm/min

Fig. 16 The specific cutting energy of contour milling and ramp milling with LAM

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4.3 Surface roughness

Surface roughness is measured by a shape measuring machine. For the ramp milling method, it was found that lower the feed rates resulted in better surface roughness. When the conventional machining results were compared and LAM, LAM improved by approximately 17.1 ~ 34 %. Fig. 17 shows the measured surface roughness results in contour milling method. Surface roughness was also better with a lower spindle speed and feed rate for the contour milling method. When the conventional machining and LAM were compared, LAM improved surface roughness by approximately 10.2 ~ 33.9 %. Fig. 18 shows measured surface roughness results in ramp milling method.

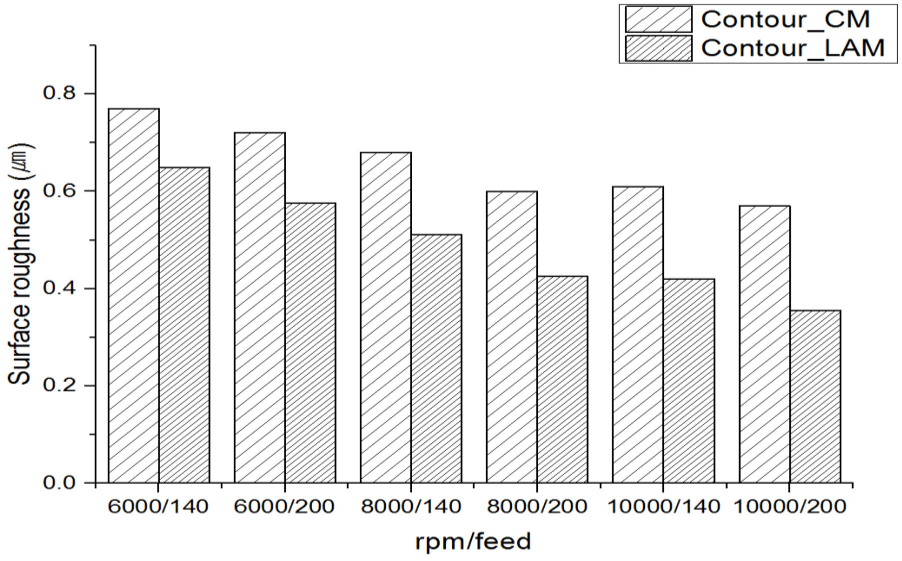

Fig. 17. Surface roughness in the contour milling

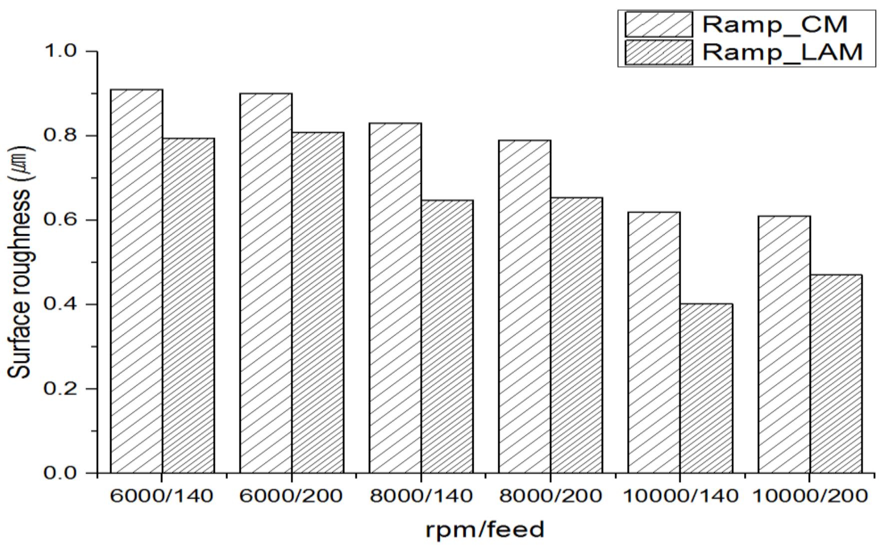

Fig. 18. Surface roughness in the ramp milling

5. Conclusion

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In this study, laser assisted machining was carried out on a curved workpiece using two surface machining methods, ramp and contour milling. The findings of this study, the following conclusion are :

(1) Before the machining experiment, a thermal analysis was performed to determine the effective depth of cut. The preheating temperature was determined to be 938 ℃ in contour milling, 928 ℃ in ramp milling and depth of cut was 0.25 mm at the laser power 100W. Machining experiment was performed by attaching additional axes to the 5-axis machining center for efficient surface preheating.

(2) The machining experiment results showed that in order to decrease the cutting force during contour milling, feed rate was a more important parameter than spindle speed. In the ramp milling, spindle speed was the more important parameter. The reason for cutting force decrased in the LAM, due to the materials was softend by laser heat soure, the decreased in vibration of cutting tool in the machining.

(3) The cutting force during contour milling was decreased by up to 39.6 % using LAM, and during ramp milling was decreased by up to 15.6 %. And better surface roughness was achieved with contour milling than with ramp milling. In both method, the feed rate had a greater effect on surface roughness than spindle speed. It is considered that the effect of decreasing the cutting force and surface roughness was decreased due to the bending of the tool in the ramp milling. And machining area of contour milling is more smaller than ramp milling, the preheating effect of contour milling was more effective than ramp milling.

(4) Compared were the SCE of contour milling and ramp milling in the machining of inconel718, at a feed rate 140 mm/min with ramp milling, decrease rate of SCE was biggest under the all machining conditions in LAM. The contour milling confirmed that was no significant difference in SCE under all machining conditions. This can be explanation by the preheating effect of contour milling was more effective than ramp milling in the LAM.

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Therefore, contour milling is recommended for curved workpiece machining with LAM.

(5) LAM was demonstrated to be superior in efficiency for machining inconel 718 compared to CM. The analyses in this study can be used to develop guidelines for three dimensional laser assisted machining. In conclusion, LAM was demonstrated to be one of the most effective TAM methods.

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