Cutting Temperature and Laser Beam Temperature Effects on Cutting Tool Deformation in Laser-assisted Machining

J. W. Jung, C. M. Lee

***Abstract*— Laser-assisted machining uses primarily laser power to heat the local area before the material is removed. It not only efficiently reduces the cutting force during the manufacturing process but also improves the machining characteristics and accuracy with regard to difficult-to-machine materials. The prediction of relative deformations between the cutting tool and workpiece is important to improve the accuracy of machined components.**

This paper presents the deformation errors caused by thermal effects in the laser-assisted machine tool using finite element method.

Key word— Laser-assisted machining (LAM), Deformation, Accuracy, Finite element method (FEM)

I. Introduction

Laser-assisted processing is one of the emerging fields in advanced manufacturing. The advantages that make the lasers increasingly attractive in industrial production include coherence, focusability, attractive, very high power intensity, power shaping capability and ease of automation with in-process sensing [1]. It also offers the potential to realize innovative design with high flexibility, a high processing speed, and good quality in many manufacturing processes. The capital investment may be higher, but this is offset by the benefits gained in many applications.[2]

Increasing demand for advanced difficult-to-process materials and the availability of high-power lasers have stimulated interest in research and development related to laser machining.[3]

Increasing interest in the use of lasers for manufacturing can be attributed to several unique advantages, which are generally applicable to the entire range of materials processing applications, such as high productivity, noncontact processing, elimination of finishing operations, adaptability to automation, reduced processing cost, improved product quality, greater material utilisation, minimal heat-affected zone (HAZ) and green manufacturing, etc. [4].

Materials processed by laser beam machining, range from metals and alloys to inorganic as well as organic non-metals, composites and rocks, etc. [5]. Pulsed Nd:YAG laser beam can be effectively used for cutting of silicon nitride ceramics and proper selection and controlling of laser beam machining process parameters can generate good quality cut surface during cutting of engineering ceramics [6]. Nd:YAG laser machining system can be continuously operated from a few watts to several hundred watts, but in most applications pulsed operation is preferred. Taper formation is the most important characteristics during laser micro-hole percussion drilling operation due to the inherent focusing characteristics of the laser machining process [7].

This paper presents the deformation errors caused by thermal effects in the laser-assisted machine tool. Laser-assisted machine tool performs the localized heating and cutting process simultaneously. So, the heats generated by localized heating process as well as the cutting process are conducted into cutting tool. In order to predict deformation errors, the heats from the two heat sources have to be analyzed simultaneously and thermal distortion have to be calculated. The objective of this paper is prediction of thermal distortion by laser power and cutting temperature. Sequence of this paper consists of three steps. First step, the commercial software Simdesigner was used to analyze temperature distribution of material removal plane by moving heat source. Second step, after defining result of the analysis first step, commercial software AdvantEdge was used to calculate the cutting temperature by modeling as simple orthogonal cutting. Third step, the commercial software Simdesigner was used to analyze thermal distortion by inputting the calculated cutting temperature and force by the second step. The results can be used to increase the cutting accuracy by compensating thermal distortion prior to laser-assisted machining.

II. Laser-assisted machining

A. Laser-assisted machining modeling

Fig. 1 shows schematic for laser-assisted machining of a workpiece. The angle difference between the laser heating and the material removal plane is 180°, as shown in Fig. 1. Type of laser beam is a CO_2 laser and Gaussian beam.

However, this paper ignores Gaussian beam in the finite element method. Table 1 presents specifications of the laser beam. The laser beam is used to heat workpiece before the material is removed.

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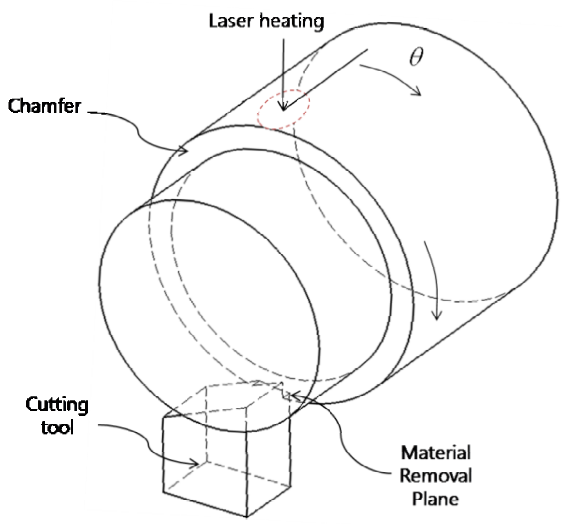


Fig. 1 Laser-assisted machining of a cylindrical workpiece

Table 1 Laser specifications

Type	CO_2
Shape	Cycle
Profile diameter	3mm
Power	319W

B. Analyses steps

The Fig. 2 shows three analyses steps for the deformation of cutting tool in laser-assisted machining. The three analyses steps are similarly composed of the real laser-assisted machining, i. d., after heating the workpiece by moving laser beam, cutting analysis step is performed for the material removal.

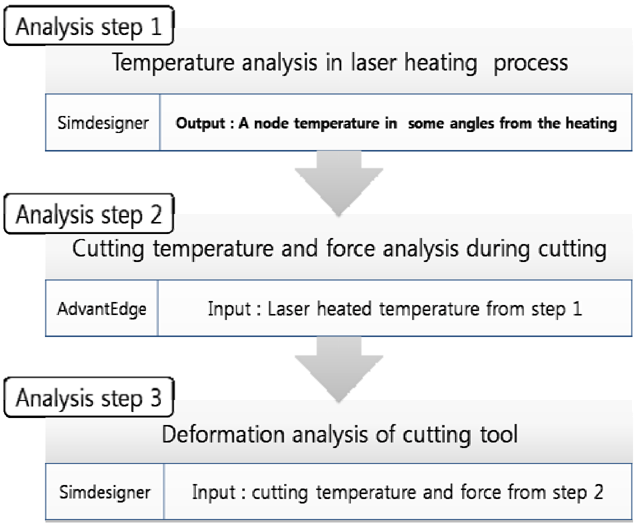


Fig. 2 Three analyses steps for the deformation prediction of cutting tool

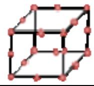
1. In order to obtain temperature distribution of arbitrary location θ using Simdesigner, it is needed to define boundary condition and input variables for moving heat source.
2. The results of the analysis step 1 and cutting conditions are used to obtain the cutting temperature and force during cutting by using AdvantEdge.
3. The results of the analysis step 2 are used to obtain the deformation of cutting tool using Simdesigner.

III. Finite Element Modeling

A. Finite element modeling of the analysis step 1

For the case of the analysis step 1, in order to obtain temperature distribution of material removal plane, it is needed to define finite element model. Mesh information of the analysis step 1 is shown in Table 2 and Fig. 3. Dimension of a cylindrical workpiece is ø16 x 30mm, the rotation speed is 440rpm and heat transfer coefficient of air is 11.2W/m²℃.

Table 2 Mesh information of a cylindrical workpiece

Mesh type	Hexahedron (Parabolic/20node) 
Mesh size[mm]	1 x 0.33
Elements number	17,460
Node number	75,384

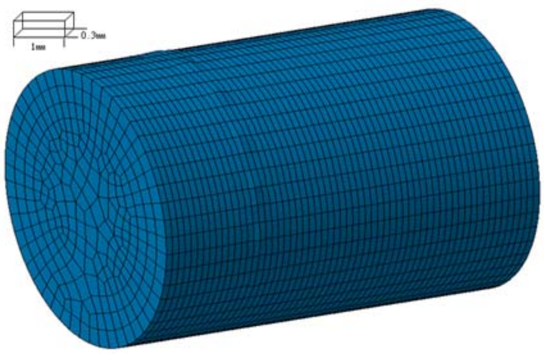


Fig. 3 Mesh of a cylindrical workpiece

The rotation speed 440rev/min amount to 3mm/0.0081387s in order to model moving heat source of laser beam. Time step used for the analysis step 2 is 0.00406938s, which is half of 0.0081387s and total time is 0.0732483s for transient analysis.

Table 3 Material properties of a cylindrical workpiece(Si_3N_4)

Young's modulus [GPa]	300
Poisson's ratio	0.3
Density [kg/m^3]	3,200
Thermal conductivity [W/m-℃]	16.9
Specific heat [kJ/kg-℃]	0.72

Moving heat source conditions for the transient analysis, nine heat areas are heated by moving heat source of 319W, the heating time and rate is shown in Fig. 4. The material properties for the workpiece Si_3N_4 are shown in Table 3

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[8].

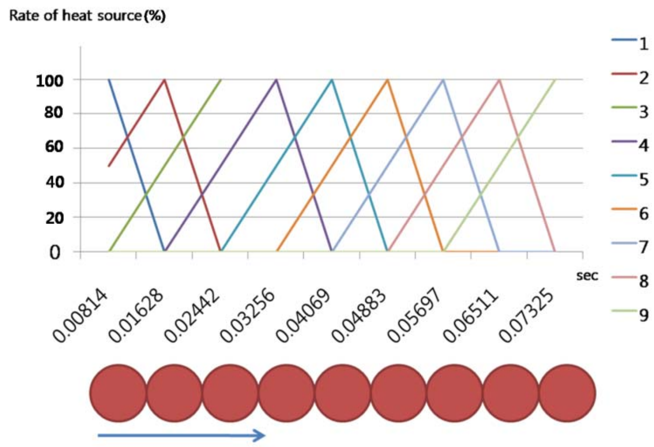
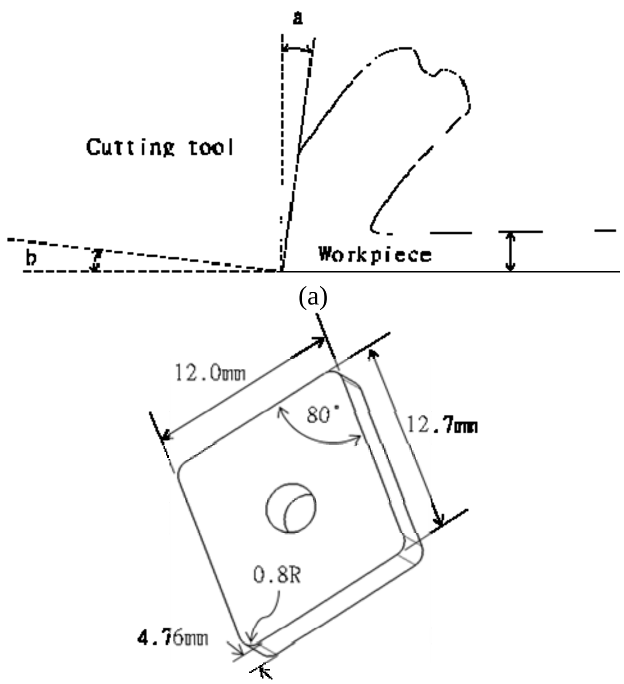


Fig. 4 A transient analysis conditions

B. Finite element modeling of the analysis step 2



(b)

Fig. 5 Rake, relief angle and geometry of a cutting tool

Table 4 Cutting conditions

<table>
<tr><td rowspan="2">Turning workpiece size</td><td colspan="2">Height[mm]</td><td colspan="3">Length [mm]</td></tr>
<tr><td colspan="2">8</td><td colspan="3">5</td></tr>
<tr><td rowspan="2">Standard oblique tool modeler</td><td>Edge radius[r]</td><td>Side rake angle[a]</td><td colspan="2">Back rake angle[c]</td><td>Relief angle[b]</td></tr>
<tr><td>0.02</td><td>-6</td><td colspan="2">0</td><td>6</td></tr>
<tr><td rowspan="2">Turning the analysis step parameters</td><td>Feed [mm/tooth]</td><td>Depth of cut [mm]</td><td>Length of cut[mm]</td><td>Cutting speed [m/min]</td><td>Initial degree [℃]</td></tr>
<tr><td>0.013</td><td>0.89</td><td>3</td><td>21.7</td><td>The results of step 2</td></tr>
</table>

2D analysis of AdvantEdge is carried out in the analysis step 2. A geometry and material data of a tool insert are obtained from tool manufacturer.

Fig. 5 shows rake, relief angle and geometry of a cutting tool. Cutting conditions are shown in Table 4. Mesh information of the analysis step 2 is shown in Table 5.

Table 5 Mesh information of the analysis step 2

Maximum element size[mm]	0.1
Minimum element size[mm]	0.02
Max. number of nodes	12,000
Mesh type	Triangle(CST)

C. Finite element modeling of the analysis step 3

Fig. 6 shows 3D model of the cutting tool and generated mesh using automation mesh(tetrahedron) of CATIA V5 due to complicated geometry of the holder.

The mesh information of the cutting tool is shown in Table 6 and material of the cutting tool is shown in Table 7[9].

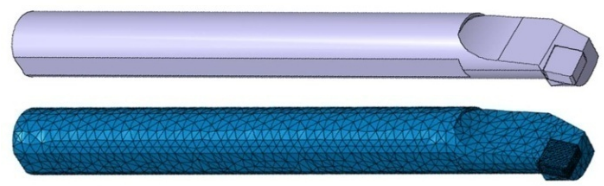


Fig. 6 3D model and mesh of the cutting tool

Table 6 Mesh information of the cutting tool

Mesh type	Tetrahedron (Parabolic/10node) 
Mesh size[mm]	(Insert)1 / (holder)4
Elements Number	12,629
Node Number	20,333

Table 7 Material properties of the cutting tool

	SAE4140 [holder]	CBN [insert]
Young's modulus [GPa]	205	680
Poisson's ratio	0.29	0.22
Density [kg/m^3]	7,861.1	3,120
Thermal conductivity [W/m-℃]	33	100
Specific heat [kJ/kg-℃]	0.56	0.7

The result of temperature in analysis step 3 is obtained using thermal workbench in Simdesigner. Next, after defining the result of thermal workbench, the deformations of the cutting tool are obtained using static workbench in Simdesigner.

IV. ANALYSIS RESULTS

A. Result of the analysis step 1

Fig. 7 shows temperature distribution by the analysis step 1.

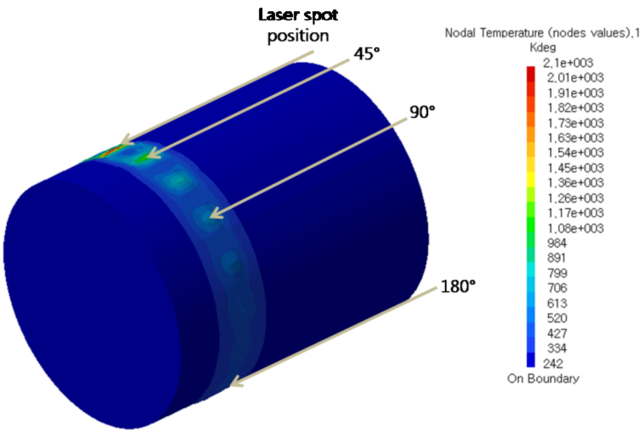
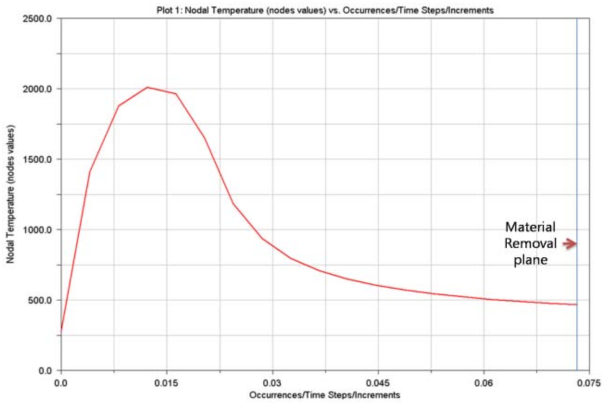
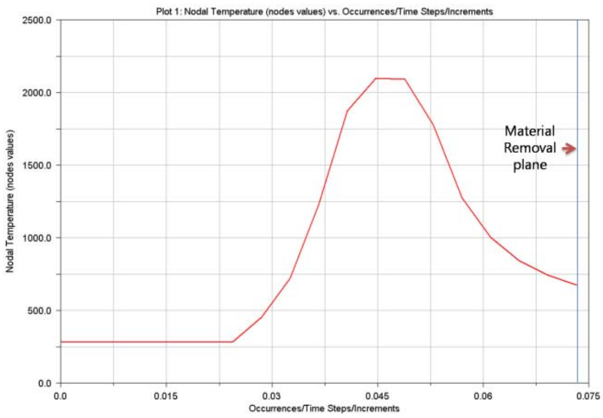


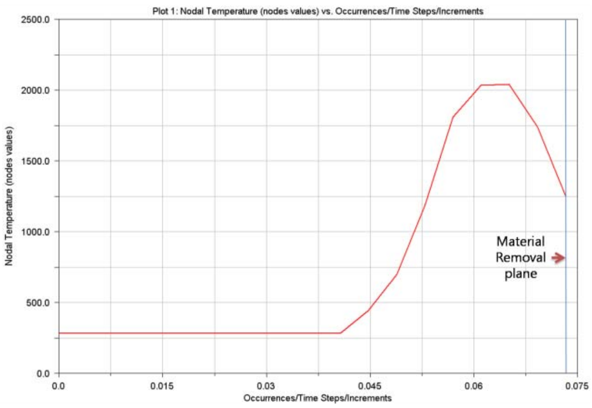
Fig. 7 Temperature distribution by the analysis step 1



(a) 180° plane from the laser heating



(b) 90° plane from the laser heating



(c) 45° plane from the laser heating

Fig. 8 Temperature variations of 180°, 90°, 45°planes from the laser heating

The maximum temperature of moving heat source is 1826.9℃. The temperature distribution of some regions higher than other regions through the moving heat source line is supposed to be occurred due to discontinuous moving heat source and mesh size.

Fig. 8 show temperature variations of 180°, 90°, 45° planes from the laser heating.

Table 8 Mean temperature at material removal planes

Location from the laser heating	180°	90°	45°
Mean temperature[℃]	197.4	397.8	960.9

Table 8 shows mean temperature at material removal planes in the path of moving heating source for analysis step 2. The mean temperature of 180° plane from the laser heating is the lowest as 197.4℃ because the material removal plane is far from laser heating. The mean temperature of 90° plane is 397.8℃ and 45° plane is 960.9℃. The closer location from the laser heating is defined, the higher mean temperature is occurred.

The analyzed mean temperature is used as initial temperature of analysis step 2.

B. Result of the analysis step 2

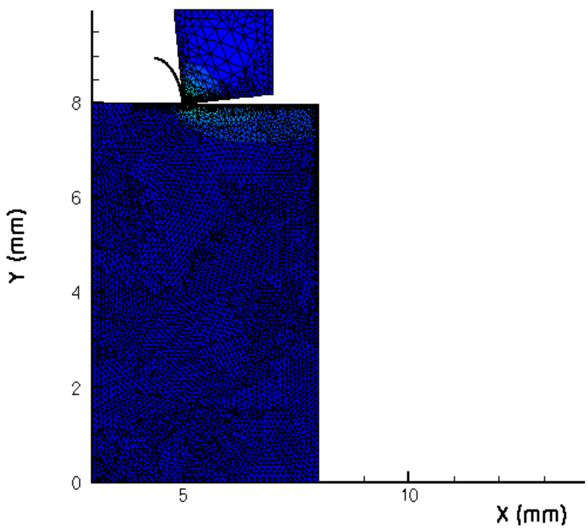
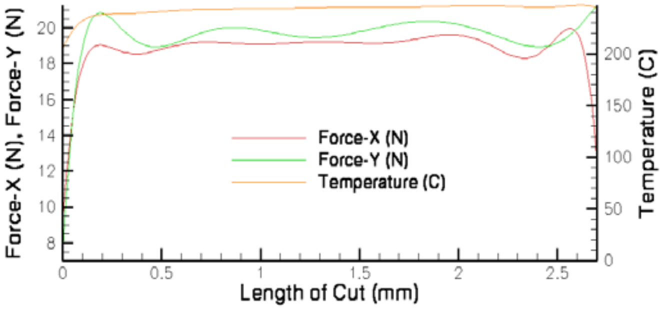


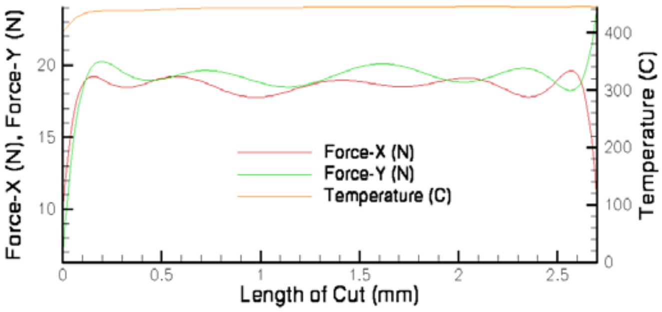
Fig. 9 A cutting simulation

Fig. 9 shows a cutting simulation of the analysis step 3. The simulation is performed to obtain peak temperature and cutting force.

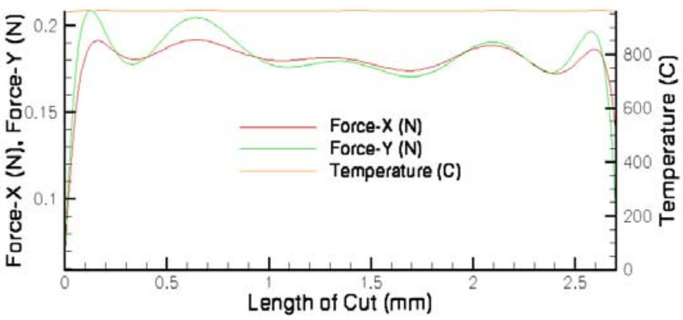
Fig. 10 show peak temperature(℃) and x, y-direction force(N) of the cutting tool by AdvantEdge. The peak temperature analyzed by mean temperature 197.4 is 240.3℃, 421.1℃ by 397.8℃ and 961.1℃ by 960.9℃. The cutting force analyzed by mean temperature 197.4℃ is 18.2~20.0N, 17.6~19.3N by 397.8℃ and 0.2~0.3N by 960.9℃.



(a) Result by mean temperature 197.4℃

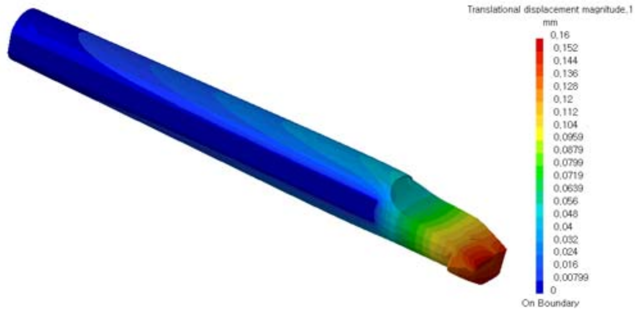


(b) Result by mean temperature 397.8℃

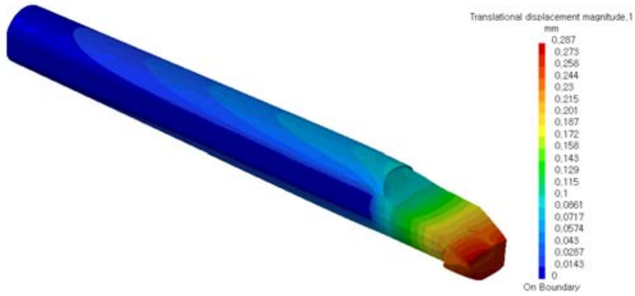


(c) Result by mean temperature 960.9℃

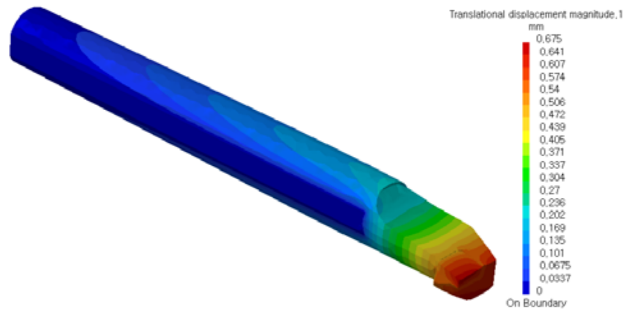
Fig. 10 Peak temperature variations and forces by analysis step 2



(a) 180° plane from the laser heating



(b) 90° plane from the laser heating



(c) 45° plane from the laser heating

Fig. 11 Deformations of the cutting tool

The peak temperature is increased from the mean temperature due to cutting thermal effects during cutting. And the higher mean temperature is defined, the lower cutting force is occurred because the workpiece is softened by laser heating.

The peak temperature and cutting force of analysis step 2 are used as input variables of the analysis step 3.

C. Result of the analysis step 3

Fig. 11 show deformations of the cutting tool by the cutting temperature and force at 180°, 90°, 45° planes from the laser heating. Maximum deformations are 0.16mm at the 180° plane from the laser heating, 0.287mm at the 90° plane and 0.675mm at the 45° plane.

The closer location from the laser heating is defined, the higher deformation error is occurred. Thus, the location from the laser heating is important for deformation errors of the cutting tool in laser-assisted machining.

V. Conclusion

The prediction of relative deformations between the cutting tool and workpiece is important to improve the accuracy of machined components using finite element method (FEM). This paper presents prediction of thermal distortion by laser power and cutting temperature. Sequence of this paper consists of three steps. First step, the commercial software Simdesigner was used to analyze temperature distribution of material removal plane by moving heat source. Second step, after defining result of the analysis first step, commercial software AdvantEdge was used to calculate the cutting temperature by modeling as simple orthogonal cutting. Third step, the commercial software Simdesigner was used to analyze thermal distortion by inputting the calculated cutting temperature and force by the second step.

1. The peak temperature is increased from the mean temperature due to cutting thermal effects during cutting. And the higher mean temperature is defined, the lower cutting force is occurred because the workpiece is softened by laser heating.
2. The closer location from the laser heating is defined, the higher deformation errors are occurred. Thus, the

location from the laser heating is important for deformation errors of the cutting tool in laser-assisted machining.

3. The results can be used to increase the cutting accuracy by compensating thermal distortion prior to laser-assisted machining.

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