Paper:

Minimizing Burrs and Defects on Microstructures with Laser Assisted Micromachining Technology

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Molding technology is widely used to manufacture optical components because of its high efficiency. Along with the quick development of miniaturization in industry, the detrimental effects of previously negligible burrs and defects on mold surfaces have become significant to the performance of components, so these problems should be minimized. In this study, a laser assisted micromachining method was developed to solve this problem during the fabrication of periodic microstructures on a molding material of electroless nickel-phosphorus (NiP) plating. The transient temperature distributions of the workpiece under laser irradiation and the change in the maximum shear stress during the laser assisted micromachining process were simulated to set appropriate experimental conditions. Then, periodic micropyramid structures were fabricated by both conventional cutting and the laser assisted cutting processes. Results show that defects largely decreased on machined structures with the assistance of laser irradiation. The decrease in specific cutting force and the change of chips' morphology were also utilized to analyze the reasons for this improvement.

Keywords: laser assisted micromachining, burrs and defects, microstructures, electroless NiP plating

1. Introduction

Molding technology is generally used to replicate structures on materials such as glass and polymers to fabricate functional optical components at a high rate of efficiency [1–3]. Electroless nickel-phosphorous (NiP) plating with an amorphous structure is a widely used mold material owning to its excellent mechanical properties and good machinability [1–4]. Therefore, structures are generally fabricated on NiP plating surfaces using cutting technology. Recently, the miniaturization of industrial components has attracted a lot of attention and achieved many improvements [5], but this miniaturization has made previously negligible burrs and defects on structures become very detrimental to the functional performances of the components. **Fig. 1** demonstrates a typical example of burrs and defects on a retroreflective structure fabricated using a conventional cutting technique. The required optical properties of glass or polymer components, such as reflectivity and transmissivity, will be decreased by these defects. When the sizes of periodic structures are decreased to dimensions of several micrometers or even much smaller, burrs and defects of submicrometer scale also greatly decrease the required performances [6, 7]. Conventional deburring technologies can be used to remove burrs, and some new techniques are capable of removing burrs of microfeatures [8–10], but they are incapable of repairing defects. Besides, form accuracy is generally decreased in deburring processes, and the increased costs also have to be considered. When burrs are decreased to several-micrometer or even submicrometer dimensions, most of the conventional deburring methods seem to be inadequate. Therefore, new micromachining technologies capable of minimizing burrs and defects should be developed to solve this problem.

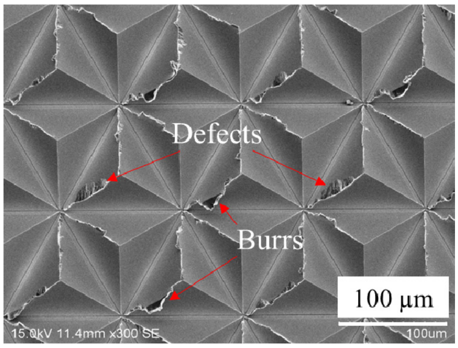

Fig. 1. A typical retroreflective structure with burrs and defects.

Laser assisted machining (LAM) is a thermal-assisted machining process in which the work material is locally softened by means of laser irradiation before being machined [11]. LAM has already garnered a lot of attention for machining hard-to-machine materials [12–14] because

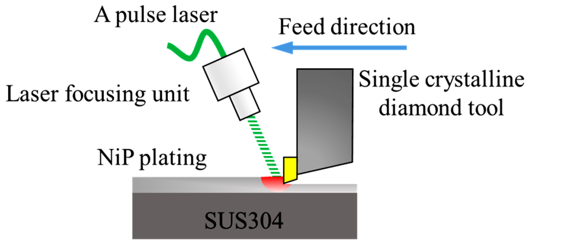

Fig. 2. Schematic of laser assisted micromachining process.

their mechanical strength and hardness can be decreased by the heat softening. Therefore, the quality of machined surfaces can be improved with a prolonged tool life at a high rate of machining efficiency. Ductile plastic deformation can be obtained with few cracking occurrences with the help of laser irradiation, which can be used to explain the improved machinability and surface quality [14]. The enhanced machinability obtained with heat softening also has the potential to be used to minimize burrs and defects generated in the mechanical micromachining process. That potential was investigated in this study.

There have also been reports on improving quality of machined surfaces by preheating the entire workpiece with an induction heating method [15]. Local preheating methods have also been investigated with other external heat sources [16]. Preheating the entire workpiece to a high temperature may introduce undesirable microstructural changes in workpieces, and thermal distortion is also highly detrimental to the required precision if fine surface structures are required. The thermal efficiency is also relatively low. Compared to other local thermal-assisted machining techniques, LAM has some advantages [16]. One advantage is that the diameter of the laser spot can be concentrated to micrometer or even nanometer dimensions at a high power density. As a result, only the small area of material to be machined is efficiently heated, and this serves to minimize the area affected by heat. The fast heating rate of laser irradiation can also obtain a large thermal gradient along the depth direction, which has the benefit of producing a high surface temperature without leaving much thermal damage on the machined surfaces. The light path can be also freely controlled. All of these merits make micromachining under laser irradiation possible. Therefore, a laser assisted micromachining method was developed to fabricate microstructures on NiP plating surfaces in this study.

The purpose of this study is to verify the efficiency of LAM for fabricating microstructures on surfaces while producing fewer burrs and defects than those produced by conventional cutting. **Fig. 2** schematically shows the design of the laser assisted micromachining process that was performed by locally heating the work material just ahead of a diamond tool using a laser beam with a small incident angle. A pulse laser (Nd: YAG) was used because of its high heating rate. The large thermal gradient of the workpiece can ensure a high surface temperature with few detrimental effects on the machined subsurface.

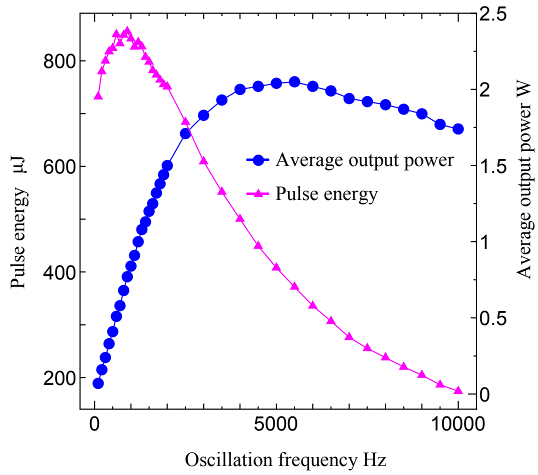

Fig. 3. Average output power and pulse energy versus the oscillation frequency of the laser beam.

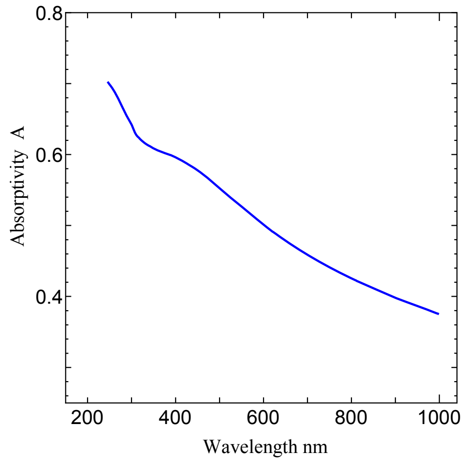

Fig. 4. The absorptivity of light in the NiP plating versus the light wavelength.

2. Simulations of Distributions of Temperature and Shear Stress

One of the challenges of LAM is to ensure that the heating rate is beneficial to the removal of the work materials at a low level of shear stress without causing thermal damage to the tool or machined surfaces [17]. Therefore, the transient temperature distribution of the workpiece and the change in shear stress in the material removal process under laser irradiation should be analyzed so that the desired experimental conditions for effective machining may be set. The laser input parameters, including average power, spot diameter, and scanning speed, among other parameters such as the light absorptivity of the work material, finally determine the temperature distribution.

The average power of the pulse laser was first measured using a thermal sensor. **Fig. 3** shows the measured average power and pulse energy versus the oscillation frequency. A stable output power for the pulse laser was obtained under the oscillation frequency of 7.5 kHz with

Table 1. Conditions for simulations of heat conduction under laser irradiation.

Parameters	Values
Laser wavelength	532 nm
Average output power	1.9 W
Diameter of laser beam spot	0.3, 0.5, 0.7, 1.0 mm
Absorptivity	0.536
Workpiece	NiP alloy plated on SUS304 ($1.0 \times 1.0 \times 1.1$ mm^3)
Thickness of NiP plating	0.1 mm
Material density	NiP: 5.02; SUS304: 15.0 W/(m · K)
Specific heat capacity	NiP: 7.9; SUS304: 8.03 g/(cm^3)
Thermal conductivity	NiP: 0.48; SUS304: 0.502 J/(g · K)
Initial temperature	20 °C

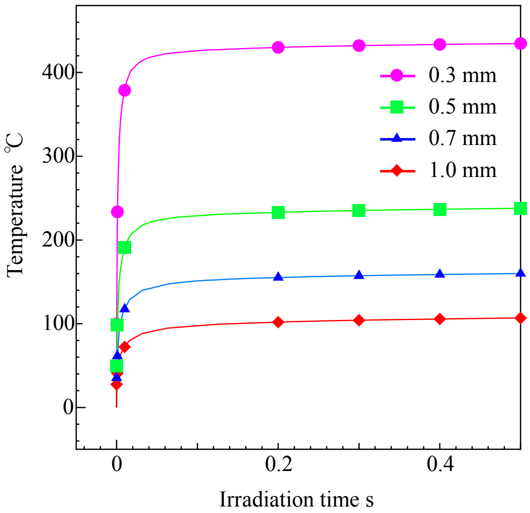

Fig. 5. Changes of surface temperature versus irradiation time with different diameters of laser beam spot.

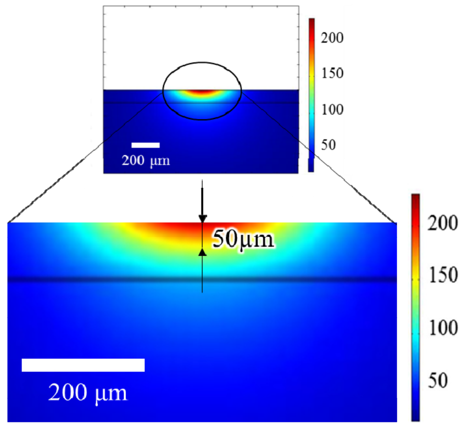

Fig. 6. Typical simulation results of temperature distribution in a workpiece after 0.1 s irradiation with a beam spot diameter of 0.5 mm.

a power of 1.9 W. The absorptivity of laser irradiation in the NiP plating can be calculated by using the following equation:

$$A = 1 - R = 1 - \frac{(n-1)^2 + k^2}{(n+1)^2 + k^2} \quad . . . . (1)$$

where R is the reflectivity, n is the refractive index, and k is the extinction coefficient. By referencing the data in [18], the absorptivity of the laser beam in the NiP plating can be plotted against its wavelength, as shown in **Fig. 4**. Based on the measured stable average power, the calculated absorptivity, and other parameters listed in **Table 1**, a finite element method was used to simulate the temperature distribution by employing a commercial software of COMSOL Multiphysics.

During LAM, the thermal energy of laser irradiation is transferred to the work material. The governing equation for the heat transfer is the following:

$$\rho C_p \frac{\partial T}{\partial t} = \nabla \cdot (k \nabla T) + q_{in} \quad . . . . (2)$$

where ρ is material density, C_p is specific heat capacity, T is temperature, t is time, k is thermal conductivity, and q_{in} is the energy generated by the laser irradiation. In this study, the laser energy is represented as a volumetric heating source with an ideal Gaussian intensity profile. The attenuation of the laser power within the material was described by the Beer-Lambert law, and the power density in the workpiece was finally expressed by the following equation:

$$q_{in} = \frac{8 \varepsilon Q_0}{\pi d^2} \exp \left\{ - \frac{8 \left(x^2 + y^2\right)}{d^2} \right\} \quad . . . . . . (3)$$

where q_{in} is the laser beam power density, Q_0 is the average laser beam power, ε is the absorptivity of laser power on the surface, and d is the laser beam diameter. The boundary condition for the top surface is a combination of the thermal radiation of the laser energy and convection heat transfer through the air. Thermal insulation boundary conditions are defined on the bottom and lateral surfaces. **Fig. 5** plots top surface temperature versus irradiation time with different diameters of the beam spot, and **Fig. 6** shows a typical temperature distribution after 0.1 s laser irradiation with a beam spot of 0.5 mm. It can be seen that the highest temperature is determined by the beam spot diameter under a certain laser output power. Temperature above 150 °C can be obtained up to a depth of 50 μm.

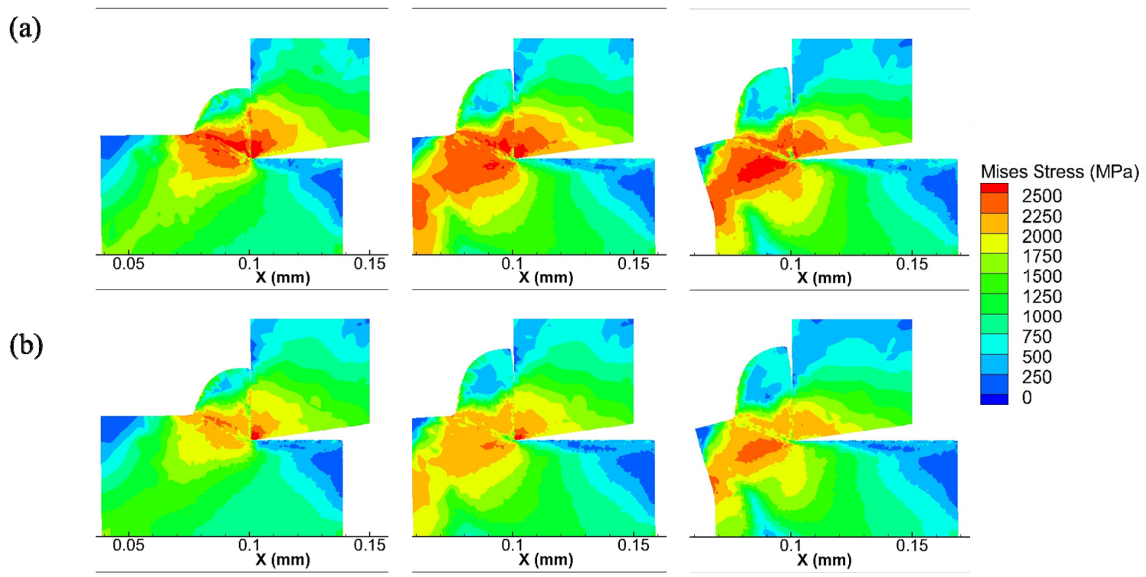

Fig. 7. The distributions of shear stress during material removal processes at temperatures of (a) 20°C and (b) 200°C.

Table 2. Conditions for cutting simulations at different temperatures.

Parameters	Values
Rake angle	0°
Clearance angle	8°
Tool material	Single crystalline diamond tool
Work material	MP35N
Initial temperature	20 °C, 200°C
Depth of cut	10 μ m
Cutting speed	1200 mm/min

To evaluate the effects of temperature rise on the shear stress distributions while material is being removed using LAM, orthogonal cutting processes under temperatures of 20 and 200°C with a single crystalline diamond tool were simulated using commercially available software, AdvantEdge FEM (Three Wave Systems). The simulations were done under the conditions listed in **Table 2**. A nickel alloy MP35N with properties near to those of the NiP alloy was utilized because NiP plating does not appear in the material database of AdvantEdge FEM. The work material was set with an elastic body, and the tool with a rigid body was used in the simulations. The four sides and the bottom of the workpiece were rigidly fixed. **Fig. 7** shows the shear stress distributions at different temperatures. These data demonstrate that a rise in temperature will decrease the maximum shear stress in the material removal process. The change in specific cutting forces with the temperature rise will be shown in the subsequent experiment. Stress distributed around the cutting tip before the tool leaves the workpiece generally results in burrs or defects on exit edges [19]. The stress can be diminished by heating the removal area locally, as shown in the simulation results, and this seems to help minimize burrs and defects. However, the deformation mechanisms of amorphous NiP alloys are unclear [20]. In other words, its ductile-brittle transition or other effects caused by the temperature changes cannot be accurately predicted. Furthermore, the amorphous NiP plating is thermodynamically unstable, and the heat treatment may lead to its crystallization [21], which makes it a harder and more brittle material. Therefore, cutting experiments should be done under increased temperatures to investigate the effects of laser irradiation on burrs and defects by combining these findings with the simulation results.

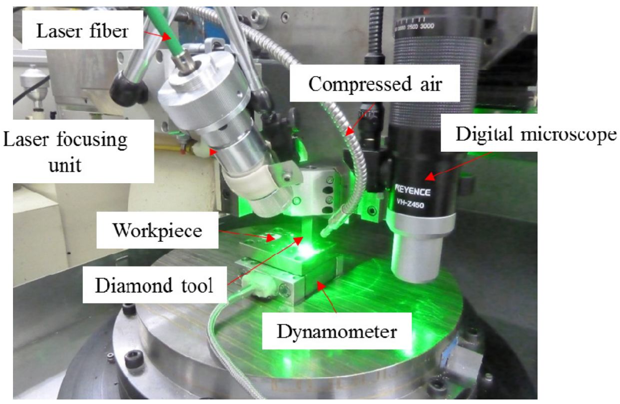

Fig. 8. Setup of laser assisted micromachining experiment.

3. Experiments and Discussion

Figure 8 is a picture of a practical laser assisted micromachining process. A five-axis, numerically controlled, ultraprecision cutting machine (MIC-300, Nagase Integrex Co., Ltd.) was used. As this machine has a resolution of 0.1 nm on the XYZ axes and 0.00001° on the BC axes, it is capable of ultraprecision machining for the fabrication of very fine structures. The laser focusing unit was mounted on the ultraprecision machine with a small

Table 3. Conditions of microgroove and micropyramid array fabrication.

Parameters	Microgrooving	Fabrication of micropyramid array
Workpiece	NiP (Phosphorus content: 10%)	
Depth of cut	10 μm	1.0 (0.6, 0.3, 0.1) μm
Cutting speed	1200 mm/min	1000 mm/min
Cooling system	Compressed air	
Temperature	23.0 °C	

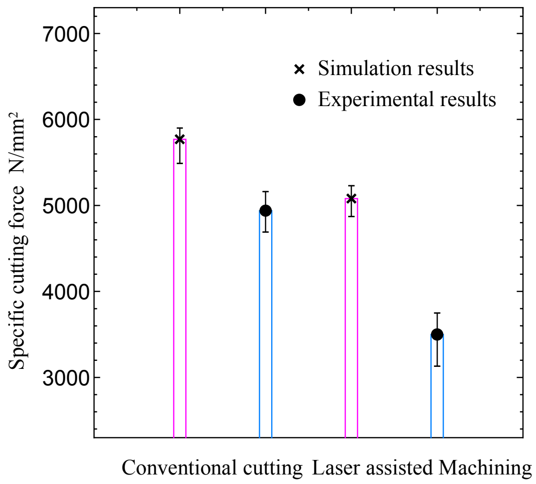

Fig. 9. Comparison of specific cutting forces in laser assisted micromachining and conventional cutting.

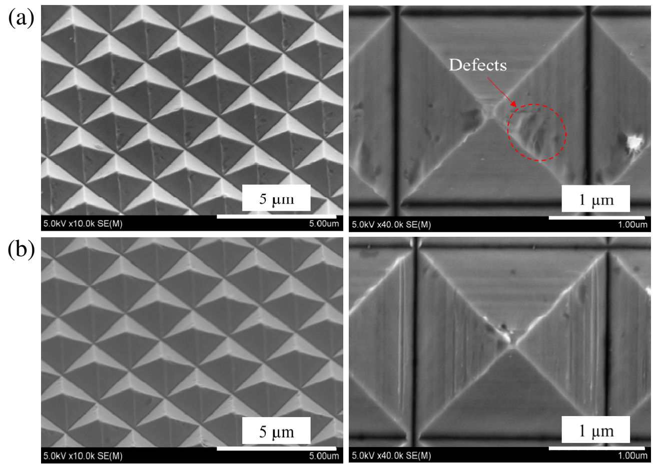

Fig. 10. Micropyramid arrays fabricated using (a) conventional cutting and (b) laser assisted micromachining.

incident angle. Compressed air was used to remove debris immediately in the LAM process to protect the machined surface and laser head. A three-axis dynamometer (MiniDyn 9256A2, Kistler) was mounted under the workpiece to measure the cutting forces. The diameter of the laser spot was first measured using a simple laser irradiation process on a workpiece coated with printing ink, and the test results showed that the spot was approximately 0.5 mm in diameter. A single crystal diamond tool with the tip angle of 90°, rake angle of 0°, and clearance angle of 8° was used in the cutting processes. All the LAM experiments were performed with the pulse laser with an average power of 1.9 W. Other test conditions are listed in **Table 3**. The machined surfaces were observed with a field emission scanning electron microscope (SM-71010, JEOL Corporation).

First, the effects of laser irradiation on cutting forces were investigated through microgrooving experiments under the condition listed in **Table 3**. **Fig. 9** compares the specific cutting forces of conventional cutting and LAM with both the simulation and experimental results. The specific cutting forces were decreased approximately 30% with the assistance of laser irradiation, higher than the approximately 12% decrease in the simulation result. The experimental results verified that using laser irradiation for the thermal softening of work material will lead to a reduction of flow stress, just as that was found through simulation. Therefore, we can conclude that the thermal softening effect plays a major role, although the possible crystallization of amorphous NiP plating may lead to an increase of hardness under this condition. Then, to verify the effect of laser irradiation on minimizing burrs and defects, periodic micropyramid structures were fabricated under the conditions shown in **Table 3**. A total depth of cut of 1 μm was achieved by continuous cutting processes in three successive steps with depths of cut of 0.6, 0.3 and 0.1 μm, respectively. **Fig. 10** shows the FE-SEM images of the structures fabricated. It was found that surface defects greatly decreased with the assistance of laser irradiation while the burrs on the edges of structures seemed to remain unchanged.

To further demonstrate the reasons for the observed phenomena in the LAM processes, the morphology of chips generated during the microgrooving experiments was also observed with a scanning electron microscope (SU1510, Hitachi). The results of these observations can be seen in **Fig. 11**. A typical infinite helix chip in conventional cutting process became a twisted chip in LAM, meaning that the chip curl decreased or mostly disappeared. Smaller curl diameter with the same cross-sectional geometry of cutting chip indicates that more strain accumulated during the material deformation process [22]. Segmented, saw-toothed chips with periodic slippages can be observed on each chip, but the slippage spacing is larger in LAM chips, as the enlarged images show. This indicates the slippages easily propagate and become bigger in LAM. The deformation processes are

(a)

(b)

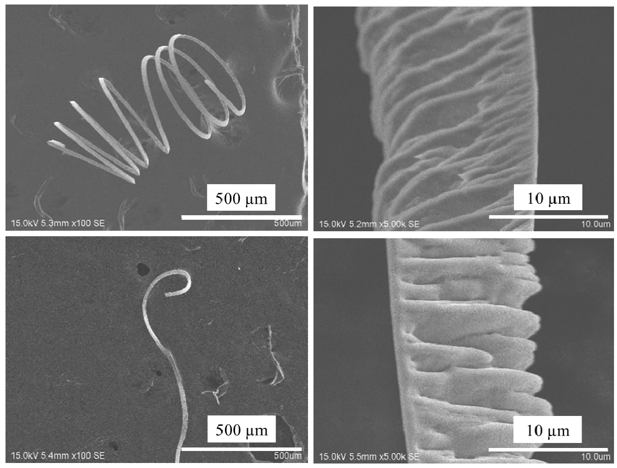

Fig. 11. Morphology of chips generated in (a) conventional cutting process and (b) laser assisted micromachining.

not similar, and less strain is required for material removal in LAM. These results can explain what causes the minimization of defects in LAM. By decreasing the depth of cut to several hundreds of nanometers or even smaller, the size of the burrs in both conventional cutting and the LAM process can be kept at a very low level. However, the material deformation mechanisms of amorphous NiP alloy are different from those of crystalline metals, and this should be paid more attention to in future work to get a better understanding, experimentally and theoretically, of chip generation mechanisms.

4. Conclusion

This study has verified that it is feasible to use laser assisted micromachining to fabricate periodic microstructures with fewer burrs and defects than when conventional cutting processes are used. A pulse laser was used, and the temperature distributions and shear stress in the cutting processes under laser irradiation were simulated. Laser assisted micromachining experiments were carried out in conditions based on the simulation results. Findings can be summarized as follows.

(1) Irradiation with the pulse laser heated the surface of the workpiece quickly with a large thermal gradient, and the maximum shear stress during the material removal process decreased with the rise in workpiece temperature.

(2) Laser irradiation has a valid softening effect on the work material. This was verified by a 12% decrease in the specific cutting force in the simulation and a 30% decrease in the microgrooving experiment.

(3) Surface defects on the microstructures fabricated by means of laser assisted micromachining were found to be significantly reduced. The effectiveness of laser irradiation on burr minimization was not verified, although the decrease in cutting forces and the changes in chip morphology seemed to serve to decrease burrs.

(4) In future work, the changes in material removal mechanisms under various laser irradiation conditions should be further studied to address more completely the phenomena observed in this study.

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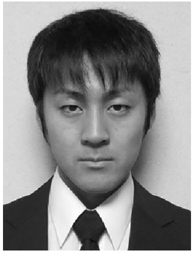

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Membership in Academic Societies:
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