Tool Run-out Correction Technology Using Laser On-the-Machine Tool*

Keiji OGAWA**, Heisaburo NAKAGAWA**, Satoshi WATANABE** and Gou UKAWA**

** Department of Mechanical Systems Engineering, The University of Shiga Prefecture, 2500 Hassaka-cho, Hikone-shi, Shiga 522-8533, Japan
E-mail: ogawa@mech.usp.ac.jp

Abstract
This paper proposes a new method for correction of tool run-out on a machine tool using a laser. The shank part of the tool attached on the machine spindle is irradiated with the laser beam. The thermal stress caused by laser irradiation at the irradiated part can make a very small deformation. First, the deformation patterns based on the thermal stress are shown. Second, experiments are carried out in order to investigate the influences of laser irradiation conditions on the deformation. Finally, a few case studies are performed using a cutting tool and succeeded in reducing the tool run-out to sub-microns.

Key words: Laser, On-the-Machine Tool, Tool Run-out, Correction, Deformation, Stress

1. Introduction
The development of higher precision machine tools and improvement of tool shape dimension accuracy have achieved high-precision machining. However, the tool run-out, which exists at the interface between the tooling holder and the tool, has been a very important factor in high-precision machining because it might influence on variations of cutting force and affect accuracy of dimension and surface quality of the workpiece (1)-(3). Moreover, it could shorten tool life. Therefore, technology for the correction of tool run-out is needed. Thus far, tool run-out has not been able to be corrected to zero, even if some new tooling holders are used that consist of machine elements for correction or a shrinkage fitting-type mechanism (4). Therefore, the present study proposes a new method for correction of tool run-out on the machine tool using a laser source.

2. Mechanism of Tool Run-out Correction by Laser
Figure 1 illustrates the tool run-out in case that the used tool is an end-mill. Figure 1(a) shows the offset error caused by unconformity of the set-up position between the tool and spindle axis center. Figure 1(b) shows the alignment error caused by the unconformity of the set-up angle of the tool to the spindle axis center. Tool run-out can be seen from one or both of the above reasons.
Figure 2 illustrates a flow of the proposed method of tool run-out correction using a laser on the machine tool. First, the tool run-out is measured. Second, the proper laser irradiation position and conditions based on a database are decided. Third, the laser beam irradiation is carried out and then the tool is deformed. Fourth, the tool run-out is measured again. If the tool run-out is smaller than that of the target value, the process is finished. If
not, the above processes are repeated until the value reaches the target.

The present study supposes that material of the tool shank is steel or cemented carbide. Figure 3 shows the deformation mechanism of the steel tool. The laser-irradiated part of the tool shank experiences thermal expansion because the temperature of the surface around the irradiated part rises rapidly. Therefore, the tool is deformed in the opposite direction of the laser-irradiated side. Because the thermal expansion is tied down, the compressive stress is caused at the laser-irradiated part, and tensile stress is caused around the area. When the stress caused by laser irradiation is larger than the yield stress of
the tool material, or when the phase transformations occur in the case where the tool material is tool steel or high-speed steel material, the tool deformation patterns are classified as follows. Figure 3(a) illustrates the deformed tool at moment of laser irradiation. Figure 3(b) illustrates a pattern of no final deformation (elastic deformation). This pattern can be seen in the case in which stress occurring in laser irradiation is smaller than the yield stress. The tool has plastic deformation to the laser irradiation side as illustrated in Figure 3(c) when the stress is larger than the yield stress. The irradiated part with plastic deformation has tensile stress from thermal shrinkage in this case. Moreover, in the case where the temperature rises to the phase-transformed level, the deformation occurs by the phase transformation as in Fig. 3(d). The tool is deformed to the opposite side of the laser irradiation by the volume expansion when the martensite transformation is caused at the pearlitic phase in the case of carbon steel without quenching. Meanwhile, the tool is deformed to the laser irradiation side by volume shrinkage when the pearlite transformation is caused at the martensite phase in the case of high-speed steel with quenching. Both plastic deformation and deformation with phase transformation might take place as in Fig. 3(e).

3. Experimental Method

3.1 Laser Processing System On-the-Machine Tool

Figure 4 shows on-the-machine laser processing system used in this study. A YAG laser with a wavelength of 1.06-µm and Gaussian-type energy density distribution was conducted to a lens unit mounted on the spindle of the machine tool by an optical fiber. Using the laser and the optical fiber without a complex optic system such as one using many mirrors, flexible laser treatment is possible on-the-machine tool. The laser irradiation conditions of laser power \( P \), irradiation time \( t_i \), and laser-spot diameter \( S_d \) were changed as shown in Table 1. Here, the laser-spot diameter was changed by controlling the laser focusing position.

3.2 Used Specimen and Evaluation Method of Results

Two types of specimen material are used in this study: tool steel (JIS: SK3) and cemented carbide, referred to as SK and WC-Co, respectively. First, a rectangular solid specimen was used because the influence of laser irradiation conditions on the tendency of tool deformation was evaluated. The specimen was a section 5 mm x 5 mm. The laser irradiation was performed in the vertical direction, whereas the specimen was fixed in a horizontal direction and the end was fastened as shown in Fig. 5. The deformation of the other free end was measured in the vertical direction using a displacement sensor. The bending angle was estimated by this and the distance of the irradiation point from the free end of the specimen. Here, the
bending angle was defined as positive in the case of bending to the upper side (+z direction in Fig. 5). The identification of phase transformation in the case of the tool steel bar was performed by the hardness of the material after laser irradiation. That is, the case in which the Vickers hardness of the material is 500 or more is defined as martensite-transformed.

4. Results and Discussion

4.1 Time History of Tool Deformation

Figure 6 shows a time history of the deformation angle. It can be seen that the deformation angle in laser irradiation steeply decreases with time in both cases of SK and WC-Co. Moreover, the magnitude of the deformation angle in SK is larger by twice or more than that in WC-Co at the moment. This might be due to the difference of the thermal expansion coefficient of each material. The expansion coefficient of SK is approximately $10 \times 10^{-6}$ 1/K. On the other hand, that of WC-Co is approximately $6 \times 10^{-6}$ 1/K. However, the deformation angle of both specimens increases rapidly after laser irradiation. Finally, the deformation angle becomes constant. The angle is determined as the bending angle $\theta_s$ in the present study. The value of SK is about 10 times larger than that of WC-Co. Here, the displacement of 1 µm at the tool end is equivalent to $\theta_s$ being 0.1-mrad when the tool shank part is irradiated with a laser beam at a point 10-mm from the tool end.

4.2 Variation of Deformation with Laser Conditions

It is considered that control of the provided thermal energy is easy in laser processing, which is an advantage of this process. Therefore, in this section, the influence of laser irradiation conditions on bending angle $\theta_s$ is evaluated.

Figure 7 shows the variation of bending angle $\theta_s$ with laser power. In case of SK, the bending angle $\theta_s$ is almost zero, which means elastic deformation, with small laser power of around 75-W in the case of a 2.0-mm spot diameter. However, that increases linearly with laser power. As the laser power increases, the martensitic expansion can be confirmed and the material melts is occurred. This tendency can be observed in both the 2.0-mm and 2.5-mm spot diameter. However, in the case of diameter larger than 2.5-mm, higher laser power is needed to make the bending angle $\theta_s$ start increasing. The reason that $\theta_s$ increases linearly might be that the generated thermal stress increases with input energy and also increases linearly with laser power. Moreover, this seems to be smaller in the case of a large spot diameter with gradual distribution of laser-energy density. In case of WC-Co, the
bending angle is very small but the tendency of bending angle changes with laser power is similar with that of SK.

Figure 8 shows the variation of bending angle $\theta_s$ with laser irradiation time. In case of SK, the bending angle $\theta_s$ is almost zero, which means elastic deformation, with small laser power of around 0.5-s in the case of 125-W laser power. However, $\theta_s$ increases rapidly until about 1.5-s, and after that it increases slightly with laser irradiation time. In case of WC-Co, the tendency of bending angle changes with irradiation time is similar with that of SK.

Figure 9 shows the variation of bending angle $\theta_s$ with laser-spot diameter. In case of SK, the bending angle $\theta_s$ is almost zero, which means elastic deformation, in large spot diameter of around 2.7-mm in the case of 150-W laser power. However, that increases
linearly with decreasing spot diameter. As the spot diameter decreases further, the martensitic expansion can be confirmed. This tendency can be observed with both 100-W and 150-W laser power. In case of WC-Co, same tendency can be observed with that of SK. It is shown that bending angle \( \theta_s \) clearly changes with laser irradiation conditions. These results of SK above are similar with those represented in research papers (5),(6) about the principle and applications of laser forming technology for steel plate. It can be supposed that the deformation mechanism of WC-Co specimens depends on stress because similar tendencies can be obtained to the SK specimens.

### 4.3 Influence of Phase Transformation on Variation of Deformation

Here, focusing on the influence of phase transformation in case of SK, it is found that phase transformation might have little influence because the bending angle \( \theta_s \) does not increase in the minus direction in Figs. 7(a) to 9(b). Therefore, the influence is evaluated in this section using SK specimens, which are annealed, quenched, and tempered SK, as shown in Table 2. The result is shown in Fig. 10. It is clear that the bending angle \( \theta_s \) is larger in the order of quenched, tempered, and annealed in the same laser irradiation condition. Moreover, the laser power at starting deformation is different from the each specimen. Volumetric expansion by phase transformation from pearlite to martensite might cause the smallest bending angle because of the annealed condition. On the other hand, the larger bending angle of quenched or tempered might be caused by volumetric shrinkage by reverse phase transformation. Therefore, it is shown that phase transformation also influences the bending angle.

### 4.4 Influence of Residual Stress on Variation of Deformation

The residual stress might influence on the bending angle \( \theta_s \) because the proposed method depends on the stress generated by laser irradiation. Therefore, it is investigated using various specimens with residual stress. Here, these specimens are prepared by grinding the surface of the specimen in various conditions and its residual stress is
measured by X-ray stress measurement equipment. Figure 11 shows the result. It can be seen that the residual stress also affects the bending angle $\theta_s$ in both SK and WC-Co specimens. The bending angle $\theta_s$ increases in the minus direction from the tensile residual stress and in the plus direction from the compressive one. The phenomenon might be observed by the release of residual stress.

Figure 12 shows the influence of residual stress on the relation between bending angle $\theta_s$ and laser power in SK specimens. The deformation occurs from the release of residual stress at a certain laser power. The influence of residual stress on the bending angle becomes larger because the area of residual stress released might become wider with higher laser power. That is, using such an annealed SK, the deformation occurs by residual stress release at first. Next, the deformation takes place by plastic deformation. Finally, the deformation is demonstrated by phase transformation. Therefore, the estimation of bending angle is difficult because it does not increase linearly.

5. Run-out Correction Technology Using Laser

5.1 Exception of Influence of Residual Stress on Specimen by Laser Pre-irradiation

A new process is proposed in this section because it is clear that it is difficult to correct tool run-out with high accuracy because of the residual stress. The process chart is shown in Fig. 13. A process of release of residual stress around the laser irradiation area by laser pre-irradiation is added to Fig. 2. The effect was examined using SK specimens. Figure 14 shows the residual stress at the surface of the specimen. It can be seen that the residual stress changes by laser irradiation. The residual stress of the specimen with about -300-MPa initial residual stress increases with laser power. Moreover, it becomes about 0-MPa at a laser irradiation of 125-W. After that, the residual stress increases with laser power as well as in the case of around 0-MPa initial residual stress. That corresponds to the result shown in Fig. 7(a), in which the deformation starts at about 125-W. Figure 15 shows the result of the effects of laser pre-irradiation. In this figure, (a) and (c) are results without pre-irradiation for initial residual stresses of -300 and 0 MPa. On the other hand, the case of Fig. 15(b) is the result with pre-irradiation. As shown in this figure, pre-irradiation is effective because the bending angle $\theta_i$ is almost the same in both cases.
5.2 Case Study of Tool Run-out Correction of End-mill

In this section, case study based on fundamental experiment results shown above is carried out. However, the section shape of practical tool is circular in general, although that of the specimen used in the fundamental experiments was square. Therefore, the influence of section shape on bending angle was evaluated using specimens of circular section shape in various diameters. Figure 16 shows the results. The bending angle decreases with diameter and laser power. Specimen used in fundamental experiments which have a square...
section of 5 mm x 5 mm is equivalent to circular shape of 6-mm diameter. They have almost same stiffness. Therefore, the results in fundamental experiment could be applied to circular shape specimen like cutting tool shank. The laser irradiation conditions are decided based on them. Here, WC-Co tools are focused on because these are often used in high-precision machining such as fine-shape die manufacturing. However, WC-Co has a very small bending angle $\theta_s$ compared with SK in the same laser irradiation condition as shown above. Therefore, it is considered that an increase in the number of irradiations is effective. Figure 17 shows the result. The bending angle $\theta_s$ changes with the number of laser irradiation. However, it is very small, with a different order of magnitude in the case of SK. Moreover, melted parts are confirmed with the larger number of irradiations. Therefore, the irradiation part is changed as shown in Fig 18. From the figure, it is found that bending angle $\theta_s$ might be decided by interval distance. This process was performed using a WC-Co end-mill as a case study. Figure 19 shows the result. It is shown that tool run-out is reduced from about 3-µm to 1-µm or less in the case of a tool-shank diameter of 4-mm by laser irradiation. In the case of a tool-shank diameter of 6-mm, tool run-out is corrected from about 4-µm to 1-µm or less by four times the number of irradiations. Therefore, the effectiveness of the proposed method regarding tool run-out correction using laser on the machine tool is established.

5.3 Feasibility Study of Tool Run-out Correction of WC-Co Ball End-mill

Feasibility study was carried out using a WC-Co ball end-mill with 6-mm diameter and 2 flutes. Initial tool run-out was 8-µm and it was corrected to 0.1-µm by laser irradiations.
on the machine tool. Table 3 shows an end-milling condition. Inclined plane was cut using a machining path on condition of contouring line operation. Machined material was aluminum alloy (JIS: A5052). Figure 20 shows cut surface photographs of machined surface before and after tool run-out correction by laser. The surface end-milled after tool run-out correction by laser (Fig. 20(a)) looks smoother than that before (Fig. 20(b)). Figure 21 shows results of surface roughness measured with a stylus type tester. It can be confirmed that both concave side and ridgeline of machined surface are smoother. The maximum height roughness Rz (JIS) was improved from 1.2-μm to 0.8-μm and the arithmetic average roughness Ra (JIS) was also improved from 0.3-μm to 0.2-μm by this tool run-out correction method. Therefore, it was shown that the proposed method of tool run-out correction technology using laser on-the-machine tools can have a practical use.

This proposed method could be applied not only to cemented carbide tools but also to steel tools. Moreover, a small-diameter grinding wheel with steel shank or shrinkage fit tool holder made of steel, which are often used under severely controlled conditions of tool run-out.

<table>
<thead>
<tr>
<th>Table 3 End-milling condition</th>
</tr>
</thead>
<tbody>
<tr>
<td>Spindle speed min⁻¹</td>
</tr>
<tr>
<td>Normal depth of cut mm</td>
</tr>
<tr>
<td>Feed speed mm/min</td>
</tr>
<tr>
<td>Pick feed mm</td>
</tr>
<tr>
<td>Inclination angle deg.</td>
</tr>
<tr>
<td>Coolant</td>
</tr>
</tbody>
</table>

Fig. 20 Effect of tool run-out correction by laser (Photograph of machined surface)

(a) After correction (run-out: 0.1 μm)   (b) Before correction (run-out: 8 μm)

Fig. 21 Effect of tool run-out correction by laser (Surface profile of machined surface)

(a) After correction (run-out: 0.1 μm)   (b) Before correction (run-out: 8 μm)
6. Conclusion

A tool run-out correction method using laser on-the-machine tool was proposed. The mechanism of deformation was explained and some experiments were performed. Our conclusions are summarized as follows:

1. Adjusting laser irradiation conditions, tool run-out correction using a laser on-the-machine tool can be carried out by control deformation caused by thermal stress.
2. Not only thermal stress generated by laser irradiation, but the residual stress before irradiation also influences the deformation.
3. It was demonstrated that not only tool run-out of a steel tool but also that of a cemented carbide tool can be corrected to sub-microns by the proposed method.
4. It was shown that machined surface quality such as roughness can be improved by this method.

References