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Influence of Cutting Temperature on Affected Layer in Cutting of Aluminum Alloy Castings with PCD tool

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Abstract
In this study, the influence of cutting temperature on the machining-affected layer and residual stress during the cutting of aluminum alloy castings (Al-Si7Mg) using PCD tools was investigated. The results showed that, although little deformation was observed in the microstructure near the finished surface, changes in the residual stress were confirmed at the outermost surface. Furthermore, it was clarified that the tensile stress on the workpiece surface increased with an increase in the cutting temperature caused by an increase in the cutting speed. In addition, it was found that, in the extremely low-speed range where nearly no heat is generated by cutting, compressive stress due to mechanical factors occurs on the finished surface.

Orthogonal cutting, affected layer, cutting temperature, residual stress, aluminum alloy casting

1. Introduction

Aluminum alloys are metallic materials with superior machinability compared with steel. In recent years, significant advancements in machine tool motion accuracy and cutting tool manufacturing technology have enabled cutting speeds of several thousand millimeters per minute for aluminum alloy machining using diamond tools [1]. However, machining-affected layers occur in aluminum alloy cutting, similar to steel, which can lead to a deterioration in product performance and safety [2]. Most previous studies on machining-affected layers in aluminum cutting have focused on conventional cemented carbide tools, whereas research on diamond tools such as PCD, which have become widely used in recent years, remains scarce [3]. Therefore, this study investigates the effects of cutting speed, tool geometry, and cutting temperature on the machining-affected layer and the residual stress during the cutting of aluminum alloy castings (Al-Si7Mg) using PCD tools.

2. Experimental Method

To accurately measure the machining-affected layer and the residual stress caused by cutting, the surface of the workpiece must be free from damage prior to machining owing to preliminary processing. For this reason, the test specimens were repeatedly machined under the cutting conditions shown in Table 1, gradually reducing the depth of cut from 0.1 mm to 0.003 mm in six steps, to create a surface with minimal machining-affected layer and residual stress. Orthogonal cutting of the aluminum alloy castings (ISO: Al-Si7Mg) was then performed using PCD tools under the conditions listed in Table 2. The workpiece material was removed from the aluminum wheels, and a dedicated orthogonal cutting machine was used. Residual stress on the machined surface was measured using a portable X-ray residual stress measuring device (μ-X360S, Pulstec Industrial Co., Ltd.). Measurements were performed on the machined surface in both the cutting direction (parallel) and cutting width direction (perpendicular). To eliminate measurement errors caused by surface irregularities, X-rays were irradiated from two directions (forward and reverse) at each measurement point and the average value was calculated. Four points were measured on each machined surface, and their average was considered as the residual stress value for the cutting condition. The cutting temperature was measured using the tool–workpiece thermocouple method.

3. Results and discussion

Figure 1 shows the microstructure of the workpiece cross-section. The cutting direction was from right to left, and the upper edge of the figure represents the machined surface. The image on the right shows the same location after cutting to a thickness of 0.1 mm. A comparison of the crystal shapes before

Table 1 Cutting conditions for specimen preparation

Tool	PCD
Rake angle [deg]	10
Relief angle [°]	6
Cutting speed [m/min]	0.05
Depth of cut [mm]	0.1, 0.05, 0.025, 0.01, 0.005, 0.003

Table 2 Cutting conditions for orthogonal cutting

Rake angle [°]	5, -5
Depth of cut [mm]	0.100
Cutting width [mm]	2
Cutting speed [m/min]	0.01, 0.1, 1, 10, 100

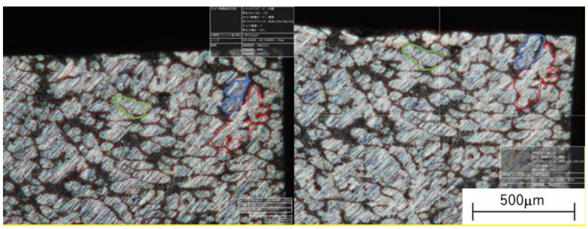

Figure1. Microstructure of the workpiece cross-section (Right: before cutting, Left: after cutting)

and after cutting revealed no significant deformation, as indicated by the area circled in blue. Furthermore, no plastic flow layer is detected on the finished surface. These observations confirm the absence of a machining-affected layer from the microstructural analysis of the finished surface. Figure 2 shows the residual stress measurement results on the finished surface plotted as a semi-logarithmic graph with the cutting speed on the horizontal axis. The results indicate that changes in the rake angle did not affect the residual stress. Regarding the cutting speed, no change in residual stress was observed below 1 m/min; however, above 1 m/min, the tensile stress increased with cutting speed. The occurrence of tensile stress during cutting has also been reported in studies on high-speed cutting of steel, and similar results have been observed for aluminum alloy castings [4]. Figure 3 shows the cutting-temperature measurement results obtained using the tool–workpiece thermocouple method. Although calibration experiments were conducted to derive the calibration coefficient for determining cutting temperature from the thermoelectric voltage between the PCD tool and aluminum alloy casting, accurate coefficients could not be obtained; therefore, the figure shows the thermoelectric voltage. Below 1 m/min, nearly no voltage is generated, indicating negligible heat generation during cutting. Above 1 m/min, the voltage increased with cutting speed. This result is consistent with the residual stress measurements shown in Figure 2, suggesting that the increase in cutting temperature due to the increased cutting speed leads to increased residual stress on the finished surface. Furthermore, regarding the effective measurement depths of residual stress and cutting temperature, X-ray residual stress analysis is sensitive primarily to an extremely shallow region near the specimen surface, whereas the tool–workpiece thermocouple method measures the thermoelectric voltage generated at the tool–workpiece contact interface. Although the exact correspondence between the measurement depths of these two methods cannot be strictly defined, both techniques can be regarded as providing information related mainly to the near-surface region of the workpiece. The mechanism is as follows. During machining, the region near the cutting point tends to expand owing to the temperature increase but is constrained by the surrounding cooler regions, resulting in tensile stress. The greater the cutting speed, the larger the temperature difference and, thus, the greater the tensile stress. Therefore, the tensile stress observed at cutting speeds above 1 m/min can be attributed to thermal effects. Furthermore, Figure 2 shows that compressive stress occurs at cutting speeds below 1 m/min, where nearly no heat is generated. Focusing on the thrust force shown in Figure 4, the thrust force is large at cutting speeds below 1 m/min. When the thrust force is large, the material on the finished surface tends to plastically deform and spread but is constrained by the surrounding regions, resulting in

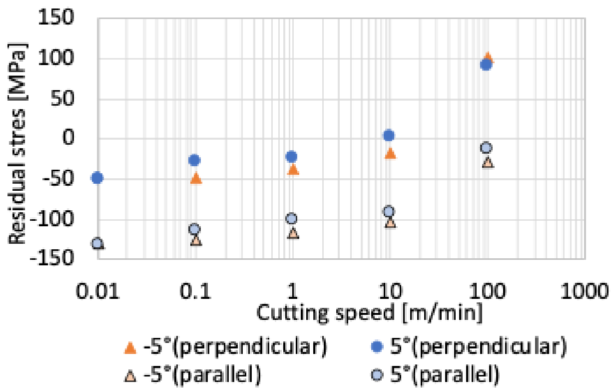

Figure2. Residual stress

compressive stress. Therefore, the compressive stress at cutting speeds below 1 m/min is considered to be caused by mechanical factors.

4. Conclusion

In this study, the influence of cutting temperature on the machining-affected layer and residual stress during the cutting of aluminum alloy castings (Al-Si7Mg) using PCD tools was investigated. The results showed that, although little deformation was observed in the microstructure near the finished surface, changes in the residual stress were confirmed at the outermost surface. Furthermore, it was clarified that the tensile stress on the workpiece surface increased with an increase in the cutting temperature caused by an increase in the cutting speed. In addition, it was found that, in the extremely low-speed range where nearly no heat was generated by cutting, compressive stress due to mechanical factors occurred on the finished surface. Moreover, differences in the rake angle had only a minimal effect on the residual stress on the machined surface.

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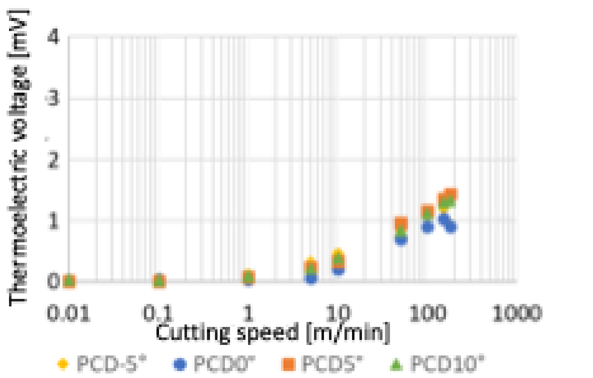

Figure3. Measurement results of thermoelectric voltage by the tool–workpiece thermocouple method

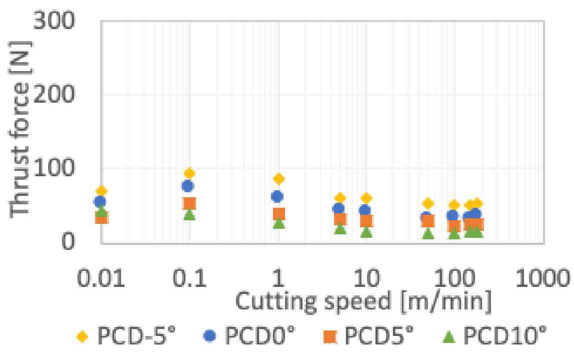

Figure4. Cutting speed and thrust force