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Influence of Cutting Edge Shape on Residual Stresses of Cut Surface*

(Effects of Nose Radius and Cutting Edge Roundness)

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Abstract

In order to obtain basic information on the improving the surface integrity of machined surfaces, the relationship between the residual stress of cut surfaces and the cutting edge shapes of cutting tools was examined. Dry facing on a lathe was performed with cutting tools that had various nose radiuses and cutting edge roundnesses. The residual stresses of the cut surfaces were measured by X-ray diffraction method. The results obtained are as follows. When the rake angle was about zero degrees, it found that the nose radius barely affected the residual stresses of the cut surfaces. However, when the negative rake angle was large, the nose radius significantly affected the residual stress. The residual stresses of the cut surfaces shifted compressive side when there was an increase in cutting edge roundness. The residual stress of a cut surface is kept in a high compressive state even though the cutting force decreases greatly due to grinding removing the rake side part of the cutting edge roundness.

Key words: Residual Stress, Stress Distribution, Cutting Tool, Edge Shape, Cutting Force, Force Ratio, Surface Generation Phenomenon

1. Introduction

Residual stress is generated on the surface layer of metal under a machining process like cutting or grinding. It is known that the magnitude and distribution of this residual stress changes according to machining conditions and kind of material (1), but much remains to be clarified as to the generation mechanism of residual stress. In this regard, it is generally held that the fatigue life of a material can be improved if compressive residual stress exists on the material's surface, and for this reason, a shot peening process may be applied to machine parts that may deteriorate from fatigue such as aircraft parts and turbine blades so as to achieve a compressive type of residual stress (2). It is clear, however, that this approach increases the total number of process steps leading to a drop in productivity, and problems related to part precision must also be considered. In response to these issues, a cutting tool with a burnishing pin attached has been developed to generate compressive residual stress on the cut surface in the cutting of an aluminum alloy (3).

In a previous report (4), we clarified the influence of rake angle and contact width of flank face on the residual stresses of a cut surface with the aim of generating strong compressive residual stresses directly on a finished surface by a cutting edge and achieving strong, high reliability machined parts. In this report, we investigate the influence of nose

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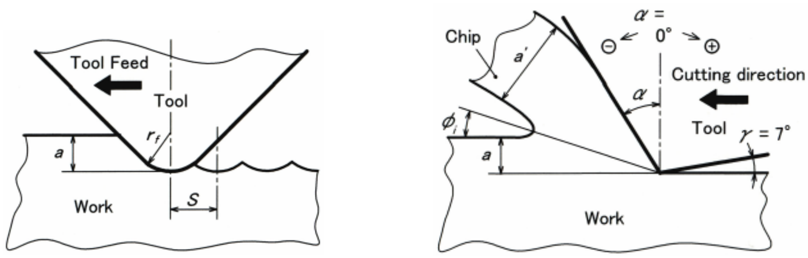
radius and cutting edge roundness on the residual stress of the cut surface. In order to obtain basic and general data for design of cutting tools, we performed unidirectional cutting in the experiments described using single point tools to systematically vary the nose radius and cutting edge roundness.

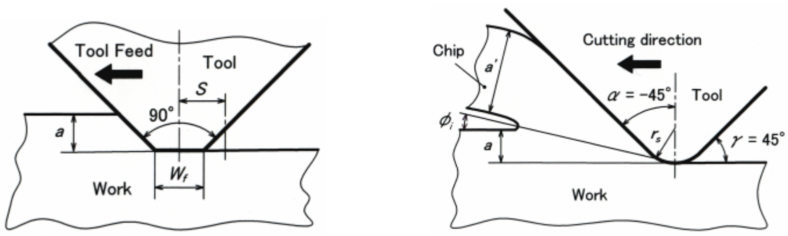
2. Experimental Apparatus and Method

2.1 Cutting edge shapes

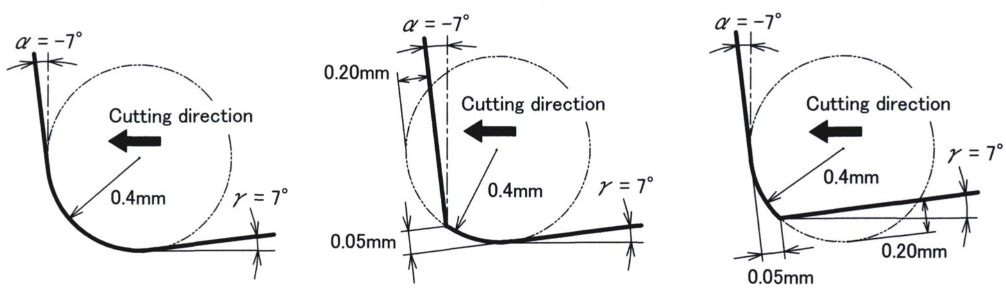
As shown in Fig. 1 defining the cutting edge specifications used in metal cutting, the cutting edge shapes used were obtained by varying nose radius (front projected radius) r_f as shown in Fig. 1(a) and cutting edge roundness (side projected radius) r_s as shown in Fig. 1(b). The effect of cutting off a portion of the cutting edge roundness of the cutting edge on residual stress and cutting forces was also investigated as shown in Fig. 1(c). Nose radius r_f and cutting edge roundness r_s were varied in the range of 0, 0.2, 0.4, and 0.8 mm. However, due to the fact that the roughness of the cut surface increased significantly for the case of r_f = 0 mm, that data was excluded from the experiment results. The experiment of Fig. 1(a) investigating the influence of nose radius r_f was performed for rake angles α of 0°, -50°, and -60°, and the experiment of Fig. 1(b) investigating the influence of cutting edge roundness r_s was performed for front-projected contact widths w_f of 0.2 and 0.4 mm. In addition, Fig. 1(c) shows the cutting edge shapes obtained by grinding and cutting off a portion of cutting edge roundness. As shown, two cutting edges that had been given a roundness of 0.4 mm were each cut off by 0.2 mm, one on the rake side and the other on the flank side, and in the



(a) Nose radius r_f



(b) Cutting edge roundness r_s



No cutting off / Rake side cutting off / Flank side cutting off

(c) In case of tip portion cutting off

Fig.1 Symbols used in metal cutting

experiment, the respective effects of these cutting off were compared. Here, the cutting edge apex angle and front projected contact width w_f not shown in the Fig.1 were set to 90° and 0.4 mm, respectively. In all cases, the cutting edge material was carbide tool that was grinded and shaped into a variety of shapes as described above.

2.2 Cutting experiments and residual stress measurement

In the cutting experiments, a 15mm (W)×65mm (L)×13.5mm (T) workpiece consisting of S55C annealed steel was attached to the face plate of the main spindle of a lathe so as to cut in the longitudinal direction of the workpiece with a rotating circle diameter of 180 mm [(4)]. And next, front face dry cutting was performed at cutting speed V = 150 m/min, depth of cut a = 0.1 mm, and tool feed rate S = 0.12mm/revolution. Cutting forces were measured by a three component piezo dynamometer manufactured for this study. Residual stresses of the cut surface were measured by an X-ray stress measurement [(5)] that applies the nonlinear least-squares method to the X-ray method ($\theta - 2\theta$ parallel beam method) and approximates the diffraction profile by a Gaussian curve. A personal computer was used to input measurement data and perform associated calculations. The residual stress distribution in the depth-wise direction of the cut surface was determined by applying sequential corrosion removal to the cut surface.

3. Residual Stress Distribution Patterns of cut surface

In our previous report [(4)], the results of investigating how different rake angles α and contact widths of flank face w affect residual stresses showed that the distribution of residual stress on the cut surface could be classified into three types of characteristic patterns as shown in Fig. 2. In the figure, σ_1 denotes residual stress in the cutting direction and σ_2 residual stress in the tool feed direction. Type I represents a type of residual stress distribution that is often seen in typical cut surfaces, and Type II represents the case in which residual stresses σ_1 and σ_2 have significantly different distribution forms indicating

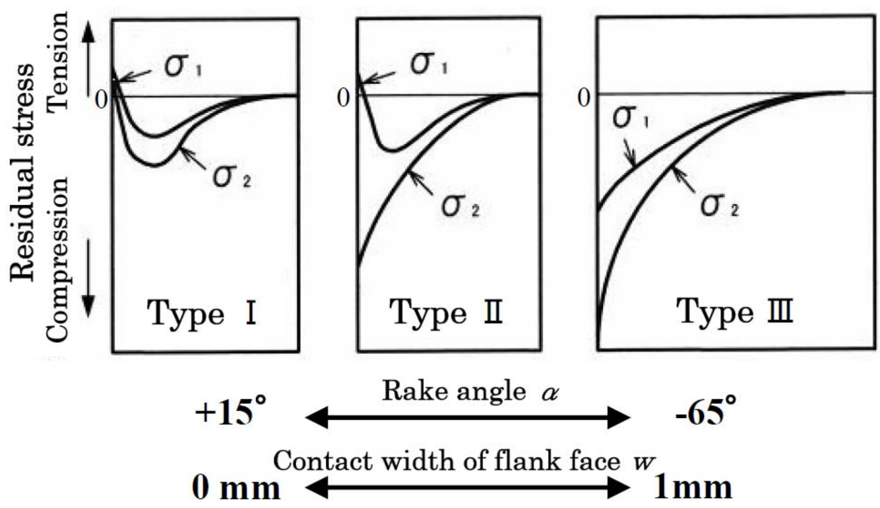


Fig.2 Typical forms of residual stress distribution of cut surface

the appearance of notable anisotropy in residual stress of the cut surface. In Type III, the distributions for residual stresses σ_1 and σ_2 are both very similar to that of a burnished surface having a strong frictional effect. Such residual stress distributions are thought to occur because of different surface generation phenomena in cutting, and in this report, we investigate the influence of nose radius and cutting edge roundness on the state of residual stresses of the cut surface based on these basic pattern classifications.

4. Experiment Results and Discussion

4.1 Influence of nose radius on residual stress of cut surface

Figs. 3(a) – (c) show the results of investigating the influence of nose radius r_f on residual stress distribution for rake angle α of 0°, -50°, and -60°, respectively. For α = 0° in Fig. 3(a), the residual stress distribution follows Type I of Fig. 2 regardless of the nose radius meaning that a typical distribution pattern for residual stress of the cut surface appears. It can therefore be said that the influence of nose radius on the residual stress distribution is small near α = 0°. However, if rake angle α becomes somewhat large in the negative direction, a remarkable change in the state of residual stress due to nose radius r_f can be observed as shown in Figs. 3(b) and (c). First, for α = -50° in Fig. 3(b), a significant change appears in the surface residual stress pattern between r_f = 0.2 mm and r_f = 0.4 mm in a process where nose radius r_f increases. This distribution pattern changes from Type II to Type I. Next, for α = -60° in Fig. 3(c), the distribution pattern boundary point shifts this time between r_f = 0.4 mm and r_f = 0.8 mm, but this noticeable change in distribution pattern from Type II to Type I is essentially the same as the behavior shown for α = -50°. This change can be explained as follows. When cutting with a tool having a large negative rake angle, the generation of chips due to cutting can be observed but chips flow is difficult. As a result, a good amount of work material gets displaced in a direction lateral to cutting during material removal. Since this material is left on a surface layer making up part of the cut

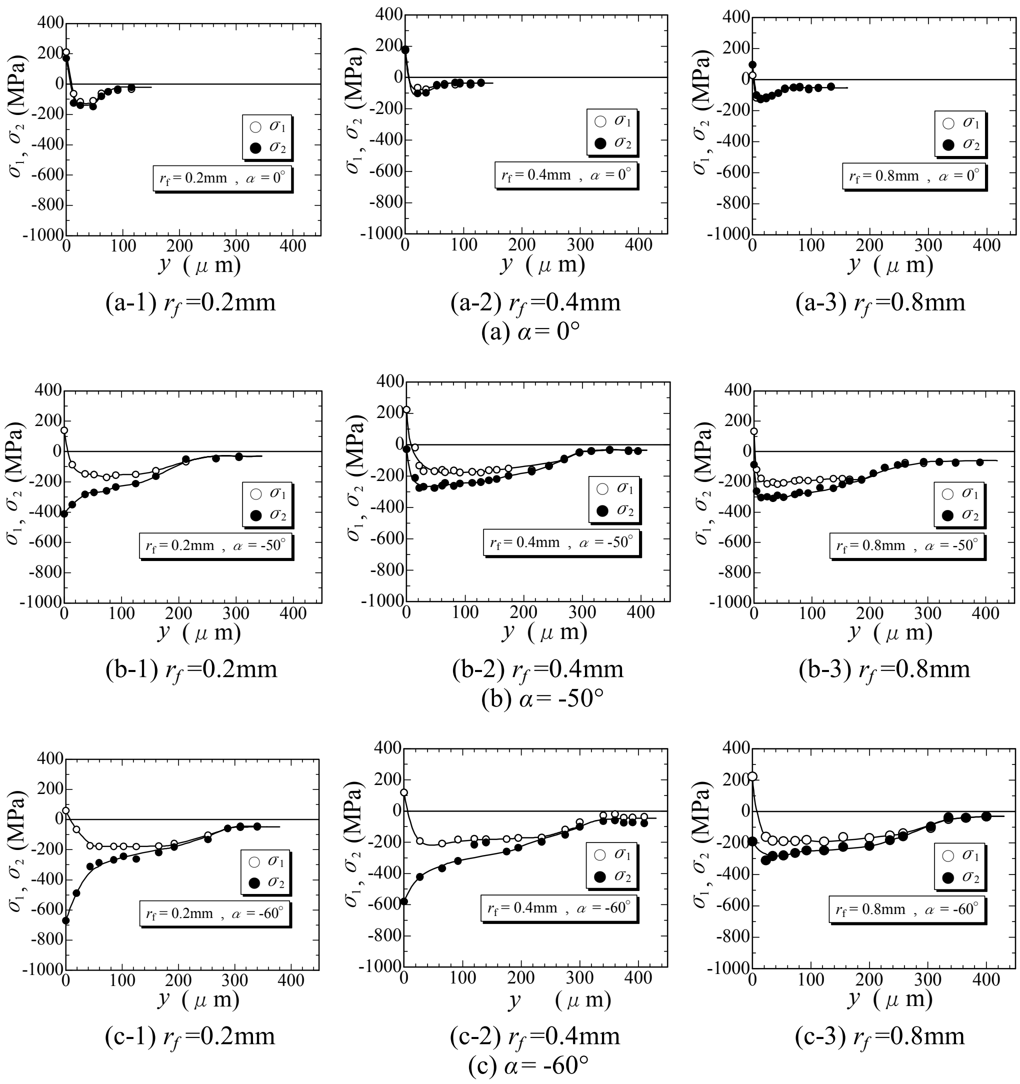


Fig.3 Influence of nose radius r_f on residual stress distribution

surface, a notable anisotropy in residual stress pattern occurs between the cutting direction and the tool feed direction (Type II in Fig. 2). However, as nose radius increases, the front projected area of the cutting edge (cutting direction) likewise increases causing the characteristic residual stress layer described above to be removed by cutting as the subsequent cutting edge passes. This results in a change to Type I of Fig. 2. Note here that nose radius for which the residual stress distribution pattern changes from Type II to Type I is larger for α = -60° than α = -50°. As rake angle α becomes larger in the negative direction, the burnishing effect during material removal and the displacement of material to the side of cutting edge becomes large making for a larger area of influence. Thus, to eliminate the affected area, a larger nose radius becomes necessary.

4.2 Influence of cutting edge roundness on residual stress of cut surface

The influence of cutting edge roundness on the process of generating a cut surface is considered to be quite large even when making an evaluation based on the results of analyzing cutting forces [(6)]. In the following, we investigate the effects of setting cutting edge roundness r_s to various values, namely 0, 0.2, 0.4, and 0.8 mm, on the residual stress distribution and cutting forces.

First, for the case of cutting edge roundness r_s = 0 mm shown in Fig. 4(a), the residual stress distribution pattern of the cut surface takes on the Type I of Fig. 2 indicating a typical residual stress distribution of a cut surface. However, if the edge of the cutting tool is now given a roundness of 0.2 mm, residual stress σ_2 in the tool feed direction becomes strongly compressive compared to that in the cutting direction revealing notable anisotropy in the state of residual stress of the cut surface. Now, if cutting edge roundness r_s becomes even larger, residual stresses σ_1 and σ_2 shift even further to the compressive side as shown in Figs. 4(c) and (d) revealing a change in distribution pattern from Type II of Fig. 2 to Type III. In addition, the depth of residual stress layer increases along with increasing the cutting edge

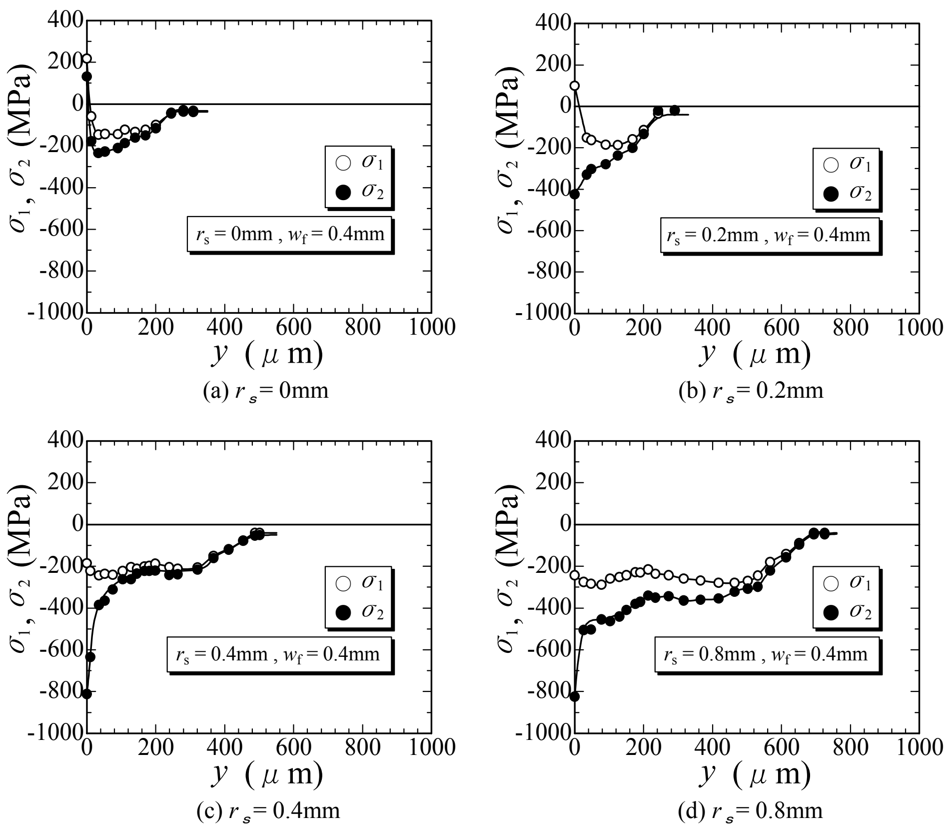


Fig.4 Influence of cutting edge roundness r_s on residual stress distribution (α= -45°, w_f= 0.4mm)

roundness reaching a depth of 650 μm at r_s = 0.8 mm. This is thought to occur because rubbing, that is, the burnish effect (plastic deformation of the thin layer directly below the surface), during surface generation becomes stronger as the roundness of the cutting edge increases. Although the results of studying the influence of cutting edge roundness for a front projected contact width w_f of 0.2 mm are omitted here, they revealed that the values of residual stress shifted somewhat to the plus side compared to the case of w_f = 0.4 mm. Qualitatively speaking, however, the results for w_f = 0.2 mm showed similar behavior as those for w_f = 0.4 mm. It can therefore be considered that cutting edge front projected contact width w_f has little influence on the state of residual stress caused by cutting.

Figs. 5 and 6 show change in cutting forces and cutting force ratio corresponding to change in residual stress distribution caused by different values of cutting edge roundness. First, Fig. 5 shows the influence of cutting edge roundness r_s on tangential cutting force Q and normal cutting force P. Here, with rake angle α set to -45°, $Q < P$ even for r_s = 0 mm. The results of this figure also show that the rate of increase of cutting force with respect to increase in cutting edge roundness r_s is greater for normal cutting force P than tangential cutting force Q, which indicates that the $Q < P$ relationship intensifies as radius r_s increases. This can be explained as follows. As the cutting edge roundness increases, the frictional interaction between the cutting edge and workpiece increases causing frictional resistance to increase. Increase in material removal resistance, however, is thought to be small, and as a result of a larger contact area, increase in the value of the measured tangential cutting force is small compared to the increase in normal cutting force. If we now calculate cutting force ratio Q/P based on the measurement results for cutting forces shown in Fig. 5, we can see that Q/P decreases as cutting edge roundness r_s increases as shown in Fig. 6.

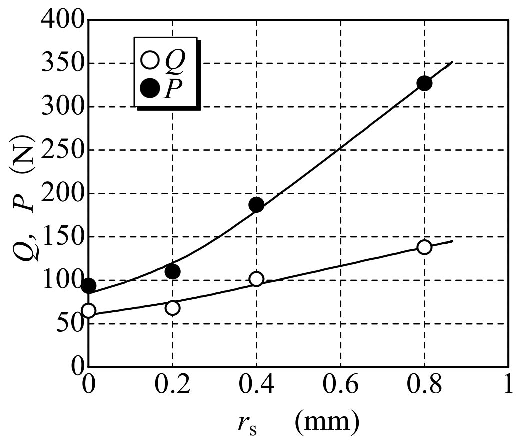


Fig.5 Influence of cutting edge roundness r_s on cutting forces (α= -45°, w_f= 0.4mm)

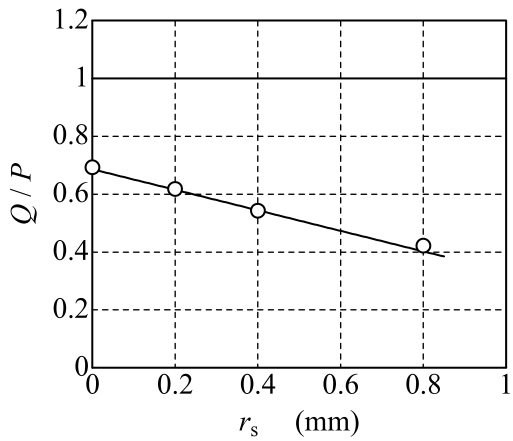


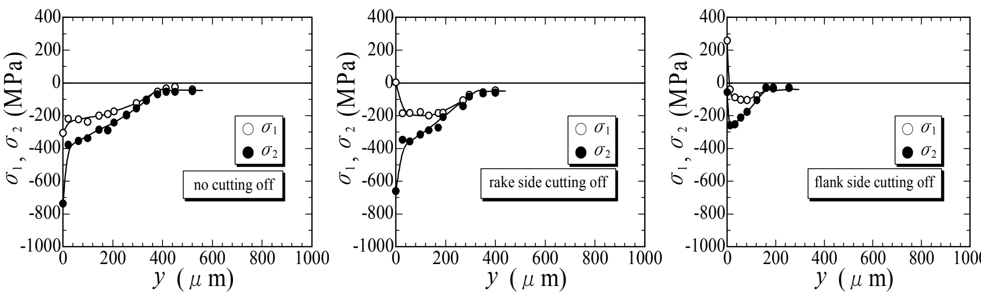
Fig.6 Influence of cutting edge roundness r_s on cutting force ratio (α= -45°, w_f= 0.4mm)

Considering the above change in residual stress distribution due to cutting edge roundness and the accompanying changes in cutting forces and cutting force ratio, it can be seen that residual stress of the cut surface shifts to the compressive side in accordance with the relative increase in the normal cutting force, i.e. decrease in the cutting force ratio, and that the depth of residual stress layer increases as well. This type of behavior also appeared in our previous report [4] investigating the influence of rake angle and contact width of flank face on residual stress of the cut surface. Thus, with the results presented here, it is shown over an even broader scope that the state of residual stress, which changes according to the values of various cutting-edge specifications, exhibits a strong correlation with the normal cutting force and cutting force ratio.

4.3 Change in residual stress and cutting forces after cutting off part of the cutting edge roundness

As described in the previous section, giving roundness to the cutting edge has a big effect in terms of generating strong, compressive residual stress on the cut surface. However, this effect is also accompanied by an increase in cutting forces. Thus, with the aim of finding a countermeasure to that increase, we grinded and cut off part of the cutting edge roundness as shown in Fig. 1(c) and investigated its effect.

Fig. 7 shows change in residual stress distribution due to differences in the cut off portion of cutting edge roundness. Fig. 7(a) shows residual stress distribution of the cut surface for no cutting off, and Figs. 7(b) and Fig. 7(c) show residual stress distribution when removing a portion of the cutting tool from the rake side and flank side, respectively. For the case of Fig. 7(c) in which a portion of the cutting tool has been cut off on the flank side, a residual stress distribution pattern following Type I in Fig. 2 appears. This distribution pattern is qualitatively similar to that of the case of no cutting edge roundness (as in Fig. 4(a) where r_s = 0 mm) indicating that the effect of giving roundness to the cutting edge is essentially lost. However, for the case of Fig. 7(b) in which a portion of the cutting tool has



(a) No cutting off (b) Rake side cutting off (c) Flank side cutting off

Fig.7 Influence of cut off portion on residual stress distribution

been cut off on the rake side, the depth of residual stress layer decreases somewhat compared to the no cutting off case of Fig. 7(a), but on the other hand, strong compressive residual stress exists in the cut surface. In particular, surface residual stress in the tool feed direction to the cutting direction (value of σ_2 at y = 0 mm) is extremely compressive similar to the case of no cutting off in Fig. 7(a). Thus, when grinding and cutting off part of cutting edge roundness on the rake side, the effect of giving roundness to a cutting edge still remains to a sufficient degree.

Finally, Fig. 8 shows change in cutting forces when cutting off a portion of cutting edge roundness. These results show that both cutting forces—tangential force Q and normal force P—decrease significantly when cutting off a portion of cutting edge roundness on either the rake side or flank side compared to no cutting off. However, on considering these results together with the results for residual stress distribution in Fig. 7, we can see that,

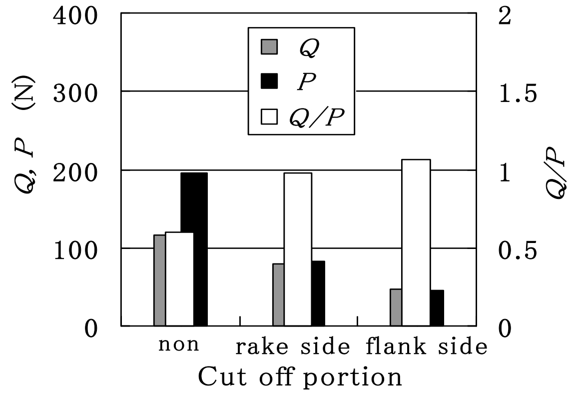


Fig.8 Influence of cut off portion on cutting forces and force ratio

when cutting off a portion of cutting edge roundness on the flank side, a ridge line will be formed where the cutting edge roundness and the flank face grinding surface meet thereby eliminating most of the burnishing effect when generating a cut surface and causing the strong compressive residual stress state to disappear as well. In contrast, when cutting off a portion of cutting edge roundness on the rake side, the chips flow on the rake surface during metal removal is good and cutting forces decrease relative to the case of no cutting off. Yet, during surface generation, a portion of the cutting edge roundness that remains behind the rake surface (on the flank surface side) makes contact with the final finished surface so that the cut surface after the cutting edge passes enters a state of strong compressive residual stress due to a burnish effect.

According to previous study [(4)], cutting forces showed a tendency to increase in cutting tools of a type that generates highly compressive residual stress. In the study reported here, however, it has been shown that adjusting the shape of the cutting edge appropriately can also reduce cutting forces significantly while generating somewhat large compressive residual stresses on the cut surface.

5. Conclusion

The results of investigating cutting edge shape with the aim of generating highly compressive residual stress on a cut surface are summarized as follows:

(1) The influence of nose radius on residual stress distribution is relatively small near a rake angle of 0°, but a big change in the pattern of the residual stress distribution due to nose radius appears as the rake angle increases in the negative direction.

(2) The influence of cutting edge roundness on residual stress is large. The state of residual stress of the cut surface shifts to the compressive side with increase in cutting edge roundness and the depth of residual stress layer increases at this time.

(3) Shift of residual stress to the compressive side and increase in the depth of residual stress layer corresponds to a relative increase in normal cutting force, that is, to a decrease in cutting force ratio.

(4) Grinding and cutting off a portion of cutting edge roundness parallel to the rake surface has the effect of decreasing cutting forces significantly while generating highly compressive residual stress on the cut surface.

References

(1) Yonetani, S., *Occurrence of the Residual Stress and Countermeasure (in Japanese)*, (1975), p.164, Yokendo Ltd..

(2) Society of Shot Peening Technology of Japan ed., *Method and Effect of Shot Peening (in Japanese)*, (1997), p.5, Nikkan Kogyo Shimbun, Ltd..

(3) Segawa, T. et al., Development of Cutting-Burnishing Combined Tool and Its Basic Performance, *Journal of the Japan Society of Precision Engineering*, Vol.72, No. 7(2006), pp.909-913.

(4) Mizutani, H. et al., Influence of Cutting Edge Shape on Residual Stresses of Cut Surface (Effects on Rake Angle and Contact Width of Flank Face), *Transactions of the Japan Society of Mechanical Engineers(C)*, Vol.72, No.715 (2006), pp. 929-933.

(5) Wakabayashi, M. et al., X-ray Stress Measurement Approximating Diffraction Profile with Gaussian Curves by Using Method of Nonlinear Least Squares, *Journal of the Society of Materials Science*, *Japan*, Vol.39, No.441 (1990), pp. 620-625.

(6) Kondo, E. et al., Cutting Force Acting on Blunt Cutting Edge (1st Report), *Transactions of the Japan Society of Mechanical Engineers(C)*, Vol.66, No.651 (2000), pp. 3760-3765.