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ORIGINAL ARTICLE

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Prevention of exit burr in microdrilling of metal foils by using a cyanoacrylate adhesive

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Abstract In the microdrilling of metal, an exit burr forms due to plastic deformation of the remnant material when the drill approaches the bottom of the hole. In this work, a cyanoacrylate adhesive was applied at the exit surface to prevent the exit burr. The copy papers smeared with cyanoacrylate were layered at the exit surface in a uniform coat. The cyanoacrylate can be easily removed by immersion in acetone. The cyanoacrylate layer was effective in preventing exit burr in the drilling of low-hardness materials, such as aluminum or copper. In the case of harder materials, however, such as 304 stainless steel, the cyanoacrylate layer failed. In this case, backup foil adhered with cyanoacrylate was shown to be effective in burr prevention.

Keywords Burr · Cyanoacrylate · Drilling · Metal

1 Introduction

As the demands for microcomponents increase in industry, effective methods for machining microholes are required. There are several methods to make microholes, including electrical discharge machining, ultrasonic machining, laser beam machining, electro chemical machining and mechanical microdrilling. Among these methods, mechanical microdrilling is widely used because it produces holes with good roundness, straightness and surface roughness in a short process time.

In the mechanical microdrilling of metals, however, an exit burr forms with various sizes and shapes. When the drill approaches the bottom of the hole, plastic deformation occurs. As the drill advances, the stress increases along the edge or at the center of hole exit. When the stress exceeds the tensile strength, fracture in the remnant material starts. Through this process, an exit burr forms [1, 2]. Various factors influence the burr formation in microdrilling, such as feedrate, spindle speed, tool wear and drill geometry. Burr height also varies according to these factors [3, 4].

Because exit burr degrades the quality of parts and causes trouble when the parts are assembled, a deburring process is necessary. But the mechanical deburring of a microhole is very difficult because it is hard to locate the hole; and a chemical deburring process is not suitable because it can distort the hole shape. Therefore, exit burr prevention is preferable in microdrilling. To reduce exit burr, variable feedrate has been used [5] or ultrasonic vibration can be applied to the drill [6]. Using these methods, exit burr was reduced, but not prevented.

In the previous research focusing on the microdrilling of glass, a backup glass plate with liquid adhesion was shown to be effective in the prevention of the exit cracks. This is because the tensile stress near the edge of hole exit is reduced by the backup glass plate, as shown in Fig. 1. Figure 2 shows the hole exits drilled without backup and with backup adhered with water in glass [7].

In this work, a new method using cyanoacrylate adhesive is suggested to prevent exit burr in the microdrilling of metal foils. Through a series of microdrilling experiments in aluminum, cop-

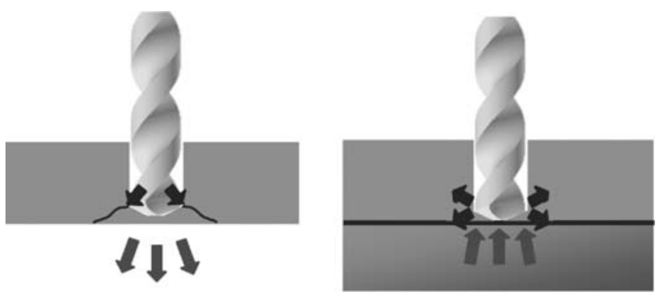

Fig. 1. Schematic diagram of backup effect on exit crack prevention in glass

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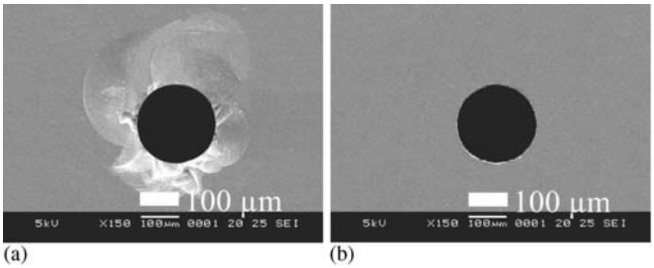


Fig. 2a,b. Shape of hole exits according to the kinds of backup (conditions: 0.5 mm thick glass, F 0.2 mm, 30 000 rpm, and 0.25 μm/rev): **a** without backup **b** with backup adhered with water [7]

per and 304 stainless steel, it is shown that the suggested method is effective in prevention of exit burr.

2 Experimental procedures

The drilling tests were conducted on a vertical microdrilling machine. The spindle is attached to the Z-axis. Maximum rotational speed of the spindle is 125 000 rpm. The thrust force was measured using a piezo-electric load washer (Kistler 9117A). The tools were tungsten carbide drills with diameters of 0.1 and 0.2 mm. The point angle of the drills was 130°. The test materials were aluminum, copper and 304 stainless steel. The mechanical properties of test materials are listed in Table 1. The thickness of test materials were 0.2 mm when the 0.1 mm drill was used, and 0.5 mm when the 0.2 mm drill was used.

Experiments were carried out with various backups using cyanoacrylate adhesive, water, copy paper and metal foil. The experiment was first conducted without a backup at various cutting conditions. Secondly, metal foil was applied as a backup at the same cutting conditions. The thickness and material of the metal foil were identical to the test material. Two foils were constrained mechanically, as shown in Fig. 3. Additionally, water was used for adhesion. Thirdly, cyanoacrylate adhesive (LOCTITE 401) was used as a backup. The material properties of the cyanoacrylate are listed in Table 2. Cyanoacrylate was coated at the exit surface with a similar thickness to the test material. In order to coat the cyanoacrylate uniformly, copy papers smeared with cyanoacrylate were layered at the exit surface using a plastic roller. Experiments were conducted 12 h after coating. The thickness of one sheet of paper was 100 μm, and three sheets of paper were used. The copy paper backup was removed within fifteen minutes by immersion in acetone using an ultrasonic cleaner. Finally, metal foil adhered with cyanoacrylate was applied as a backup in each condition. Two foils with 0.5 mm in thickness were separated within five minutes by immersion in acetone using an ultrasonic cleaner. The results of the burr formation were observed with scanning electron microscope (SEM) images. Cutting conditions are listed in Table 3. The rotational speed of the spindle varied from 10 000 rpm to 60 000 rpm, and feedrate varied from 0.02 μm/rev to 4.2 μm/rev, according to the drill diameter and test material.

Table 1. Mechanical properties of test materials

	Aluminum	Copper	304 Stainless steel
Yield strength	15 (MPa)	205 (MPa)	205 (MPa)
Tensile strength	40 (MPa)	290 (MPa)	515 (MPa)
Young's modulus	62 (GPa)	123 (GPa)	193 (GPa)
Hardness	43 (HV)	84 (HV)	160 (HV)

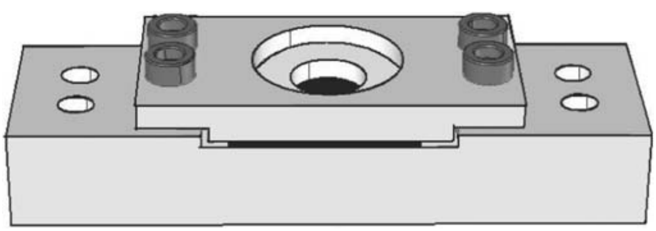


Fig. 3. Jig for the mechanical constraint

Table 2. Material properties of cyanoacrylate

Chemical type	Ethyl cyanoacrylate
Shear strength	18 ∼ 26 (MPa)
Tensile strength	12 ∼ 25 (MPa)
Young's modulus	3.5 (GPa)
Hardness	6.3 (HV)

Table 3. Cutting conditions for experiments

Spindle speed	10000 ∼ 60000 (rpm)
Cutting speed	6.3 ∼ 37.7 (m/min)
Feed rate	0.02 ∼ 4.2 (μm/rev)
Cutting fluid	None

3 Experimental results

3.1 Aluminum

Figure 4 shows the SEM images of the hole exits in aluminum with a diameter of 0.2 mm and a depth of 0.5 mm, which were machined at 60 000 rpm and 0.3 μm/rev. Figure 4a shows the case without a backup, and features a large side burr and a cap. Figure 4b and c are the cases drilled with backup foil and backup foil adhered with water, respectively. These two images also show side burr, which was spread widely because the burr was pressed between the two foils by the thrust force. Figure 4d,e and f are holes which were drilled with backups of cyanoacrylate. A hole exit drilled with cyanoacrylate coating is shown in Fig. 4d. Figure 4e shows the hole exit drilled with the backup foil adhered with cyanoacrylate, and Fig. 4f with a copy paper backup smeared with cyanoacrylate. In the latter three methods, clean holes were obtained. These results indicate that the backup methods using cyanoacrylate are effective in the prevention of exit burr in the microdrilling of aluminum. Among

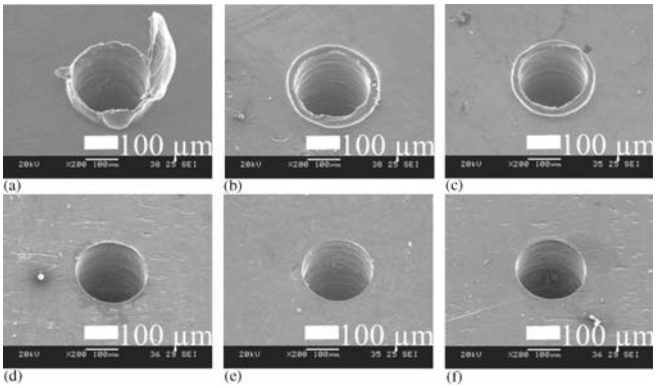


Fig. 4a–f. Shape of hole exits according to the kinds of backup (conditions 0.5 mm thick aluminum foil, F 0.2 mm, 60 000 rpm, 0.3 µm/rev, 37.7 m/min): **a** without backup **b** with backup foil **c** with backup foil adhered with water **d** with cyanoacrylate backup **e** with backup foil adhered with cyanoacrylate **f** with copy paper backup smeared with cyanoacrylate

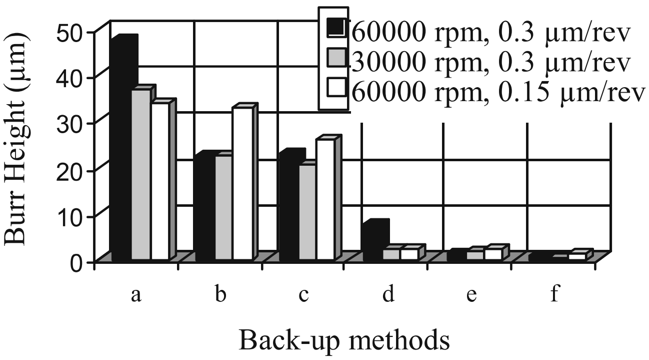


Fig. 5a–f. The burr height according to the kinds of backup (conditions: 0.5 mm thick aluminum foil, F 0.2 mm): **a** without backup **b** with backup foil **c** with backup foil adhered with water **d** with cyanoacrylate backup **e** with backup foil adhered with cyanoacrylate **f** with copy paper backup smeared with cyanoacrylate

these methods, most convenient and easy to control method is the copy paper backup smeared with cyanoacrylate.

The burr height of hole exits drilled with a 0.2 mm drill is shown in Fig. 5, according to the backup methods. The burr height is defined as the height of the material that rose above the exit surface. The burr height was measured by a 3D surface profiling system (SIS-1200, SNU PRECISION). Three samples were measured at each condition and five radial lines were measured per each sample. The burr heights in Fig. 5 are the average values. Figure 6 shows the profile of exit burr with backup foil, which was measured in the direction of the center of hole from a surface.

Figure 7 shows the holes drilled with a copy paper backup smeared with cyanoacrylate in other cutting conditions. Figure 7a shows the hole drilled at 30 000 rpm and 0.3 µm/rev, and Fig. 7b shows the hole drilled at 60 000 rpm and 0.15 µm/rev. The two hole exits had little burr.

Figure 8 shows the holes which were machined by a 0.1 mm drill. Figure 8b is the hole drilled with a copy paper backup smeared with cyanoacrylate. The hole is very clean in compar-

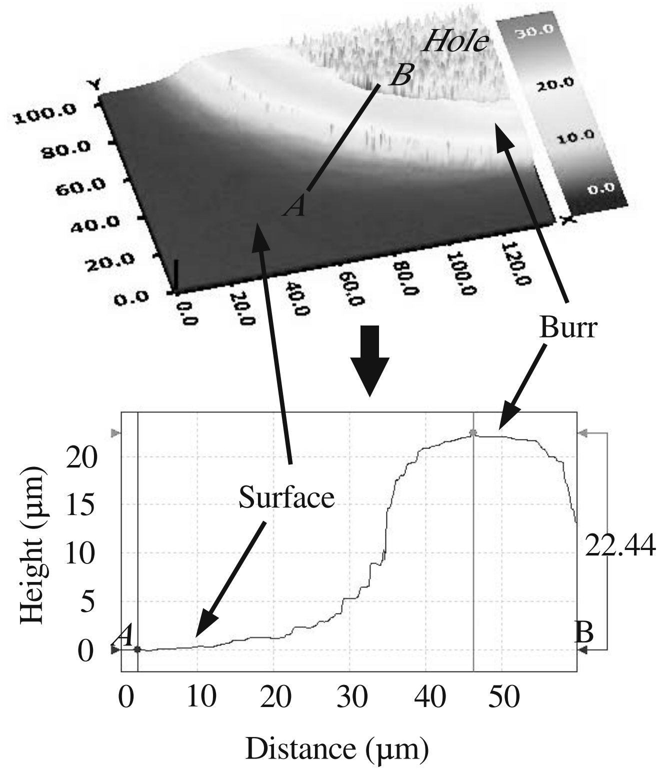


Fig. 6. Profile of exit burr with backup foil (conditions: 0.5 mm thick aluminum foil, F 0.2 mm, 60 000 rpm, 0.3 µm/rev, 37.7 m/min)

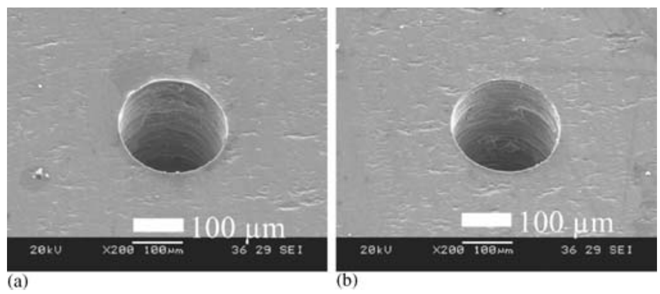


Fig. 7a,b. Hole exits drilled with copy paper backup smeared with cyanoacrylate (conditions: 0.5 mm thick aluminum foil, F 0.2 mm): **a** 30 000 rpm, 0.3 µm/rev, 18.8 m/min **b** 60 000 rpm, 0.15 µm/rev, 37.7 m/min

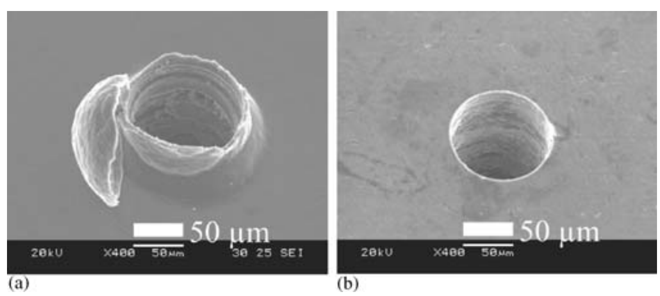


Fig. 8a,b. Shape of hole exits according to the kinds of backup (conditions: 0.2 mm thick aluminum foil, F 0.1 mm, 30 000 rpm, 0.02 µm/rev, 18.8 m/min): **a** without backup **b** with copy paper backup smeared with cyanoacrylate ison with the hole drilled without a backup. Based on these results, it is shown that the backup methods using cyanoacrylate are effective in prevention of exit burr in microdrilling of aluminum under various cutting conditions.

3.2 Copper

Experiments were also conducted with copper. The results are similar to those with aluminum. Figure 9a and b show the hole exits drilled at 30 000 rpm and 0.1 μm/rev without a backup and with a copy paper backup smeared with cyanoacrylate. In the case a copy paper backup smeared with cyanoacrylate, exit burr is not observed. But even in the case without a backup, exit burr height was not very high. For a 0.1 mm hole, the effect of a copy paper backup smeared with cyanoacrylate is also validated in Fig. 10.

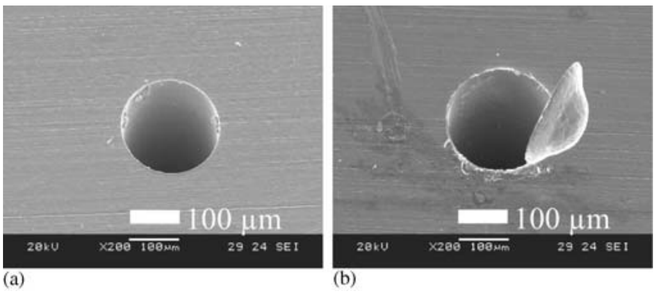


Fig. 9a,b. Shape of hole exits according to the kinds of backup (conditions: 0.5 mm thick copper foil, F 0.2 mm, 30 000 rpm, 0.1 μm/rev, 18.8 m/min): **a** without backup **b** with copy paper backup smeared with cyanoacrylate

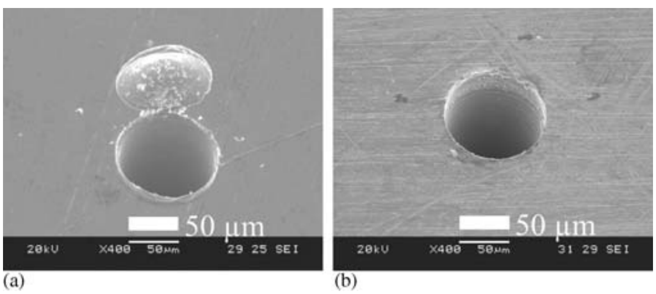


Fig. 10a,b. Shape of hole exits according to the kinds of backup (conditions: 0.5 mm thick copper foil, F 0.1 mm, 30 000 rpm, 0.02 μm/rev, 18.8 m/min): **a** without backup **b** with copy paper backup smeared with cyanoacrylate

3.3 304 Stainless steel

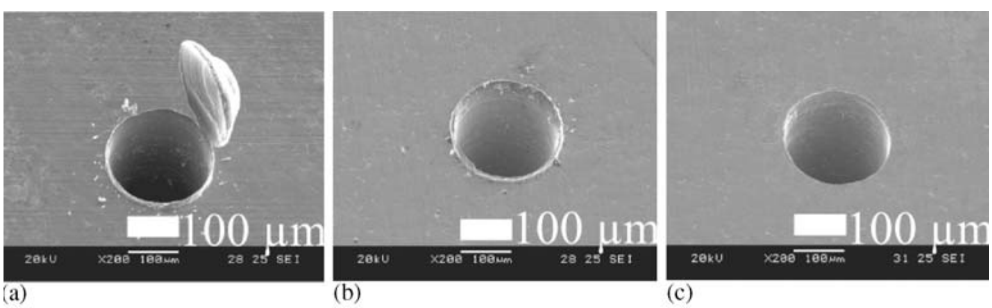
Figure 11 shows the holes drilled at 30 000 rpm and 0.3 μm/rev with a 0.2 mm diameter drill in 304 stainless steel. Although the exit burr height of stainless steel is lower than that of aluminum, the side burr with a cap is formed, as shown in Fig. 11a. To prevent exit burr, the same methods were applied to 304 stainless steel. However, the copy paper backup smeared with cyanoacrylate was not effective, as shown in Fig. 11b, because the cyanoacrylate layer could not support the thrust force. The exit burr height increased in this case. For stainless steel, the backup foil adhered with cyanoacrylate was effective in preventing burr, however, as shown in Fig. 11c.

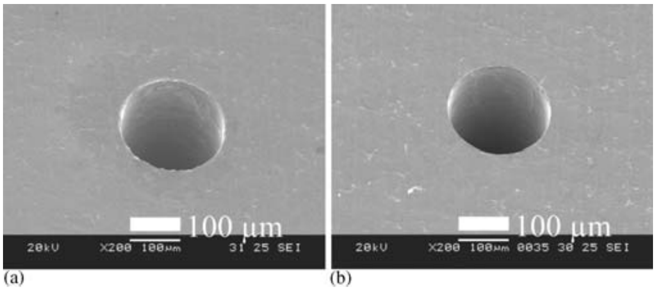
Figure 12 shows the hole exits drilled with a 0.2 mm drill in 304 stainless steel with a backup foil adhered with cyanoacrylate under other cutting conditions. The holes were very clean in all instances, demonstrating the effectiveness a cyanoacrylate-adhered backup in preventing exit burr in 304 stainless steel. Similarly, as shown in Fig. 13 for a 0.1 mm hole in 304 stainless steel, the backup foil adhered with cyanoacrylate was also shown to be effective.

3.4 Effect of backup on burr prevention

In drilling, if the stress exceeds the yield strength at the exit of a hole, a burr forms because of plastic deformation at the hole exit. To study the effect of backup using cyanoacrylate on burr prevention, the stress distributions around the hole exit were observed through finite element analyses. Finite element analyses were performed using ANSYS. The stress distributions in the following five conditions were investigated: aluminum without a backup, aluminum with a copy paper backup smeared with cyanoacrylate, copper with a copy paper backup smeared with cyanoacrylate, 304 stainless steel with a copy paper backup smeared with cyanoacrylate, and 304 stainless steel with a backup foil adhered with cyanoacrylate. Supposing that the hole is symmetrical with respect to the center axis, a half 2D model was used. Also, supposing that the backup plate is not separated from the workpiece when the cyanoacrylate is used, the gap between workpiece and the backup plate was modeled using contact element. The thrust forces used in the analyses were 0.4 N in aluminum, 4 N in copper, and 7 N in 304 stainless steel; these were measured during the experiments. Finally, it was supposed that two- thirds of total thrust force was applied

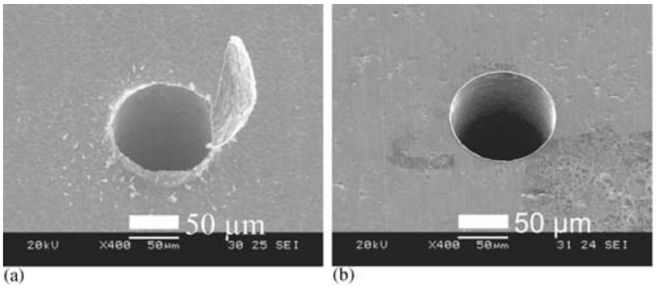
Fig. 11a–c. Shape of hole exits according to the kinds of backup (conditions: 0.5 mm thick 304 stainless steel foil, F 0.2 mm, 30 000 rpm, 0.3 μm/rev, 18.8 m/min): **a** without backup **b** with copy paper backup smeared with cyanoacrylate **c** with backup foil adhered with cyanoacrylate





(a) (b)

Fig. 12a,b. Hole exits drilled with backup foil adhered with cyanoacrylate (conditions: 0.5 mm thick 304 stainless steel foil, F 0.2 mm): **a** 60 000 rpm, 0.2 µm/rev, 37.7 m/min **b** 10 000 rpm, 4.2 µm/rev, 6.3 m/min



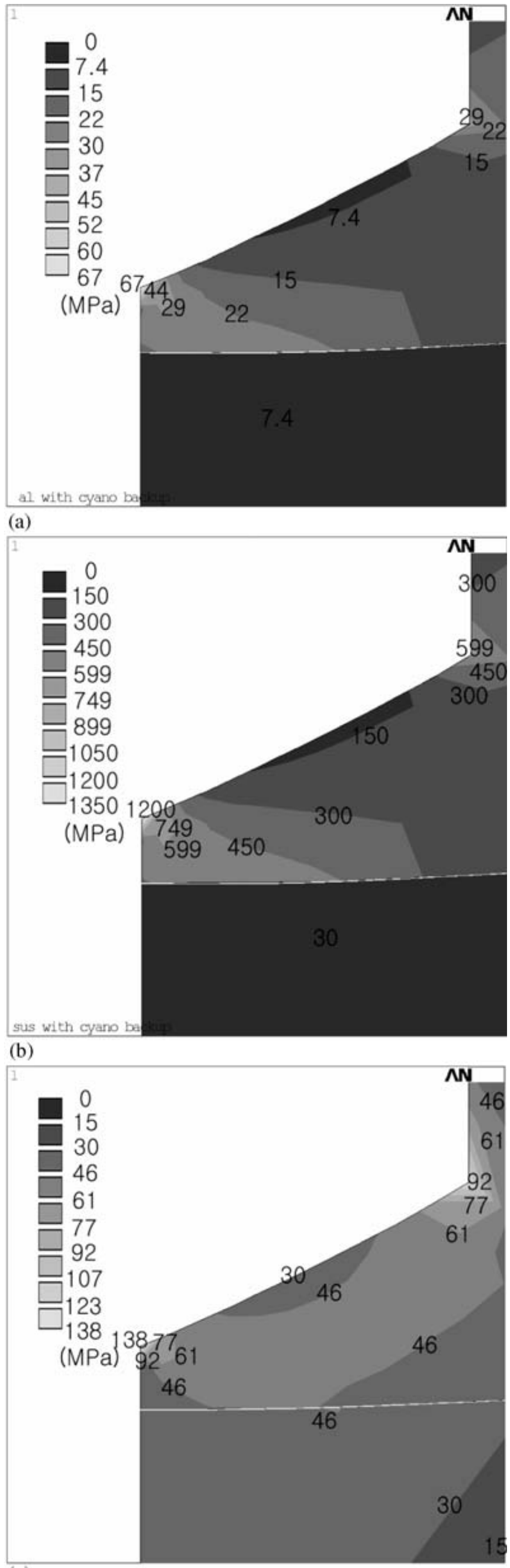
(a) (b)

Fig. 13a,b. Shape of hole exits according to the kinds of backup (conditions: 0.2 mm thick 304 stainless steel foil, F 0.1 mm, 30 000 rpm, 0.02 µm/rev, 18.8 m/min): **a** without backup **b** with backup foil adhered with cyanoacrylate

at chisel part, and the remaining force was uniformly applied at cutting edge.

In the case of aluminum without a backup, the stress acting on hole exit was about 30 MPa, which is two times larger than the yield strength of aluminum. In the case with a copy paper backup smeared with cyanoacrylate, although the stress around the hole exit was still slightly over the yield strength, the stress acting on the backup layer was about 40% of the tensile strength of cyanoacrylate. Hence, a copy paper backup smeared with cyanoacrylate could sustain the deformation of aluminum. Figure 14a shows the result of this case. When the copy paper smeared with cyanoacrylate adhesive was used in copper, the stress around hole exit was below the yield strength of copper, and the stress acing on the backup layer was 30% of the tensile strength of cyanoacrylate. Accordingly, the deformation of copper was also prevented. In the case of 304 stainless steel with a copy paper backup smeared with cyanoacrylate, the backup layer yielded and could not prevent the deformation of remnant material, as shown in Fig. 14b. This was because the stress acting on the backup layer was about 30 MPa, which is larger than the tensile strength of cyanoacrylate. When 304 stainless steel foil adhered with cyanoacrylate was used, the stress acting on hole exit and backup was reduced to about 20% of the yield strength of 304 stainless steel, as shown in Fig. 14c. Accordingly, the deformation of the workpiece was not observed in this case.

Exit surfaces of holes with different drilling depths are shown in Fig. 15. The figures show the exit surfaces at drilling depths in 20 µm increments from 490 µm. In the case without a backup,



(a) (b) (c)

Fig. 14a–c. Von Mises' equivalent stress according to FEM analysis: **a** in the case of aluminum with copy paper smeared with cyanoacrylate **b** in the case of 304 stainless steel with copy paper smeared with cyanoacrylate **c** in the case of 304 stainless steel with backup foil adhered with cyanoacrylate

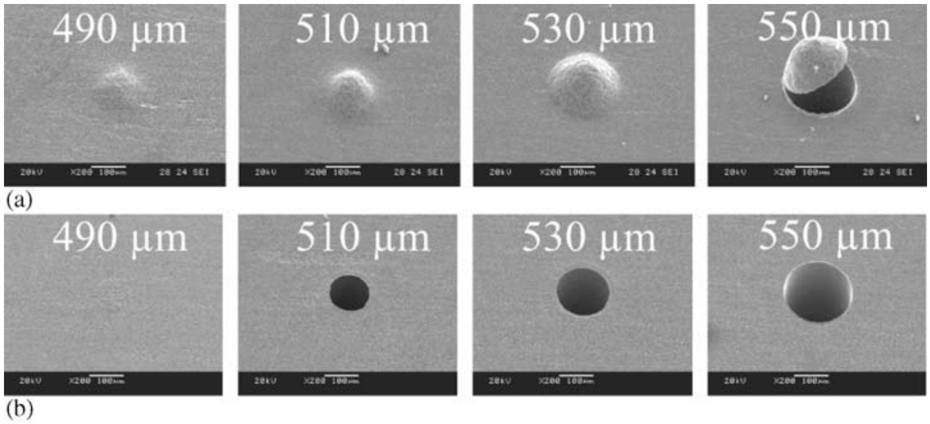


Fig. 15a,b. The process of burr formation according to the backup methods (conditions: 0.5 mm 304 stainless foil, F 0.2 mm, 30 000 rpm, 0.2 μm/rev, 18.8 m/min): **a** without backup **b** with backup foil adhered with cyanoacrylate

the remnant material was plastically deformed outward and fracture occurred at the edge of hole as the drill progressed. In the case with a backup foil adhered with cyanoacrylate, the plastic deformation of the remnant material was not observed.

4 Conclusions

In the microdrilling of metal, a burr forms at the exit surface due to plastic deformation of the remnant material. In this research, various backup methods were applied to prevent exit burr. Among these methods, cyanoacrylate adhesive and a copy paper backup smeared with cyanoacrylate were effective in preventing exit burr in the microdrilling of low hardness metals, such as aluminum and copper. However, in the case of a harder material, such as 304 stainless steel, a cyanoacrylate layer and copy paper backup smeared with cyanoacrylate failed. In this case, backup foil adhered with cyanoacrylate was shown to be effective in burr prevention. Backup using cyanoacrylate was effective because it obstructed plastic deformation of remnant material.

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