Improving High Precision and Continuous Process of Ultra-Fine Piercing by SiC Fiber Punch*

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A newly developed ultra-fine micro piercing has been demonstrated successfully with only a few technical points that need improvement. The die material is mild steel and the strength of the die is equal or sometimes smaller than that of the pierced material. Therefore, pierced scrap accumulated in the die hole may stop the punch advancement. If the pierced material rises up unevenly from the die, a lateral force acts on the punch and the punch defect advances and thus results in shaving the surface of the hole. In this study, the advancing defects were suppressed by using a decompression chamber under the die. In doing so, the scrap is sucked away from the die hole at each stroke and the foil, material to be pierced, is pulled down through two holes that are 1 mm apart from the die hole. The results of our experiment show a high precision continuous ultra-fine piercing process can be carried out with relative ease for various engineering materials.

***Key Words*:** Plastic Forming, Ceramics, Formability, SiC Fiber, Ultra-Fine Piercing, Vacuum System, Precision

1. Introduction

In recent years, the demand for highly functional products has prompted the development of advanced techniques for micro piercing. In our previous papers[1],[2], it was pointed out that ceramics could be used as a rigid, strong and flawless tool for small holes. The piercing system consisted of a punch, a SiC fiber 14 μm in diameter, made by us. In this system the ultra-fine piercing process was precisely controlled in which very small values of punch force and stroke were measured by highly sensitive sensors that are logged to personal computer. Experimental results have reveled that round and sharp-edged holes can be obtained for aluminum, beryllium copper and stainless steel foils[3], but the tool life was too short to put this method into practice. In this research, the reasons for this problem were investigated and countermeasures were proposed. The results of the continuous piercing tests show that the improved system was effective for aluminum and beryllium copper foils.

2. Outline of This Method

In this method, a ceramic fiber filament of SiC with a diameter of about 14 μm and on sale as "Nicalon", is used as the punch. Table 1 shows the mechanical properties of the fiber, which is as strong and rigid as hard metals. Additionally, it has high galling resistance, a characteristics of ceramics. Therefore, this fiber is not only available for piercing

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Table 1 Properties of SiC fiber

Diameter	14 μm
Density	2.55 g/cm^3
Tensile strength	2.75 GPa
Young's modulus	196 GPa

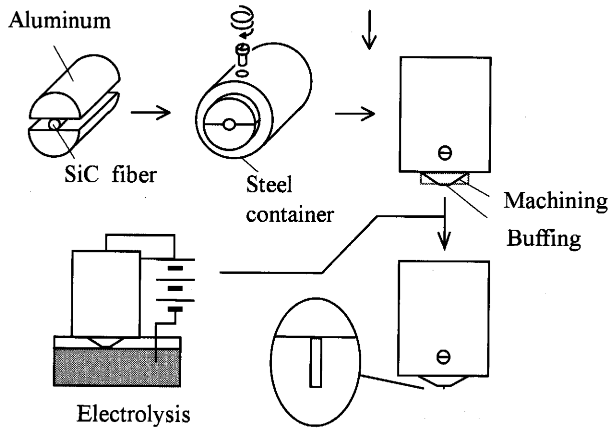


Fig. 1 Fiber punch made by buffing and electrolysis

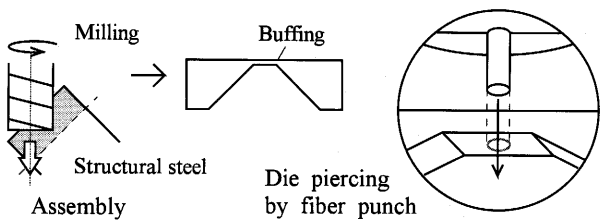


Fig. 2 Die making process

punch, but also can pierce the die, which enables die hole making and matching of tools at a time.

The procedure of making punch unit is illustrated in Fig. 1. First, a fiber is clamped with a pair of semi-cylinders made from aluminum and they are inserted into a steel container. By screwing semi-cylinders, the fiber is indented into the aluminum and held to the container by the friction force acting on the interfaces. Subsequently, the end face of the cylinder is machined into a cone shape where the fiber end is rough fractured face. In order to make it smooth and flat, the top face of the cone is buffed and lapped, resulting in a good punch edge. After that, the finished face is subjected to the electrolytic polishing, during which aluminum is dissolved while the ceramic fiber remains. This operation is continued until the height of the fiber is about 50 μm and the fiber punch unit is completed.

As shown in Fig. 2, a bridge-shaped die is made from structural steel by milling. Next, the top face is lapped so that the center portion of the die is as thin as about 20 μm. The finished die block and punch unit are mounted on a micro press as illustrated in Fig. 3.

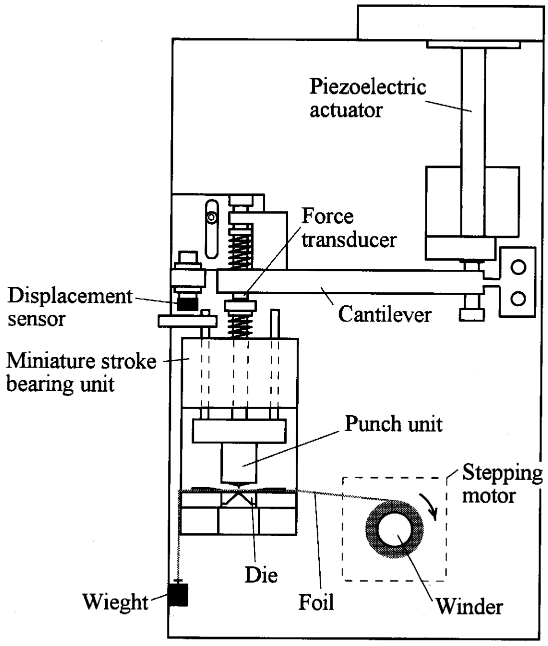


Fig. 3 Schematic of micro press

As the punch unit descends, the center of the bridge die is pierced by the fiber. Since the punch and die have already been mounted on the press, both axes coincide without additional alignment.

The micro press, shown in Fig. 3, is driven by a piezoelectric actuator that can exert 800 N with 68 μm stroke. Load transducer and displacement sensors are integrated to provide force-stroke diagrams.

3. Continuous Process by Former Method

3.1 Experimental procedure

Piercing experiments were conducted for conditions of no lubricant and punch speed of 3.8 - 6.4 μm/sec. In general, lubrication is necessary for shearing to reduce wear or galling. On the contrary, in micro piercing, it is undesirable because viscosity of lubricant isn't negligible and affects the piercing behavior, that is, it slides the foil on the die face and causes a lateral force to the punch. In this experiment, a ceramic punch is used; therefore, wear or adhesion will be less in spite of no lubrication. The tested foil is put on the die face, with one end fixed to a winder, the other end attached to a weight, so that tension prevents the foil from flapping during the piercing process. In addition, the winder rotates by a stepping motor and the foil moves by a certain pitch every piercing process. A personal computer and a few programs for calibrating control the operations, force measuring, automatic continuous working etc. are developed. Beryllium copper alloy, Be-Cu 25 1/4H, of 15 μm thickness were mainly used as test material. This metal has good formability, high conductivity and high strength. Furthermore the tensile strength can be increased to 1.5 GPa by age hardening, that is, a comparable strength of stainless steel.

3.2 Appearances of sheared surface and punch force-stroke curves

Figures 4, 5 and 6 show the scanning electron micrograph of pierced holes at the beginning of piercing and at the 200th and 1 000th piercing cycles, respectively. Figure 7 shows the influence of tool wear on punch force and accuracy. At the beginning, shown in Fig. 4, the hole is truly round, its edge is sharp, and the sheared surface looks to be smooth and burnished. The punch stroke-force curve of Fig. 7 (a) shows that the punch force reaches the maximum at 30% stroke of the thickness and separation occurs at 100% stroke. Although the punch force decreases abruptly once after the separation, it increases and reaches the second maximum at 150% stroke and the decreasing rate of the force is smaller than that at

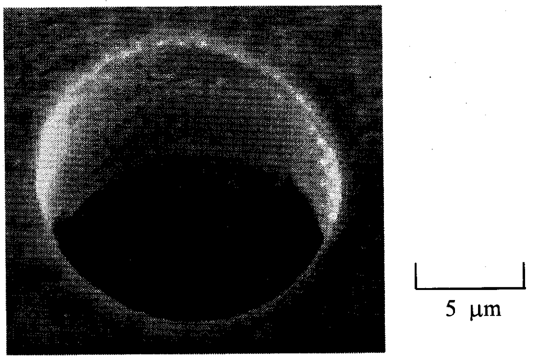


Fig. 4 Configuration of pierced hole at beginning of piercing

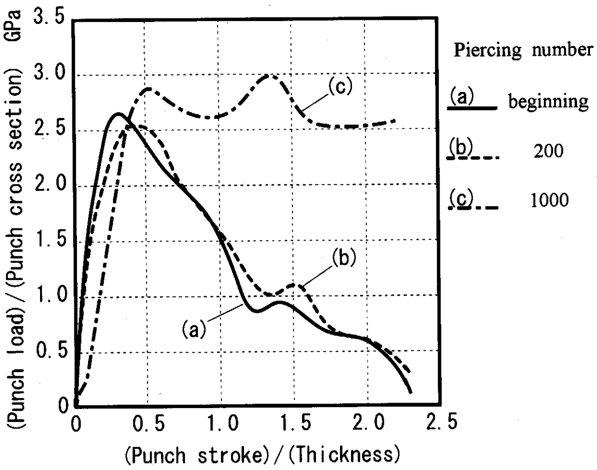


Fig. 7 Punch stroke-force curves

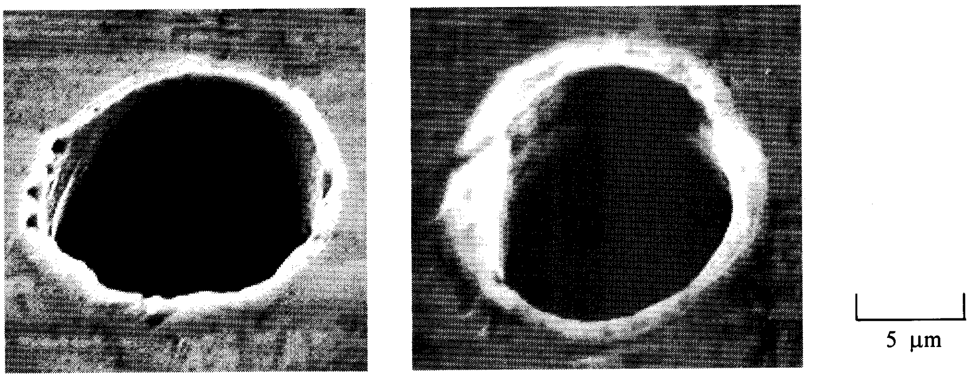


Fig. 5 Configuration of pierced hole at the piercing number of 200

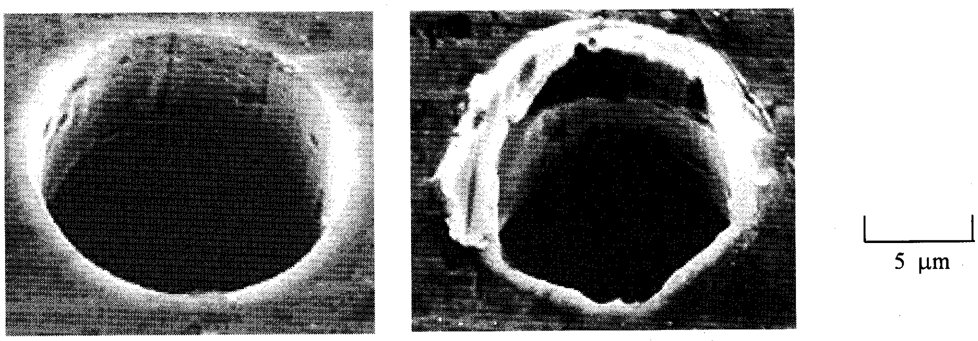


Fig. 6 Configuration of pierced hole at the piercing number of 1 000

100% stroke. The punch force after 100% stroke is caused by friction of pierced scrap. A scrap pierced immediately before this process remains in the die hole and the punch push one scrap in 100 - 150% stroke but must push two scraps after 150% stroke. Therefore the punch force after 150% stroke is larger than in 100 - 150% stroke.

With regard to the configuration of the hole observed from the punch side at the 200th piercing shown in Fig. 5, the edge of the hole distorted on the right and left sides and becomes elliptical. This fact suggests that the punch suffers a lateral force, bends and advances inclined into the material, as shown in Figs. 9(1) and (2). In Fig. 7 is shown the characteristics of increasing the clearance at the value of the maximum punch force shown in curve (b), at 200th piercing cycle, becomes smaller than that of curve (c) at the beginning and the stroke of the maximum punch force at the former becomes later than that of the latter. Therefore the die wears but the fiber punch does not wear because die material is softer than punch material.

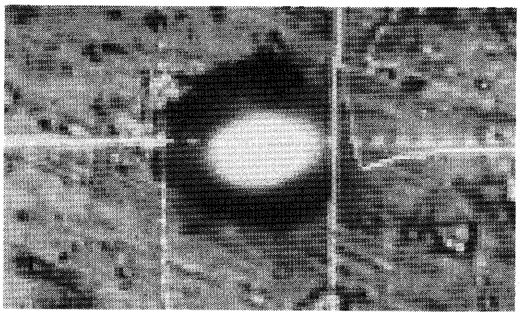


Fig. 8 Die hole after 1 000 piercing (Laser microscopy)

The configuration of the hole at the 1 000th piercing cycle is shown in Fig. 6. The fractured area occupies 50 - 60% of the pierced surface and larger burrs appear. The punch stroke-force curve at this time is extraordinary different from those at the beginning and the 200th piercing cycle. The punch force does not reduce over 200% stroke and becomes the overall maximum at 140% stroke. The observation of the die through a scanning laser microscope, shown in Fig. 8, reveals that the diameter of the die hole enlarges from 14 μm to 22 μm and beryllium copper sticks to the die edge.

3. 3 Tool wear

Based on the above-mentioned experimental facts the die wear mechanism is considered to proceed through the process shown in Fig. 9.

(1) The material rises up from the die surface.

(2) Unbalanced material rising-up generates a lateral force that acts on the punch and then leans the punch.

(3) The punch hits and shaves the die hole side-surface owing to the advancement of a slanted punch defect that eventually enlarges the diameter of the die hole and a bump is formed on the die hole side-surface.

(4) As the clearance between punch and die increases owing to the die wear, residual-bending moment in a scrap increases and much punch force needs to remove the scrap.

(5) Further increase of die wear leads such unexpected deformation, as extrusion or shaving of the scrap.

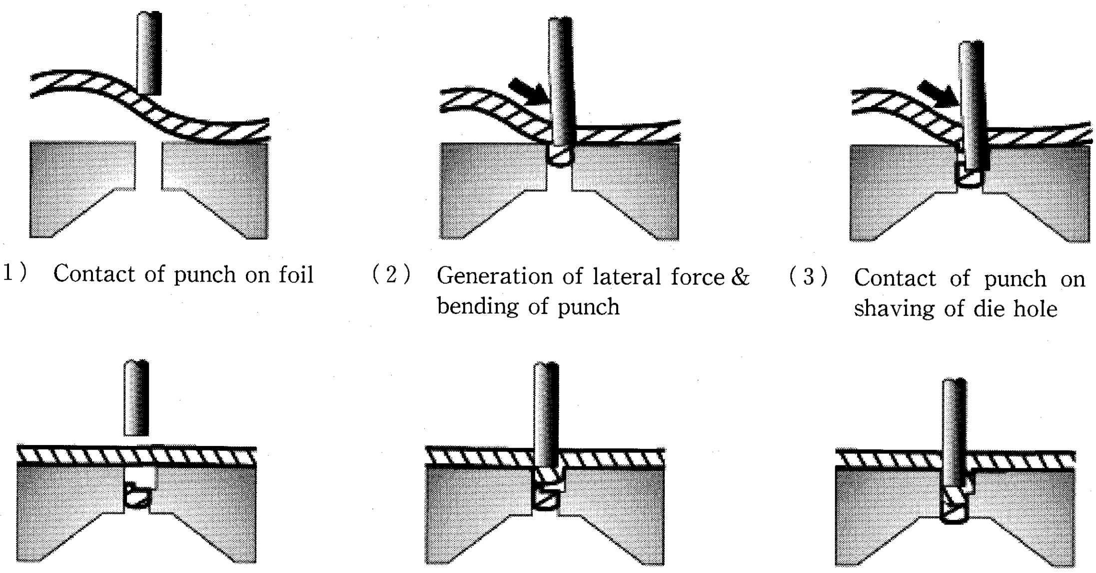


Fig. 9 Process of die wear

4. New Die Design

If a conventional constrain mechanism is used, the foil material may rise up, as shown in Fig. 9, because of the extraordinary small pierce dimension. In order to solve this problem, the foil to be processed is pulled down right on the die by decompression created below the foil. Figure 10 shows the decompression chamber under the die, which is enclosed by a front panel made from transparent acrylic resin, an acrylic bottom with a joint to a decompression pump, and the die. The foil is pulled down through two 0.6 mm diameter holes that are 1 mm apart from the die-hole and the scrap is sucked into the chamber through the die-hole.

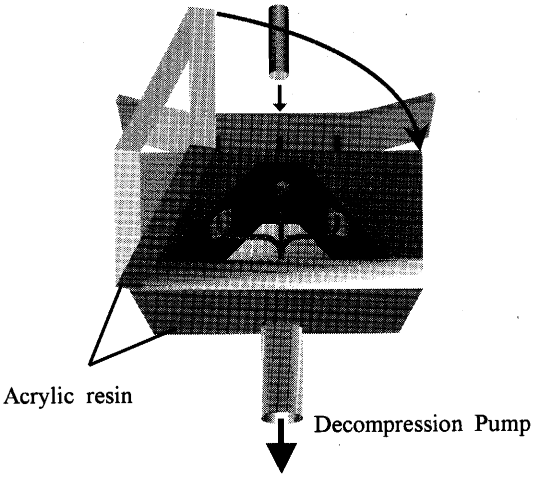
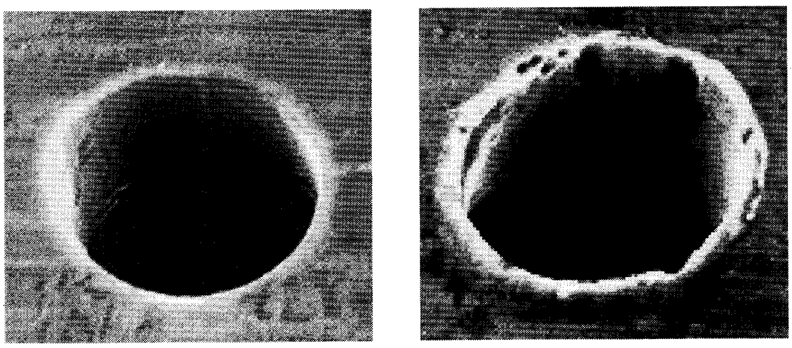


Fig. 10 Decompression system

5. Continuous Process by Using Newly Designed Die

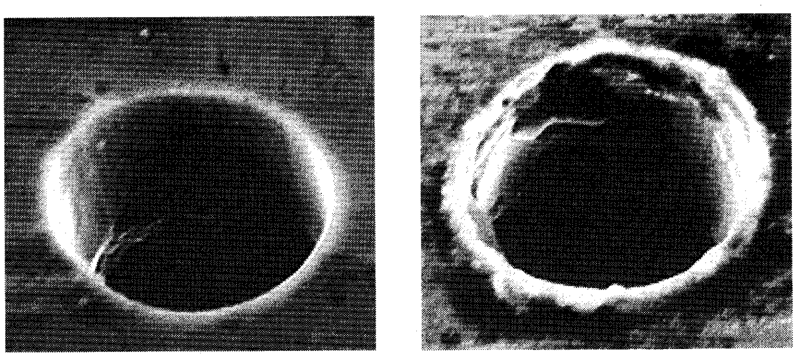
5.1 Results and considerations

Figures 11 and 12 show the scanning electron micrograph of pierced holes at the 200th and 1 000th piercing, respectively, in the process by using a newly designed die, and Fig. 13 shows the punch stroke-force curves. In these SEM photographs, shear drops are hardly observed, the shape of the hole is circular and pierced side-surface on the punch side surface is smooth surface, though burrs are observed on the die side surface at the 1 000th piercing cycle. A noticeable difference of punch stroke-force curves from those of the previous process is that the second maximum punch force at 150% stroke vanished, and this proves that the scrap does not stick or remain in the die-hole any longer. Such phenomena, sticking of the scrap on to the die-hole side surface or the punch misalignment that arose in the previous processes have not



Punch side surface　　Die side surface

Fig. 11 Configuration of pierced hole at the piercing number of 200



Punch side surface　　Die side surface

Fig. 12 Configuration of pierced hole at the piercing number of 1 000 happened. However a little increase of the clearance may be evident by the fact that the maximum value of punch force decreases with increase of piercing numbers shown in Fig. 13. Actually the diameter of the die-hole after the 1 000th piercing cycle was measured to be 16 μm by a laser microscopy. Therefore in order to prevent fundamentally the wear of die in a number of piercing, the die material must be changed to some kind of hard tool alloy material.

5.2 Configuration of the punch used in continuous piercing

Figure 14 shows the SEM photograph of the fiber punch after using it for 1 000 piercing cycles. The experimental results show that no significant rupture or wear in piercing beryllium copper. Moreover, the fiber punch was proved to be superior in its strength when used for very small dimensions, or adhesion and seizure does not happen even without lubrication, inherent characteristics of ceramics.

5.3 Influences of decompression and material on the process

Figure 15 shows comparisons of punch stroke-force curves with and without decompression for various materials. For aluminum and beryllium copper, the punch force after the first maximum decreases and the second maximum vanish due to decompression. However, there is hardly any influence of decompression in the case of stainless steel. Crack initiation in the fiber punch was observed after many piercing cycles of the stainless steel, and this is caused by the material's characteristics of high strength and high work hardening.

6. Conclusions

Improvements of ultra-fine piercing with a fiber punch were studied in order to conduct a continuous process with high accuracy, and the followings were clarified.

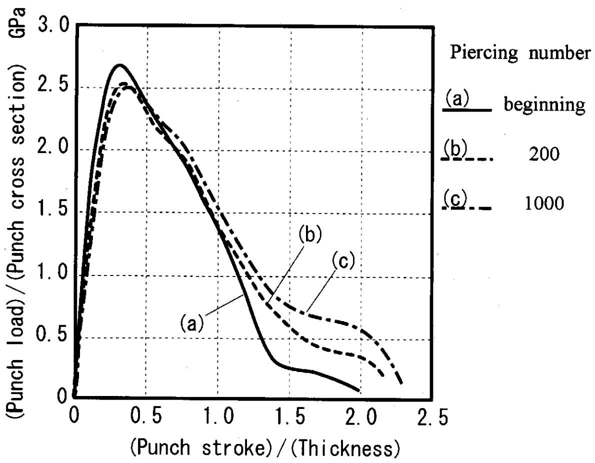


Fig. 13 Punch stroke—force curve (with decompression system)

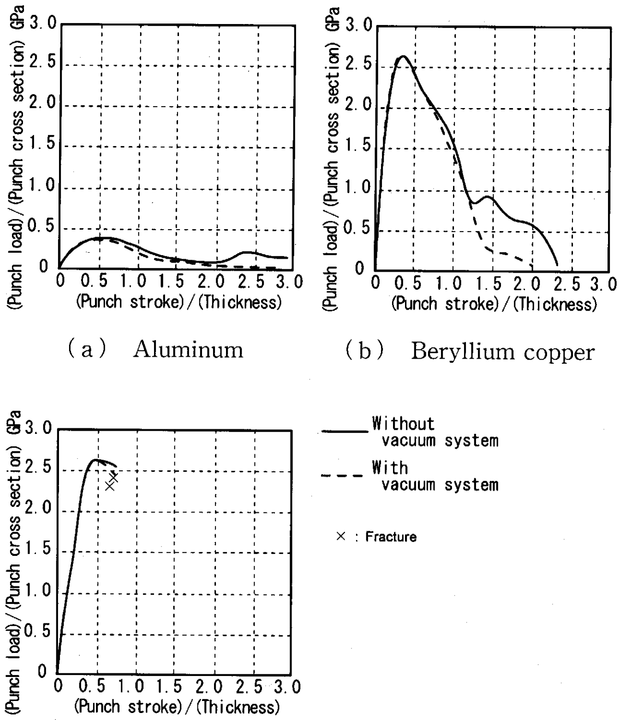
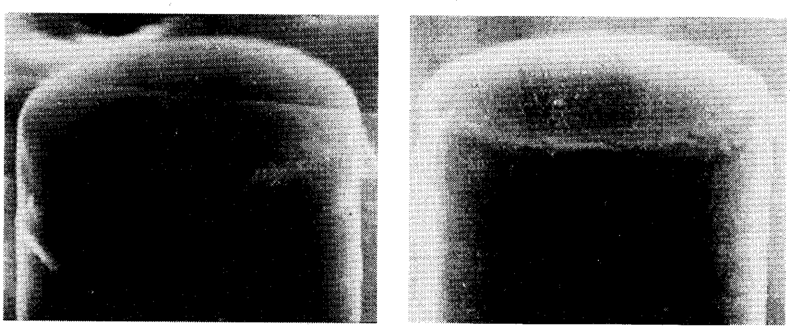


Fig. 15 Punch stroke—force curve for each material



Before piercing　　After 1000 piercing

Fig. 14 Punch head configuration

(1) Scrap can be sucked down through the die-hole by decompression, and then over-load on the punch after the maximum is ridded of.

(2) Foil material is pulled down on the die surface through two 0.6 mm diameter holes that are 1 mm apart from the die-hole by decompression, material rise-up is constrained, and thus horizontal force that acts on the punch is suppressed and shaving of scrap does not occur.

(3) For high piercing cycles, the use of the decompression process shows a little wear on the die surface. Therefore the material of die must be considered in the future.

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