Full Paper

THE EFFECT OF PUNCH GEOMETRY ON PUNCHING PROCESS IN TITANIUM SHEET

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Graphical abstract
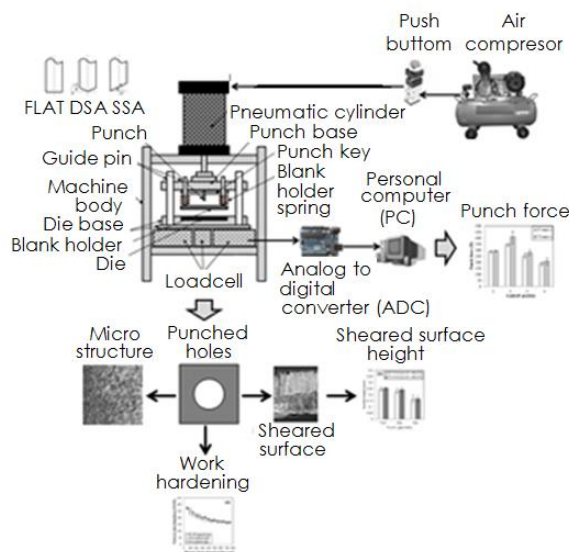
Abstract

Reducing punch force, increasing the sheared surface, and improving the work hardening have been real challenges in developing a punching process, and the right selection of punch geometry can resolve these challenges. Selecting the appropriate geometry, however, has been difficult to do since the effect of punch geometry on the punching process is rarely studied, and therefore, this study aims to investigate the effect of punch force, sheared surface, and work hardening by using commercially pure titanium sheets. The punching process under the study employed three different punch geometries, namely flat (FLAT), single shear angle (SSA) and double shear angle (DSA) with a shear angle of 17°, while the Punch velocity used was 35mm/s and 70 mm/s. The results show that the punching process using SSA and DSA punch geometry with the punch velocity of 35 mm/s reduces the punch force by 18% and 13% consecutively compared to that of FLAT with the same velocity. However, the sheared surface quality seems to decline as the rollover height increases by about 48% and 32%. Moreover, the burnish height decreases by 34% and 7% and the resulted work hardening improves by 4.7% and 2.3% respectively. The study concludes that SSA and DSA punch geometry can be best used to reduce punch force and increase work hardening, but apparently fail in increasing the sheared surface quality.

Keywords: Punching process, punch geometry, punch force, CP-Ti

1.0 INTRODUCTION

The forming process has been applied in the manufacture of sheet metal components, such as medical equipment, electronics, and automobiles [1], [2]. In the forming process, some researchers have already conducted research about drawing, blanking, and punching processes [3-33].

In the drawing process, various analyses and experiments have been carried by Colgan and Monaghan [3], and Yoshihara *et al*. also studied the effect of blank holder force control on magnesium alloy [4]. In addition to that, Palumbo and Tricarico investigated warm deep drawing process of circular aluminum alloy specimens with numerical and experimental analyses [5], and the severity of forming has been predicted by Shirin *et al*. by using an inverse finite element and extended strain-based forming limit diagram [6], while Irthiea and Green used soft die-simulation and experiments for the evaluation of micro deep drawing [7]. Moreover, Aminzahed *et al*. investigated the effect of holder

pressure and size on the rectangular micro deep drawing [8], Lou *et al.* conducted a study about the effect of surface roughness on the micro deep drawing of circular cups [9], and the tool geometry effect on the limiting drawing ratio has been researched by Behrens *et al.* [10].

In the blanking process, the effect of clearance and punch velocity on the quality of blank parts on copper [11] and brass [12] was investigated, and Maiti *et al.* studied the effect of several process parameters with the finite element method [13]. Canales *et al.* [14] researched the sheet metal blanking process by using numerical simulation, and Guy *et al.* [15] used cryogenic treatment for the improvement of a lifetime for fine blanking tools.

The punching process continues to develop for achieving the optimum quality of punched holes with lower punch force. Punch force and punched holes are affected by some parameters, such as clearance, punch velocity, material temperature, punch wear, and punch-die geometry. The effect of these parameters has been studied by using various materials, such as brass, steel, stainless steel, aluminum, and pure titanium [16-29]. Xu *et al.* [16] have investigated the effect of punch velocity and clearance on the sheared surface and surface roughness in brass material. They found that punch velocity increases, burnish height increases, and surface roughness decreases, while clearance increases, burnish height decreases.

In aluminum, the electropulsing method was used for investigating the effect of material temperature on the punch force and sheared surface [17] suggesting that the material temperature increases along with the current density. As the current density increases, punch force and hardness near the sheared surface decreases, while the burnish height increases. On another occasion, Chen *et al.* [18] experimentally investigated the flat ISE punch in single-crystal aluminum and shows the presence of significant indentation size effects on both pyramidal and strip punch indentation geometries. When the indenter diameter is increased, the hardness of the plastic deformation decreases, and when the punch width increases, the punch pressure declines.

In steel, Soares *et al.* [19] employed Abaqus software for analyzing the effect of clearance on the quality of punched holes. When clearance increases, the burr height increases as well. Larue *et al.* also conducted a study about the effect of punch velocity on the punch force [20] and found that when Punch velocity increases, the punch force also increases. Yokoi *et al.* [21] investigated the fracture phenomena in hole expansion tests, whilst Local strain mapping in the quantification of large deformation has been conducted by Nakada *et al.* with the combination technique of electron backscatter diffraction and digital image correlation methods [22]. Warm and hot punching had been developed by Mori *et al.* to investigate the effect of temperature on the punch force and the sheared surface [23]. The method of local heating resistance was also developed by Mori *et al.* [24], [25] suggesting that when material temperature increases, the punch force decreases, and the burnish height increases. According to Kolleck *et al.* [26], die geometry can affect the punch force and springback. Die geometry with a chamfer in cutting edge can reduce punch force and increase springback. The finite element method was used by Singh *et al.* to study the design of punch geometry [27] finding that in SSA punch geometry, the punch force decreases with an increasing shear angle, while in DSA punch geometry, the lowest radial deformation uses a shear angle of 17°-22°. However, Singh *et al.* did not investigate the effect of both geometries on the sheared surface and work hardening.

In addition to that, Gurun *et al.* [28] compared their experimental results with fuzzy logic for investigating the effect of a punch shear angle and clearance on the punch force. The error between fuzzy logic and experiment is quite small. Punch force reduces by 80% when the shear angle is 16°, but Gurun *et al.* did not observe the sheared surface and hardness. Moreover, they only used one type of punch, SSA. Actually, the effect of DSA punch geometry and clearance on the punch force was studied by Kutuniva *et al.* [29] and found that when the shear angle and clearance increase, the punch force decreases. The punch force reduces by 57 % compared to a flat punch force when a shear angle of 14° is used. While to get high quality sheared surface with a low punch force, a shear angle of 7° was used. However, this study only compared two punch geometries and did not investigate the work hardening that occurred. Campbell & Gill [30] similarly investigated the effect of flat punch indentation size by using an analytical model. The analytical results show that as the punch width decreases, there occurs an increase in the indentation pressure, the relative size of the plastic zone, and the elastic component of the deformation. The plastic region starts to form at the edge of the punch in each case, and when the punch width decreases, the punch pressure increases. A punch with a large edge radius demonstrates increasingly large elastic contributions to the initial loading stage, with increasingly localized plastic hardening around the edges as the indentation width decreases. The punch with small edge radius results in little plastic hardening at the edges and growth of the edge plastic zones via load transfer until they meet in the middle and form a roughly hemispherical plastic zone under the indenter.

In pure titanium, some researches carried out an investigation on the effect of tool wear on the shape of micro-holes [31], the effect of planetary stirring processing time on the finishing of punched micro-holes [32], and the effect of carbon nanotubes on the tool wear [33].

Based on the literature review, the process parameters have different effects on each material. It also appears that the punch process has been

extensively studied. However, there is still little research on the punching process on titanium sheets as the existing research still focuses on punch wear. In the development of the punching process in the manufacture of medical equipment, not only problems of punch wear are encountered but the effect of process parameters on the performance of the tool and the quality of the product should also be investigated. In the literature, there are studies on the effect of punch geometry on aluminum [18] and steel [28],[29] though that on titanium has not been carried out. Moreover, the investigation in steel is still limited to the effect of punch geometry on the punch force and sheared surface, not discussing that of work hardening. Therefore, this study aims to investigate the effect of punch geometry on the punch force, sheared surface, and work hardening in commercially pure titanium sheets.

2.0 METHODOLOGY

In this study, the testing steps are shown in Figure 1. A pneumatic punch machine was used for the punching test, while the schema of the punching test is shown in Figure 2. The experiment was carried out by using three different punch geometries, namely flat (FLAT), single shear angle (SSA), and double shear angle (DSA). The shear angle on SSA and DSA used was 17°, and the punch geometry is shown in Figure 3. The punch was fabricated by means of a grinding machine with a punch diameter of 1.7 mm. The clearance of punch-die used was 20 µm. The punch material was high-speed steel (HSS) SKH9, and the material used in this experiment was a commercially pure titanium sheet with a thickness of 0.4 mm. Two kinds of punch velocity were applied, namely 35 mm/s and 70 mm/s. Four load cells (Zemic L6E) were attached on the bottom die to measure the punch force, while the capacity of the load cell was 500 N for each.

The sheared surface was measured by a digital microscope (Dino-lite AM4515 series) and the results of the measurement are illustrated in Figure 4. The hardness was measured on the cross-section of the punched hole by Vickers microhardness test (BUEHLER) with a load of 100 grams, and the position of hardness measurement is shown in Figure 5.
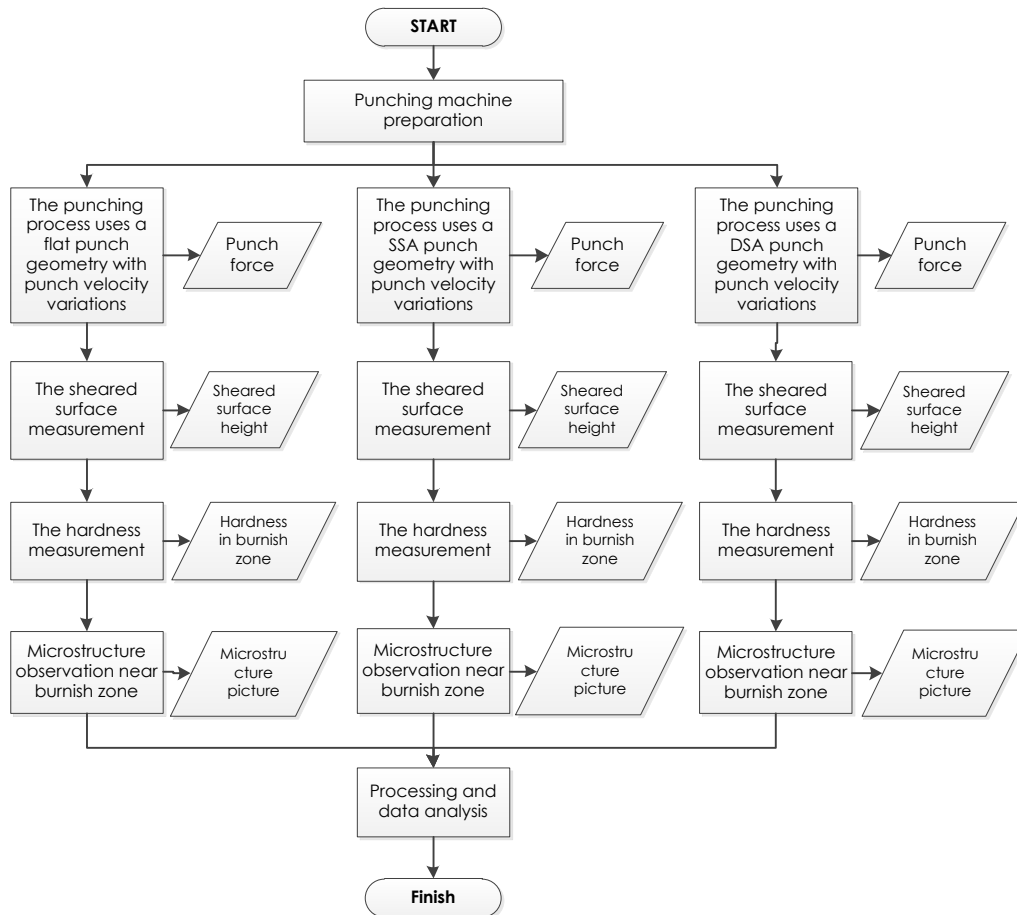

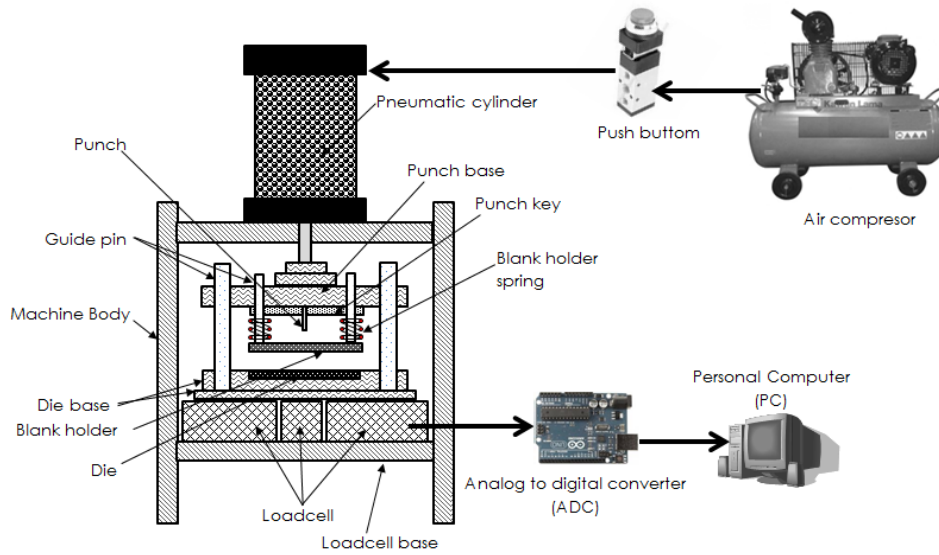**Figure 1** Flowchart of the steps of the experiment
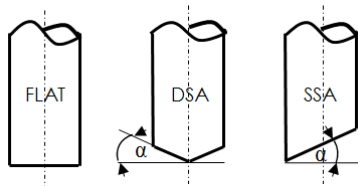
Figure 2 Schematic of punching test

Figure 3 Punch geometry
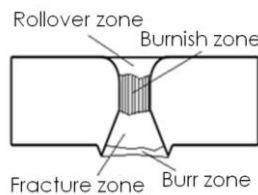
Figure 4 Sheared surface of the punched hole

Figure 5 Position of hardness testing

3.0 RESULTS AND DISCUSSION

3.1 Punched Force

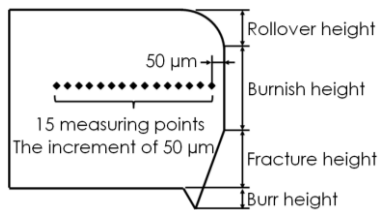The experiment employing three different types of punch geometry shows that the punch force can be affected by punch geometry and punch velocity. Figure 6 shows the punch force as observed during the experiments. It shows that FLAT punch geometry has a bigger punch force. When SSA punch geometry was used, the punch force is smaller than that when DSA punch geometry was applied. In addition, the punch force at the punch velocity of 70 mm/s is greater than that at the punch velocity of 35 mm/s. In the punching process using SSA punch geometry with the punch velocity of 35 mm/s, therefore, the punch force reduces by 18% compared to that if FLAT punch geometry with the same velocity is applied. Additionally, the punch force reduces by 13% when the punching process uses DSA punch geometry. Thus, it is found that in the punching process using SSA and DSA punch geometry with the punch velocity of 70 mm/s, the punch force reduces by 17% and 11% respectively.
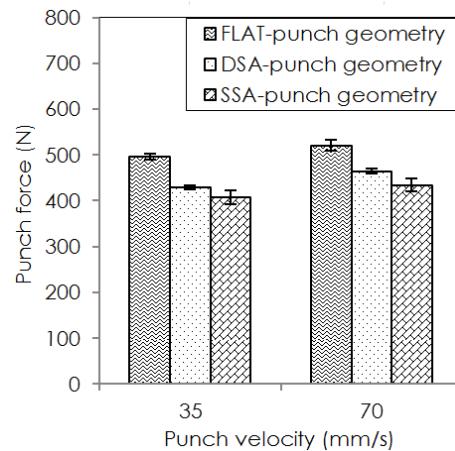

Figure 6 Punch force with different punch geometry and punch velocity

Moreover, the punch force reduces in the presence of a shear angle on the punch. This may happen because when the punching process it experiences a change in C2 clearance (the initial clearance) as shown in Figure 7a. C2 clearance at FLAT punch geometry was smaller than that in DSA and SSA punch geometry at the initial penetration (see Figure 7b). Greater clearance causes a smaller punch force [13], [34]. The phenomenon of decreasing punch force can also be seen in the slug produced. The greater clearance causes a bending moment to increase [35], thus the slug thickness produced is thinner. The observation of slug thickness is shown in Figure 8, where the slug when using SSA punch geometry is thinner than that when both FLAT and DSA punch geometry are used, while the slug with

DSA punch geometry is thinner than that with FLAT punch geometry. Based on pure shear of the punching mechanism which was assumed by Singh [27], it is shown that the instantaneous punch force (F_p) (equation 1) is directly proportional to the thickness of the slug produced [27]. When the slug thickness is small, the punch force is also small.

$$F_p = \frac{1}{3} \pi \sqrt{3}\, D\, h\, C \left[k \ln\left(\frac{h_0}{h}\right) \right]^n \tag{1}$$

where D is the punch diameter, h is the slug thickness, C is the stress characteristic, k is the shear factor, h_0 is the thickness of the punched hole, and n is the strain-hardening exponent.
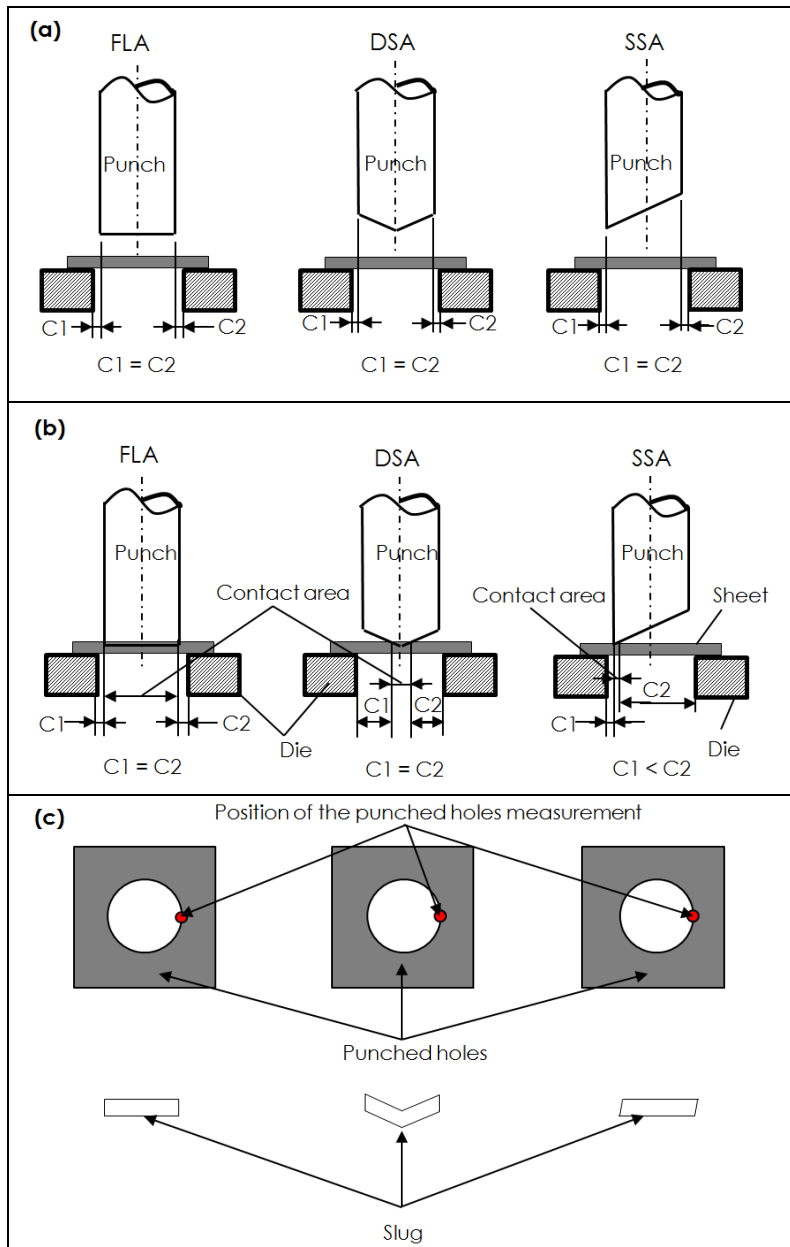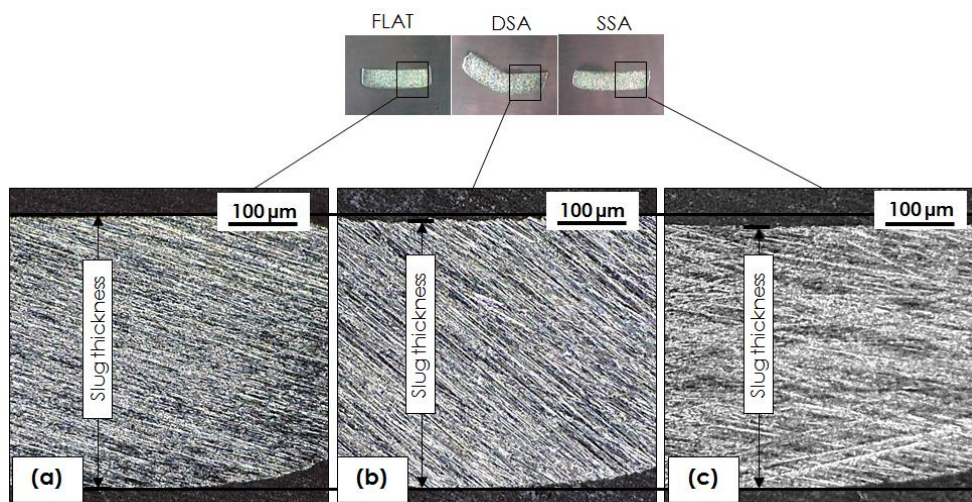

Figure 7 Ilustration of punching process

Figure 8 Slug cross-section when using punch geometry: (a) FLAT, (b) DSA, and (c) SSA

Punch force increases along with the rise of punch velocity. This is due to the increase of velocity causes an increase in the momentum rate in the punch movement. Based on Newton's statement of the second law of motion, the rate of change of momentum of an object is equal to the net force applied [36]. Therefore, if the punch velocity increases, the punch force also increases. The investigation conducted by Larue *et al*. also found that the punch force is directly proportional to the momentum rate [20] where force is directly proportional to mass and velocity but is inversely proportional to the time needed for cutting. When the punch velocity increases, the cutting time reduces and the cutting force increases. This phenomenon is also seen when using FLAT punch geometry. The cutting time with a velocity of 35 mm/s is greater than that when using the punch velocity of 70 mm/s, where the cutting time required by each is 33 ms and 71 ms.

3.2 Sheared Surface

Observation of the sheared surface of punched holes was carried out in the area as shown in Figure 7(c). This area was chosen because it seemed to have the smallest burnish. This prediction, based on clearance (C2), is greater than C1. The punching process uses a large clearance that will result in a short burnish height [16].

The analysis results of the sheared surface are shown in Figure 9. This figure shows that in the punching process using FLAT punch geometry, the rollover zone resulted is the smallest. In addition, the burnish zone resulted was biggest. When it uses SSA punch geometry, the rollover zone resulted is bigger than that when using DSA punch geometry, and the punching process uses DSA punch geometry, the burr zone resulted is the biggest.

The measurement results of the sheared surface height are presented in Figure 10. Rollover height (Figure 10(a)) at punch velocity of 35 mm/s using DSA and SSA punch geometries increases by about 32% and 48% respectively compared to that with FLAT punch geometry. Rollover height at punch velocity of 70 mm/s using the same punch geometries was increased by 36% and 104% respectively. Burnish height (Figure 10(b)) resulting from DSA and SSA punch geometry with the punch velocity of 35 mm/s decreases by 7% and 34% consecutively compared to that with FLAT punch geometry. At the punch velocity of 70 mm/s, using both DSA and SSA, the burnish height decreases by 6% and 35% respectively. Decreased burnish height will be followed by an increase in fracture height. Figure 10(c) shows that fracture height increases by 7% and 53% when using DSA and SSA punch geometry with the punch velocity of 35 mm/s. At the punch velocity of 70 mm/s with the same punch geometries, the fracture height increases by 4% and 53%. Besides, the burr height at the punch velocity of 35 mm/s using DSA and SSA punch geometry also increases by 58% and 41% compared to that with the other punch geometry, FLAT, as seen in Figure 10(d). At the punch velocity of 70 mm/s, the burr height increases by about 35% when using DSA but decreases by 5% when using SSA punch geometry.

Punch geometry can affect the sheared surface apparently because it is influenced by the initial clearance (C2). The difference in C2 clearance between punch geometries of FLAT, DSA and SSA is shown in Figure 7. C2 clearance on SSA punch geometry is greater than that in FLAT and DSA while in DSA, it is greater than that of FLAT. Greater clearance will result in higher rollover and shorter burnish. This may be due to the growth of the bending moment in the blank among the punch-dies [35]. This phenomenon is also shown in the results of

finite element simulations by Kwak, *et al*. [34], that the sheared band distribution is proportional to the clearance. The fracture begins earlier in the case of large clearance because the material quicker reaches the effective strain limit of fracture at the sheared plane. This is possibly the reason why punch geometry affects the sheared surface.
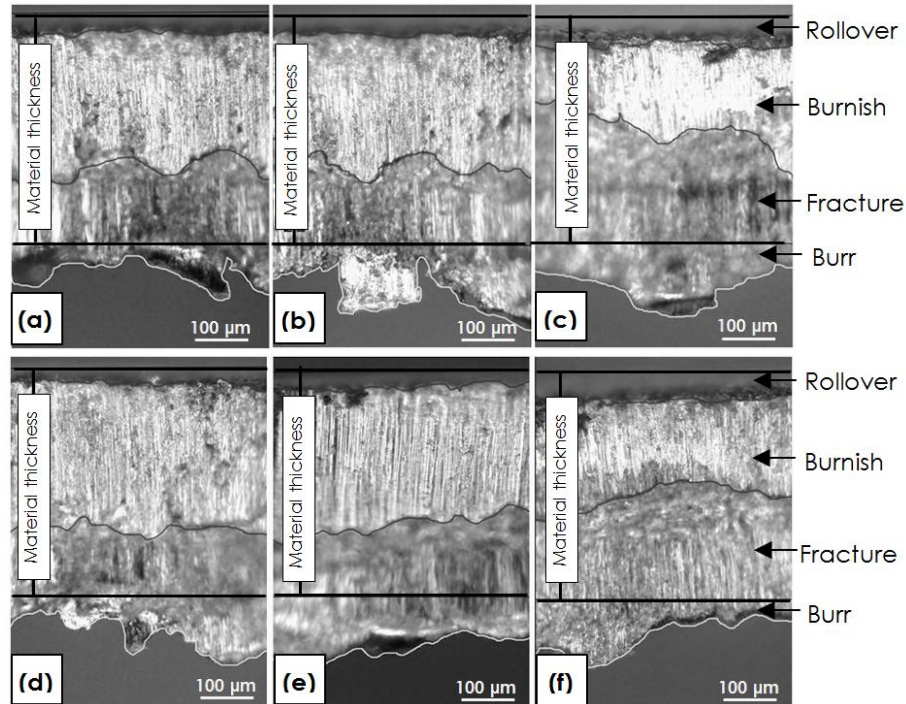
Figure 9 The shape of sheared surface on commercially pure titanium sheet on the condition of (a) FLAT, 35 mm/s, (b) DSA, 35 mm/s, (c) SSA, 35 mm/s, (d) FLAT, 70 mm/s, (e) DSA, 70 mm/s, and (f) SSA, 70 mm/s
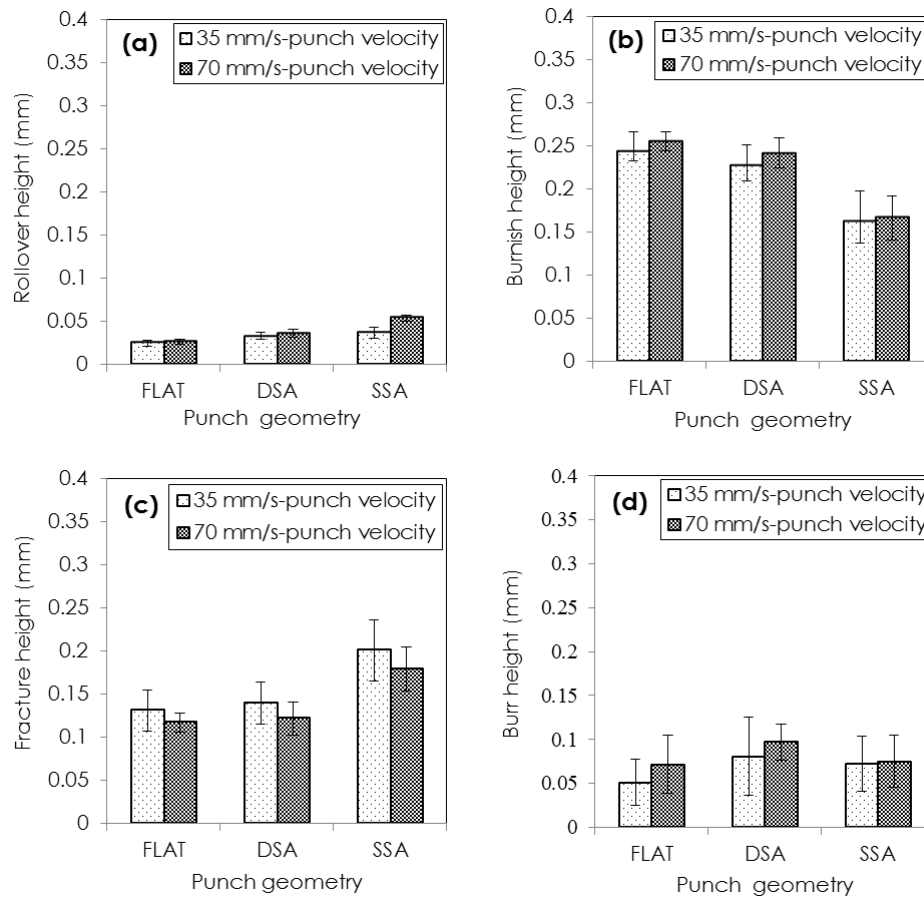
Figure 10 The height of sheared surface with different punch type and punch velocity; (a) rollover height, (b) burnish height, (c) fracture height, and (d) burr height

3.3 Work Hardening

The punching process produces the material strengthening near the sheared surface as caused by plastic deformation [37]. This apparently results from the generation and movement of dislocation within the material's crystal structure [38]. This phenomenon is called work hardening. The distribution of hardness near the sheared surface is shown in Figure 11. The figure shows that when SSA punch geometry is applied, the increase of hardness is the biggest. However, the increase of hardness when using the FLAT punch geometry is the smallest. This shows that the work hardening increases along with the shear angle on the punch. Work hardening seems to increase because C2 clearance (see Figure 7) in DSA and SSA punch geometry is greater than that in FLAT punch geometry. When clearance increases, the bending moment induced by the punch becomes greater [35], so the plastic zone formed is larger. This later causes the work hardening to increase likewise the shear angle on the punch.

The increase of hardness due to plastic deformation can be seen in the microstructure changes near the sheared surface. Plastic deformation will cause changes in microstructure from equiaxed grains to be elongated grains [39]. Microstructure observation was carried out on a cross-sectional burnish area when using the punch velocity of 35 mm/s by means of a metallographic microscope (OLYMPUS C-35AD-4). The results of the observation are shown in Figure 12. Based on Hall-Petch's theory, there is an inverse relationship between the hardness and grain size [40-42], and finer grain size will result in higher hardness. The shape of elongated grains when using DSA punch geometry seems to be finer compared to that when using FLAT punch geometry. While when SSA punch geometry is used, the shape of elongated grains is finer than that in DSA punch geometry. Therefore, when using DSA punch geometry, the increase of hardness is greater than that in FLAT punch geometry. Whereas in SSA punch geometry, the increase in hardness is the highest.
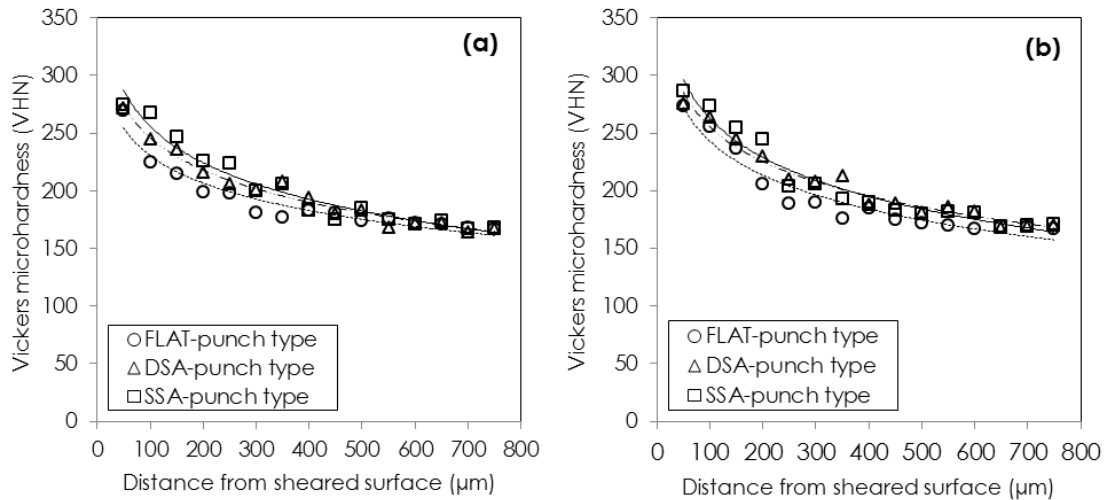
Figure 11 Hardness distribution with punch velocity: (a) 36 mm/s, and (b) 69 mm/s
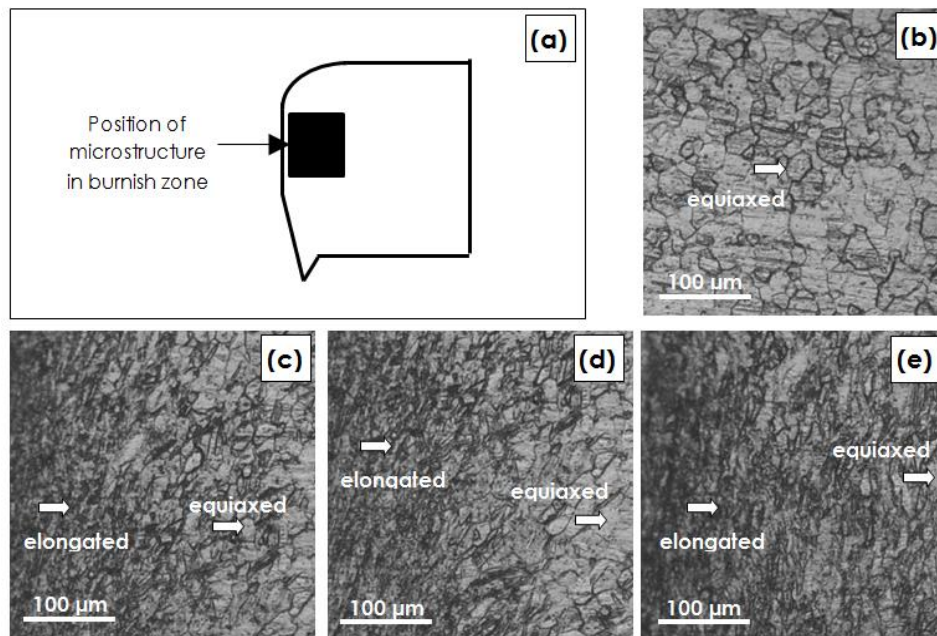
Figure 12 Microstructure of burnish zone when using punch velocty 35 mm/s : (a) microstructure position, (b) raw material, (c) FLAT, (d) DSA, and (e) SAA

4.0 CONCLUSION

Based on the experiment and analysis results conducted, it can be concluded that punch geometry affects the punch force, sheared surface, and work hardening. In the punching process using the DSA and SSA punch geometry, the punch force decreases and work hardening increases, but the rollover height increases and the burnish height decreases. In other words, FLAT punch geometry having high quality sheared surface is the best. While DSA and SSA punch geometry have their advantages in smaller punch force and higher work hardening.

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