

Optimisation of punch speed to improve cut surface quality of straight-plate implants produced by progressive punching

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Keywords

straight-plate implant
punch speed
progressive punching
sheared zone
surface roughness
hardness

History

Received: 11-05-2026

Revised: 26-08-2026

Accepted: 06-09-2026

Abstract

The main issue with straight-plate implant fabrication using progressive punching with a 60 μm clearance is the high work hardening and the low burnish zone height percentage on the cut surface. It requires an optimal punch speed to increase burnish height and reduce work hardening. The purpose of the present study is to optimise punch speed to improve the cut surface quality of straight-plate implants. Cut surface parameters such as the sheared zone, roughness and hardness were the examined attributes. The punch speeds used were 5, 8, 12 and 16 mm/s. The findings showed that the optimal punch speed for manufacturing straight-plate implants is 12 mm/s. This condition results in an average burnish zone height of approximately 209 μm (34.9 % of the material thickness) and a burnish surface roughness of approximately 1.13 μm . The surface roughness meets the medium roughness standard (1–2 μm). The average hardness near the sheared zone was 192 HV. The work hardening near the sheared zone was 32 HV. Optimisation results demonstrate the capability to address issues related to reducing work hardening and increasing burnish depth during the fabrication of straight-plate implants using progressive punching. The results of the present study on progressive punching technology can contribute to the development of more efficient and cost-effective manufacturing processes for straight-plate implants.

1. Introduction

Mandibular fractures are repaired using straight-plate implants manufactured via the die-sinking electrical discharge machining (EDM) method [1]. However, this method has several drawbacks, such as limited tool life, relatively long fabrication times, reduced hardness and the formation of a recast layer on the cut surface [2]. This layer has defects, such as ruptures, perforations or stress-induced cracks, which degrade the component's mechanical properties. It can also increase resistance to scraping and attrition [3]. The materials' resistance to corrosion and fatigue can be reduced by surface cracks under tensile strain [4]. Other procedures are still required to improve the hardness, rust resistance and fatigue

endurance of EDM-made straight-plate implants. Manufacturing straight-plate implants will cost much more due to the additional operations required. This could increase the cost of producing straight-plate implants. Through the forming process, this problem can also be eliminated. Benefits of the forming process include high-volume efficiency, excellent surface polish and remarkable precision [5]. It was previously used to create metal sheeting for electronics, medical devices and automobiles [6]. A variety of forming techniques have been developed, including punching, drawing and blanking. The final product quality during the punching process is affected by process variables, such as temperature, punch form, clearance and punch speed [7,8]. Punch speed has been studied with numerous materials and hole shapes.

The influence of punch speed on circular-shaped punching was researched by Kurniawan et al. using titanium [9]. Increasing the punch speed from 10



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to 35 mm/s and from 10 to 70 mm/s increased the punching force by 51 and 71 N and the burnish height by 0.006 and 0.047 μm , respectively. Xu et al. used brass to investigate the impact of punch speed on circular holes [10]. Punch speeds of 1.1, 5, 10, 20 and 50 mm/s were used in the study. Two linear motor drives were used. The study findings indicate that the punch speed affected the sheared zone and surface roughness. The burnish height can be increased by around 32 % and the surface roughness decreased from 0.105 to 0.040 μm , as the punch speed increased from 5 to 50 mm/s.

Gotoh and Yamashita used aluminium to investigate the influence of punch speed on the production of circular holes [11]. A drop-hammer-type punching tool with a punch speed range of 0.1–10 mm/s was used in the examination. The findings indicated that at a punch speed of 10 mm/s, the hardness distribution in the sheared zone was nearly uniform and moderate. Along the shearing direction, the hardness fluctuated between high and low values at a punch speed of 0.1 mm/s. Mahardika et al. [12] reported that increasing punch speed in the C-shaped punching process of titanium increased the punching force and the burnish zone height. The burnish zone on the outside radius (O-radius) was higher than on the straight side (S-side), while the strain hardening rate (work hardening) on the S-Side was approximately 15 % lower.

Meng et al. used copper to analyse the impact of punch speed on the punching of circular-shaped specimens [13]. The progressive punching machine employed in this study had punch speeds of 0.01, 0.05, 0.1 and 0.5 mm/s. Changing the punch speed from 0.01 to 0.05 mm/s, the hardness near the top surface increases from 55 to 65 HV. However, the resulting hardness decreases from 65 to 62 HV as the punch speed increases from 0.05 to 0.1 mm/s. Larue et al. investigated the effects of punch speed in circle punching using steel [14]. A horizontal punch tool with punch speeds of 5–25 mm/s is used in this technique. The findings showed that punching force increased with increasing punch speed. The impact of punch speed on the interlaminar characteristics of punched composite laminates was examined by Gholizadeh et al. [15]. The study's findings indicate that both the damaged area size and the punching force can be increased by decreasing the punch speed.

The literature clearly shows that studies on the effect of punch speed have been conducted on steel, aluminium, composite materials and titanium. However, the investigations were limited

to creating a single hole, namely a circular hole and a C-shaped hole. The creation of multiple punctures by progressive-type punching for the production of implants has been studied. However, the investigated parameters were limited to clearance. It has not been examined how punch speed affects the cut surface quality of straight-plate implants. Furthermore, the burnish level produced is below 50 % of the material thickness. These constraints complicate the selection of punching parameters for producing straight-plate implants. This is an important issue since producing straight-plate implants with progressive punching requires precise parameter settings to meet implant standards, namely moderate surface roughness (1–2 μm) [16,17]. Therefore, the present study aimed to optimise punch speed to improve the cut surface quality of straight-plate implants. The impact of punch speed on the cut surface quality of straight-plate implants is also investigated. The hole investigated is made by a B-shaped punch. The sheared zone height, surface roughness and hardness are all considered when evaluating the cut surface quality of straight-plate implants. The expected cut surface quality should have a burnish height greater than 29 % of the thickness, a surface roughness of 1–2 μm and a hardness range near the cut surface of about 160–200 HV.

2. Material and methods

Titanium with 99.8 % purity (Nilaco, Japan) was used to fabricate straight-plate implants. The workpiece had a hardness of 160 HV and dimensions of $300 \times 10 \times 0.6$ mm, in a rectangular shape. The straight-plate implant geometry aligns with Indonesian implant requirements [1]. The geometry of the straight-plate implant is shown in Figure 1. The straight-plate implant geometry is divided into three sections: the straight side (S-Side), outside radius (O-Radius) and inside radius (I-Radius). The width of the S-Side is 1.28 mm and the diameters of the I-Radius and O-Radius are 1.7 and 5.84 mm, respectively. The investigation in the present study is limited to the S-Side and O-Radius.

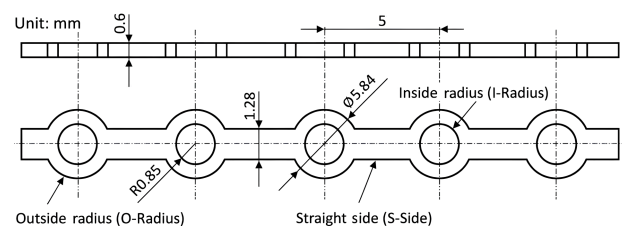


Figure 1. Straight-plate implant geometry; adapted from Kurniawan et al. [18], licensed under CC BY-NC 4.0

The progressive punching uses five punches arranged sequentially to create a straight-plate implant, as shown in Figure 2. A circular punch is used to create the I-Radius hole. A rectangular-shaped punch is applied to remove the side. It represents the workpiece's forward motion limit. The B-shaped punch creates the O-Radius and the S-Side.

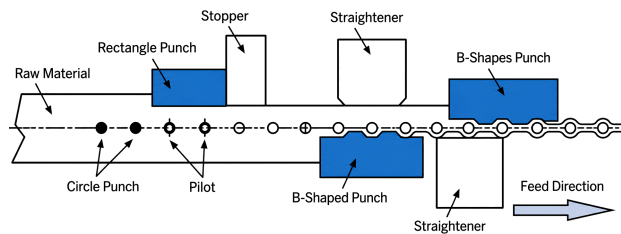


Figure 2. Schematic illustration of a progressive punch; adapted from Kurniawan et al. [18], licensed under CC BY-NC 4.0

High-carbon, high-chromium tool steel (JIS SKD11) was used for the die and punch. The material is hardened to 60 HRC prior to punch and die manufacturing. The punch employed a flat type with a clearance of 60 μm [18]. A 20-ton hydraulically driven progressive punch was employed in the production of the straight-plate implant, as shown in Figure 3. The punch speeds for the punching process were 5, 8, 12 and 16 mm/s.

Dino-Lite AM4515 digital microscope with 20–220 $\times$ magnification capability was used to view and measure the sheared zone. The sheared zone was measured at the rollover and burnish heights, as shown in Figure 4. Measurements were made on the O-Radius and the S-Side. Five S-Side surfaces and five O-Radius surfaces were used to measure the height of the sheared zone.

The S-Side and O-Radius surfaces were used to measure surface roughness. Surface roughness measurements were performed on the burnished region of the S-Side and O-Radius surfaces. A Mitutoyo SJ-201 roughness tester was used to measure the surface roughness. The surface roughness parameter measured is the arithmetical mean height (R_a). The stylus is made of diamond and has a tip radius of 5 μm . Surface roughness was measured using a 600 μm stylus movement [18]. Five S-Side and five O-Radius surfaces were used to measure the surface roughness.

The hardness of straight-plate implants was determined using a Future-Tech Vickers microhardness tester. According to some previous studies [14], hardness was measured using a 100-gram load and a 10-second loading period. Measurements were made on the S-Side and O-

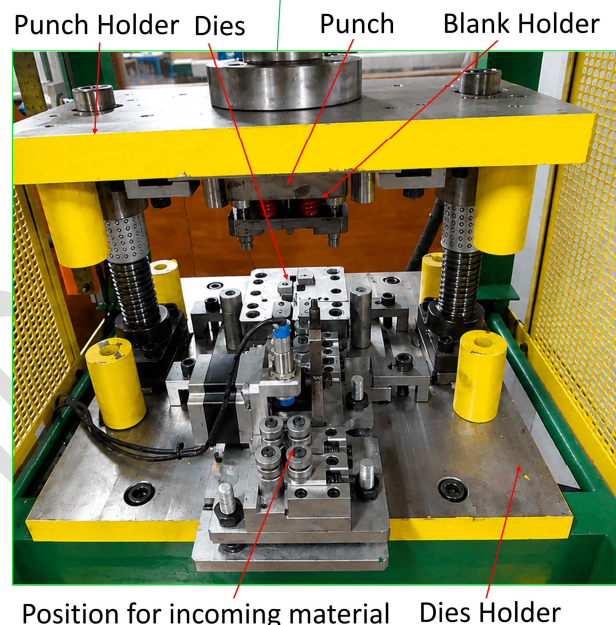


Figure 3. Progressive punching machine

Radius cross-sections, as shown in Figure 5. The distance between each measurement point was 50 μm . For each specimen, the hardness values obtained from five measurement points were averaged. Subsequently, the average hardness values from three different specimens were also averaged to obtain the final hardness value. This value was used to evaluate the effect of punch speed on material hardness in the vicinity of the shear zone.

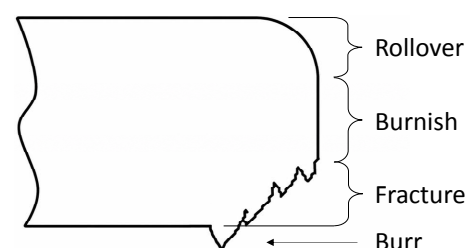


Figure 4. Sheared zone geometry; adapted from Kurniawan et al. [18], licensed under CC BY-NC 4.0

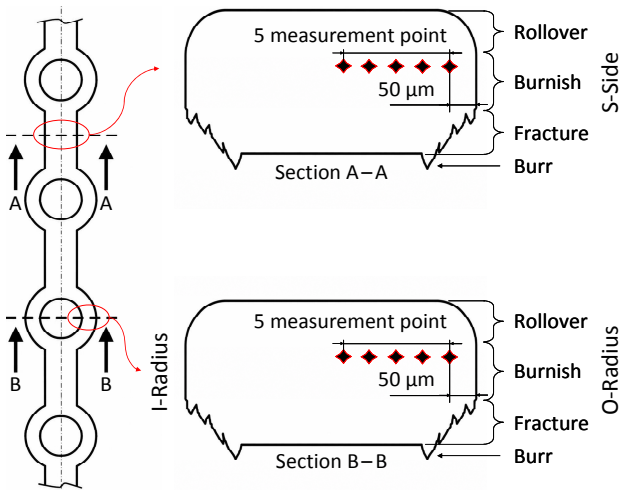


Figure 5. Hardness measurement position near the sheared zone of the straight-plate implant; adapted from Kurniawan et al. [18], licensed under CC BY-NC 4.0

Measurements were made on three different specimens to account for experimental variability and estimate the standard deviation. If the data results show a linear trend and some overlap is noticed between the standard deviation error bars, this overlap indicates considerable variability in the measurements, making it difficult to determine the statistical significance of differences between data groups based solely on visual inspection. Therefore, an analysis of variance (ANOVA) was performed to determine whether the noticed differences between the groups were statistically significant, as described by Okoye and Hosseini [19]. To analyse the measurement data, which include interactions between standard deviations, the present study used ANOVA. The variance test findings are obtained by comparing the probability value (p -value) with 0.05 (α -value) and the square of the mean (F -value) with the square of the mean

critical (F_{crit} -value). Once the p -value is smaller than the α -value and the F_{crit} -value is smaller than the F -value, the data is deemed to have noteworthy variation. On the contrary, the data is deemed to have no noteworthy variation when the F_{crit} -value is higher than the F -value and the p -value is higher than the α -value [18].

3. Results and discussion

3.1 Sheared zone on the straight-plate implant

A progressive punch machine with four punch-speed conditions has successfully manufactured a straight-plate implant, as shown in Figure 6. The sheared zone morphology on the straight-plate implant is shown in Figure 7. The burnished zone height is uneven. The shortest burnish zone is achieved when punching at a punch speed of 5 mm/s. The highest burnish is formed when the punching process uses a punch speed of 16 mm/s. The rollover shape has the opposite phenomenon from burnish. The lowest rollover occurs at a punch speed of 16 mm/s and the highest at 5 mm/s. The rollover on the O-Radius appears higher than on the S-Side. The burnish on the S-Side appears higher than on the O-Radius.

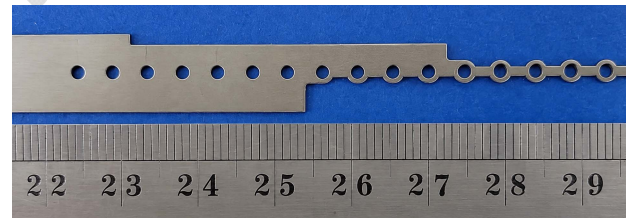


Figure 6. Straight-plate implant produced using progressive punching at a punch speed of 16 mm/s

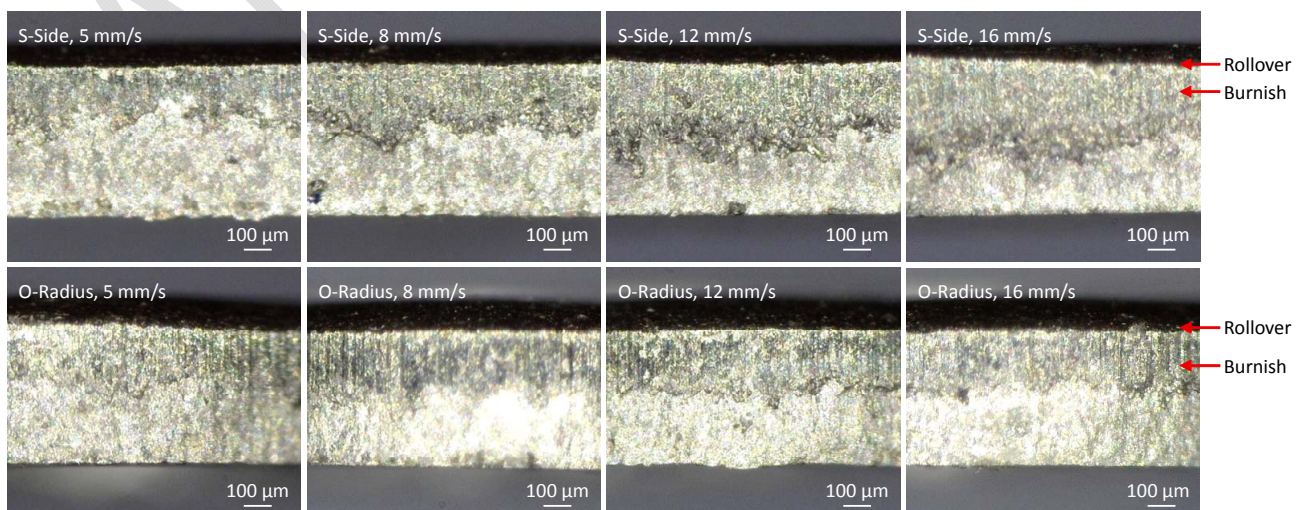


Figure 7. Sheared zone shape with different punch speeds

The impact of punch speed on the sheared zone of the straight-plate implant is depicted in Figure 8. Figure 8a shows that, in the rollover zone, the standard deviation ranges at punch speeds of 5 and 16 mm/s on the S-Side overlap with the ranges at 8 and 12 mm/s. At the O-radius, the standard deviation range for a punch speed of 5 mm/s overlaps with that of 8 mm/s, the range for 8 mm/s overlaps with that of 12 mm/s and the range for 12 mm/s overlaps with that of 16 mm/s. This indicates that the differences in rollover height across these punch speeds cannot be clearly distinguished. Consequently, there is insufficient evidence to conclude that rollover height decreases as punch speed increases. In the burnish zone (Fig. 8b), overlaps in standard deviation ranges occur between punch speeds of 5 and 8 mm/s and between 8 and 12 mm/s. This pattern is observed at the O-radius. This indicates that differences in burnish height between punch speeds with overlapping standard deviation ranges cannot be clearly distinguished. Therefore, an ANOVA test is required to evaluate the significance of the data differences.

Table 1 presents the ANOVA results for the rollover and burnish zones. The p-value is smaller than the α -value and the F_{crit} -value is smaller than the F-value for both the cut edge and punch speed. This situation occurs in the rollover and burnish zones. This finding implies significant variation in rollover and burnish heights across punch speeds and cut edges. Therefore, it can be concluded that rollover height for the S-Side is lower than that for the O-Radius. Meanwhile, the burnish zone for the S-Side is higher than that for the O-Radius. The rollover and burnish increase with increasing punch speed. A small increase in material elongation that happens when the punch and material collide could be the cause of this phenomenon of enhanced rollover and burnish heights. The possibility of an inelastic collision converts some of the kinetic energy into thermal energy, in accordance with conservation of momentum and energy [20]. Furthermore,

based on the cutting steps of the punching process [12], the punch continues to move downward after the burnish is created until the burr is released. In the burnished area, the punch movement generates heat and friction. This heat and friction may have contributed to the burnished height. This is in line with a previous study [9] which found that high punch speeds result in higher burnish heights.

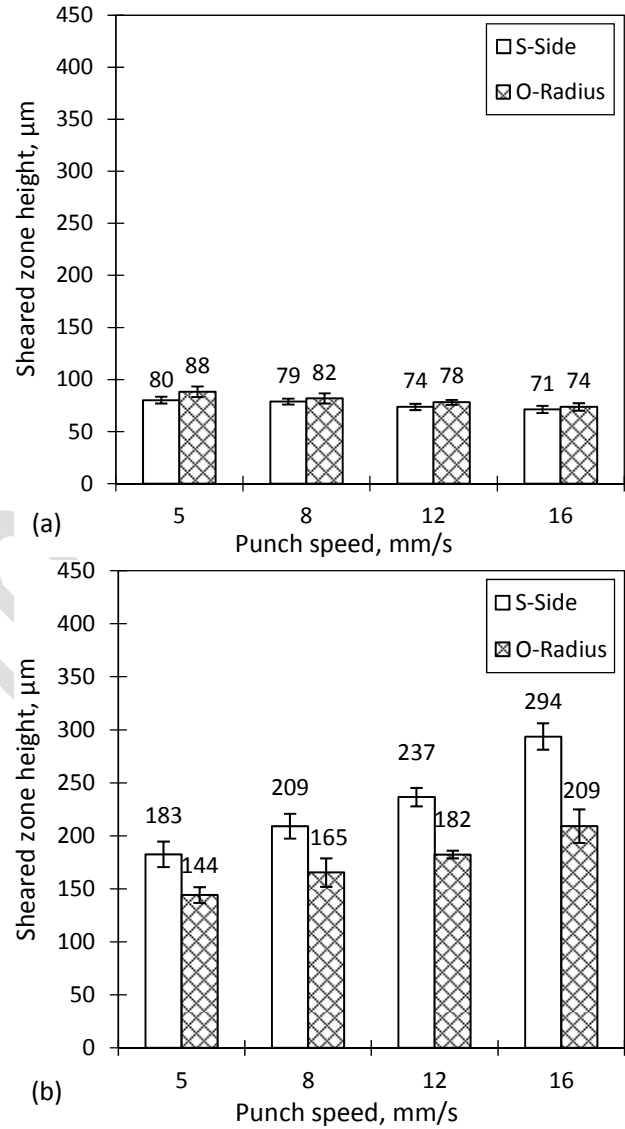


Figure 8. Effect of punch speed on the height of the sheared zone: (a) rollover and (b) burnish

Table 1. ANOVA test results for sheared zone height with the punch speed variations

Source of variation	Sums of squares	Degrees of freedom	Mean square	F-value	p-value	F_{crit} -value	Significance
Rollover zone							
Cut edge	198	1	198	14.721	0.001	4.149	yes
Punch speed	781	3	260	19.319	0.000	2.901	yes
Burnish zone							
Cut edge	30,581	1	30,581	243.896	0.000	4.149	yes
Punch speed	41,959	3	13,986	111.548	0.000	2.901	yes

The burnish zone for the S-Side is longer than that for the O-Radius because of differences in grain movement during the forging process of the B-shape punching, as seen in Figure 9. On the O-Radius, where grain movement occurs in both directions, the S-Side only has one direction. According to earlier research, sheet grain movement in both directions within the deformation zone has a lower compressive stress than one-directional grain movement [12]. This tiny compressive stress raises the burnish height by delaying the fracture set and increasing rollover height. As a result, the burnish zone on the S-Side is longer than that of the O-Radius and the rollover height on the S-Side is shorter. On the O-Radius, the rollover heights were approximately 88, 82, 78 and 74 μm at punch speeds of 5, 8, 12 and 16 mm/s, respectively. Meanwhile, the resulting burnish heights were approximately 144, 165, 182 and 209 μm at the same punch speed. On the S-Side, the rollover heights were approximately 80, 79, 74 and 71 μm at punch speeds of 5, 8, 12 and 16 mm/s, respectively. Meanwhile, the burnish heights at the same punch speeds were approximately 183, 209, 237 and 294 μm . These results exceed those reported in previous research [18], underscoring the importance of the present study and its potential impact on the field.

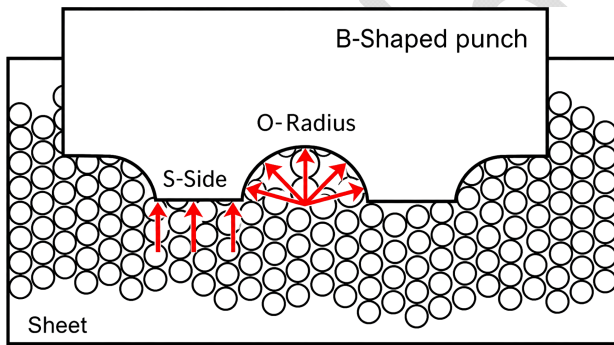


Figure 9. Direction of grain movement during a B-shaped punching operation (red arrows show grain movement); adapted from Kurniawan et al. [18], licensed under CC BY-NC 4.0

3.2 Surface roughness of sheared zone on the straight-plate implant

The surface roughness measurement results in the sheared zone are shown in Figure 10. The surface roughness levels obtained with punch speeds of 5 (Fig. 10a), 8 (Fig. 10b), 12 (Fig. 10c) and 16 mm/s (Fig. 10d) follow the same trend. Figure 10 also shows the overlap of standard deviations. The O-Radius and S-Side exhibit the same phenomenon. In addition, Figure 10a shows the

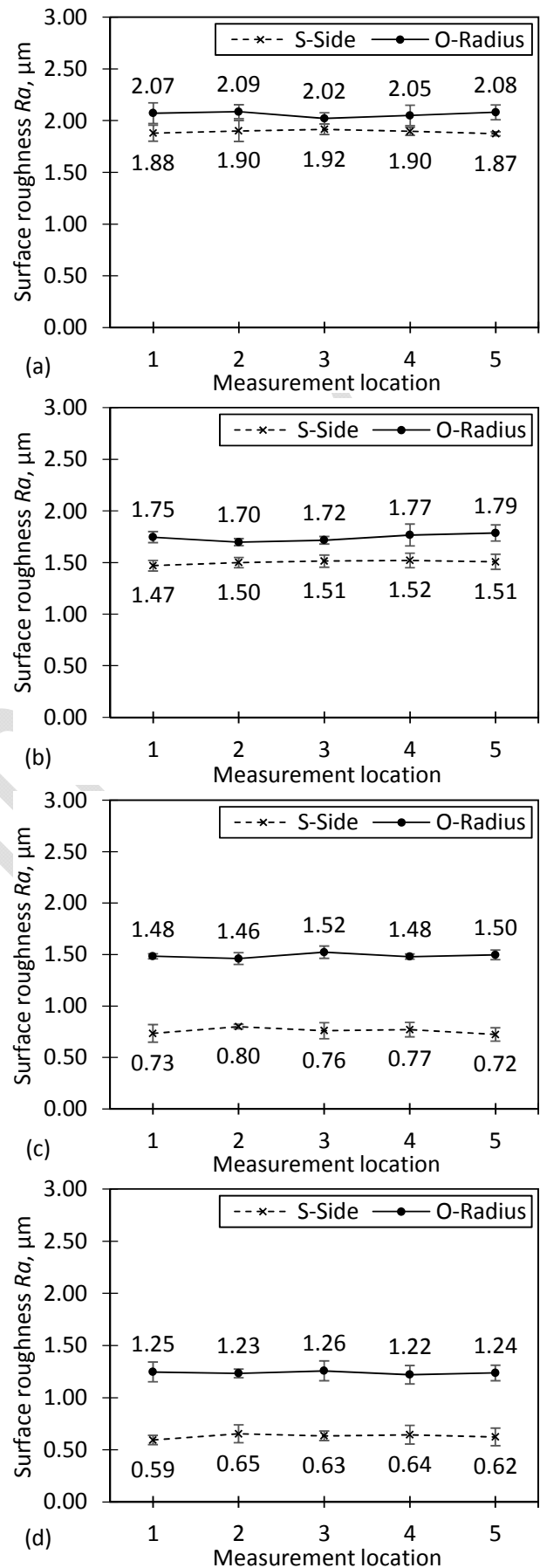


Figure 10. Surface roughness value of the sheared zone with the punch speed of: (a) 5 mm/s, (b) 8 mm/s, (c) 12 mm/s and (d) 16 mm/s

overlap of standard deviation between O-Radius and S-Side at measurement locations 1, 3 and 4. This situation indicates ambiguity regarding the significant variation in the surface roughness data. However, a clear trend is visible, and it is worth noting the significance of the differences in the data. Thus, an ANOVA test was applied to examine the ambiguity of data variance across measurement locations and sheared zones.

A summary of the ANOVA test findings is displayed in Table 2. The table indicates that the F_{crit} -value is higher than the F-value and the p-value is higher than the α -value at each measurement location. This occurs at punch speeds of 5, 8, 12 and 16 mm/s. This finding indicates a negligible variation in the surface roughness data. Thus, the data indicate that the surface roughness is uniform across all measurement locations. This means that the surface roughness produced during the 1st to 5th punching processes is the same. In other words, progressive punching can produce consistent surface roughness at the O-Radius and S-Side. Table 2 also indicates that the F_{crit} -value is smaller than the F-value and the p-value is smaller than the α -value in the sheared zone. This occurs at 5, 8, 12 and 16 mm/s. This finding indicates significant variation in the surface roughness data at the O-Radius with respect to the S-Side. Thus, this data indicates that the surface roughness is not uniform in the shear zone. In other words, progressive punching can produce a surface roughness on the S-side that is smaller than that at the O-Radius. This occurs because the punch-die contact during S-Side cutting is more uniform. This results in a

more stable distribution of cutting stress. As a result, the burnish zone is more dominantly formed in the sheared zone, and the burnish tends to be flatter and longer. Meanwhile, the punch-die contact during O-Radius cutting is uneven. This causes an uneven distribution of stress, making the material more susceptible to microtears. As a result, the fracture zone is more dominantly formed in the sheared zone, and the fracture tends to be more uneven and longer. The phenomenon of punch-die contact stress, as reported by previous researchers using the finite element method [21], shows that the average stress on the punch during radius-edge cutting is higher than during straight-edge cutting. A high average stress will result in a long fracture zone in the sheared zone. A long fracture zone will make the sheared surface rougher. Therefore, the surface roughness on the O-radius is rougher than the S-Side. The average surface roughness produced on the S-Side was approximately 1.89, 1.50, 0.76 and 0.63 μm at punch speeds of 5, 8, 12 and 16, respectively. Meanwhile, the average surface roughness produced on the O-Radius was approximately 2.06, 1.74, 1.49 and 1.24 μm at the same punch speed variations. These results show the same phenomenon as in previous research [18].

The effect of punch speed on surface roughness of the sheared zone is presented in Figure 11. Figure 11 shows that the standard deviations do not overlap between different punch speeds and between S-Side and O-Radius cuts. This indicates a significant difference in the data. These results indicate that the average surface roughness decreases with increasing punch speed. This

Table 2. ANOVA test results for surface roughness of the sheared zone with the punch speed variations

Source of variation	Sums of squares	Degrees of freedom	Mean square	F-value	p-value	F_{crit} -value	Significance
Punch speed of 5 mm/s							
Sheared zone	0.214	1	0.214	27.105	0.000	4.351	yes
Measurement location	0.002	4	0.001	0.064	0.992	2.866	no
Punch speed of 8 mm/s							
Sheared zone	0.433	1	0.433	69.175	0.000	4.351	yes
Measurement location	0.011	4	0.003	0.448	0.773	2.866	no
Punch speed of 12 mm/s							
Sheared zone	4.014	1	4.014	800.252	0.000	4.351	yes
Measurement location	0.005	4	0.001	0.237	0.914	2.866	no
Punch speed of 16 mm/s							
Sheared zone	2.785	1	2.785	313.587	0.000	4.351	yes
Measurement location	0.003	4	0.001	0.072	0.990	2.866	no

phenomenon occurs in S-Side and O-Radius cutting. The decrease in surface roughness is caused by an increase in punch speed, which can lengthen the burnish zone. This is due to increased material elongation when the punch collides with the material. A portion of the kinetic energy is converted into heat during an inelastic collision [22]. In addition, during the punching process after burnishing, the punch continues to move downward until the burr is released [5]. The movement of the two parts in contact causes friction and generates heat at the contact surface [23]. According to earlier studies [12], the punch's action therefore creates friction and heat in the burnished area. This heat and friction can increase the height and smooth the burnished surface. As a result, when punch speed is higher, surface roughness is lower. The highest average surface roughness in O-Radius cutting is around $2.06\ \mu\text{m}$ with a punch speed of $5\ \text{mm/s}$, and the lowest surface roughness is $1.24\ \mu\text{m}$ with a punch speed of $16\ \text{mm/s}$. On the SS-Side, the highest average surface roughness is approximately $1.89\ \mu\text{m}$ at a punch speed of $5\ \text{mm/s}$, and the lowest surface roughness is $0.63\ \mu\text{m}$ with a punch speed of $16\ \text{mm/s}$. These results are lower than the average surface roughness reported in previous research [18].

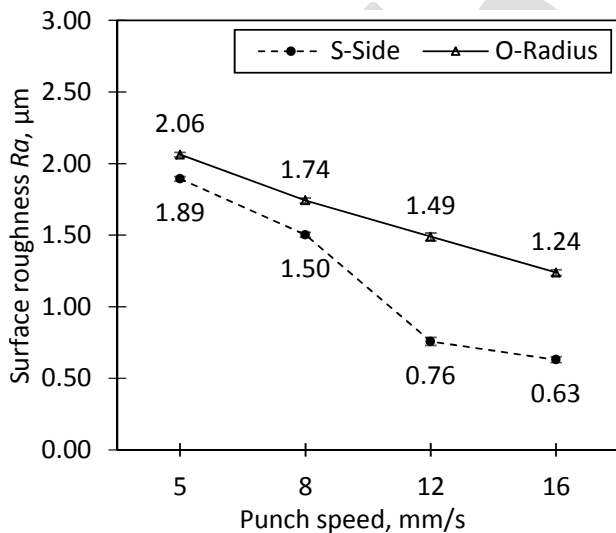


Figure 11. Punch speed effect on surface roughness of the sheared zone

3.3 Hardness near the sheared zone on the straight-plate implant

The punch speed effect on hardness near the sheared zone is displayed in Figure 12. Figure 12 shows that the standard deviation values for the O-Radius do not overlap for punch speeds of 5, 8, 12 and $16\ \text{mm/s}$. This phenomenon also occurs at

the S-Side. However, the standard deviation value for O-Radius overlaps with the standard deviation value for S-Side. This condition occurs at speeds of 5, 8 and $16\ \text{mm/s}$. Overlapping standard deviations are marked with red circles. This indicates uncertainty regarding the significance of the difference in hardness data when standard deviation values overlap. Data uncertainty was analysed using ANOVA.

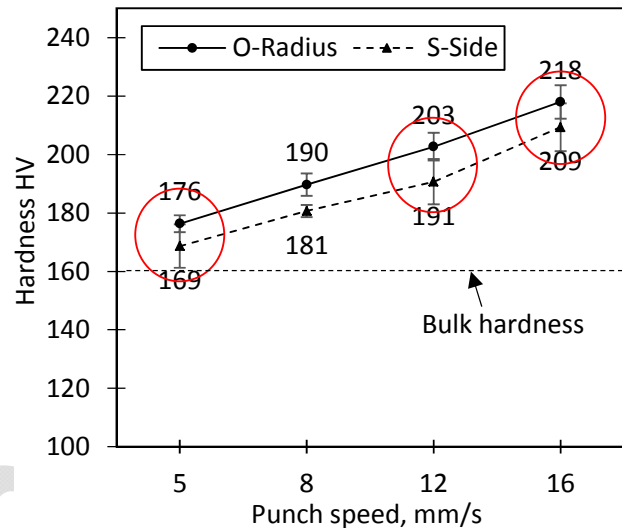


Figure 12. Punch speed effect on hardness near the sheared zone

The results of the ANOVA test are presented in Table 3. The table shows that the F_{crit} -value is smaller than the F-value and that the p-value is smaller than the α -value for both the sheared zone and punch speed. It indicates significant differences in the hardness data, even though the standard deviations overlaps. It can be concluded that the average hardness near the S-Side is lower than that near the O-Radius. In addition, it can be concluded that the average hardness near the sheared zone increases with increasing punch speed.

The hardness near the S-Side and O-Radius exceeds the bulk hardness due to work hardening. It occurs after the ductile material undergoes plastic deformation [24]. Through micropiercing, plastic deformation is introduced into the machining process sequence, just as in the cutting of materials [25]. Consequently, during the cutting and piercing of titanium-based materials, work hardening can occur after plastic deformation [26]. The increase in hardness and strength of ductile materials indicates the work hardening effect [27]. This phenomenon is similar to the punching process for C-shaped holes [12], as reported in previous studies.

Table 3. ANOVA test results for hardness near the sheared zone

Source of variation	Sums of squares	Degrees of freedom	Mean square	F-value	p-value	F _{crit} -value	Significance
Sheared zone	522.667	1	522.667	10.523	0.005	4.494	yes
Punch speed	5509.000	3	1836.333	36.973	0.000	3.239	yes

The hardening on the S-Side is lower than the O-Radius because of variations in particle movement throughout the forging operation, as demonstrated in Figure 9. As a result, the plastic deformation on either side can also differ. More plastic deformation occurs when grain movement occurs in both directions rather than in only one. Previous studies have reported that higher hardness values result from greater plastic deformation [12]. Work hardening increases with punch speed because the flow stress rises. This is due to the increased strain rate. Based on dynamic stress modelling (Johnson-Cook model) [28], the flow stress is directly proportional to the strain rate. This can be interpreted as the greater the strain rate, the greater the flow stress. As a result, the work hardening that occurs is greater.

Furthermore, the development of the burnish zone is closely linked to the localised plastic deformation occurring during the initial stage of the punching process. As the punch penetrates the titanium sheet, intense plastic shear deformation takes place around the cutting edge, leading to strain accumulation and localised work hardening. This localised plastic deformation plays a crucial role in determining the hardness distribution near the titanium cut surface. During punch penetration, high stress concentrations around the cutting edge cause the material to undergo plastic deformation before cracks initiate and propagate. Such deformation increases dislocation density and induces strain hardening, thereby raising local hardness, particularly in the region adjacent to the cut surface. As the distance from the cutting edge increases, the degree of plastic deformation diminishes. Consequently, the work hardening effect subsides and the hardness tends to revert toward the bulk hardness value. Thus, the hardness distribution indicates the extent and depth of plastic deformation during the formation of the burnish zone. Variations in punch speed can influence the strain rate, deformation localisation and the timing of crack initiation, thereby resulting in differences in the degree of work hardening and the noticed hardness trends. The hardness near the S-Side cut edge is 169, 181, 191 and 209 HV

when using punch speeds of 5, 8, 12 and 16 mm/s, respectively. The hardness near the O-Radius cut edge is 176, 190, 203 and 218 HV with the same punch speed variations. With punch speeds of 5 and 8 mm/s, work hardening was smaller than in previous research [18].

The primary limitations of the present study include the restriction of the investigation to the analysis of the cut surface profile, surface roughness and hardness. Furthermore, the study was limited to a specific B-shaped punch and did not examine circular holes. Testing was conducted on titanium material. Punch speeds were limited to 5, 8, 12 and 16 mm/s, with a punch-die clearance of 60 µm. Consequently, the findings must be interpreted within these constraints and cannot be directly generalised to different conditions without further validation. Regarding implementation, the results are expected to apply to conditions relatively similar to those in the present study, specifically, hole geometry, punch speed and the test material. Variations in these conditions could influence the effectiveness and outcomes of the study's application. In principle, the results of the present study are reproducible provided that the methodology, research design, data collection procedures, parameters and analysis methods described are consistently followed. To facilitate reproducibility, methodological stages and key parameters employed in the research have been clearly outlined. Researchers or practitioners wishing to apply these findings should pay particular attention to the hole shape, punch-die clearance, punch speed and the type of test material.

4. Conclusions

The effect of punch speed on the progressive punching process was evaluated based on the surface quality of straight-plate implants. The study showed that increasing the punch speed from 5 to 16 mm/s reduced rollover and surface roughness while increasing the burnish zone and hardness in the shear zone. At a punch speed of 16 mm/s, the highest burnish height values (209 µm at the O-Radius and 293 µm at the S-Side), the

lowest roughness values (1.24 and 0.63 μm), and the highest hardness values (218 and 209 HV) were achieved. Based on optimisation results, a progressive punching process combining a 60 μm clearance and a punch speed of 12 mm/s was deemed suitable for producing high-quality implants.

Optimising the combination of punch shape, punch speed and clearance to increase burnish height using the Taguchi method represents a promising area for future research. Furthermore, the corrosion resistance, flexural strength of straight-plate implants and punch force require further investigation to understand better how punching parameters influence deformation and cutting mechanisms.

Acknowledgement

The researcher would like to thank the Faculty of Engineering at Pancasila University for its support in this research on the manufacture of straight-plate implants with a progressive punching machine.

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