



Micro-Progressive Punching (μ PP): A New Method for Manufacturing Micro-Plate Implant

Yani Kurniawan^{1,2*}, Dede Lia Zariatini^{1,2}, Dhatu Allegra Tsumu¹, Bambang Sulaksono¹

¹Department of Mechanical Engineering, Faculty of Engineering, Pancasila University, Jakarta, Indonesia

²Green Product and Process Studies, Faculty of Engineering, Pancasila University, Jakarta, Indonesia

*Correspondence email: yani.kurniawan@univpancasila.ac.id

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Abstract: Manufacturing of micro-plate implants using die-sinking EDM requires a processing time of about 5 hours, and there is a decrease in hardness below the raw material. To speed up the manufacturing time and prevent a decrease in material hardness, a new method is needed to manufacture micro-plate implants. This study introduces the micro-progressive punching (μ PP) method to manufacture micro-plate implants. In addition, the quality of micro-plate implants such as the shape of the cutting surface and hardness produced using the μ PP method were also investigated. The investigation results show that the μ PP successfully made micro-plate implants with a processing time of about 10 minutes. The shape of the cutting surface has an average relatively short burr height of about 24 μ m. The Hardness of the resulting micro-plate implants increased near the cutting surface with an average of about 10% of the raw material. These findings show that μ PP can be employed as a substitute method for producing micro-plate implants.

Keywords: micro-plate; implants; μ PP; cutting; hardness



SDGs Problem Solving

Research and problem-solving in this study align with SDGs Chapter #9 by introducing an innovative micro-progressive punching method that improves manufacturing efficiency, reduces processing time, and enhances product quality. This technological advancement supports sustainable industrial innovation and strengthens resilient, cost-effective medical manufacturing systems.

Conflict of Interest Statement: The author(s) declares that the research was conducted in the absence of any commercial or financial relationship that could be construed as a potential conflict of interest.

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1. INTRODUCTION

Micro-plate implants are facial implants and function to connect cracked or broken jaw bones. Micro-plate implants have been made using die-sinking EDM (Kurniawan *et al.*, 2022). The manufacture of micro-plate implants using die-sinking EDM has several problems, such as relatively long processing time (Kurniawan *et al.*, 2024), decreased material hardness (Kurniawan *et al.*, 2023), and short tool life. In addition, the EDM die-sinking process produces a white layer on the cutting surface (Kumar, Kumar and Kumar, 2013). Although this layer can increase resistance to abrasion and erosion, it also contains flaws like holes, cracks, or induced stresses that harm the mechanical qualities of components (Lee and Tai, 2003; Yan, Tsai and Huang, 2005). Particularly when subjected to tensile strain (Kumar and Dhingra, 2018), surface crack flaws can lessen the materials resilience to fatigue and corrosion (Muthuramalingam, Mohan and Jothilingam, 2014). This condition shows that the micro-plate implants fabricated by the die-sinking EDM still require additional processes to increase the hardness and resistance to corrosion and fatigue. The additional processes carried out will cause additional costs in the manufacture of micro-plate implants. This will affect the high price of micro-plate implants. The forming process is another way to solve this issue. It offers many benefits, including good surface finish, excellent precision, and good effectiveness with large quantities (Groover, 2010). The forming technique has been used to produce sheet metal parts for vehicles, electronics, and medical equipment (Vollertsen, Schulze Niehoff and Hu, 2006). There are multiple steps involved in the forming process, including blanking (Zheng, Zhuang and Zhao, 2019), drawing (Tiwari, Rathore and Bodkhe, 2022), and punching (Latorre, Casellas and Costa, 2023). The punching process has been researched and developed with titanium.

Mahardika *et al.* (Mahardika *et al.*, 2024) have investigated the non-symmetric punching process parameters on pure titanium material with C-shaped holes. The investigation found that punch force improved as punch velocity increased. Compared to the straight side, the burnish height was 0.038 mm greater on the radius side. The burnish increased with increasing punch speed. The work hardening on the straight side was around 15% less compared to the radius side. Kurniawan *et al.* (Kurniawan *et al.*, 2019) have investigated the heating effect on the circular punching process. A pneumatic punch machine has been utilized as the equipment for testing. The findings indicate that striking cold while preheating can lower punch power, increase burnish height, and lessen work hardening. The punch force has a 17.8% decrease at a 150 °C preheating temperature with a 35 mm/s velocity as compared to without preheating. However, the height on burnish has increased by about 41.6%. Hardening has lowered by 27% in the punching process with preheating. The impact of punch shape on the punching process has been explored by Kurniawan *et al.* (Kurniawan, Mahardika and Suyitno, 2020) on titanium sheets. According to the findings, punching with SSA and DSA punch geometries at a 35 mm/s punch velocity lowers the punch force by 18% and 13%, respectively, as compared to FLAT at the same velocity. Despite this, there appears to be a decrease in the sheared surface quality with an increase of roughly 48% and 32% in rollover height. Additionally, the work hardening that results improves by 4.7% and 2.3%, respectively, as the burnish height drops by 34% and 7%. The study comes to the conclusion that while SSA and DSA punch geometries seem to be ineffective in improving the sheared surface quality, they are effective in lowering punch force and boosting work hardening. Kurniawan *et al.* (Kurniawan, Mahardika, and Suyitno, 2020) have also examined the punch velocity effect on circular punching. A pneumatically

driven punch machine with a speed of 10, 35, and 70 mm/s was utilized for the punching operation. The outcome demonstrates that for each of the speed values of 35 and 70 mm/s, there was an increase in punch force of 51 and 77 N as compared with a 10 mm/s punch speed. In addition, burnish height also increased by 0.006 and 0.047 μm , respectively. It suggests that punch speed affected the burnish height and punch force. Burnish height and punch power increase with improving punch speed.

Guo and Tam ([Guo and Tam, 2014](#)) have studied the tool wear effect on the shape of micro-holes. The experimental results show that the micropunch experienced a unique wear loss during the initial micropunching phase, which was associated with a loss in cobalt (Co), according to the results. There was some debris on the hole's surface when the diameter of the punched microholes was adjusted appropriately. Subsequently, the punch had a phase of quasistability, characterized by minimal wear loss and relatively steady punched hole diameters. The micro punch wear rate significantly increased as the punch count surpassed approximately 1500. Both Co and tungsten carbide (WC) losses were the cause of the wear loss. The diameter of the micro holes changed in proportion to the large bulk debris that was adhered to the punched hole. Punch wear, debris attachment, and hole diameter reduction were all more pronounced with an increase in punch number. Back then, WC was mostly the dominant. Using orbital spinning and plain sand grains, Guo and Tam ([Guo and Tam, 2012](#)) examined the impact of processing duration on the completion of micro-hole punching. The explored hole has a round form. For the purpose of completing the microholes created by punching, planetary stirring was suggested. The abrasive was made of natural sand. In a basin, the foil specimen was submerged in abrasive grains. Both orbital and rotational movement were applied to the bowl. In order to shield the specimen from harm from collisions with the bowl, no fastening was needed. Sand grains were able to finish various areas of the hole, including the inner wall, due to planetary stirring. It was shown that micro holes may be finished effectively. The inner wall and its surrounding debris were removed. The burrs surrounding the edges were essentially removed. Large foil pieces that were extracted by the punch were frequently adhered to the hole's edge. These pieces had significant erosion. The fresh grains with their sharp cutting edges and rather loose packing initially had a fast completion rate. As time went on and the packing became more constricted, the rate decreased. Using natural sand to finish micro-holes. Mostly in the periphery, accumulation first began. Afterwards, the inside wall revealed its location. At last, sand granules the size of microns filled the aperture. Most of the finishing in the present setup was completed in the first ten to twenty minutes. It took around thirty minutes to process the micro holes enough. Carbon nanotubes (CNTs) have been studied by Guo and Tam ([Guo and Tam, 2012](#)) in relation to extending the tool's lifetime of WC/Co micropunches. A portion of the micropunches were developed with CNTs. Micropunches both containing and excluding carbon nanotubes (CNTs) were used to punch Ti specimens. Confocal microscopy, microscopy with scanning electrons, digital balancing, and other techniques were used to quantify the wear loss, surface roughness, and hole sizes of the micropunches. The findings indicated that following the run-in phase, a protective layer formed with CNTs. The micropunch's useful life might be increased by up to 35% by the protective coating without influencing the diameter of the punched holes.

Some existing literature shows that the punching processes have been investigated for making hole variety, such as circular and non-symmetric. The punching process has been successful in making

holes with sizes ranging from micrometers to millimeters. This indicates that the punching process has the potential to be used to make micro-plate implants. The punching method on titanium strips has been examined by producing circular and C-shaped holes. This is still limited to making one hole (single punch). Making B-shaped holes with multiple holes (progressive punch) has not been investigated. In addition, the investigations that have been carried out focus on punch force, cutting surface, hardness, and tool wear, while the level of burnish and fracture surface roughness has not been investigated. The purpose of this work is to analyze the suitability of the μ PP process for producing micro-plate implants. The hole shapes investigated are circular and B-shape with multiple holes. The quality of micro-plate implants such as the shape of the cut surface, and hardness are also studied.

2. METHODOLOGY

Pure titanium from Nilaco, Ltd. Japan with dimensions of 300 x 10 x 0.6 mm and Hardness of 160 VHN was used for the micro-plate implant material. The microplate implant has three geometric, namely an inside radius (IR), an outside radius (OR), and a straight side (SS), as demonstrated in Figure 1. The manufacturing process of micro-plate implant used a hydraulically driven progressive punch with a capacity of 10 tons as shown in Figure 2.

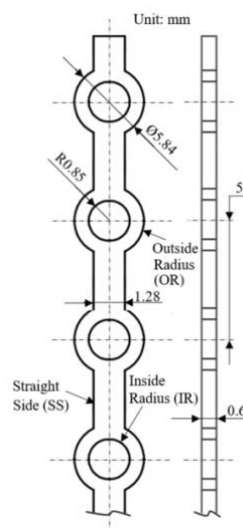


Figure 1. Dimension of microplate implant

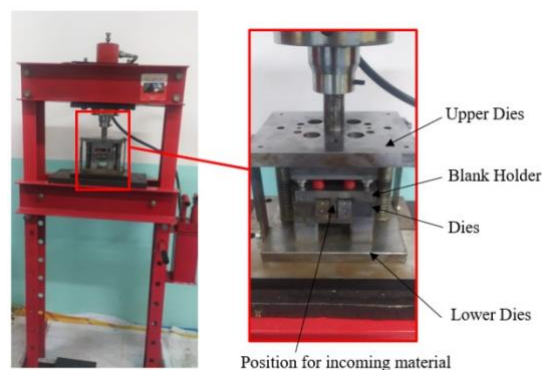


Figure 2. μ PP machine

The progressive punch used 5 punches in sequence as shown in Figure 3. The punch and dies materials used SKD 11 with hardening. The punch and dies were made by wire EDM. The clearance of punches and dies used 20 μm . The cutting surfaces were observed and gauged using a digital microscope (Dino-lite AM4815 Series, Taiwan). The cutting surfaces were observed at the circular and B-shaped holes as shown in Figure 4. The circular holes were observed at the IR. The B-shaped holes were observed at the SS and OR.

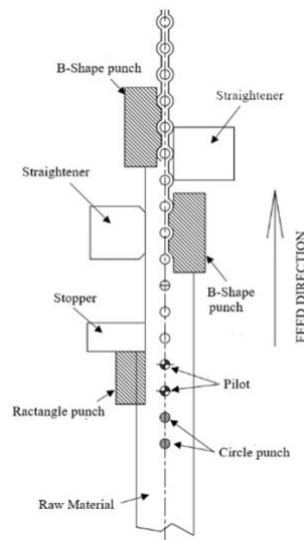


Figure 3. Schematic of μPP process

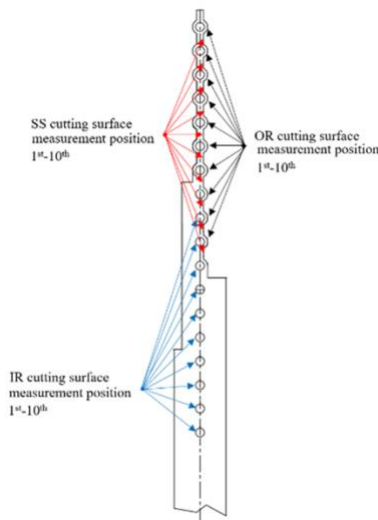


Figure 4. Cutting surface measurement and observation position

Vickers micro hardness tester (Future-tech FM-310, Japan) was used to measure the hardness of the micro-plate implant. A 100-gram load and 10-s loading duration were used for hardness measurement at room temperature based on ref. (Mahardika *et al.*, 2024). Hardness measurements were conducted on three cross-sections of the cutting side surface, namely IR, SS, and OR as shown in Figure 5. The microstructure was observed to study the phenomenon of increasing hardness. The microstructure was observed using a metallographic microscope (Olympus, Japan). Analysis of variance (ANOVA) was used in statistical analysis to assist with the quantitative data analysis from

this investigation. By identifying significant factors or their interactions, ANOVA can determine each factors contribution (Dugard, Todman and Staines, 2010; Okoye and Hosseini, 2024; Pratama *et al.*, 2024).

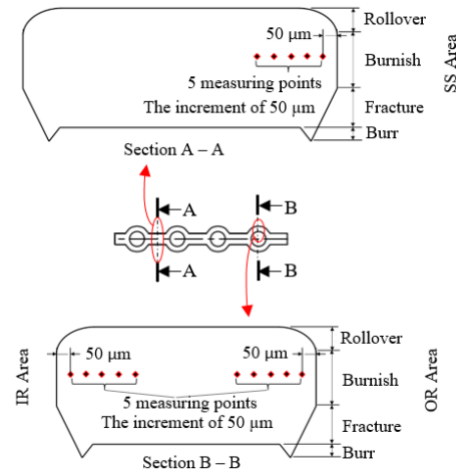


Figure 5. Hardness measuring location on microplate implants

3. RESULTS AND DISCUSSION

3.1. Cutting Surface of the Implant Micro-Plate

Micro-plate implants were successfully fabricated using a μ PP machine. Figure 6 shows the micro-plate implants produced by the μ PP machine. The cutting edges produced on the circle holes (red circle marks) look sharper than the edges of the B-Shape holes (red pentagons and hexagons marks). The edges of the B-shape holes look sharper on the SS (red pentagons marks) compared to the edges on the OR (red hexagons marks). The form of the cutting edge will affect the shape and cutting surface. The shape of the cutting surface on the micro-plate implant is shown in Figure 7. Figure 7 shows that the rollover formed on IR is higher than on SS and OR. This is in line with the cutting edge formed, where a sharp cutting edge will form a shorter rollover than a blunt cutting edge. The burnish surface formed on IR is higher than on SS and OR. The fracture surface on IR looks higher than on SS and OR. However, the burr formed on IR looks shorter than on SS and OR.

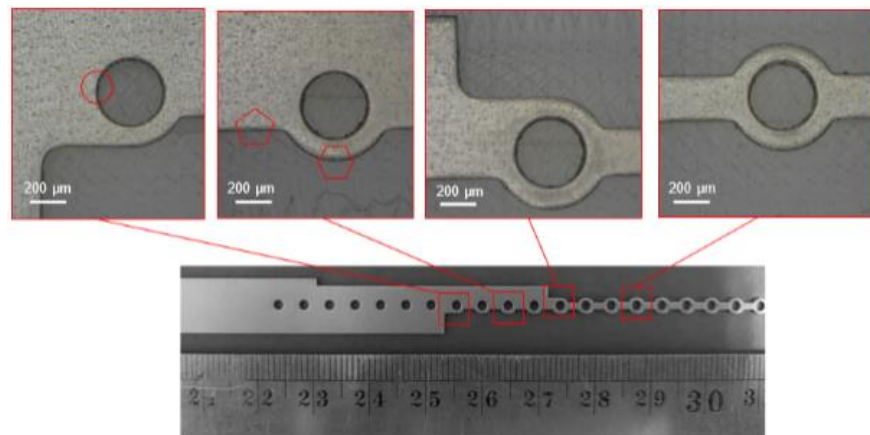


Figure 6. Micro-plate implant produced using a μ PP machine

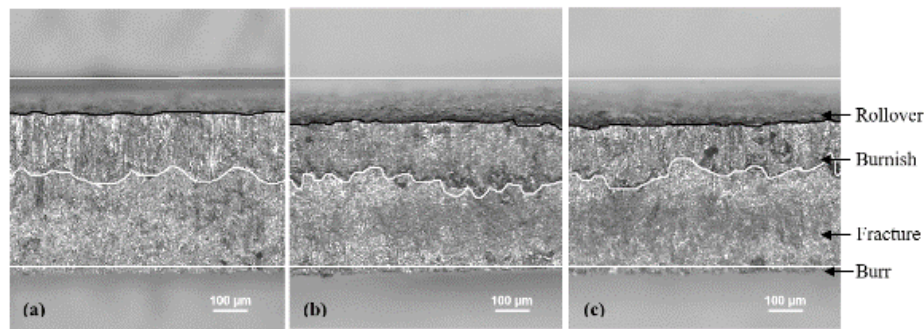


Figure 7. Shape of cutting surfaces on: (a) IR; (b) SS; and (c) OR micro-plate implants

The shape of the cutting surface on IR, SS and OR is demonstrated in Figure 8. On the IR (Figure 8a), SS (Figure 8b), and OR (Figure 8c) cutting surfaces present that the rollover, burnish, fracture, and burr appear to fluctuate. However, the standard deviation (STDEV) at each measurement position intersects when a horizontal line is drawn. In addition, STDEV on burnish also intersects with fracture when a horizontal line is drawn. This indicates that there is no certainty of significant data differences at each measurement position. This also occurs between burnish and fracture. The uncertainty of surface height at each measurement position was analyzed using the ANOVA test.

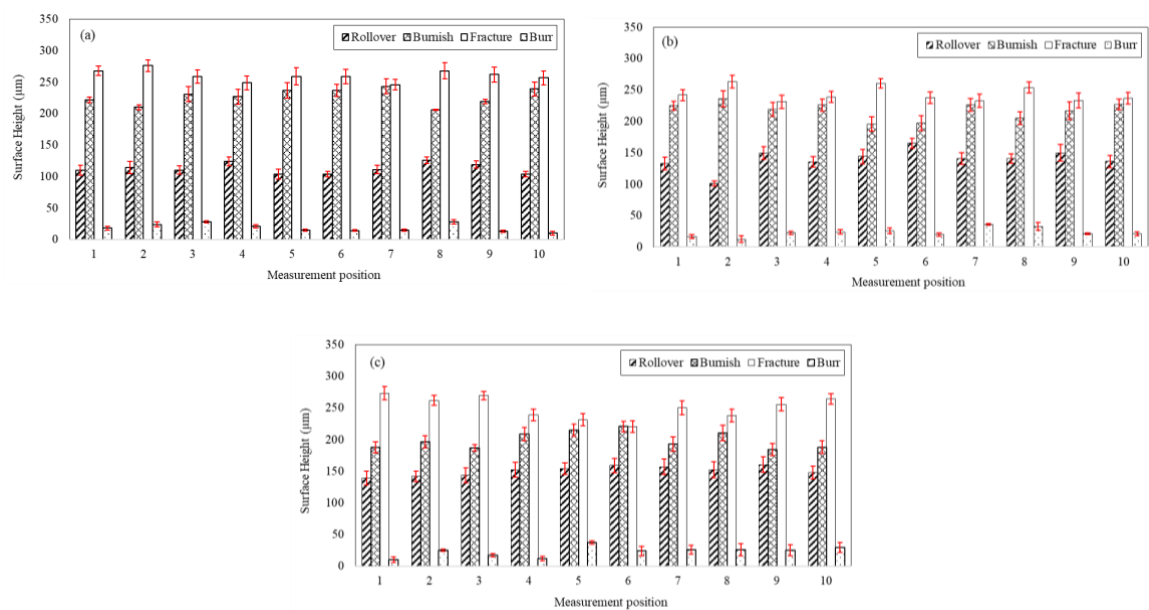


Figure 8. Cutting surface heights on: (a) IR; (b) SS; and (c) OR micro-plate implants

The findings of the ANOVA test for surface height are displayed in Table 1 (for IR), Table 2 (for SS), and Table 3 (for OR). The three Tables show that the mean square ratio (F) is greater compared to the mean square critical ratio (F-critical), and the probability value (P-value) is lower than 0.05 on surface height. This indicates that the results of the surface height in burnish and fracture have significant data differences. As a result, it can be stated that surface height in burnish is higher than fracture. The three Tables also demonstrate that F is lower compared to F-critical on measurement position, and the P-value is larger than 0.05. This indicates that the surface height at each measurement position does not have a significant data difference.

Table 1. ANOVA test results for surface height on IR

Source of Variation	SOS	dof	MS	F	P-value	F-critical	Significance
Surface height	1098871	3	366290	3828.153	0.000	2.719	Yes
Measurement position	262	9	29	0.304	0.971	1.999	No
Error	7655	80	96				
Total	1115736	119					

SOS, sum of squares; dof, degrees of freedom; MS, mean square

Table 2. Results of the surface height ANOVA test on SS

Source of Variation	SOS	dof	MS	F	P-value	F-critical	Significance
Surface height	887041	3	295680	2540.139	0.000	2.719	Yes
Measurement position	547	9	61	0.522	0.854	1.999	No
Error	9312	80	116				
Total	913192.5	119					

SOS, sum of squares; dof, degrees of freedom; MS, mean square

Table 3. Results of the ANOVA test for surface height on OR

Source of Variation	SOS	dof	MS	F	P-value	F-critical	Significance
Surface height	910557	3	303519	2366.901	0.000	2.719	Yes
Measurement position	1806	9	201	1.565	0.140	1.999	No
Error	10259	80	128				
Total	933894.9	119					

SOS, sum of squares; dof, degrees of freedom; MS, mean square

As a result, it can be stated that the surface height of rollover, burnish, fracture, and burr at each measurement position is the same. The fracture formed is the highest compared to rollover, burnish, and burr on the three cutting surfaces. On IR, the average heights of rollover, burnish, fracture, and burr formed are 113, 229, 259, and 20 μ m, respectively. On SS, the highest average surface heights in sequence are fracture, burnish, rollover, and burr. The average heights on each surface are 243, 227, 139, and 23 μ m. On OR, the order of the shortest average heights is burr, rollover, burnish, and fracture. The average heights on each surface are 24, 151, 199, and 250 μ m. The rollover height on the OR surface is 8% higher than SS and 34% higher than IR. This is due to the difference in grain movement on each cutting edge.

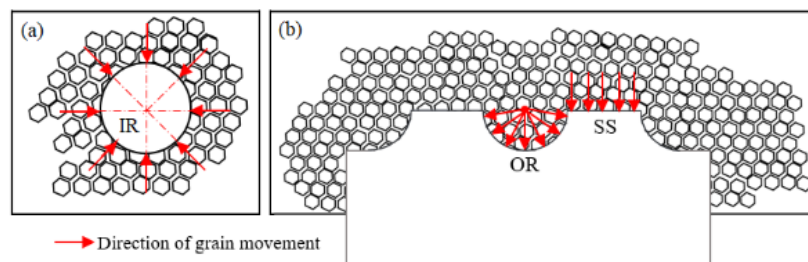
**Figure 9.** Grain movement illustration on: (a) circular; and (b) B-shaped holes

Figure 9 shows the grain moves during the making of circular and B-shaped holes. In OR cutting, grain moves happen away from the radius centre. In SS cutting, grain movement occurs in one direction. In IR cutting, grain moves to the radius centre direction. In contrast to the one direction and away from the radius centre, grain movement centred on the radius requires higher compressive stress to carry out deformation movement (Mahardika *et al.*, 2024). This causes the height of the rollover formed to be shorter when the punch penetrates the grain movement centered on the radius as reported in previous research (Kurniawan *et al.*, 2019).

3.2. Hardness of Micro-Plate Implant

The hardness of the micro-plates implant fabricated with the μ PP process is displayed in Figure 10. Figure 10 shows several intersecting STDEV values when a horizontal line is drawn. At OR, the STDEV intersects between measurement distances of 50, 100, and 150 μ m. At SS, the STDEV intersects between measurement distances of 50, and 100 μ m. At the 100 μ m measurement position, the STDEV intersects between SS and OR. At the measurement positions of 150 μ m and 200 μ m, the STDEV intersects between SS and IR. The intersecting STDEV indicates significant uncertainty of measurement data differences. Consequently, it cannot be concluded that hardness is higher when it is closer to the cutting edge, and hardness at OR is higher than IR and SS. The uncertainty of hardness value at each measurement position was analyzed using the ANOVA test.

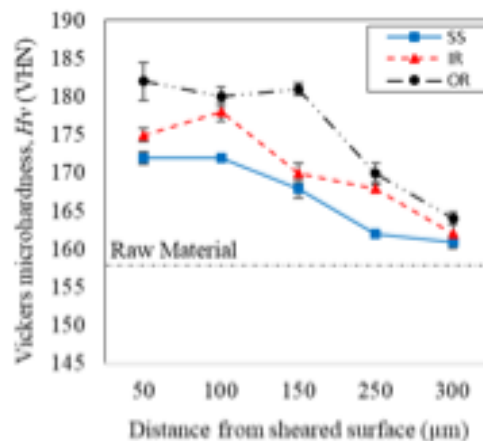


Figure 10. Hardness value of micro-plate implant in cross-section

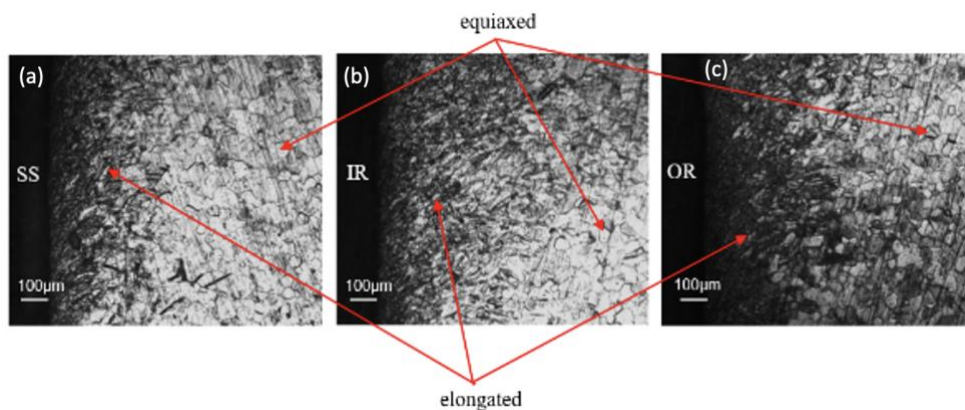
Table 4 presents the ANOVA test results for hardness. The P-value is lower than 0.05, and the F is larger than the F-critical on the cutting surface and measurement position. These results indicate that the hardness value at each measurement position and cutting surface have significant data difference. Therefore, it can be concluded that hardness is higher when the position is closer to the cutting surface. The hardness near the cutting surface is higher due to plastic deformation (Gotoh and Yamashita, 2001). This appears to be the result of the dislocations forming and moving inside the materials crystal structure (Meng *et al.*, 2015). This phenomenon is called work hardening (Abe *et al.*, 2019). Increasing hardness near the cutting surface is also caused by plastic deformation from cold working, as several investigations have demonstrated (Tang *et al.*, 2018; Kurniawan, Mahardika, and Suyitno, 2020; Matsuno *et al.*, 2021).

Table 4. ANOVA test results for hardness

Variation Source	SOS	dof	MS	F	P-value	F-critical	Significance
Cutting surface	1659.333	14	118.524	18.757	0.000	2.064	Yes
Measurement position	549.733	2	274.867	43.498	0.000	3.340	Yes
Error	176.933	28	6.319				
Total	2386.000	44					

SOS, sum of squares; dof, degrees of freedom; MS, mean square

The hardening enhancement results are noteworthy also because the hardness values obtained indicate a dependence on the cutting-edge shape (SS, IR, and OR). The cutting shape affects work hardening because the grain moves differently during the punched process (Mahardika *et al.*, 2024). Each side experiences a distinct plastic deformation because of the variations in the directions of grain movement. The direction of grain moving away from the radius centre will produce greater plastic deformation compared to the direction of grain movement approaching the radius centre. However, the grain moving direction approaching the radius centre will produce greater plastic deformation compared to the direction of grain movement in the same direction. A larger hardness corresponds to larger plastic deformation. The hardness value in IR is higher than SS. However, the hardness value in OR is higher than IR.

**Figure 11.** Microstructure images on the cutting surfaces of: (a) SS; (b) IR; and (c) OR

Microstructure experiments were conducted in the burnished area in SS, IR, and OR to verify the work hardening behaviour in the circular and B-shaped punching operations. Figure 11 shows the observed microstructures in SS, IR, and OR. A transition from an equiaxed to an elongated grain structure is visible in the SS, IR, and OR microstructure images. The hardness value close to the cutting side is harder than the part far from the cutting side due to the grain transition from equiaxed to elongated (Arab, Chen and Guo, 2019). The hardness near the cutting edges of SS, IR, and OR were about 172, 175, and 182 VHN, respectively. These results were higher than the hardness of micro-plate implants fabricated by die-sinking EDM (Kurniawan *et al.*, 2024).

4. CONCLUSION

Research has been done on the quality of micro-plate implants made with μ PP with the following conclusions: μ PP using hydraulic driven power has successfully created micro-plate implants. The formed micro-plate implant cutting surface differs between SS, IR, and OR surfaces. The IR cutting

surface has shorter rollover and burr than SS and OR. In addition, the burnish formed on the IR cutting surface is also the highest. The difference in rollover, burnish and burr heights between the IR and SS surfaces are 26.98, 11.52, and 2.78 μm , respectively. While the difference in rollover, burnish and burr heights between the IR and OR surfaces are 38.15, 29.90, and 2.80 μm , respectively. hardness near the cutting edge of the micro-plate implant has differences in IR, SS, and OR due to work hardening. The highest increase in hardness occurs on the OR surface, while the lowest increasing hardness occurs on the SS. The increasing hardness that arises on the IR, SS, and OR surfaces are 9.4%, 7.5%, and 13.7%, respectively. It is anticipated that future studies would maximize the punch process settings to raise the height of the burn. In addition, mechanical testing is needed to determine the quality of micro-plate implants produced by μPP .

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