Increasing of Stretch Formability on Hole-flanging Parts of Aluminum Alloys by Smooth Sheared Surface

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Abstract

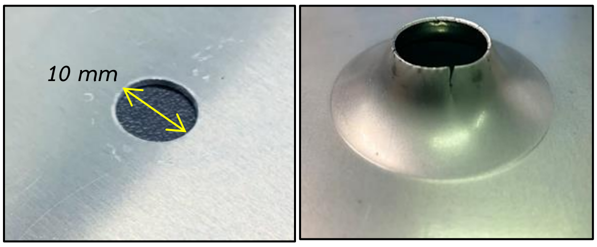
Aluminum alloy is a lightweight material that fractures often occur during stretch forming, especially in the hole-flanging parts. However, the stretch formability of aluminum alloy increased by improving a smooth-sheared surface. The resistance of materials to edge fracture in complex shape forming is typically measured using the hole expansion ratio (HER). This paper presents the concave piercing punch design to increase smooth sheared surface which induces the increasing stretch formability of aluminum alloy. The effect of a smooth-sheared surface on stretch formability was examined via a hole expansion test (HET). The aluminum alloy grade AA1100, and AA5052 of 1.2 mm of thickness with three levels of clearance 5%t, 10%t, and 15%t were used in the experiments. The HER of aluminum alloy is influenced by a smooth sheared surface from conventional and concave piercing punch with varied clearances. In the experimental aspect, the clearance level and shape of the piercing punch, which are factors for the stretch formability of aluminum alloy, were observed by hole HER. The concave piercing punch design improves the hole expansion ratio more than a conventional piercing because a smooth sheared surface around the hole edge increases the hole expansion ratio.

***Keywords*:** Aluminum alloy, Clearance, Hole expansion ratio, Piercing punch, Sheared surface

I. INTRODUCTION

Aluminum alloys offer a combination of low density and high strength, making them an excellent choice for vehicle body construction. Compared to traditional steel, aluminum alloys have approximately one-third the density, which translates into a considerable reduction in weight. Aluminum has several advantages that make it suitable for EV battery enclosures. Firstly, it has a low density, which means it is lighter than many other metals. This helps to reduce the weight of the vehicle, which in turn improves energy efficiency and extends the driving range. However, edge failure is one of the significant problems associated with forming operations, as shown in Fig.1. Thus, a new technique to increase stretch formability is essential. Some of the relevant research studies are summarized below.

Based on the findings of Gang *et al.* [1], it can be concluded that using ample clearance in the blanking process has a detrimental effect on forming quality. To ensure better quality outcomes, selecting an optimal clearance value that balances the desired level of material deformation, dimensional accuracy, and surface finish is advisable. Mori *et al.* [2] focused on understanding the relationship between the quality of the sheared edge and the stretch flange ability of high-strength steel sheets. By enhancing the sheared edge quality, they aimed to increase the material's formability and reduce the likelihood of failure during forming processes. Zhou [3] proposed expanding holes on the pulsed electromagnetic force using an electromagnetic cold-expansion process. Choi *et al.* [4] demonstrated that increasing the clearance and utilizing a negative inclined angle can benefit both the trimming load and the sheared edge quality when working with DP980 material. These findings provide valuable insights for optimizing the trimming process in manufacturing DP980 components. Tekiner *et al.* [5] studied the effect of different clearances on the quality of sheared edges on aluminum sheets. They observed the clearance decreasing with the smooth-sheared and punch force increases. While the clearance increases, the die roll increases; on the contrary, sheared surface decreases. The study conducted by Sasada and Togashi [6] focused on investigating the influence of clearance on the rollover behavior of aluminum A1100P-O using image processing techniques. The rollover phenomenon refers to the folding or buckling of material during a metal-forming process. Adnan *et al.* [7] investigated the effect of clearance on the burr on the mild steel, brass, and aluminum in the blanking process. However, the effect of the clearance and burr height achieved by their report is beneficial solely for single-sheet blanking. Komgrit and Pongsakorn [8] revealed that the inclined trimmed punch could improve the quality of the sheared surface. Won *et al.* [9] introduced a new design for two-stage blanking to enhance the edge stretch ability of third-generation advanced high-strength steels (AHSS). The proposed design has undergone experimental validation using sheared edge tensioning, sheared edge quality, and microhardness tests. Park *et al.* [10] studied analyzing the effect of the hole-edge condition on the hole-expansion ratio (HER) of ferrite-bainite (FB) dual-phase steel. They confirmed that the damage caused by punching is critical to the formability of dual-phase steel. Prasad *et al.* [11] focused on investigating the influence of temper conditions on the edge formability of AA7075 alloy sheets using hole expansion tests. The researchers examined different tempers, including W-temper conditions, and employed punching and drilling techniques for hole preparation. Hance *et al.* [12] focused on investigating the impact of pre-hole shearing methods, such as punching, milling, wire-EDM cutting, laser cutting, and others, on the resulting damage at the edge of the hole. They aimed to assess the different levels of damage caused by these methods. In essence, several researchers have found that the specific technique employed to prepare a hole affects the quality or characteristics of the central hole's edge. Since the HER parameter is sensitive to the condition of this edge, selecting the hole preparation method becomes crucial in determining the value or behaviour of HER [13]–[15]. From the literature review, stretch formability is an interesting topic for research papers. However, the increase in stretch formability on hole-flanging parts based on a smooth sheared surface from simple and quick die setups has yet to be reported. This research paper presents an alternative pre-hole shearing process designed to address the challenges faced by the industry in terms of setup complexity. A piercing punch with a concave shape is proposed for pre-hole shearing before the hole expansion test to increase the smooth sheared surface. The mechanism of the increase in hole expansion ratio is discussed with experiments on AA1100 and AA5052 sheets.



(a) Original shape (b) Final shape

(c) Hole flanging application

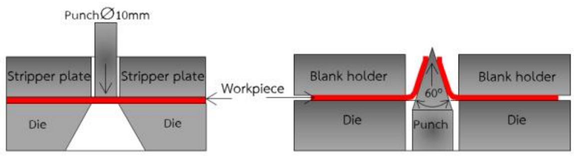
Figure 1: Hole flanging application

II. EXPERIMENTAL SETUP

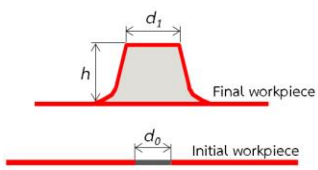
A. The Overview of Hole Flanging Operation

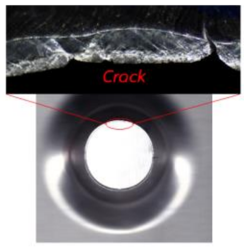
The following hole flanging experiment (as schematically illustrated in Fig. 2) was conducted: (a) pre-hole shearing, (b) hole flanging test, (C) measurement and analysis, and finally, (d) obtained hole flanging workpiece. To improve the quality of the hole surface that induces the increasing hole flanging ability, we provided two types of punch, a conventional punch and the concave punch design, as shown in Fig. 3. For the pre-hole piercing process, tool steel with high carbon and high chromium grade JIS SKD11 was used to make a punch and die.

The pre-hole shearing apparatus is also shown in Figure 3. Three levels of piercing clearance (5%, 10%, and 15% of thickness) were applied to this experiment. In this work, the pre-hole shearing was performed dry conditions. For guidelines of the hole expansion test, we followed according to ISO 16630:2009 [16]. The diameter of the hole was 10 mm. The increasing hole expansion ratio can be calculated by equation 1. An aluminum AA1100, and AA5052 sheets (thickness 1.2 mm) with dimensions of 100×100 mm were employed as workpiece material in the pre-hole shearing experiments.



(a) Pre-hole shearing (b) Hole flanging test





(c) Measurement & analysis (d) Hole flanging workpiece

Figure 2: Schematic illustrations of hole flanging operation

$$\% \text{ HER} = \left[\frac{(d_1 - d_0)}{d_0}\right] \times 100 \quad (1)$$

where d_0 = *Diameter of the initial hole (10 mm)*

d_1 = *Diameter after rupture: mm (Average value)*

The mechanical properties of the workpiece materials are listed in Table 1. To robust experimental data, every experiment was repeated five times for each material workpiece.

Table 1: Mechanical properties

Mechanical properties	Materials workpiece	
	AA1100	AA5052
Yield strength (MPa)	105	165
Tensile strength (MPa)	122	220
Elongation (%)	17.58	20.22

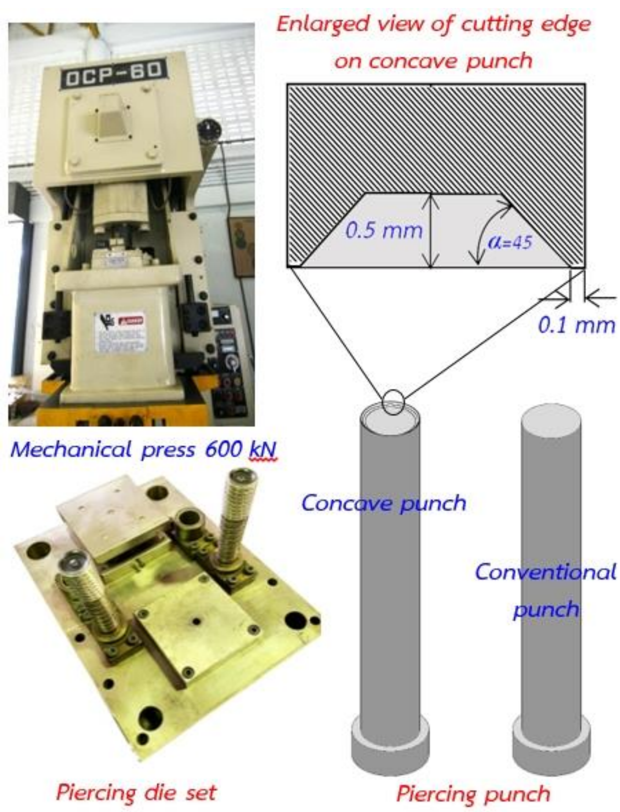


Figure 3: Pre-hole shearing apparatus

B. Hole Flanging Apparatus

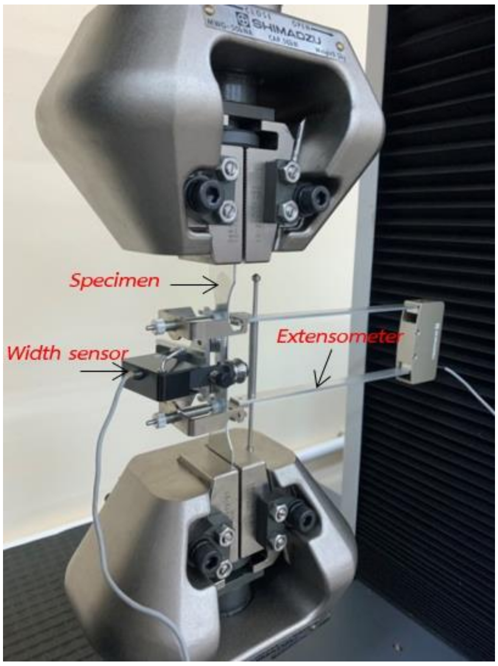
Hole expansion tests were conducted according to ISO 16630:2009 on the universal testing machine (ERICHSEN Model 134), as shown in Fig. 4. A punch diameter of 50 mm with a conical head and an angle of 60° was used. The driving speed of the conical punch was 10 mm/min. The testing would be stopped when a crack propagation across the edge of the deformed sample workpiece occurred.

Figure 4: Hole flanging apparatus

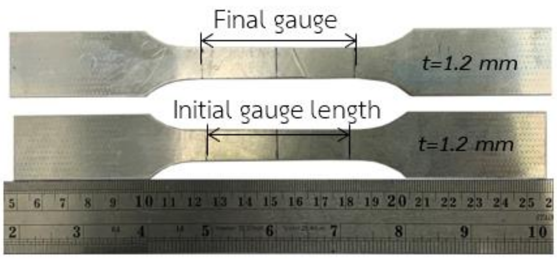
III. Finite Element Preparation

There are still many problems in sheet metal forming to be addressed in the real stamping industry. The finite element method will lead the way in advanced solutions that give you an understanding of the die design concept. To obtain the true stress-strain for the finite element analysis, the uniaxial tensile test according to JIS 13B standards with Shimadzu extensometer and width sensor was placed on the specimen as shown in Fig. 5.

To investigate the mechanism of cutting edge during piercing, an FE simulation (code DEFORM 2D) was conducted. The detail of the finite element setup is given in Table 2. The finite element model with a two-dimensional model (axis symmetry) was used to observe and investigate the deformation of a workpiece during piercing as shown in Fig.6. The solution algorithm employed in these Finite Element Model (FEM) simulations relies on the iterative Newton-Raphson method. Large plastic deformation would have occurred in the cutting edge of the workpiece therefore elastic calculation behavior will be discarded in this material model. The rectangular type with four-node elements (3,000 elements) was used for the finite element model. A fine element region is created in the cutting zone, followed by the application of adaptive remeshing. The automatic remeshing function was determined every three steps to control the excessive deformation on the workpiece during simulation. It prevents issues of element distortion, mesh tangling, or element size mismatch, which can affect the accuracy and stability of the simulation results. The plastic properties of workpiece materials are assumed isotropic and described by the Von Mises yield function. The number of simulation steps 120 with a punch displacement of 0.05 mm per step was applied to finite element simulation control. Tooling and workpiece material contact is ensured with a kinematic contact condition established through master-slave surface pairs in the initial step. In accordance with preceding research findings [8], an appropriate friction coefficient for the contact surface model falls within the range of 0.10 to 0.12, as defined by the classical Coulomb friction law.



(a) Universal testing machine for tensile test



(b) Sample workpiece

Figure 5: Uniaxial tensile test

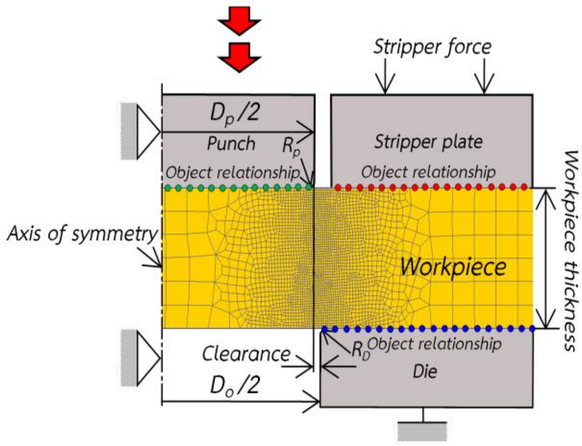


Figure 6: Finite element model for conventional piercing

Table 2: Finite element set up

Detail of finite element	
Tooling	Rigid body
workpiece	Elasto-Plastic
Flow curve	AA1100 $\bar{\sigma} = 168\varepsilon^{0.21}$ AA5052 $\bar{\sigma} = 388\varepsilon^{0.28}$
Mesh	3,000
Friction coefficient	0.12
Tip radius	0.02 mm

IV. RESULTS AND DISCUSSION

A. Performance of a Concave Punch on Quality of the Cutting-Edge Workpiece

As well known, the piercing die can produce a large number of workpieces in a short time. Before the piercing process, the cutting edge of the workpiece should be present. Figure 7 shows the details of cutting zones on a sheared edge of a workpiece. The characteristics zone on a sheared edge consisted of four points: die roll, sheared surface, fracture surface, and (θ) tearing angle.

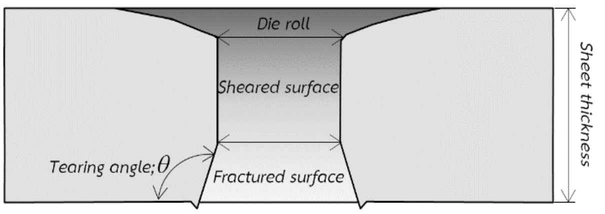
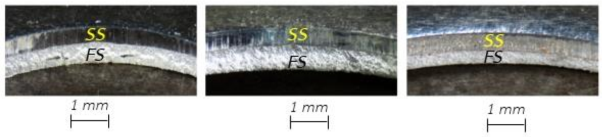


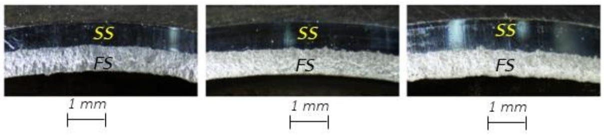
Figure 7: Characteristic zones on a workpiece obtained from piercing die

Figure 8 displays photos of cutting edges workpiece aluminum grade AA1100 and AA5052 corresponding with the experimental results of conventional punch and concave punch. For the case of conventional punch, the quality of the hole surface was poor (small sheared surface. Meanwhile, we obtained a large sheared surface from the new design, as shown in the concave punch condition.

From these results, we ensure that the concave punch can generate a large sheared surface by responding with all piercing clearance.

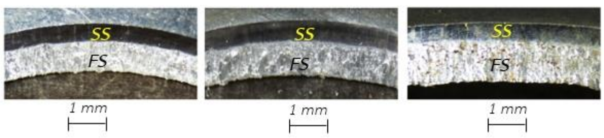


(a) Cutting edge of AA1100 from conventional punch



(b) Cutting edge of AA1100 from concave punch

(c) Cutting edge of AA5052 from conventional punch



(d) Cutting edge of AA5052 from concave punch

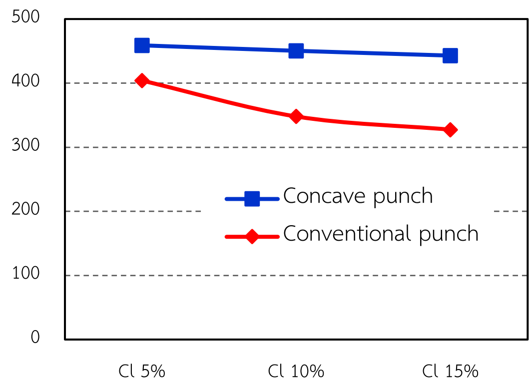
Remark: SS: Sheared surface, FS: Fracture surface

Figure 8: Cutting edge of workpiece obtained from various piercing clearances

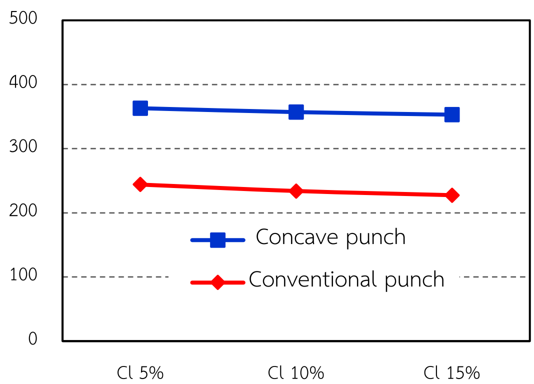
Generally, it is known that the quality of cutting-edge obtained from the piercing process depends on clearance levels [1-3]. Although, a narrow clearance can generate a large sheared surface. However, a problem with a high wear rate on a punch will occur. In addition, the die setup is complicated and needs labour-high skills. Therefore, a piercing process with large clearance is better than a narrow clearance.

Figure 9 shows the sheared surface results of the AA1100, and AA5052 workpieces obtained from conventional and concave punches with various piercing clearances. On the cutting edge of AA1100 material with conventional punch, a sheared surface rapidly decreases with the clearance increasing at 15%t. Meanwhile, a sheared surface obtained from the concave punch slightly decreased (see Fig.9 (a)). Figure 9(b) shows the tendency sheared surface of AA5052 obtained from conventional and concave punches. The results showed that a sheared surface pieced from a concave punch was more significant than a conventional punch. When the clearance increases, the sheared surface would be slightly decreased.

From the experimental results, we confirmed that the concave punch can generate a large of the sheared surfaces of all workpieces. Moreover, the concave punch can produce cutting-edge high-quality from a large clearance. This is a good advantage of the concave punch design over the conventional punch.



(a) AA1100 material



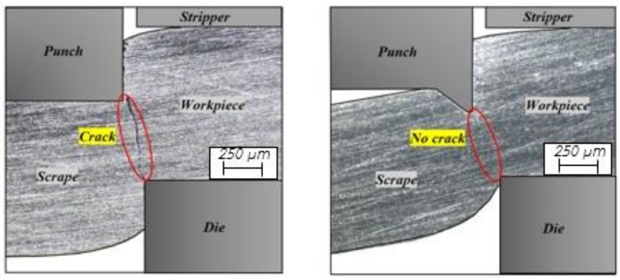
(b) AA5052 material

Figure 9: Summarized of sheared surface obtained from conventional punch and concave punch

B. Cutting Edge Analysis by FEM

Figure 10 shows the experimental results on the AA1100 sheets of clearance cross-section 10%t with similar depth penetration of conventional punch and concave punch designs.

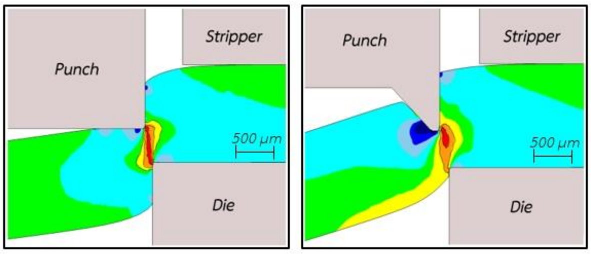
The crack propagation occurred on the cross-section of the workpiece from the conventional punch, as shown in Fig. 9 (a)). In contrast, the concave punch designs can proceed with a deep stroke without cracking (see Fig. 9 (b)). We can keep a large sheared surface from these results since the concave punch designs did not generate quick crack propagation, so sheared surface would be increased.



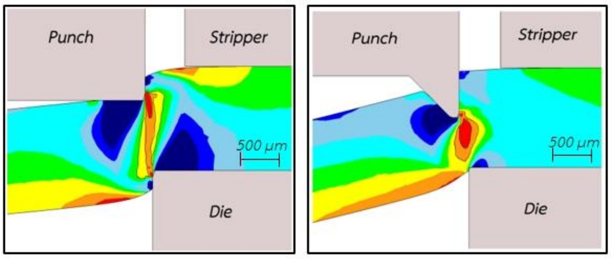
(a) Conventional punch (b) Concave punch

Figure 10: Cracking during deformation of AA1100 with a constant piercing clearance of 15%t

The stress distribution during piercing of the AA1100 workpiece pieced by conventional punch and the concave punch designs with a constant piercing clearance of 10%t is given in Fig. 11. In the case of pieced by conventional punch, both materials, the tensile stress appeared under the stripper plate thus the large die roll becomes large. In addition, we found that the intensity of tensile stress expanded from the punch to the die at the shallow stroke (see Fig.11 (a)). For this reason, the crack propagation on cutting the workpiece from the conventional punch would occur faster than the new designs. For the concave punch designs, the expansion of intensity tensile stress occurred at the deep stroke (see Fig.11 (b)). When the crack propagation is delayed, the sheared surface will be increased. From the above mention, we can generate a small die roll, a large sheared surface, and a fine surface texture with no narrow piercing clearance. That is a good advantage of this technology over the other processes.



(a) AA1100-Conventional punch (b) AA1100-Concave punch



(c) AA5052-Conventional punch (d) AA5052-Concave punch

Figure 11: Mean stress distribution during piercing of the AA1100 workpiece pieced by a conventional punch and the concave punch design with a constant piercing clearance of 15%t

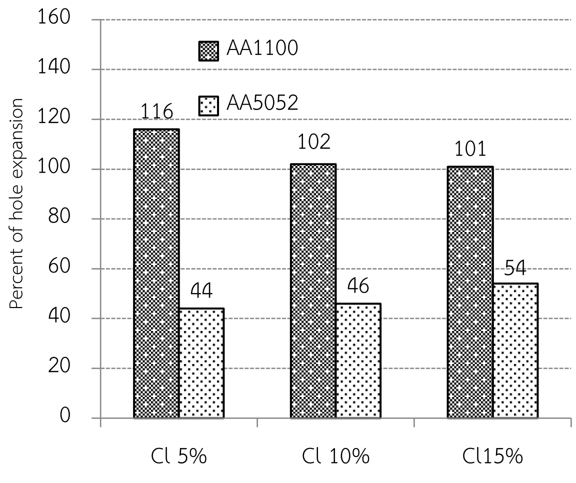
C. Effect of Concave Punch on Stretch Flanging Ability

Stretch flanging ability is commonly quantified by hole expansion ratio (HER). It is a simple method to understand edge fracture on materials. Fig.12 shows the HER obtained from the conventional and concave punches with AA1100 and AA5052 workpiece materials. The %HER can be calculated by equation 1, as shown in the previous discussion.

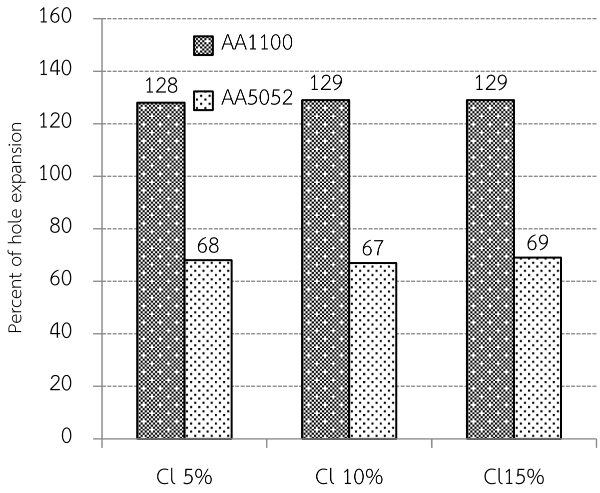
Considering the results from conventional punch (see Fig.12 (a)), it was found that AA1100 has a high %HER. When increasing a piercing clearance, the percentage of the hole expansion ratio was slightly decreased.

Table 3: Increasing of %HER obtained from the concave punch with various materials

Clearances	AA1100	AA5052
5%t	10.34%	54.54%
10%t	26.47%	45.65%
15%t	27.72%	27.72%



(a) Conventional punch



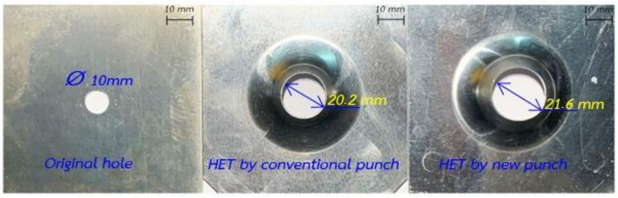
(b) Concave punch

Figure 12: Summary of HER obtained from conventional punch and concave punch

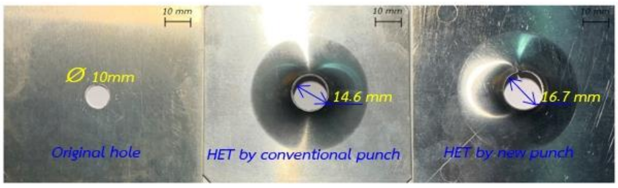
In the case of AA5052, we found the HER increased with increasing clearance. It corresponds to the cutting edge of the workpiece in Fig.8 (c). A large sheared surface can furnish a high percentage of the HER more than a small sheared surface workpiece. The results of

Fig.12(b) show that the %HER obtained from the concave punch has an almost similar trend to the results from the conventional punch. However, the %HER obtained from the concave punch has higher than a conventional punch. The increasing of %HER with AA1100, and AA5052 obtained from clearance 5%, 10%, and 15% are summarized as the table 3:

It should be noted that the concave punch can keep the HER of AA1100 and AA5052 with all clearance levels. Figure 13 shows a sample workpiece from the hole expansion test when pre-hole piercing by conventional punch and concave punch designs with a clearance of 10%. The hole size obtained from the concave punch was more significant than that pierced by a conventional punch. It is seen that a concave punch can increase hole-flanging ability.



(a) Sample of hole expansion of AA1100

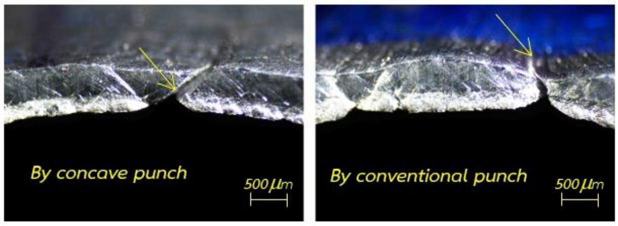


(b) Sample of hole expansion of AA5052

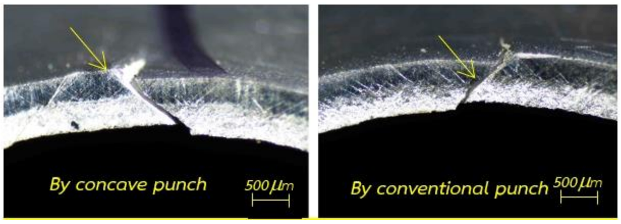
Figure 13: Hole flanging parts obtained from HET

D. The cracking on hole a flanging part

Figure 14 (a) – (b) shows a crack observation on the hole edge of AA1100 and AA5052 after the hole expansion test when using the conventional and concave punches, respectively. In the case of pre-hole by conventional punch, it was observed that a severe crack appeared on the hole edge of the workpiece. On the other hand, the concave punch has a high potential for crack protection on the hole edge of three types of aluminum sheet. The hole edge without crack leads to an increase in the hole flanging ability. Although an advantage of using the concave punch over the conventional punch has a slight increase in this work, it is necessary to develop this subject in the future.



(a) Cracking on AA1100 workpiece



(b) Cracking on AA5052 workpiece

Figure 14: Comparison of crack on hole edge after hole expansion when using concave punch and conventional punch

V. CONCLUSION

An alternative piercing punch shape has been proposed to increase the hole expansion ability of high-strength steel sheets. The research paper findings are concluded as follows:

(1) The concave shape of the punch creates a gradual and controlled deformation on the material being punched, which helps to delay the propagation of cracks on the cutting edge.

(2) Increasing the smooth sheared surface could increase the hole expansion ratio. The hole expansion ratio measures the ductility of a material, indicating its ability to undergo plastic deformation without fracture.

(3) To enhance hole expansion ability in the aluminum alloy sheet stamping industry, we suggest utilizing a concave punch profile.

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REFERENCES

[1] G. Fang, P. Zeng, and L. Lou, "Finite element simulation of the effect of clearance on the forming quality in the blanking process," *J. Mater. Process. Technol.*, vol. 122, no. 2–3, pp. 249–254, Mar. 2002.

[2] K. Mori, Y. Abe, and Y. Suzui, "Improvement of stretch flangeability of ultra high strength steel sheet by smoothing of sheared edge," *J. Mater. Process. Technol.*, vol. 210, no. 4, pp. 653–659, Mar. 2010.

[3] Z. Zhou *et al.*, "Electromagnetic cold-expansion process for circular holes in aluminum alloy sheets," *J. Mater. Process. Technol.*, vol. 248, pp. 49–55, Oct. 2017.

[4] H.-S. Choi, B.-M. Kim, and D.-C. Ko "Effect of clearance and inclined angle on sheared edge and tool failure in trimming of DP980 sheet," *J. Mech. Sci. Technol.*, vol. 28, no. 6, pp. 2319–2328, 2014.

[5] Z. Tekiner, M. Nalbant, and H. Gürün, "An experimental study for the effect of different clearances on burr, smooth-sheared and blanking force on aluminium sheet metal," *Mater. Des.*, vol. 27, no. 10, pp. 1134–1138, 2006.

[6] M. Sasada and T. Togashi, "Measurement of rollover in double-sided shearing using image processing and influence of clearance," *Procedia Eng.*, vol. 81, pp. 1139–1144, 2014.

[7] A. A. Kamarul Adnan, S. N. Azinee, N. Norsilawati, and K. A. M. Izzul, "Analysis of the influence of the blanking clearance size to the burr development on the sheet of mild steel, brass and aluminium in blanking process," *J. Achiev. Mater. Manuf. Eng.*, vol. 111, no. 1, pp. 26–32, Mar. 2022.

[8] K. Lawanwong and P. Leetrakul, "FE simulations and experimental analysis of the blade angle effect on sheared surface in trimming process of advanced high-strength steel sheet," *Arab. J. Sci. Eng.*, vol. 44, pp. 7909–7918, 2019.

[9] C. Won, W. Lee, H. Lee, Y. Kang, and J. Yoon, "Effect of two-stage press blanking on edge stretchability with third-generation advanced high-strength steels," *Int J. Adv. Manuf. Technol*., vol. 110, pp. 13–27, Aug. 2020.

[10] S. Park *et al*., "A dual-scale FE simulation of hole expansion test considering pre-damage from punching process," *Int. J. Solids Struct.*, vol. 236–237, Feb. 2022, Art. no. 111312.

[11] K. Prasad, A. S. Ebrahim, H. Krishnaswamy, U. Chakkingal, and D. K. Banerjee, "Evaluation of hole expansion formability of high strength AA7075 alloy under varying temper conditions," *IOP Conf. Ser.: Mater. Sci. Eng*., 2022, Art. no. 012038, doi: 10.1088/1757-899X/1238/1/012038.

[12] B. M. Hance, R. J. Comstock, and D. K. Scherrer, "The influence of edge preparation method on the hole expansion performance of automotive sheet steels," *SAE Tech. Paper*, 2013, doi: 10.4271/2013-01-1167.

[13] S. K. Paul, "Fundamental aspect of stretch-flangeability of sheet metals," *Proc. Inst. Mech. Eng. B*, vol. 233, no. 10, 2019, doi: 10.1177/0954405418815370.

[14] A. Karelova, C. Krempaszky, E. Werner, P. Tsipouridis, T. Hebesberger, and A. Pichler, "Hole expansion of dual-phase and complex-phase AHS steels – effect of edge conditions," *Steel. Res. Int*., vol. 80, no. 1, pp. 71–77, Jan. 2009.

[15] D. J. Branagan, A. E. Frerichs, B. E. Meacham, S. Cheng, and A. V. Sergueeva, "New mechanisms governing local formability in 3rd generation AHSS," *SAE Tech. Paper*, 2017, doi: 10.4271/2017-01-1704.

[16] *Metallic materials — Sheet and strip — Hole expanding test*, ISO 16630:2009, 2009.