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Effect of Inclined Angle in Trimming of Ultra-high Strength Steel Sheets Having Inclined and Curved Shapes

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ABSTRACT

Trimming the scrap portion of ultra-high strength steel (UHSS) components poses a significant challenge due to the inherent high strength and hardness characteristics of the material. For UHSS components with a higher geometric complexity such consisting of inclined and curved sections, sharp tilt, and small bend radius, the large trimming load results in poor sheared quality and shape defects, which commonly happen in these areas. This research investigated the effects of applying a small inclination angle to the punch in the trimming of the UHSS parts having an inclined and curved shape. The inclined punch was modified to four sets of different degrees of inclination i.e., 1°, 3°, 5°, and 10°. A comparative analysis of the trimming load, trimming energy, sheared edge quality and shape defects was conducted between these modified punches and the normal punch for their effectiveness in the trimming operation. Results showed that the application of inclination angle significantly decreased the trimming load, reduced the trimming energy, and improved the sheared edge surface quality, as well as prevented the shape defects at the inclined and curved zones as compared to the outcomes produced when trimming using the normal punch. The study suggested that the change to the punch geometry is an effective option to improve the performance of the process as well as the quality of the part, particularly in trimming the high-strength components having complex shapes.

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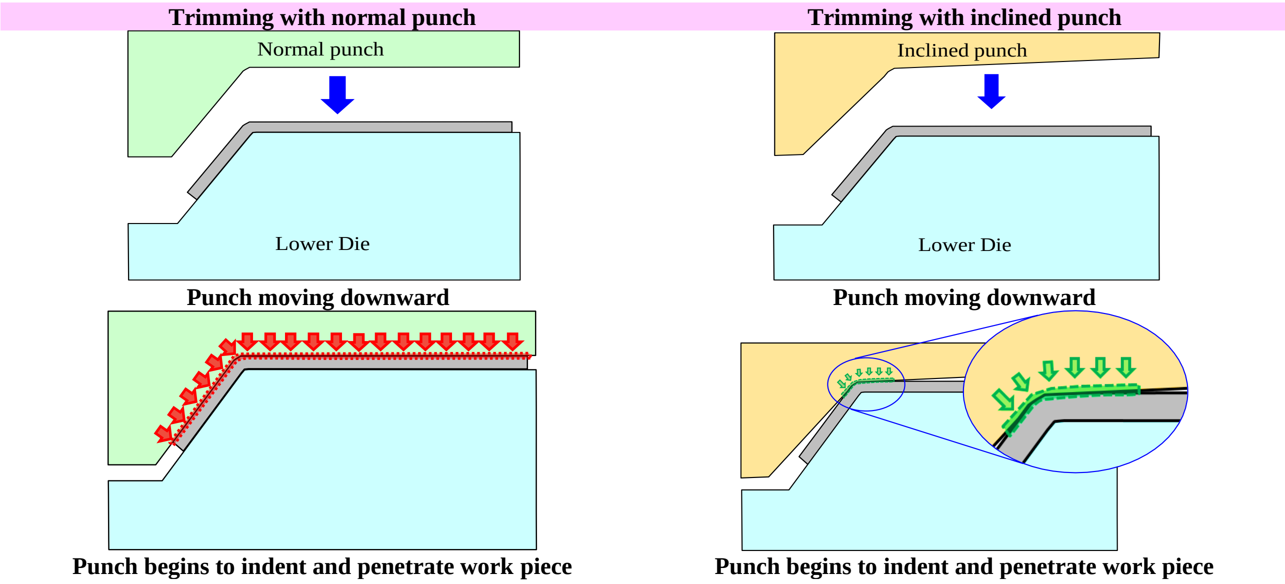

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- All surfaces of the punch are in contact and conform the work piece.
- A significant force is generated to trim the scrap at once.

- Only small and certain surface area of the punch is in contact with the work piece.
- Small force is generated to trim the scrap only at the contacted area.
- The rest area of the scrap is gradually trimmed as the punch move further downward.

1. INTRODUCTION

The concern for climate change caused by green gas emissions is spreading over the world, and all nations are beginning to determine the minimum amount of green gas allowed to be emitted for all industries. Considering that CO_2 gas emissions are the primary cause of global warming, the need for remedial action by the transportation sector, especially the automotive manufacturers, to reduce the total weight of vehicles is irrefutable [1]. In conjunction with the green policies set by the environmental agency (EA), lightweight material became a pivotal point of improvement for car manufacturers, as the less-weight vehicles will indirectly release less hazardous gases from engine combustion [2, 3]. The use of lightweight steel reduces the overall weight of a car, which indirectly improves fuel efficiency, whereas high-strength enhances the safety aspects for the passengers [4]. Various studies were conducted in the transportation sector to assess the relationship between mass reduction, crash safety, and cost-effectiveness, as well as greenhouse gas emission, in order to optimize the design and the related manufacturing process [5]. Caffrey et al. [6] investigated the critical factors affecting life cycle assessments of material choice for vehicle weight reduction.

Although steel, which is both lightweight and high strength, is essential for achieving these objectives, this type of material often has reduced formability, which limits the range of uses in many car parts manufacturing processes such as stamping, rolling, punching, and flanging. As a result, to produce steel grades by focusing on both lightweight and high strength, significant effort has been expended in research over the last decades to enhance ductility and formability with appropriate toughness and fatigue resistance concurrently [7, 8]. Among the applicable and cost-effective steels that belong to this category is ultra-high strength steel (UHSS) sheet, which has a strength of up to and above 1000 MPa [9, 10]. The application of UHSS sheets has become essential in modern car manufacturing, mainly for the chassis and the body-in-white (BIW) parts of a car, as the structure made of this material can uphold high impact force in case of any collision occurs [11, 12]. The BIW of vehicle parts, such as the front pillar, center pillar, and cross member, are stamped in a mold, followed by secondary processing, such as bending and flanging, before being moved to the finishing process [13-15]. Since the formability of the UHSS is low and the strength is high, performing the sheet metal working process, such as punching and trimming on the UHSS, is challenging [16-18].

The performance, quality, and characteristics at the sheared edge of the cutting process including blanking, punching, and trimming are determined by the process parameters, such as cutting speed, clearance, and corner radius of the punch and die [19-21]. The shape of punch and die is another critical factor in determining the part quality and shearing force. Optimizing the shapes result in a significant reduction of force, especially when trimming or cutting a high strength or thick stock [22-24]. Kolleck et al. [25] investigated the effects of increasing the die chamfer angles on the punching and stripping forces, and spring back in tight geometrical tolerances blanking of conically formed holes. Kutuniva et al. [26] proved that the cutting force of the ultra-high-strength DQ960 was reduced by the shearing angle (convex angle) of the punch. The punch force reduces by 57 % compared to a flat punch force when a shear angle of 14° is used. To get a high-quality sheared surface with a low punch force, a shear angle of 7° was used. Kurniawan et al. [27] similarly investigated the effect of punch geometry (flat shape, single shear angle (SSA), and double shear angle (DSA)) by an experiment. The results showed that using SSA and DSA punch geometry successfully reduces punch force by 18% and 13%, respectively, compared to that of flat punch geometry. FEM simulation has been performed by Bao et al. [28] to investigate the effects of the inclined edge of the punch on the blanking force and surface quality. According to the result obtained, the blanking force will decrease as the inclined edge of punch is increased in comparison to flat edge punching, and the double convex inclined edge could produce the greatest quality of the blanked surface.

Some researchers conducted experiments to the energy consumption, fatigue crack behaviour edge quality and its effect on formability during the cutting and machining processes. Shih et al. [29] used an adjustable computer-controlled shearing device to cut DP600 and the DP980 high-strength steel sheets, where it was discovered that this technique can provide a comparable outcome as compared to cutting process by high-energy laser cutting and water jet cutting procedures but with less energy consumption. Balogun et al. [30] and Zainal et al. [31] reduced the energy consumption in milling of AISI1045 steel alloy and aluminum alloy 7075, respectively, by optimizing the swept angle. Since a fatigue crack typically appears on a shear-cut edge in automotive components, Paetzold et al. [32] looked into the relationship between the shear-cutting process (die clearance and cutting edge radius) and the fatigue behaviour in cutting of DP800 high strength steel, where the result showed that the shearing technique used has a significant impact on fatigue resistance. Feistle et al. [33] reported that different cutting parameters and strategies, including single and multi-stage shear cutting, open and closed cutting lines, die clearance, and cutting-edge geometry, have a significant effect on the edge crack sensitivity. Gläsner et al. [34] created a novel two-stage shear-cutting technique (pre-cutting, trimming) that exhibits minimal dimensional tolerance and clean edges in order to minimize the sensitivity of edge cracks. Yasutomi et al. [35] discovered that the tensile residual stress on the sheared surface, which is the source for the edge crack, is significantly decreased by shearing scrap material on the sheared edge.

While previous studies have examined the effects of shear and slant angle in the cutting and trimming processes of high-strength steel sheets, the focus has primarily been on flat-shaped parts. However, there remains a knowledge gap concerning the impact of inclined angles in the trimming process of parts with intricate geometric complexities, such as those featuring inclined and curved sections. In this study, the effects of changing the inclined angles on the trimming load, trimming energy, and quality of the sheared edge in the trimming process of ultra-high strength steel (UHSS) parts having an inclined and curved shape were compared to those of trimming with the normal flat punch and investigated.

2. EXPERIMENTAL DETAILS

2. 1. Experimental Setup The experiment setup for trimming the UHSS sheet having a curved shape is shown in Figure 1. The experiments were carried out using a trimming die set which assembled at the 250 kN SHIMADZU Universal Testing Machine (UTM) as shown in Figure 2. The punch, lower die and sheet holder are made of SKH11 tool steel having a hardness of HRC50 after the heat treatment process. The JSC1180YN UHSS sheet, with dimensions of 1.22 mm x 50 mm x 40 mm in thickness, length and width, respectively, was selected as the workpiece to be trimmed. The mechanical properties of the UHSS sheet (workpiece) are given in Table 1 and were obtained from the uniaxial tensile tests, which are conducted according to the ASTM E8/E8M standard.

The top and front view of the trimming die is shown in Figure 2 (a) and (b), respectively.

The workpiece is first formed into a curved and inclined shape by a separate bending process so that a bend angle and bend radius of 60° and 5 mm are formed. Two types of punches, i.e., the normal and inclined punches were used for the experiment. The normal punch conforms to the shape of the workpiece, whereas the inclined punch has a slight inclination of the punch edges, particularly at the inclined and straight zones. Four punches with four different inclination angles, θ, i.e., 1°, 3°, 5°, and 10°, respectively, were fabricated for the experiment and h, is the highest inclination point of the inclined punch (Figure 2(c)). The 10 mm out of 40 mm in width of the workpiece, was trimmed as scrap. The workpiece before and after trimming is shown in Figure 2 (d). The inclined, curved, and straight zones at the workpiece are divided as in Figure 2 (e) for sheared edge observation. The trimming conditions were set as in

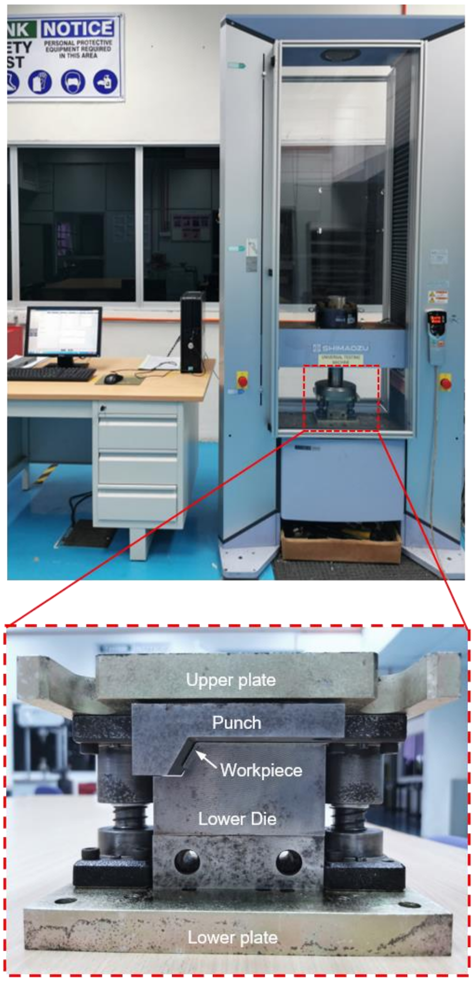


Figure 1. Setup of trimming die set and main components at the 250 kN SHIMADZU Universal Testing Machine

TABLE 1. Mechanical properties of the curved blank

Blank type	Thickness (mm)	Tensile strength (MPa)	Elongation (%)
JSC1180YN	1.22	1242	8.1

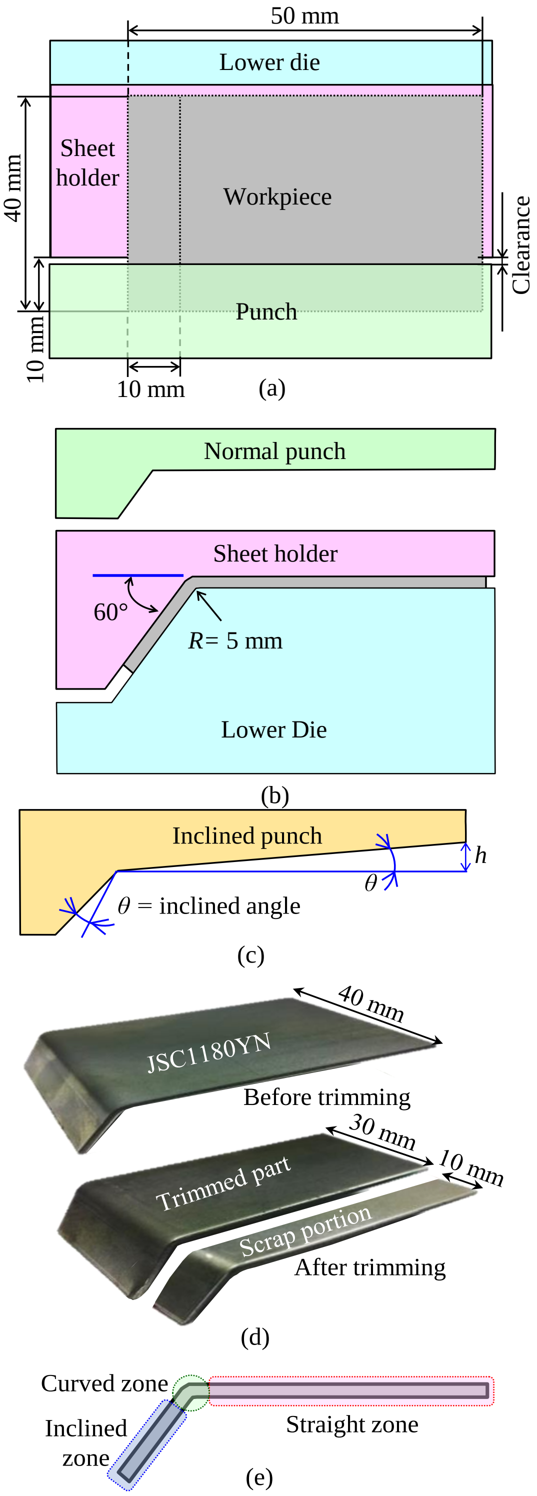


Figure 2. Experimental setup: (a) Top view (b) Front view (c) Inclined punch (d) Workpiece before and after trimming, and (e) Inclined, curved and straight zones of the work piece

Table 2 and the clearance between the punch and the lower die was set to 0.12 mm (10% of thickness). The

TABLE 2. Trimming conditions

Parameter	Set value
Inclination angle, θ	1, 3, 5, 10°
Clearance ratio to workpiece thickness, c	10 % (0.12 mm)
Trimming speed, v	4 mm/s
Bend angle	60°
Bend radius, R	5 mm

blank holder firmly held the workpiece during the trimming process until the scrap was separated from the part. For every set of inclinations, 10 pieces of blank were trimmed, and the average results were analyzed. The low-powered XOPTRON, model XST60 digital microscope with 45 times magnification is used for sheared edge observation.

3. RESULT AND DISCUSSION

3. 1. Trimming Load and Trimming Energy

The relation between the trimming load and punch stroke for trimming the JSC1180YN (UHHS) sheet metal with the normal punch and inclined punch with different inclination angles is given in Figure 3. The maximum trimming load for trimming with the normal punch is about 55 kN, whereas a significant reduction at the maximum trimming load was observed when the inclined punch is used. The trimming load was large when using the normal punch because the whole area of the punch is simultaneously in contact with the blank as the trimming punch moves downward, indenting the workpiece. Due to the large contact area between the trimming punch and the part, a huge trimming load is required to simultaneously break the total bonding force in a single cutting action. A high spike of trimming load was observed within less than 1 mm of the punch stroke. In contrast, by applying an inclination angle at the punch, even for just a slight increment of θ= 1° at the punch, the maximum trimming load was reduced by almost half. A further trend of reduction in maximum trimming load was observed as the angle of inclination was increased. The inclined surface of the punch causes the contact between the punch and the workpiece to be concentrated in a specific area (localized). As a result of this localized contact, the force exerted by the punch on the contact area of the workpiece is minimized. Kutuniva et al. [26] and Kurniawan et al. [27] validated the same pattern of cutting force behaviour during the indentation stage for punching the high-strength steel and titanium, respectively, when changing the punch shape. As the inclined angle is increased, a noticeable distinction is observed in the behaviour of the maximum trimming load is observed, particularly for the inclined punch θ=10°.

Unlike other inclined punches (θ=1°, 3°, and 5°) that exhibit a sharp peak at the maximum trimming load, the inclined punch θ=10° displays a flattened profile. When the inclined angle is too large, less area of the workpiece are indented by the punch at the beginning of the trimming process. Although the maximum trimming load is significantly reduced, the punch requires a longer stroke to complete the separation of the scrap. This can be seen from the interval of change of the trimming load from increasing to maximum and going back down (indicating initiation of fracture in the workpiece), where the change of interval is longer for the inclined punch θ=10°, compared to the others that exhibit a short change and sharp peak.

Although trimming with the normal punch results in the highest maximum trimming load, however, the punch stroke is the shortest. By changing to an inclined punch, the punch stroke to separate the part and scrap were found to become longer with an increase in inclination angle. For instance, the total trimming stroke for trimming using an inclined punch with θ= 10° is about 9 mm, which is more than three times that of trimming with an inclined punch with θ= 1°. The higher angle of inclination makes it longer for the highest inclination point, *h*, at the punch to reach and cut the blank. Bao et al. [28] thru finite element simulation found that a slant punch takes a longer time to cut the workpiece. The comparison of the percentage change in the maximum trimming load and punch stroke for trimming with the inclined punch is given in Figure 4. The application of an inclination angle θ= 3°, 5°, and 10° gave the most significant reduction in maximum trimming load, ranging from approximately 70% to 79%. Conversely, for the punch stroke, a huge increase in the percentage of up to more than 400% was observed when trimming with the same inclined punch θ= 3°, 5°, and 10°. Therefore, it is essential to optimize the inclination angle to achieve a balance between reducing the maximum trimming load and minimizing the increase in the punch stroke.

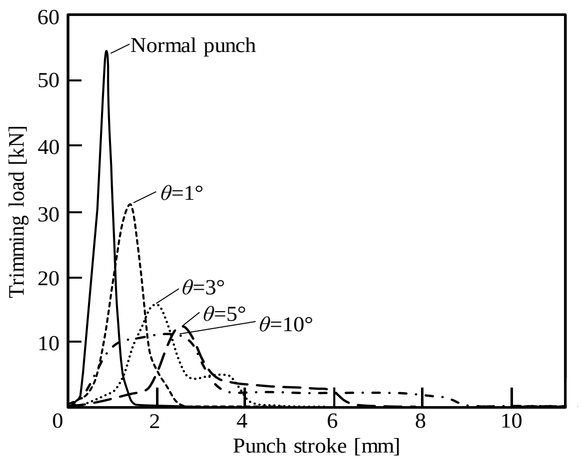


Figure 3. Comparison of load-stroke curves for trimming with normal and inclined punches

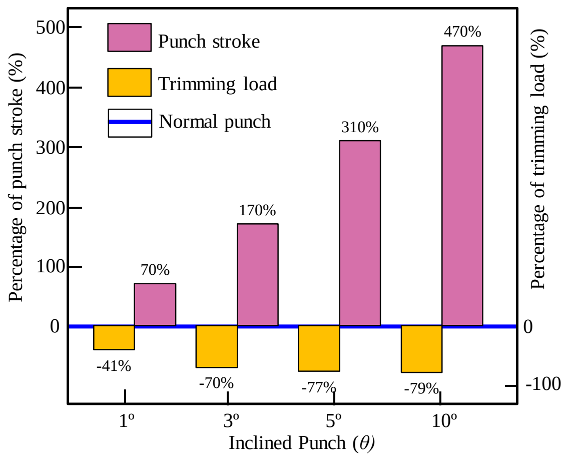


Figure 4. Percentage change in maximum trimming load and punch stroke for trimming with an inclined punch with respect to the normal punch

The energy used for trimming the JSC1180YN (UHSS) sheet using the normal and inclined punches is shown in Figure 5. The trimming energy is calculated based on the integration of the total trimming load used over the travel distance of the punch downwards until the separation of the scrap occurs, which is given by following equation:

$$W = \int_0^s F_t . ds \quad (1)$$

where *W* is the trimming energy used measured in Joule, F_t, is the trimming load, and *s* is the punch stroke. From the graph, the trimming energy for trimming with the normal punch is relatively higher than that of trimming with the inclined punch, except for the inclined punch θ= 10°. When trimming with the normal punch, despite the short total punch stroke to separate the scrap from the workpiece, i.e., less than 2.5 mm, the high load generated at the beginning of the trimming process result in a high trimming energy used. When trimming with the inclined punch, by applying the inclination angle, an expressive reduction trend in trimming energy used is obtained. The inclined punch with inclination angle θ= 3° and 5° consumed the lowest energy of about 18 Joule. As the energy consumption depends on the travel distance of the punch stroke, the energy used for trimming with the inclined punch θ= 10° is the highest as it requires the longest punch stroke to cut out the scrap. The calculation shows that the punch stroke has a high impact on energy consumption, even if the trimming load is low. The selection of proper inclination angle and other parameters is important to optimize between lowering the maximum trimming load and minimizing the trimming energy [35].

The change of energy used by the inclined punches in percentage with respect to trimming with the normal

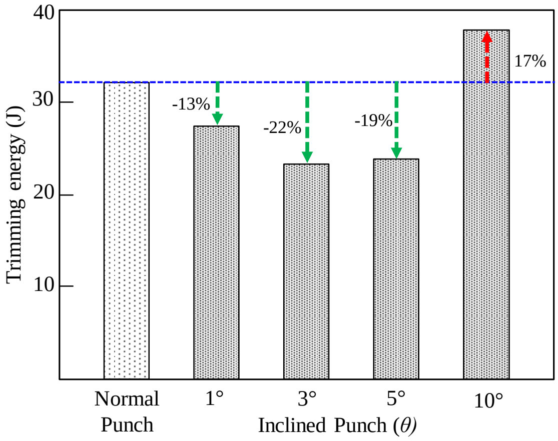


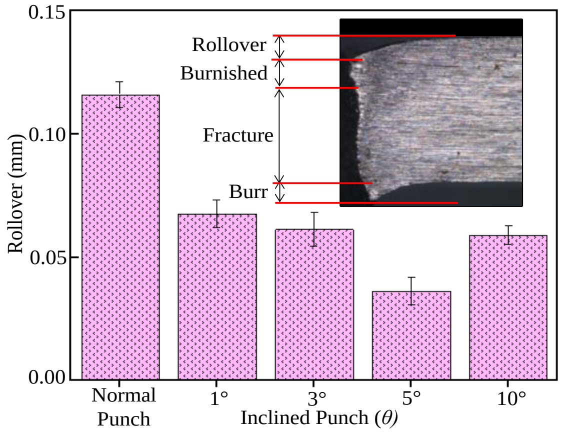
Figure 5. Trimming energy used for trimming normal punch and inclined punch

punch was compared in the same figure. The energy used by inclined punch θ= 1°, 3°, and 5° was managed to be reduced by 13%, 22% and 19%, respectively, compared with the normal punch. However, the percentage of trimming energy was found to increase by 17% for the inclined punch θ= 10°, indicating too much inclination will not optimize the process even though the trimming load is reduced.

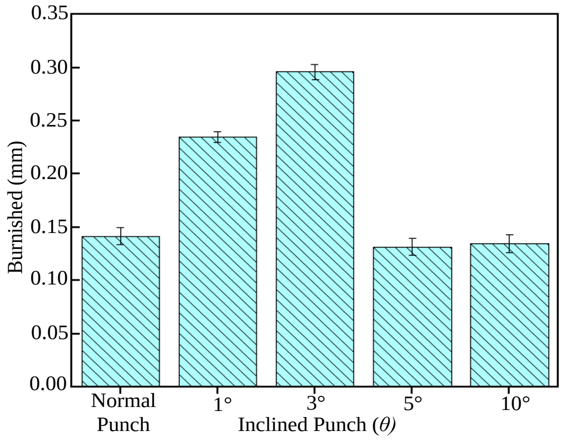
3. 2. Sheared-edge Quality The quality of the four cutting zones at the sheared edge, which are the rollover, burnished, fracture and burr, based on the height produced after trimming as is shown in Figure 6. In general, the height for rollover, fracture, and burr was decreased when trimming using the inclined punch, compared to that of trimming with the normal punch. On the contrary, the height of the burnished surface was found to increase. The decrease in heights of rollover, fracture, and burr, as well as an increase in burnished surface, indicated a successful improvement in the quality of the sheared edge. However, the detailed analysis of the heights of a rollover, burnish, fracture, and burr for different angles of inclination of the inclined punch does not exhibit a direct proportionality. The rollover height (Figure 6 (a)) was found gradually decreased with an increase in the inclination angle, except for the inclined punch θ= 10°. For the burnished surface (Figure 6 (b)), the height was proportionally increased with an increase in inclination angle, only for the inclined punch θ= 1° and 3°. Both inclined punch θ= 5° and 10° were measured to have the same burnished height.

For the fracture and burr height (Figure 6 (c) and (d)), an decrease in height was only found in the directly proportional relationship for the inclined punch θ= 1° and 3°. For the inclined punch θ= 5° and 10°, both the fracture and burr were higher. These irregular patterns of the relationship are attributed to the growth of the bending moment at the cutting area of both the inclined and straight zones (Figure 2 (c)), as a result of an increases in inclination angle.

The localized contact occurs when the inclined punch indents the workpiece at the start of the trimming stage, causing the material at the sheared plane to reach its limit of strain and force tolerance [32]. Thus, the higher



(a)



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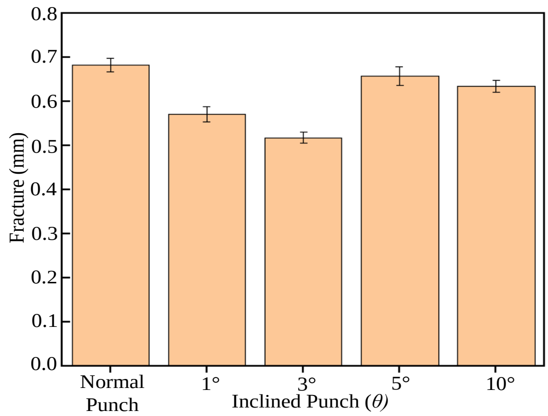
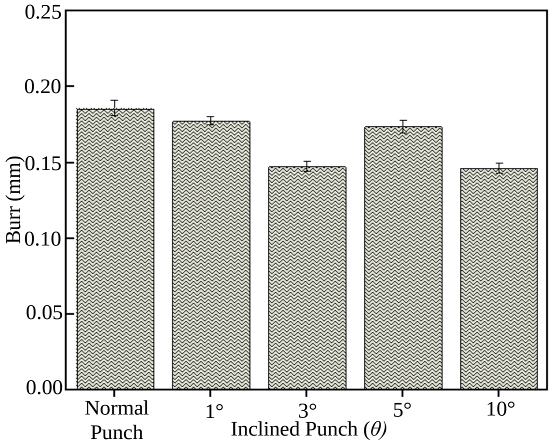


(c)



(d)

Figure 6. Height of sheared surface with different inclined punch shapes; (a) rollover, (b) burnished, (c) fracture and (d) burr

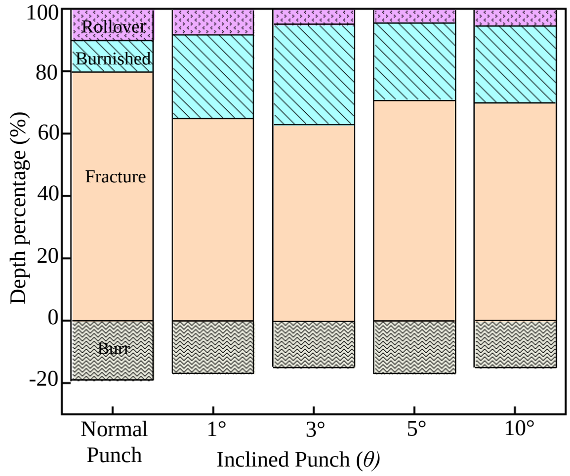


Figure 7. Depth percentage of the rollover, burnished, fracture and burr at the sheared edge for trimming with normal and inclined punches

inclination angle results in greater strain and localized force, ultimately causing the workpiece to bend. Particularly, the shape of the punch used for trimming will impact the quality of the fracture surface [36].

The depth percentage of the rollover, burnished, fracture and burr at the sheared edge for trimming with normal and inclined punches are shown in Figure 7. The depth of the fracture and burnished surfaces are the most important in determining the quality of the sheared edge, where the larger the depth of the burnished and the lower the fracture surface, the better the quality of the sheared edge. For trimming with the normal punch, a large fracture but small burnished surfaces were observed at the sheared edge. In contrast, larger burnished and smaller fracture surfaces were obtained by trimming with the inclined punch. The large trimming load produced by the normal punch, compounded by the simultaneous cutting action by the flat shape of the punch on the workpiece, creates an early point of crack at the cutting area. Therefore, large fractures are created at all zones. Contrarily, the inclined shape of the punch makes the cutting action gradually occur, thus, reducing the force. As the cutting force is gradually exerted, the point of crack at the cutting area is delayed. This created a larger burnished surface at the sheared edge.

The overall percentage of the sheared edge observed in 50 mm length is shown in Figure 8. The sheared edge from the workpiece cut by the inclined punch θ= 3º was chosen as it produced the largest burnished and smallest fracture surfaces at the sheared edge, compared to the other inclined punches. The sheared edge of the workpiece cut by the normal punch is shown for comparison. When the workpiece is trimmed by the normal punch, the percentage of the rollover, fracture, burnished and burr were found at the same level, throughout the length, observed from 0 to 50 mm. It is a

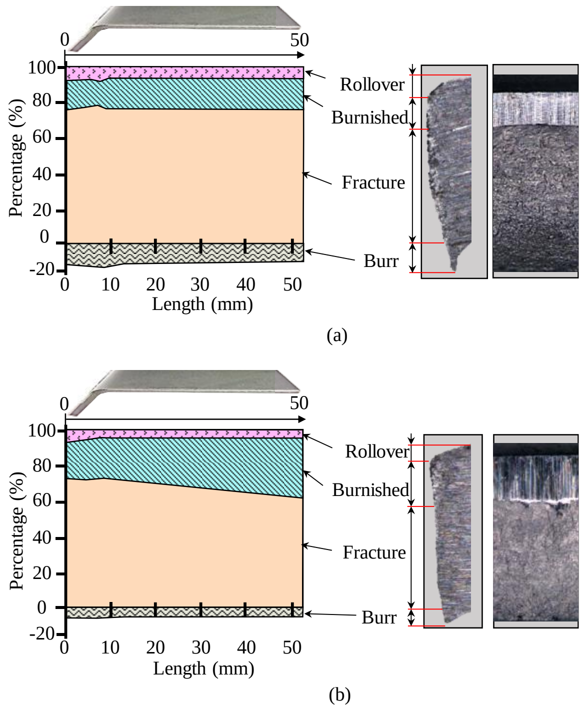


Figure 8. Percentage of the sheared edge of (a) normal punch and (b) inclined punch θ= 3°

clear indication that all zones of the workpiece (inclined, curved, and straight) were simultaneously cut in a single action and at the same time. On the other hand, when the inclined punch is used, the percentage level of the rollover, fracture, burnished, and burr were gradually changed, obviously seen at the burnished and fracture surface, whereas for the burnished surface, the percentage level was found gradually increase from 0 to 50 mm. The fracture surface, on the other hand was gradually decreased. This phenomenon is due to the gradual cutting action created by the inclined shape of the punch, which locally cuts the workpiece as the punch travel downward. As the bond between the part and scrap became weakest at the end of the length, the trimming process became easier and smoother, and thus created large burnished with small fracture surfaces.

3. 3. Shape defect The shape of the trimmed part and scrap were observed under the microscope for the shape defects analysis and compared as in Figure 9. The inclined and curved zones were chosen for the observation as these zones exhibited clear shape defects. The workpieces observed were from those were cut by the normal punch and inclined punch θ= 3º. The bent at the inclined and curved zones was found to be significant at both the part and the scrap portions when trimming with the normal punch. The high trimming force exerted by the punch on all contact areas at once, induced high stress. As the crack initiation begins, this high capacity of stress is abruptly released in a short stroke and time interval, resulting in the inclined and curved zones failing to absorb the sudden change in stress over the small area. Thus, the inclined and curved zones bent during the final stage of the separation. Choi et.al. [37] reported that the crack started near the flank edge of the punch and die and then propagated into the scrap side. For the inclined punch θ= 3°, the punch gradually indented and cut the inclined and curved zones. This prevents the stress concentration on a single area. A smooth distribution of shear stress is provided during the cutting after the initiation of the crack. As a result, the shape of the inclined and curved zones for both the part and scrap portions remained straight without any shape defects.

At higher magnification of observation (Figure 10), an uneven cut and bending shape was observed at the end tip of the workpiece at both the trimmed part and scrap, trimmed by the normal punch. However, with the inclined punch, the defect was prevented, and a straight cut was produced. The defect at the trimming line was observed and compared in Figure 11 for trimming with the normal and inclined punches. The high trimming force exerted by the normal punch induced high stress and resulted in an abrupt and sudden release of stress at the trimming line during the separation of the scrap.

At certain points of the trimming line, due to this sudden release of stress, a large and deep fracture has occurred (Figure 11(a)). Whereas no fracture was observed at the trimming line for trimming with the inclined punch θ= 3° (Figure 11(b)). The inclined surface of the punch prevented high-stress concentration at a single area of contact and therefore allowed a smooth transition of stress as the scrap was separated.

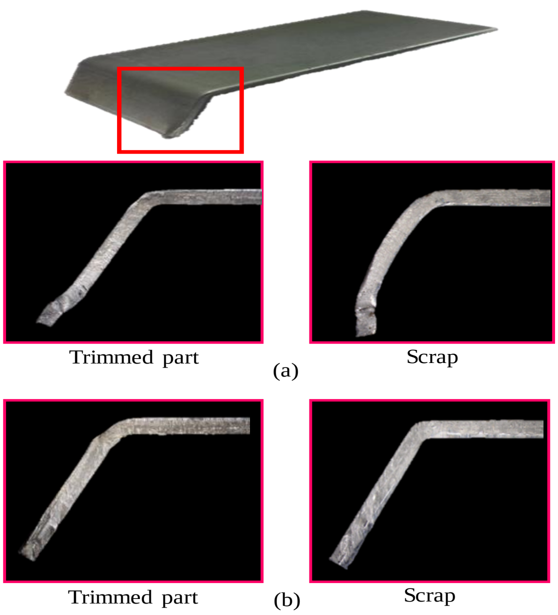


Figure 9. Shape of trimmed part and scrap after trimming process for trimming with (a) normal punch and (b) inclined punch θ=3°

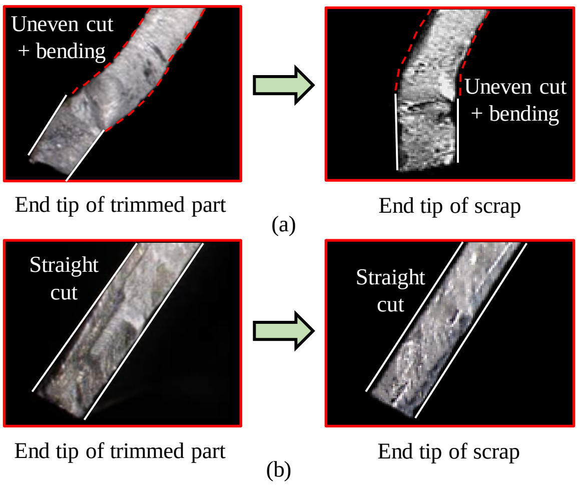


Figure 10. The shape of the end tip at trimmed part and scrap; (a) normal punch and (b) inclined punch θ= 3º

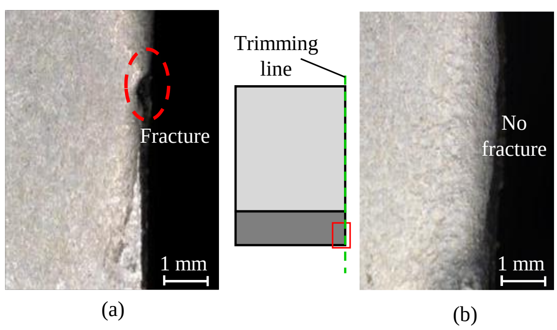


Figure 11. Trimming line at the zone with (a) normal punch and (b) inclined punch θ=3°

4. CONCLUSION

From this study, the trimming process of ultra-high strength steel, JSC1180YN, using both the normal and inclined punches was investigated. The high load produced during the indentation of the punch onto the workpiece is the significant factor for the sheared edge quality and shape defect. The results of the experiment showed that a significant reduction of the trimming load could be achieved by applying a small angle of inclination at the punch edge; however, the longer punch stroke is the drawback. The inclined punches (θ= 1°, 3°, 5°, 10°) successfully decreased the trimming load by more than half as compared to that of trimming with the normal punch. The sheared edge quality was improved, where a larger burnished surface and a smaller fracture were obtained by the inclined punch. The inclined punch θ= 3°, shows the most optimal results in terms of trimming load reduction, punch stroke distance, and improvement of sheared edge quality as compared to other inclination angles. The shape of the part also remained intact without any defects and fractures when trimming with the inclined punch.

5. ACKNOWLEDGEMENT

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Persian Abstract

چکیده

برش بخش ضایعات قطعات فولادی با استحکام فوق العاده بالا (UHSS)به دلیل ویژگی های ذاتی استحکام و سختی بالا، چالش مهمی را ایجاد می کند. برای اجزای UHSS با پیچیدگی هندسی بالاتر از جمله شامل مقاطع شیبدار و منحنی، شیب تیز و شعاع خمش کوچک، بار پیرایشی بزرگ منجر به کیفیت برش و نقص شکل ضعیف می شود که معمولاً در این مناطق اتفاق می افتد. این تحقیق اثرات اعمال یک زاویه شیب کوچک به پانچ را در برش قطعات UHSS دارای شکل مایل و منحنی بررسی کرد. پانچ مایل به چهار مجموعه با درجات شیب متفاوت یعنی ۱ درجه، ۳ درجه، ۵ درجه و ۱۰ درجه تغییر یافت. تجزیه و تحلیل مقایسه ای از بار پیرایش، انرژی پیرایش، کیفیت لبه برشی و نقص شکل بین این پانچ های اصلاح شده و پانچ معمولی برای اثربخشی آنها در عملیات پیرایش انجام شد. نتایج نشان داد که اعمال زاویه شیب به طور قابل توجهی بار پیرایش را کاهش داد، انرژی پیرایش را کاهش داد و کیفیت سطح لبه برش خورده را بهبود بخشید و همچنین از ایجاد نقص شکل در مناطق شیبدار و منحنی در مقایسه با نتایج حاصل از پیرایش با استفاده از دستگاه جلوگیری کرد. مشت معمولی این مطالعه نشان داد که تغییر در هندسه پانچ یک گزینه موثر برای بهبود عملکرد فرآیند و همچنین کیفیت قطعه است، به‌ویژه در اصلاح اجزای با استحکام بالا که دارای اشکال پیچیده هستند.