

Article

Forming a Flanged Hole When Quenching Press-Hardened Steel for Mechanical Fastening

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Abstract: The recent stringent regulations on vehicle safety and reducing CO₂ emissions have led to a continuous increase in the application of press-hardened steel (PHS) in automobiles. Similar to other high-strength steels, assembling PHS components using the common welding techniques employed in automotive production lines is significantly difficult because of the surface coating layers and the additives within. This difficulty in post-processing, attributed to its high strength, also limits the mechanical fastening of PHS components. Therefore, this study aims to develop a process for forming a structure enabling mechanical fastening by sequentially applying piercing and hole-flanging operations during the hot stamping process. Our experimental apparatus was designed to perform the hole-flanging operation after the piercing operation within a single stroke at a specific temperature during the quenching process of PHS. At high temperatures of 440 °C or higher, the hole-flanging process was conducted in a direction opposite to that of the piercing operation for creating the pilot hole. An extruded collar with a height of 8.0 mm and a diameter of 17.5 mm was achieved, which is hole expansion ratio (HER) of 82.5%.



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1. Introduction

The stringent regulations on gas emissions have forced original equipment manufacturers (OEMs) to extend the use of press-hardened components in automobiles. In recent years, multi-material body-in-white (BIW) technology, which uses aluminum, magnesium, and composites together, has been applied for the mass-production of vehicles, in addition to the application of high-strength steels to reduce vehicle weight. However, the application of traditional welding equipment, such as that used in existing automotive production lines, for combining high-strength steels or dissimilar materials is associated with many limitations [1]. The high temperature of the e-coating process required for painting also makes it difficult to apply adhesive bonding to the structural components. Therefore, mechanical fastening is considered an excellent alternative for the mixed-material architectures of lightweight automobiles. Many advanced mechanical fasteners such as self-piercing rivet (SPR) [2] and flow drill screw (FDS) [3] have been studied extensively. Although this technique is advantageous for automation, it necessitates certain constraints on the applicable strength and thickness of the target material. Hence, it is difficult to employ this approach for structural components composed of press-hardened steel (PHS).

Flanged holes in sheet metal parts are used in screw joints or as reinforcement elements for mechanical joints and bushings [4]. However, forming a flanged hole in high-strength steels is more difficult than forming one in conventional mild steel. As the strength of the steel sheet increases, edge cracking at the flanged tip is more likely to occur, even under a small deformation, due to the reduced stretch-flangeability [5,6]. The hole expansion rate (HER), a key index indicating the formability of the hole-flanging operation, decreases

linearly with an increase in tensile strength for steels exhibiting a tensile strength of 590 MPa or less [7]. The HER of advanced high-strength steels (AHSS), which feature a tensile strength of 600 MPa or higher, is maintained around 30–40% [8]; alternatively, the HER of martensitic steels featuring a tensile strength of approximately 1400 MPa is 5–25% [9,10].

The purpose of this study was to assess the feasibility of forming flanged holes in PHS for the mechanical fastening of elements. The elongation in die-quenched PHS is less than 5%, which limits the formation of flanged holes for mechanical fastening. Furthermore, the tensile strength of 1.5 GPa or higher, attained after press hardening, makes it difficult to guarantee the life of the tools used for piercing the pilot hole and the subsequent hole expansion. Alternatively, creating the pilot holes prior to press hardening, in order to reduce tool wear, is unfeasible because it is difficult to achieve precise shapes and alignment at high temperatures and under the phase transformations during quenching process. Therefore, we propose a hole-flanging process, wherein the piercing and hole-flanging operations are performed sequentially during the die quenching process. In this study, the thickness reduction, surface hardness distribution, and edge cracking of the flanged holes formed using the proposed method are evaluated through experiments and FEM simulations.

2. Experimental Setup

The experimental apparatus and the operating sequence are presented in Figure 1. The proposed method involves performing the hole-flanging operation after a piercing operation within a single stroke. This sequence could suppress the failures caused by the misalignment of the pilot hole and the hole-flanging punch. Each punch installed on the facing side of the tool acted as a die during the operation of the corresponding opposite punch.

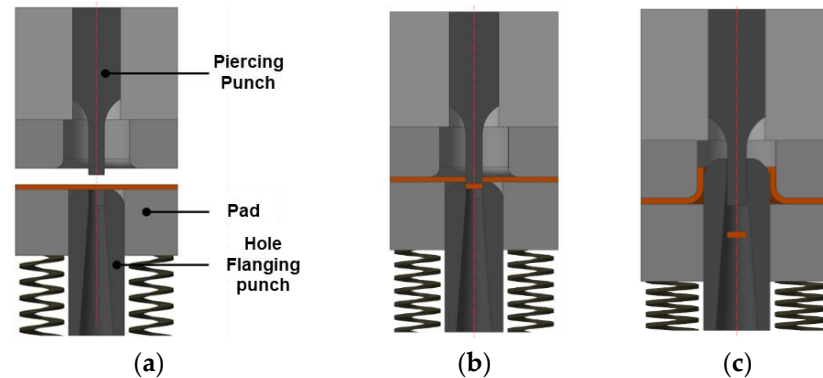


Figure 1. Concept of high-temperature, simultaneous piercing and hole-flanging process; (a) initial stage; (b) pilot hole piercing process; (c) hole-flanging process.

Figure 1b shows the first piercing operation, wherein a pilot hole with a diameter of 8 mm was formed. As the slide descends, piercing and scrap ejection were performed by inserting the piercing punch into the hole-flanging punch mounted on the opposite tool side. During this operation, the hole-flanging punch acts as a piercing die, and springs located at the bottom of the pad limit its movement. After piercing the pilot hole in the first operation, a hole extrusion process is performed using the hole-flanging punch by expanding the pilot hole to create a collar with a diameter of 17.5 mm on the cut-out openings, as shown in Figure 1c. During this second operation, the piercing punch acts as a hole-flanging die by simultaneously lowering the piercing punch and the pads supporting the material flange.

These operations are also performed at specific temperatures during the die quenching process to control the formability and tool wear of press-hardened steels. The cooling channels of the tool were designed to ensure a sufficient quenching rate in order to secure

the martensitic transformation of the PHS. In addition, the quenching rate of the flanged hole was controlled separately to ensure adequate strength during thread forming.

3. Simulations

The proposed process was verified using the finite element code, DEFORM-3D, to investigate the feasibility of simultaneous high-temperature piercing and flange hole expansion. The process of cooling the heated PHS blank to the initial temperature of the piercing process was analyzed; this was followed by sequential analyses of the piercing and hole-flanging processes. For the analysis, 1.5 GPa-grade PHS with a thickness of 1.6 mm was employed. Properties related to the phase transformation, which were required for the analyses, were calculated using JMatPro. The flow stress, elastic modulus, Poisson's ratio, thermal expansion coefficient, thermal conductivity, heat capacity, and time-temperature-transformation (TTT) curve, according to the material temperature and strain rate, are shown in Figure 2.

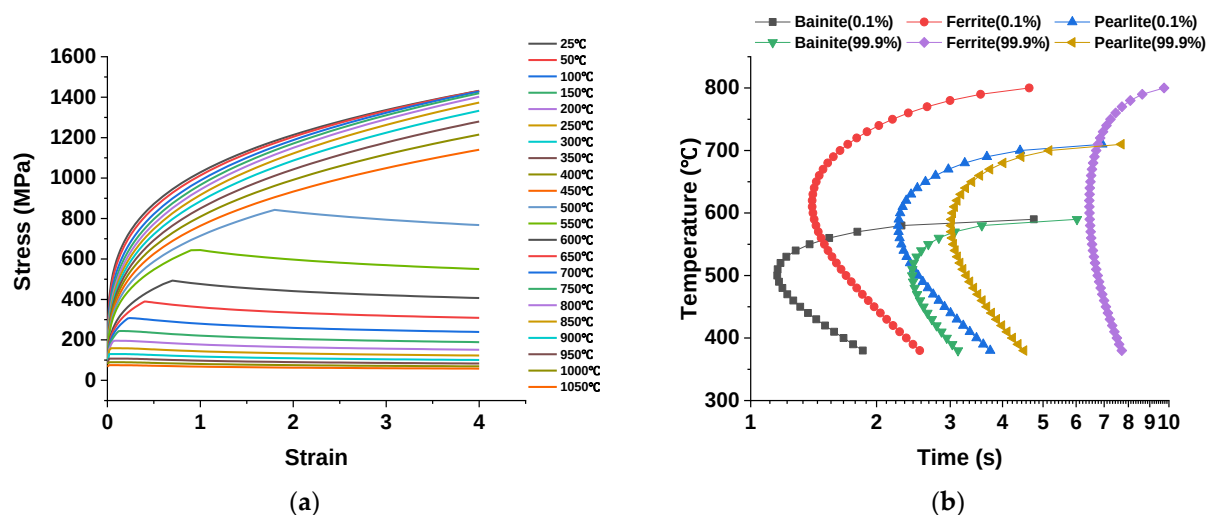


Figure 2. Material properties applied in analysis: (a) flow stress (strain rate 0.01/s); (b) TTT curve.

3.1. Simulation of the Piercing Process for Forming the Pilot Hole

The model used in the analysis featured a piercing hole diameter of 8 mm and a flanged hole expansion diameter of 17.5 mm. As shown in Figure 3a, the PHS blank is modeled as rigid-plastic, and the die is modeled as rigid body. To reduce the analysis time, a 2D axisymmetric model and a quad type mesh were applied. To improve the precision of the piercing process, we applied a fine mesh of 0.01 mm to the sheared zone. To enhance the precision of the analysis of the piercing process, a dense mesh was selectively applied to the trimmed edge. In terms of the die temperature, A temperature of 25 °C was applied for the entire die, except for the pad, to quench the flange hole expansion area. A temperature of 10 °C was applied considering the cooling channel installed to quench the flange. We applied the heat transfer coefficient of 2.1 kW/m²K and a friction coefficient of 0.12 for the contact between tools and PHS material. A punching speed of 54.1 mm/s, the same as that used in the piercing test, was applied.

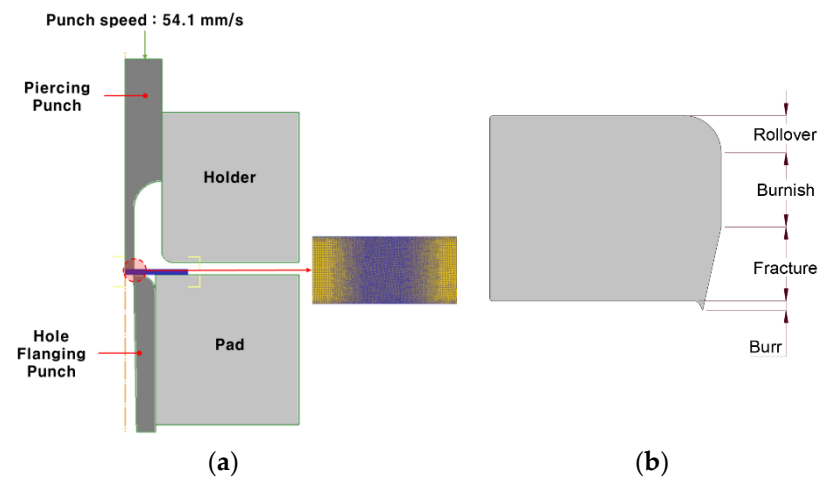


Figure 3. (a) Finite element modeling of the piercing process and analysis conditions; (b) measurement of shear plane distribution.

The shear plane quality of the pilot hole formed during the first piercing process affects the forming limit of the flange hole expansion, which is the subsequent process. Accordingly, it is necessary to apply a fracture criterion constant under which the simulated shear plane formed in the piercing process has a cross-section similar to that observed in the experimental result. The characteristics of the shear planes obtained by applying fracture threshold constants of 0.01, 0.011, and 0.012 were analyzed; these are shown in Figure 3b. Based on the analysis, conditions that afforded results similar to those observed in the piercing experiment were selected. According to the results of the shear analysis with respect to the fracture threshold constant, which are shown in Figure 4, a fracture threshold constant of 0.011 afforded a simulated shear plane cross-section that was the most similar to that observed in the experiment. Furthermore, according to the temperature and phase distribution of the material after the piercing process, as shown in Figure 5, the temperature of the region to be extruded into a collar exceeded 640 °C and the austenite volume fraction was 0.99. Hence, it was concluded that there were no issues pertaining to a decrease in formability owing to the increase in strength and the quenching before hole-flanging.

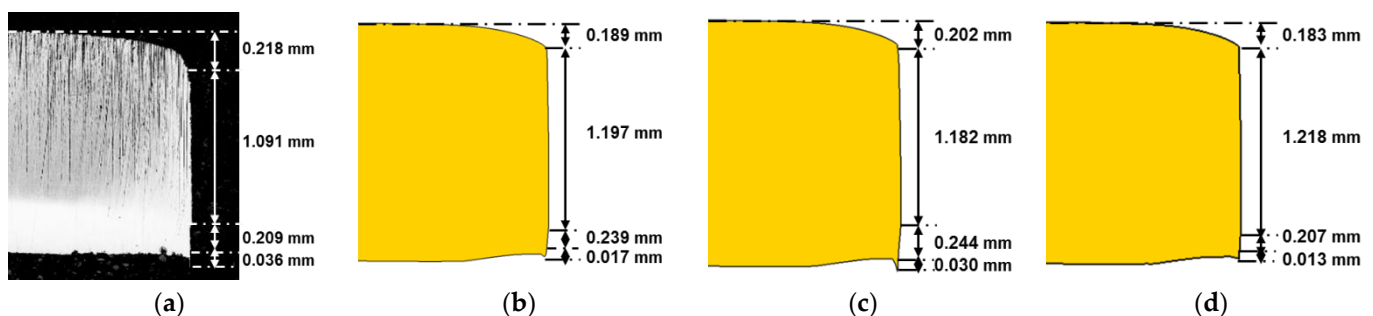


Figure 4. Comparison of the experimental and analytical shear plane distributions; (a) experimental shear plane; (b) C 0.01; (c) C 0.011; (d) 0.012.

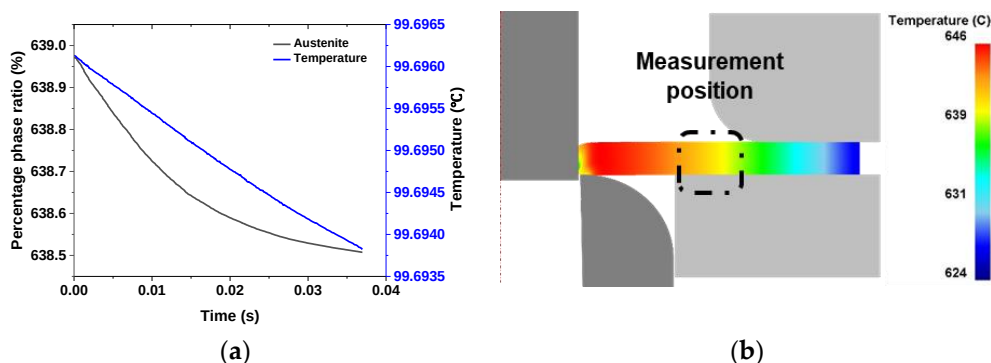


Figure 5. Material temperature and phase distribution after the piercing process; (a) austenite volume fraction/temperature change; (b) temperature distribution.

3.2. Simulation of the Hole Extrusion Process

The high-temperature flange hole expansion formability was predicted by applying the piercing analysis results described in Section 3.1. The piercing punch and holder were configured to descend at a rate of 54.1 mm/s, and a load of 191.1 N was applied on the pad through a pressure source installed on the lower side. The die was then cooled for 9 s. According to the temperature and phase distribution of the final product, which are shown in Figure 6, the temperature of the formed section was 630 °C or higher until the final forming process, and the austenite volume fraction was 0.99. After die cooling, the end of the flange hole expansion section featured an austenite distribution of 99.4% at 443 °C, whereas the cooled flange had a martensite distribution of 98.7% at 151 °C. Based on the product forming concept, it is judged that the flange hole expansion section was quenched appropriately, which suppressed the increase in strength. The thickness distribution according to the stroke used in the product forming process is shown in Figure 7; the thickness at the final forming depth was 0.948, indicating that the thickness decreased by 40%.

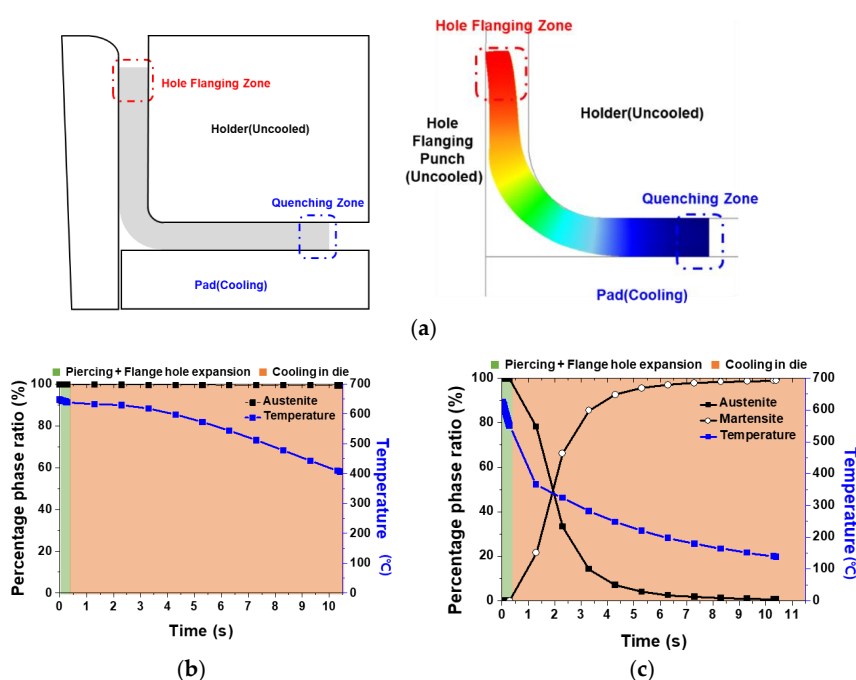


Figure 6. Change in phase distribution with respect to position during the piercing and hole-flanging process; (a) measurement positions of temperature and phase distribution; (b) percentage phase distribution at hole flanging zone; (c) percentage phase distribution at quenching zone.

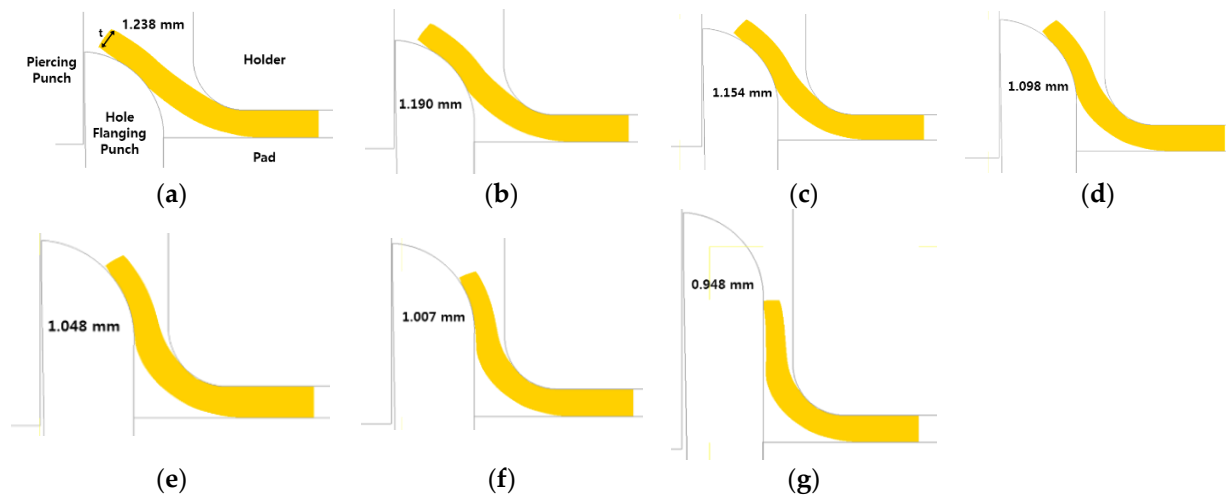


Figure 7. Change in material thickness according to stroke; (a) stroke 5 mm; (b) stroke 6 mm; (c) stroke 7 mm; (d) stroke 8 mm; (e) stroke 9 mm; (f) stroke 10 mm; (g) stroke 11 mm.

4. Experiments

4.1. Experimental Conditions

In the experiments, the piercing operation and the subsequent hole-flanging operation within a single stroke were performed using 1.6 mm-thick PHS from POSCO. The process was controlled such that, after heating to complete the transformation into austenite at 950 °C, the material was transferred to a die and formed at a temperature of 650 °C. A forming rate of 54.1 mm/s was applied for both the pilot hole piercing and the hole extrusion processes. The lower pad was maintained at 10 °C to ensure quenching conditions for the martensitic phase transformation of the material. Furthermore, a 68.8 kN of gas spring was applied to the lower pad in order to withstand the load generated during the pilot hole piercing process. The clearance between the tools is 5% of the thickness of the PHS material.

4.2. Fracture Analysis of High-Temperature Hole-Flanging Specimen

To analyze the thickness distribution and fractures occurring during the process, a sequential piercing–flange hole expansion forming experiment based on stroke height was conducted, the results of which are shown in Figure 8. As the stroke progressed, the thickness of the pilot hole edge decreased owing to the hole expansion effect. To predict the occurrence of fractures based on the change in the thickness of the piercing edge according to the stroke, the thickness of the piercing edge end was measured; these results are presented Figure 9. The thickness reduced by 18% or more for a stroke of 5 mm and by approximately 40% at the final stroke. Thus, similar to the forming analysis results, it was found that thickness tended to decrease as the stroke increased.



Figure 8. Extruded collar shape according to stroke.

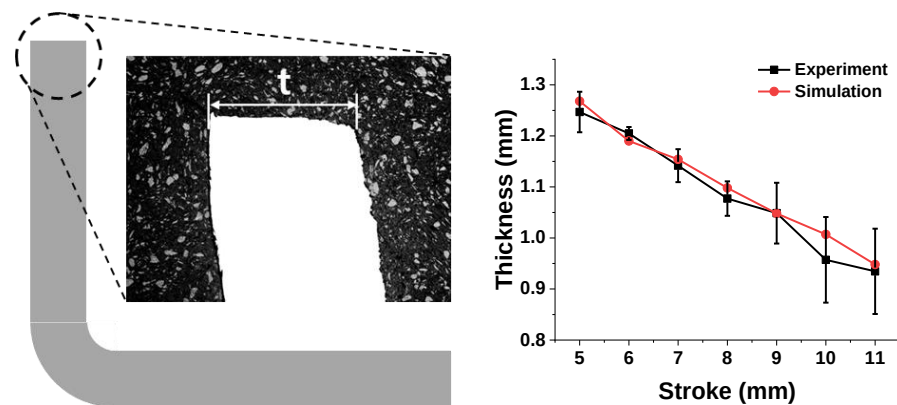


Figure 9. Change in edge thickness according to stroke.

In the hole extrusion process, the splitting (cracking) of the pilot hole limits the height and diameter of the extrusion. This splitting is strongly influenced by the quality of the shear plane created during the piercing of the pilot hole [11–14]. The shape of the flanged hole edge was measured at each stroke, and the results are shown in Figure 10. According to the crack measurements at each stroke, a crack depth of 20–30 μm was observed under a stroke of 9 mm or less, which is similar to the burr length generated during the piercing process. Crack depths of 100 μm or more occur under a stroke of 10 mm or more. This is likely because the minute cracks generated in the burr expand owing to the expansion of the hole as the stroke increases. At a stroke of 9 mm, which is before the cracks expanded inwards, the inner diameter was 14.6 mm and the HER was 82.5%. Using a flat bottom punch similar to the one applied in this study results in a lower edge stretchability than when using a spherical or conical punch [15,16]. This indicates superior hole expansion formability for AHSS (HER 30–40%) and martensitic steel (HER 5–25%) [9].

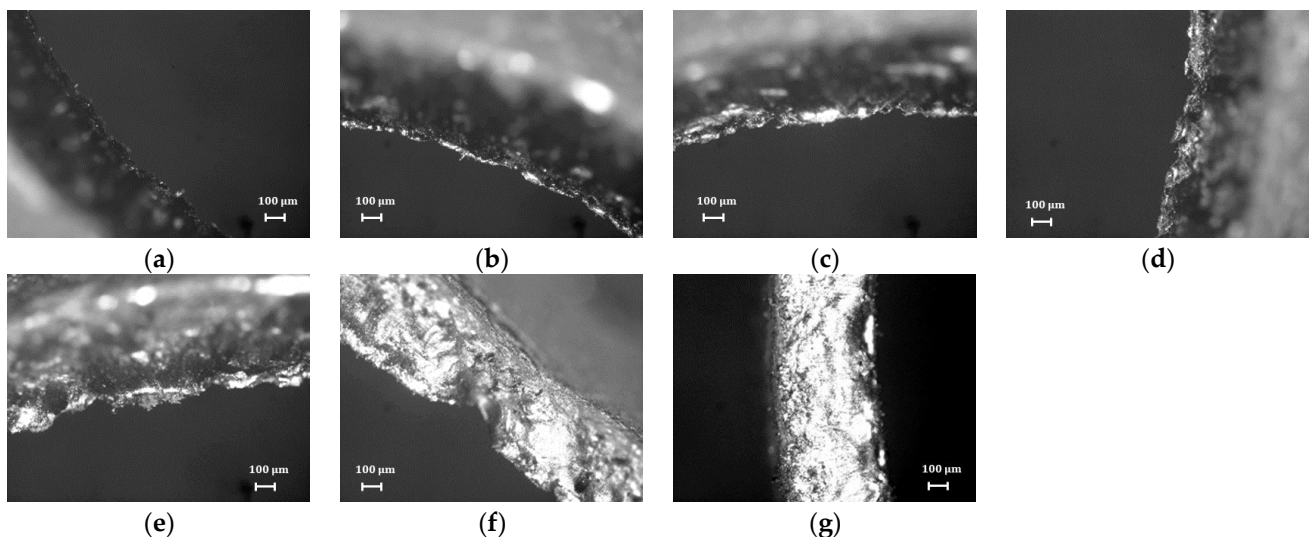


Figure 10. Edge cracks according to stroke; (a) stroke 5 mm; (b) stroke 6 mm; (c) stroke 7 mm; (d) stroke 8 mm; (e) stroke 9 mm; (f) stroke 10 mm; (g) stroke 11 mm.

4.3. Hardness Analysis for High-Temperature Hole-Flanging Specimen

To examine the efficiency of the temperature control applied during the flange hole expansion forming process, the hardness at the cross-section of the final product was measured. As shown in Figure 11a, using a Micro Vickers hardness tester, hardness was measured, starting from the end of the product flange, at 50 μm intervals by applying a

force of 980 mN for 10 s. As indicated by the hardness measurements for each location (Figure 11b), hardness was relatively low in the hole flanging section, which includes the section where strength was reduced. However, a hardness of Hv0.1 400 or higher was observed in most areas. It was concluded that, because the pad was cooled during the piercing process and the side walls of the hole flanging punch were close to each other, the side wall of the hole flanging punch was also cooled owing to heat transfer. In addition, it was judged that the end of the flanged hole exhibited low hardness because its contact with the side wall was relatively limited.

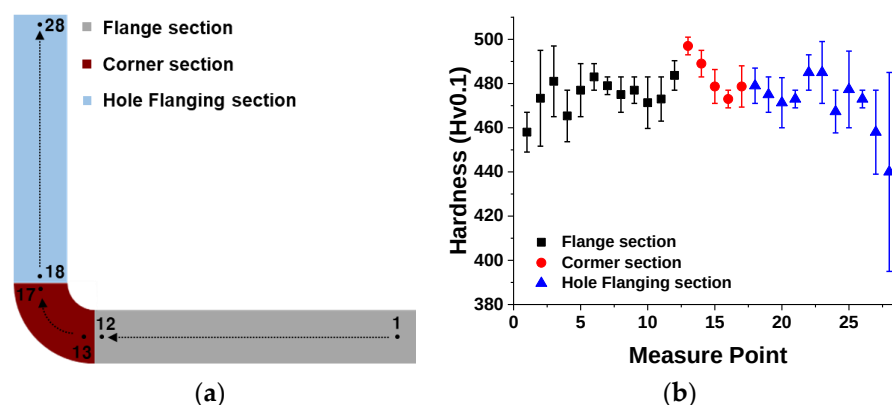


Figure 11. Hardness of hole-flanged samples; (a) hardness measurement positions; (b) hardness measurements with respect to position.

5. Conclusions

This study developed a process involving a piercing operation followed by a hole-flanging operation within a single stroke for the formation of flanged holes, which can be used for the mechanical fastening of hot-stamped components. To prevent uneven alignment defects due to thermal deformation caused by heating the hot-stamped material to high temperatures, a die structure was designed, using which a flanged hole can be formed by operating the lower pad of the material after the piercing operation within a single stroke. Using computer-aided engineering, the forming feasibility of the piercing-flange hole expansion process employing the designed die structure and the forming method was investigated. The results demonstrated that formability could be ensured because the temperature of the product was maintained at 400–600 °C during the process.

Fracture analyses were conducted considering the edge of the product end for each stroke. At a stroke of 9 mm or less, crack depths of 20–30 μm were observed in the formed product; in this case, cracks were created in the burr area generated during the product piercing process. Crack depths of 100 μm or more were noted under a stroke of 10 mm or higher. When the hole expands, the cracks generated in the burr area expand inwards, resulting in causing fractures.

As the stroke increased, thickness was reduced due to the elongation caused by hole expansion. Using tapping for mechanical fastening was considered difficult owing to the 40% reduction in thickness at the final stroke. However, the proposed high-temperature piercing-flange hole expansion process demonstrated an HER of 118% at the final stroke and an HER of 82.5% at a stroke of 9 mm (i.e., before the cracks expand inwards). As such, hole expandability increased substantially, as compared to that in general martensitic steel (HER of 5–25%); this ensured the formability of flange hole expansion for the mechanical fastening of ultra-high-strength steel plates.

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