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Geometrical and Mechanical Characterization of JSC1180YN Ultra-High Strength Steel Tailored Blanks Produced by Successive Forging

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ABSTRACT

Successive forging is a multi-stage process for tailoring ultra-high strength steel (UHSS) sheets thickness which is normally done using rolling or welding process. These two processes often have problems of long transition zone and degradation of mechanical properties. This study investigates the geometrical change and deformation at the transition zone after successive forging process. A 1.6 mm thick JSC1180YN UHSS sheet was subjected to successive forging process using a 1500-kN servo press and an automatic feeder, aiming to achieve a thickness reduction of 0.8 mm. 20 forging steps were set with a constant feed rate of 5 mm. The punch was designed with 1 mm chamfered edges to promote uniform strain distribution, while the lower die is set to be flat. The results showed that the thickness reduction to 0.8 mm was maintained within ±0.1 mm, with an increase of 0.84% in width and 8.1% in length. The geometric control was followed by an improvement in mechanical properties, where there was an increase in Vickers hardness from 415 HV to 442 HV. Tensile testing showed an increase in ultimate tensile strength of 37.5%, while a reduction in ductility was observed due to strain hardening. The tailor forged blanks maintained a high structural integrity. Successive forging can shorten the transition zone length with minimal impact on shape changes. Overall, successive forging proves to be a process that can effectively modify the geometry and mechanical performance, providing an alternative to automotive applications.

Keywords: Ultra-High Strength Steel (UHSS); successive forging; tailored blanks; geometrical variation; transition zone

INTRODUCTION

Ultra-high strength steel (UHSS) is widely used in the production of automobile body structures, primarily for body-in-white (BIW) parts like frames and crash-related components, due to its high strength-to-weight ratio, which is a key characteristic for modern automotive engineering (Li et al. 2023; Liang et al. 2021; Lee et al. 2017; Nonaka et al. 2003; Pereira et al. 2015; Van et al. 2011). Typically, UHSS has a yield strength of more than 1200 MPa, making it much stronger than conventional steel. These steels are engineered to achieve a balance between ultra-high strength, high ductility, and excellent fracture toughness, where these are essential properties for performance and safety (Pereira et al. 2015; Walp, 2007; Jaroni et al. 2010). The application of UHSS helps in vehicle lightweighting, which enhances fuel economy and lowers emissions, thus contributing to a greener and more efficient transportation sector (Merklinger et al. 2008). The strength-to-weight ratio of UHSS is three to four times more preferable than traditional steel grades, allowing thinner and lighter parts to be made without decrease in strength (Li et al. 2023; Pereira et al. 2015). UHSS is tough and strong, and therefore enhances crashworthiness, allowing the vehicle to absorb significantly more energy in collisions and provide occupants with a higher level of protection (Jaroni et al. 2010).

Successive forging of UHSS for controlling the thickness variation is relatively new in this area of applications, where the process is typically accomplished through tailored rolled blank (TRB) or tailored welded blank (TWB) (Cheng et al. 2019; Sun et al. 2018; Tajul et al. 2021; Romzi et al. 2019). Successive forging is a multi-stage method, where the punch strikes the workpiece in a series of controlled blows to progressively shape it through dynamic loads (Galiullin et al. 2021; Iliukhin et al. 2019). It generates less waste than other processing techniques (Galiullin et al. 2021; Iliukhin et al. 2019). The near-net shape capability of forging reduces material usage and the need for extensive machining, which results in lower material consumption and related costs (Galiullin et al. 2021; Iliukhin et al. 2019). Techniques that improve the life of forging dies, such as advanced die materials and die repair methods, make successive forging competitive from an economic viewpoint by lowering tooling costs (Pierronnet et al. 2005; Fairclough, 2005; Vorel et al. 2016). Successive forging processes, especially those optimized with the aid of highly advanced computer models, can become the source of rapid production cycles and reduced overall lead times, valuable for use in the automotive industries (Galiullin et al. 2021; Ikumapayi et al. 2020; Iliukhin et al. 2019). The use of computer-aided engineering (CAE) and design optimization techniques ensures that process parameters such as billet temperature, die temperature, and stroke length are finely tuned to produce high-quality forged products (Talekar et al. 2019; Ma et al. 2022; Kitayama 2024).

During initial passes of forging, strain is concentrated largely on the surface of the workpiece (Xu et al. 2024). As forging proceeds, the strain begins to penetrate towards the centre (Xu et al. 2024). Increasing the forging ratio decreases the volume and thickness of proeutectoid cementite networks and acicular structures in ultra-high strength steel (Kang et al. 2012; Zhang et al. 2024). The structures break down into discrete particles and subsequently spheroidize (Kang et al. 2012; Zhang et al. 2024). This is a significant transformation because it affects the mechanical properties and the overall geometry of the steel (Kang et al. 2012; Zhang et al. 2024; Zainon et al. 2019). Higher forging ratios also result in a more uniform distribution of small-angle martensite grains, which enhances the steel's strength, plasticity, impact toughness, and tensile strength (Hauger, 2006; Kim et al. 2016). Additionally, lower deformation temperatures result in finer and more inhomogeneous grain sizes (Hauger, 2006; Kim et al. 2016). This indicates that the combination of forging and subsequent temperature treatments significantly changes the microstructure and grain size, influencing the elastic properties and overall geometry of the steel (Hauger 2006; Kim et al. 2016; Zailani et al. 2023).

Successive forging enhances the strength of ultra-high strength steel (Hauger, 2006; Kim et al. 2016). The high forging ratios provide higher ultimate tensile strength and yield strength due to grain refinement and increased dislocation density, while showing significant strengthening by deformation twinning at the same time (Hauger, 2006; Kang et al. 2012; Zhang et al. 2024). UHSS demonstrates persistent plastic deformation under dynamic compression, with true strain exceeding 150% after the ultimate strength due to high-density dislocations and grain boundary transformation (Hauger, 2006; Kim et al. 2016). The true stress-strain curve of UHSS shows cyclic loading that has influence on mechanical properties by reducing slope of the unloading and reloading curves and increasing strain (Xu et al. 2024; Zhang et al. 2024). Flow stress increases initially to a peak and then decreases to a steady state while tensile deformation (Xu et al. 2024; Zhang et al. 2024). Successive forging process causes extensive plastic deformation, which raises the chance of brittle fracture in UHSS components (Hadi et al. 2012; Lee et al. 2010). The location of strain distribution during forging process is mostly on the surface initially but tends to extend inward towards the centre in later passes (Xu et al. 2024). Successive forging process increases the hardness of UHSS, where the high forging ratios intensify microhardness through grain refinement and dislocation density (Kang et al. 2012; Zhang et al. 2024). Formation of fine carbides and martensite grains during the process is accountable for increased hardness (Hauger 2006; Kim et al. 2016).

The transition zone in UHSS components after successive forging is a significant microstructural feature that arises because of inconsistent material flow during multi-step forming (Romzi et al. 2019; Ma et al. 2022). Transition zone has a sharp gradient in strain accumulation and forms at interfaces where less deformed material is forced into heavily worked regions (Ikumapayi et al. 2020; Romzi et al. 2019). While its formation is understood, the precise mechanisms responsible for its microstructural evolution and final characteristics are not yet fully investigated. This varying degree of plastic deformation leads to significant microstructural variations within the zone (Zhang et al. 2024; Romzi et al. 2019). The zone undergoes complex thermo-mechanical processing, with localized phase transformations and substructure evolution, that significantly influence the final microstructure (Xu et al. 2024; Hussin et al. 2011; Romzi et al. 2019). The transition zone possesses a significant change in mechanical properties (Kang et al. 2012; Romzi et al. 2019). Thus, it is essential to understand the transition zone to forecast the overall performance and integrity of UHSS components after going through successive forging. In this study, a tailored blank of ultra-high strength steel (UHSS) by successive forging was investigated, where the focus of the study is on the geometrical and transition zone changes.

METHODOLOGY

EXPERIMENT DETAILS

The concept of thickness reduction by successive forging (as illustrated in Figure 1) was introduced as an alternative replacement to the conventional rolling process, where the reduction in thickness is achieved through step-by-step compression. In this experiment, the JSC1180YN UHSS was used as the main material for investigation. The low ductility of JSC1180YN steel significantly affected its plastic deformation capability, which makes the thickness reduction by conventional rolling process ineffective and almost unachievable. This poor formability aspect (low ductility) also results in high risk of early cracking. Furthermore, the high strength and high hardness will result in an absolute high rolling force as the area of reduction is normally large in the rolling process.

The die set of successive forging consists of three main parts i.e. the punch, die, and a pneumatic feeder that feeds the steel sheet into the forging area. A low power microcontroller is used to control the feeder movement relative to the ram stroke. The dimensions of the JSC1180YN UHSS sheet are 1.6 mm x 200 mm x 100 mm in thickness, length and width, respectively. The successive forging process is carried out using a 1500-kN mechanical servo press with a forging speed of 10 mm/s. A pneumatic feeder is used to feed the sheet, where the system is programmed to synchronize the feeder movement precisely at 5 mm per stroke with the fixed ram stroke of 2.1 mm. A thickness reduction of 0.8 mm is achieved through a single pressing action, set at each feed interval, where the accuracy of thickness reduction is maintained within ±0.1 mm throughout the forging step. The steel sheet was lubricated with water soluble press oil lubricant prior to successive forging, where the ratio of press oil to water is 1:2. The mechanical properties of JSC1180YN UHSS sheet and the process parameters for successive forging on UHSS sheet are given in Table 1 and Table 2 respectively.

The punch used in the experiment featured a flat center surface with chamfered edges of C = 1 mm on both sides, as shown in Figure 2. These chamfers were implemented based on the numerical simulation findings (Ma et al. 2022), which showed that such a geometry effectively minimizes stress concentration at the contact zone during the forging of ultra-high strength steel. This design produced a more seamless transition in material flow and helped in uniform distribution of strain throughout the specimen length, thus reducing the risk of localized thinning or tearing that often occurs with sharp-edged punches (Ma et al. 2022). Figure 3 shows the die set for successive forging at the press machine.

The geometrical and mechanical changes of the JSC1180YN UHSS sheet were quantified using high-precision instrumentation. Thickness and width measurements were conducted using a digital micrometer screw gauge (Mitutoyo 342-361-30) with an accuracy of ±0.001 mm. Each measurement was repeated three times to ensure statistical reliability and a consistent average value for analysis (Sharma et al. 2023). The Vickers hardness was evaluated across the forging steps using a Vickers hardness tester (Wilson Instruments Instron 402MVD) under a constant load of 1 kgf (HV1) for a dwell time of 15 seconds. These localized hardness measurements are the method to visualize the effects of strain hardening induced by the successive forging process (Kang et al. 2012; Zhang et al. 2024).

To further evaluate the mechanical performance, tensile load, change in ultimate tensile strength and validate the hardening effects, the tensile tests were performed to the no-forged and successive forged blanks. The tests were carried out according to the ASTM E8 (mini size) tensile test standard, using a universal testing machine (100 kN Shimadzu AGX-V2). The dimensions of the tensile specimens are shown as in Figure 4. The comparison was made between the 0.8 mm no-forged and 0.8 mm successive forging blanks.

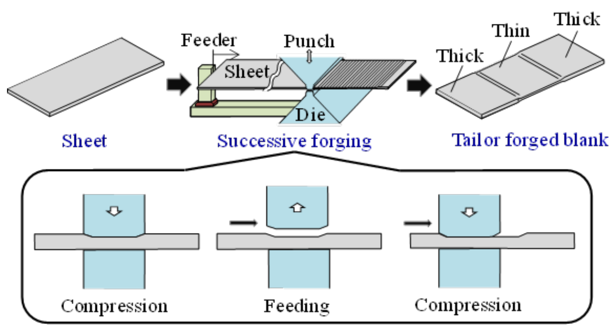


FIGURE 1. Successive forging of JSC1180YN UHSS sheet: experimental setup and progressive stages

TABLE 1. Dimensional and mechanical properties of JSC1180YN UHSS sheet

Parameter	Set Value
Length	200 mm
Thickness	1.6 mm
Width	100 mm
Tensile Strength	1242 MPa
Ductility (%)	8.1
Hardness	414 HV

TABLE 2. Process parameters for successive forging of JSC1180YN UHSS sheet

Parameter	Set Value
Ram Stroke	2.1 mm
Constant feed	5 mm per stroke
Forging speed	10 mm/s
Punch and die material	SKD 61 tool steel
Lubricant	Water soluble press oil

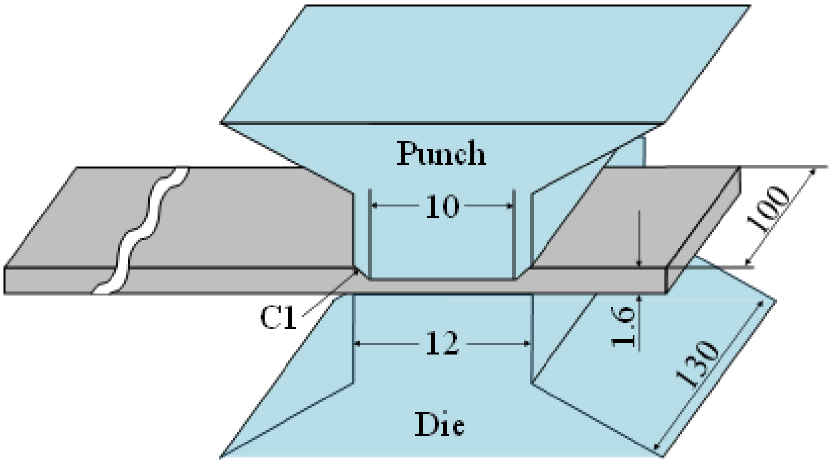


FIGURE 2. Dimensions of punch, die and JSC1180YN UHSS sheet

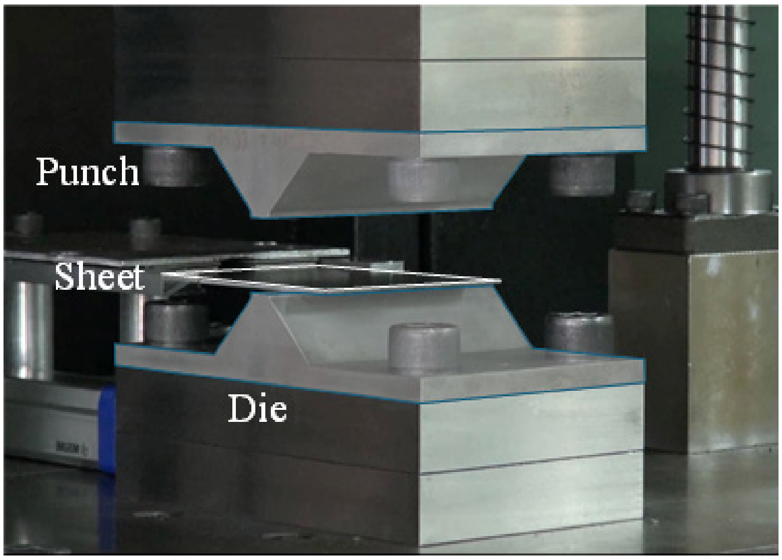


FIGURE 3. Experiment setup for successive forging of JSC1180YN UHSS sheet

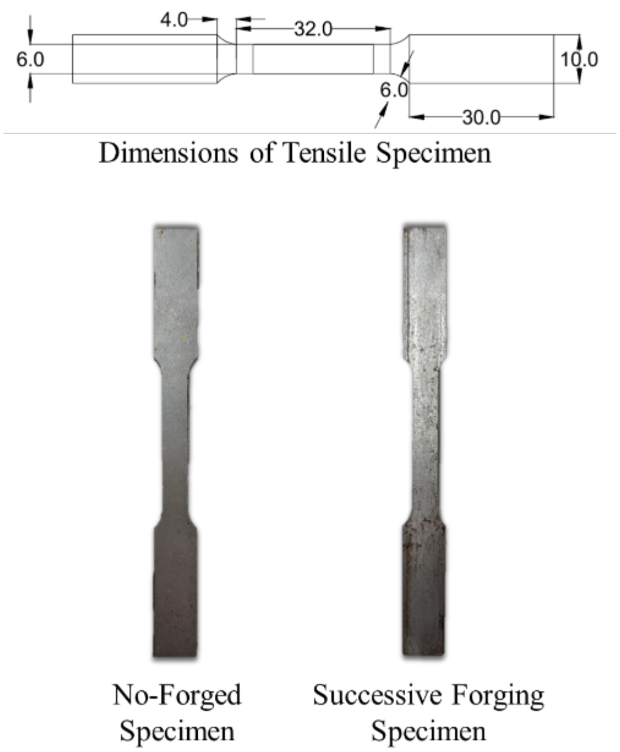


FIGURE 4. Dimensions of the tensile specimens

RESULTS AND DISCUSSION

GEOMETRICAL AND SHAPE CHANGES

In general, successive forging change the steel sheet in length, width, and surface pattern as illustrated in Figure 5. The initial shape of the workpiece is flat and rectangular, with its surface appearing relatively smooth and featureless. After successive forging, the UHSS sheet increased in length, slightly in width, while showing a series of uniformly spaced, parallel line markings across its surface. Length increased by 8.1% of it's original length (Figure 6), while just 0.84% increase in width The change in length is larger than the change in width due to the punch design. Punch design affects the deformation pattern, where the friction at the punch-workpiece interface affects material flow (Ma et al. 2022). The punch-workpiece contact surface in latitudinal direction is much larger than in longitudinal direction, thus this frictional constraint retards the plastic flow of metal on the surface in width direction.

The high forging force applied to the sheet caused the punch shape to stick to the surface and create ridge and valley patterns and line markings. Although the line markings are obvious, the depth of ridges and valleys that extend longitudinally across the successive forging area is almost negligible as in Figure 7. The targeted thickness reduction in this experiment is 0.8 mm, while the average difference between highest and lowest depth of the ridges and valleys is only 0.042 mm or 5.25% of the targeted thickness reduction The low and consistent depth of the mark pattern is related to the design of punch and die, which continuously displace and deform the material in an almost fully flat manner for every punch stroke, without compromising the targeted reduction in thickness (Sharma et al. 2023). The almost unnoticeable pattern of ridges and valleys show that successive forging is possible for a highly controlled and precise surface patterning mechanism operation for thickness reduction.

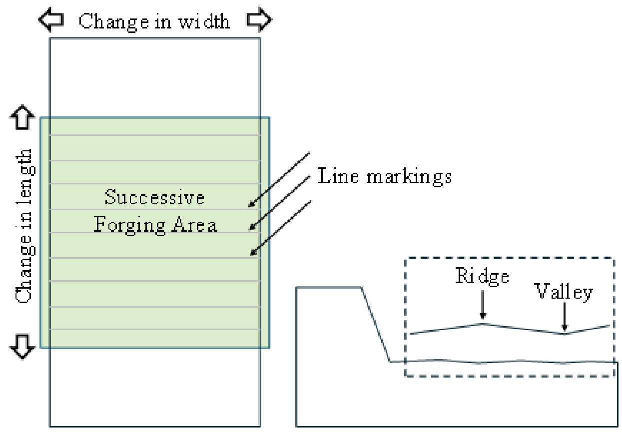


FIGURE 5. Geometrical changes at JSC1180YN UHSS sheet after successive forging

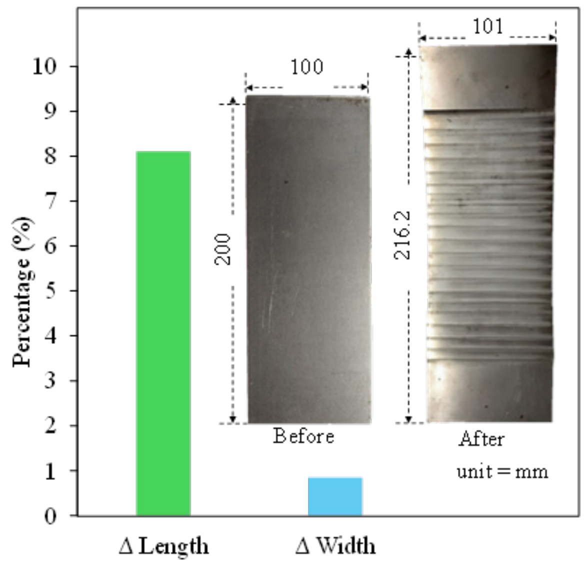


FIGURE 6. Change in length and width after successive forging

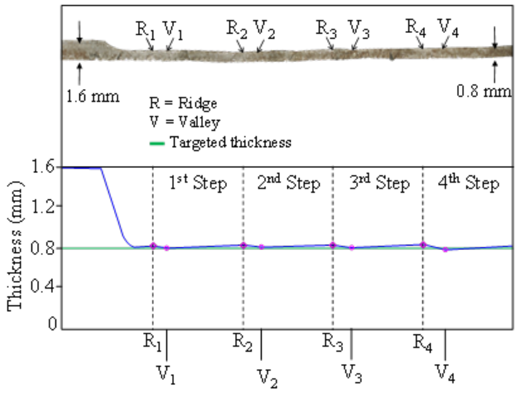


FIGURE 7. Ridge and valley height for step 1 – 4

The side view and angle of curvature of JSC1180YN UHSS sheet is shown in Figure 8. The high pressing force of the punch at every stroke results in a slight bend (upward pattern) to the workpiece. For the initial forging steps, the angle seems unnoticeable, where the sheet maintains a relatively flat profile during the initial stages of successive forging. This suggests that the first few forging steps have insufficient cumulative strain to induce significant bending. From forging step 9 onwards, the inclination becomes large and obvious, where the resultant bend continues until the final forging step. The increase in bending angle is due to the cumulative effect of plastic deformation. The progressive reduction in thickness and inherent material flow becomes more significant, causing the sheet to bend. For forging, the bending phenomenon is inevitable, especially as the sheet's formability characteristics are further altered under increasing strain (Ma et al. 2022). However, the resultant inclination throughout the process is relatively low when compared to the tailored rolled blank (Cheng et al. 2019; Sun et al. 2018; Tajul et al. 2021; Romzi et al. 2019).

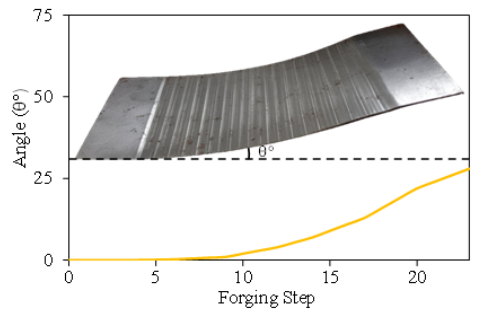
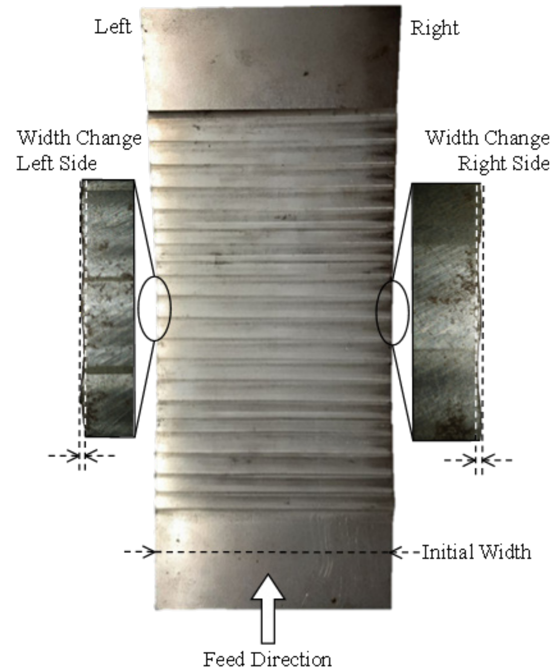


FIGURE 8. Inclination of JSC1180YN UHSS sheet after successive forging

The overview of the sheet's width profile after successive forging is presented in Figure 9(a), where the left and right side of the sheet is plotted in Figure 9(b) and 9(c). The black lines in both graphs represent the initial width, which helps to show the change in width for both sides clearer. The lines representing the width of the left and right side of the UHSS sheet after successive forging show periodic oscillations. These graphs indicate that the forging process has induced a wave-like variation in the sheet's width. Specifically, the forged width profile shows a consistent wavelength, corresponding to the periodicity of the die features. The amplitude of these width changes in the provided graphs shows the localized material flow in the transverse direction. The average width of the forged sheet also increased compared to the original, which might be lateral spreading of material during successive forging.

The initial width of the workpiece is 100.0 mm. In the first forging step, there is a sharp increase in width, reaching just above 101.0 mm. The width observed is due to the material flow caused by compressive forces acting on the UHSS sheet during the successive forging process. The following forging steps show a periodic pattern, where the width fluctuates between 100.5 mm and 101.5 mm. This phenomenon indicates the repeating cycle of material expansion and redistribution, which is affected by factors such as tool geometry, frictional conditions, and the accumulation of strain (Ma et al. 2022; Kitayama, 2024). After the second step, the graph trend is more stable, where a more consistent deformation pattern is formed as the process proceeds. Despite the fluctuations on the change in width, the final width remains within a very small range of around ±1.5 mm.



(a)

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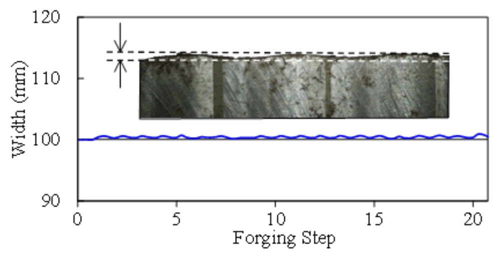
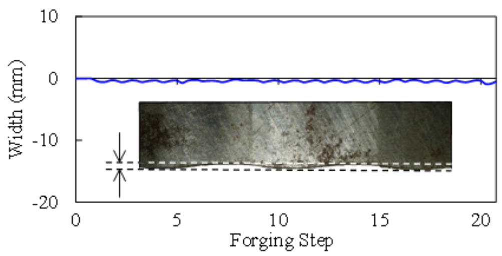


(b)



(c)

FIGURE 9. JSC1180YN UHSS sheet: (a) after successive forging, (b) change in width on left side (c) changes in width on right side

The initial width of the workpiece is 100.0 mm. In the first forging step, there is a sharp increase in width, reaching just above 101.0 mm. The width observed is due to the material flow caused by compressive forces acting on the UHSS sheet during the successive forging process. The following forging steps show a periodic pattern, where the width fluctuates between 100.5 mm and 101.5 mm. This phenomenon indicates the repeating cycle of material expansion and redistribution, which is affected by factors such as tool geometry, frictional conditions, and the accumulation of strain (Ma et al. 2022; Kitayama 2024). After the second step, the graph trend is more stable, where a more consistent deformation pattern is formed as the process proceeds. Despite the fluctuations on the change in width, the final width remains within a very small range of around ±1.5 mm.

The change in thickness of the JSC1180YN UHSS sheet after successive forging is shown in Figure 10. Upon the first forging step, a sharp reduction in thickness is observed, dropping from 1.6 mm to around 0.8 mm. The large reduction is due to the material being compressed according to the set parameters, where the expected thickness is 0.8 mm. After the initial drop, the thickness continues to decrease. The graph reveals a consistent reduction in thickness that oscillates at around 0.8 mm (±0.1mm), where the thickness gradually increases over subsequent forging steps. The minor increase in thickness occurs due to the overlapping areas between forging steps, which leads to alternating areas of greater and lesser compression (Romzi et al. 2019). The slight overall increase in average thickness after the initial drop shows that some of the effects by material flow counteract with further thinning and could increase the gap between expected thickness and actual thickness over time. Overall, the variation in thickness is considered consistent, as there are no cracks or defects formed on the forged workpiece.

The periodic oscillation of the thickness is due to the kinematic nature of successive forging. As the punch presses on the workpiece, the material flow is not perfectly uniform. There could be areas of greater compression where the punch initially contacts the undeformed material, followed by a shifting flow pattern as the punch overlaps with an already forged area. The alternating compression could be the primary cause of the thickness profile observed in a sinusoidal curve pattern. Additionally, the increasing average thickness over time might indicate the effects of work hardening. As the UHSS sheet is repeatedly deformed, its material properties change. It becomes harder and less ductile, resisting further thinning (Zhang et al. 2024). The increased resistance to deformation could lead to a slight increase in thickness observed. The finding shows that successive forging can achieve a uniform final thickness while preventing potential defects that could arise from non-uniform deformation.

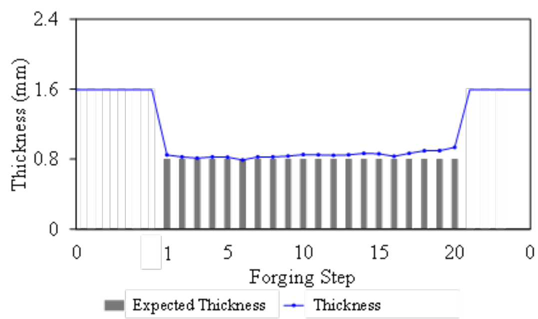


FIGURE 10. Change in thickness after successive forging

The relationship between the change in thickness and the change in width is shown in Figure 11. From the linear trend, the change in thickness was consistently accompanied by a corresponding change in width. This is due to material conservation during successive forging. The R^2 value shows that approximately 87.8% of the variation in the change in thickness can be explained by the linear relationship with the change in width, showing a reliable and predictable correlation between the two dimensions. The gradient of the line (0.7289) shows that for every 1.0 mm increase in width, there will be 0.7289 mm reduction in thickness. Under compressive forces applied during successive forging, material is displaced from the compressed direction and it flows perpendicularly to accommodate the applied strain, thus resulting in lateral expansion (increasing width) (Sharma et al. 2023). This behaviour aligns with the principle of constant volume in plastic deformation, where the overall volume remains largely unchanged (Kang et al. 2012). The result shows that width was effectively managed as a compensating dimension during thickness reduction for the UHSS sheet during successive forging.

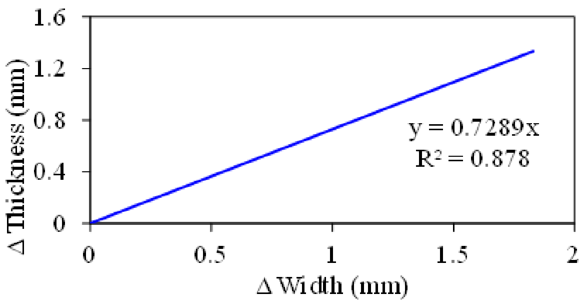


FIGURE 11. Relationship between the change in thickness and the change in width

TRANSITION ZONE AND DEFORMATION BEHAVIOUR

The side view of the JSC1180YN UHSS sheet after the first step of successive forging is shown in Figure 12. This figure shows a distinct transition zone between the sections that does and does not undergo successive forging process. The transition zone of the UHSS sheet shows a gradual reduction in thickness, where a transition phase can be observed in the graph below it. The initial thickness of the no-forged section is consistent at 1.6 mm before a sharp decline. The sharp reduction in thickness is the direct result of the compressive forces applied by the punch, which cause plastic deformation in the material. The shape of the punch is imprinted on the UHSS sheet. The transition zone itself is a region of non-uniform strain, where the material is subjected to both vertical compression and lateral displacement. The behaviour is supported by the principle of volume constancy in plastic deformation, where the material volume remains largely unchanged. Thus, the reduction in thickness is compensated by an increase in other dimensions within this zone, such as width and length (Kang et al. 2012). Furthermore, the localized strain within the transition zone can lead to work hardening, which influences subsequent forging steps and the final mechanical properties of the workpiece (Zhang et al. 2024), which will be discussed later.

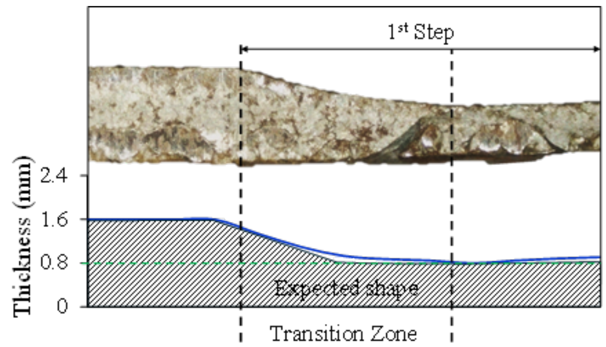


FIGURE 12. Side view of the first step of successive forging on JSC1180YN UHSS sheet

The side view of the subsequent steps on the JSC1180YN UHSS sheet after the first step (between steps 2, 3 and 4) of successive forging is shown in Figure 13. By looking at the shape of the UHSS sheet, the thickness is consistent across the successively forged steps. The observation is shown in the graph below it, where the measured thickness (blue line) is closely aligned with the expected thickness (grey area). The consistent thickness in these steps show that successive forging has achieved its purpose, where this method of thickness reduction can also refine the sheet's geometry, rather than large differences in the final thickness. Although the thickness is largely consistent, the graph does show some minor periodic fluctuations in the thickness. These subtle variations are due to the repeated and slightly overlapping contact between the forging dies and the UHSS sheet, which leads to minor differences in localized compression, but it is still within acceptable levels (Romzi et al. 2019). The overall consistency of thickness across successive forging steps shows a stable and well-controlled forging process, without compromising much for other dimensions (width and length).

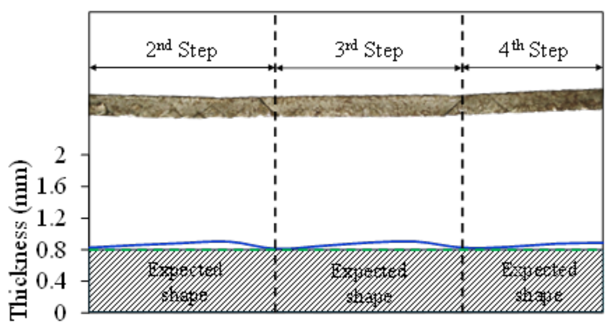


FIGURE 13. Side view of the subsequent steps of successive forging on JSC1180YN UHSS sheet

FORGING LOAD

The relationship between thickness and forging load of successive forging on JSC1180YN UHSS sheet is shown in Figure 14. The graph indicates an initial thickness of approximately 1.6 mm before the first forging step. Upon the first forging step, there is a sharp and significant drop in thickness, which is followed by an equally sharp increase in forging load, reaching a peak value of approximately 1000 kN. The phenomenon is a direct result of the compressive forces applied by the punch, which causes plastic deformation in the UHSS sheet and imprinting a shape onto the workpiece (Zhang et al. 2024). After the initial reduction in thickness, the thickness continues to decrease with minor fluctuations, while the forging load exhibits a slight decrease and then stabilizes. This result suggests that subsequent forging steps are more towards refining the geometry of the UHSS sheet rather than being a breakthrough like the initial forging step, where a lower and more consistent forging load is required. The consistency of the forging load in later steps shows that successive forging is a stable process that can achieve dimensional accuracy and prevent defects in the final workpiece. The stabilized forging load after the initial step is key to achieve the expected thickness in the UHSS sheet after successive forging.

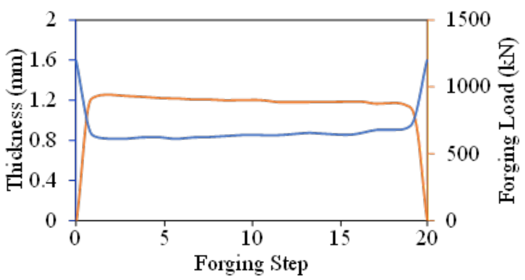


FIGURE 14. Relationship between thickness and forging load of successive forging on JSC1180YN UHSS sheet

VICKERS HARDNESS

The Vickers hardness of the JSC1180YN UHSS sheet across forging steps is shown in Figure 15 to visualise the effects of successive forging on localized strain hardening. Initially, the no-forged section exhibits a baseline hardness value of 415 HV. Upon the first forging step, there is a sharp and significant increase in hardness, which rises to a consistently high value of 442 HV. The sharp increase is a direct result of strain hardening, where plastic deformation induces a change in the material's microstructure by creating multiple dislocations, which impede further dislocation motion, thereby increasing the material's strength and hardness (Kang et al. 2012; Zhang et al. 2024). This hardened state remains consistent throughout the subsequent forging steps, showing that the material has reached a saturated work-hardened state, with minor fluctuations around an average value of 442 HV. The result is a desired outcome, as the successive forging process effectively enhances the hardness of the UHSS sheet, making it more resistant to indentation. The high hardness value shows that successive forging can help in achieving a uniform, work-hardened microstructure that is a crucial aspect to enhance performance of the UHSS sheet.

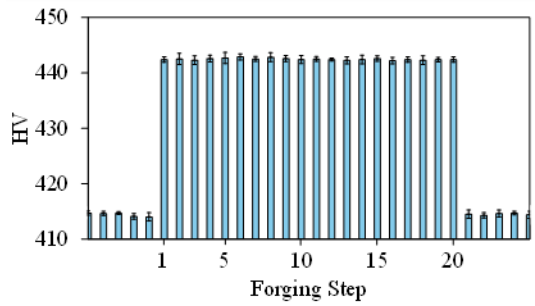


FIGURE 15. Vickers hardness of JSC1180YN UHSS sheet

TENSILE LOAD, STRENGTH AND DUCTILITY

The relationship between tensile load and stroke comparing between the no-forged and successive forging sheets is shown in Figure 16. The maximum tensile load for the 0.8 mm in thickness successive forging sheets is 4.92 kN, compared to only 3.58 kN for no-forged sheet, indicating a significant increase of 37.5% in load the sheet can withstand before necking. However, the stroke to the fracture point was found to be shortened for the successive forging sheet, as compared to the no-forged sheets.

The ultimate tensile strength and the percentage of the elongation for the successive forging and no-forged sheets were compared in Figure 17. The successive forging sheets recorded an ultimate tensile stress of 1025 MPa with 6.3% of elongation, while the no-forged is 746 MPa and 8.1% in ultimate tensile strength and elongation, respectively. The increase in strength for the successive forging blank is 37.5% as compared to the no-forged, but it came with a decrease in elongation of the sheet.

The increase in the tensile load and the ultimate tensile strength is due to strain hardening phenomenon during the successive forging process. As the punch hits the sheet, it induces plastic deformation in terms of compression, that generates a high density of dislocations and refines the grain structure. The microstructural changes create significant barriers to further dislocation motion during tensile testing. Since successive forging creates more dislocations of molecules within a small space of area (area under forged), higher stress levels are required to achieve additional deformation. The grain boundaries are in other way blocking the dislocation movement, resulting in increases of yield strength and hardness, but decrease in ductility (Kang et al. 2012; Zhang et al. 2024). The tensile test data provided a strong support for the improvement in hardness discussed earlier, proving that the hardening effect penetrates the bulk material. While the reduction in elongation confirms that the material's work-hardening capacity is partially consumed during forging, the tailor forged blank maintains a high-strength profile which is suitable for automotive applications (Xu et al. 2024).

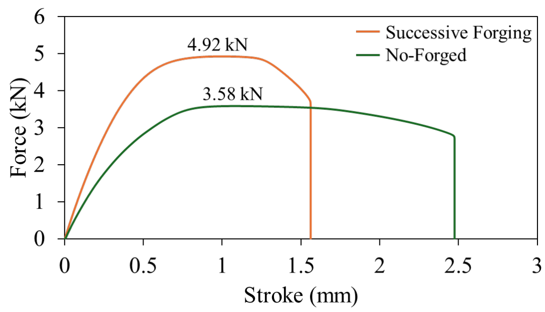


FIGURE 16. Tensile load of JSC1180YN UHSS sheet

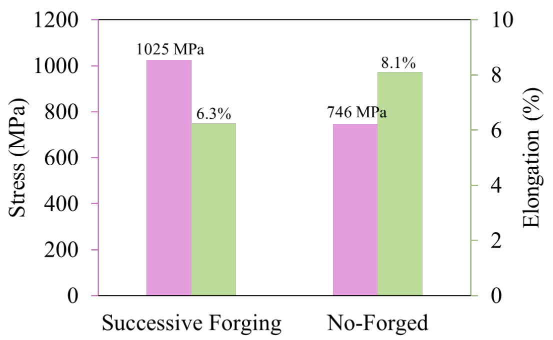


FIGURE 17. Tensile strength and ductility of JSC1180YN UHSS sheet

CONCLUSION

Successive forging proves to be a highly effective and controlled manufacturing process for producing tailored ultra-high strength steel (UHSS) components. The findings provide a detailed analysis of the geometrical and mechanical transformations that occur, confirming the process's viability as a superior alternative to traditional tailored rolled or welded blanks for the automotive industry.

The research established that the successive forging process successfully achieved the target thickness reduction, decreasing the initial 1.6 mm JSC1180YN UHSS sheet to approximately 0.8 mm. This was accomplished with minimal lateral spread, resulting in an 8.1% increase in length and a marginal 0.84% increase in width. The chamfered punch design (C = 1 mm) is effective in distributing the stress concentration and help in achieving a uniform strain distribution, which prevented defects to form on the UHSS sheet. Furthermore, the transition zone between sections that are forged and not forged was confirmed as a non-uniform strain region. This localized area is important for forecasting the overall integrity and performance of the final component.

A key finding of this investigation is the improvement of the material's mechanical properties. The Vickers hardness of the UHSS sheet increased from 415 HV1 to 442 HV1 that is stable across the forged section due to strain hardening. This was further validated by tensile testing, where the successive forged sheet showed a 37.5% increase in ultimate tensile strength, rising from 746 MPa to 1025 MPa. While the improvement in hardness and tensile strength resulted in a reduction in ductility, the successive forged sheet maintained a high-strength profile which is suitable for automotive applications.

In summary, the research showed that successive forging effectively changes the geometry and mechanical performance of the UHSS sheet, which offers a reliable and repeatable method for producing high performance and lightweight components. The consistency of the final thickness, hardness and tensile strength values is evidence to the stability of successive forging process, making it a viable solution for applications that is demanding in both dimensional accuracy and improvement in material strength.

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DECLARATION OF COMPETING INTEREST

None.

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