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Cost-Effective One-Shot Stamping of Steel-Based High-Performance Lightweight Multi-Material Structures

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Abstract. To address the challenges met in the manufacturing of state-of-the-art multi-material structures, this work employs a novel one-shot stamping process with single-stamp forming of advanced high-strength steels (AHSS)-based multi-material structures consisting of dual-phase steel (DP780) and low-cost glass fibre-reinforced polyamide 6 (GF/PA6). The effects of DP780 surface treatment and forming temperature on interfacial bonding with GF/PA6 were first assessed using double cantilever beam (DCB) tests, alongside tensile tests of DP780 to assess post-stamping performance. Sandblasting on DP780 significantly improved bonding strength compared to non-treated surface, while the interfacial fracture energy (G_C) increased with forming temperature up to 350 °C before decreasing at higher temperatures, which is attributed to PA6 squeeze-out and DP780 surface oxidation. Although the tensile strength for DP780 decreased with increasing temperature, the yield strength peaked at 350 °C, identifying sandblasting and a forming temperature of 350 °C as the optimal processing conditions for DP780. Based on the optimal conditions determined, high-quality U-shaped demonstrator components were successfully produced with good surface finish, minimal polymer squeeze-out, and no observable defects, via further optimisation of the forming conditions.

Introduction

Ongoing efforts have been made to improve fuel efficiency in the automotive industry to meet the urgent and growing demand for reducing carbon footprint and enhancing vehicle energy efficiency through the substitution of lightweight materials. Polymer matrix composites, notably continuous fibre-reinforced polymers (FRPs) [1], together with commonly used alloys such as high-strength steels and aluminium alloys [2,3], have therefore attracted increasing attention.

Multi-material structures, composed of alternating layers of metal and FRP sheets, were initially developed for aviation to enable the forming of lightweight structures due to high strength-to-weight ratio, corrosion resistance and improved fatigue resistance [4]. In recent years, driven by increasingly stringent CO_2e regulations and lightweighting demands, such structures have also attracted growing interest in automotive industry, particularly for high-performance and safety-critical components that require high structural strength at reduced weight. Several demonstrator and pre-production applications have shown that multi-material concepts can effectively balance structural performance, weight reduction, and cost in automotive body-in-white structures. Such structures have demonstrated great potential in achieving comparable structural performance while offering up to a 25% weight reduction compared to full-metal automotive counterparts [5].

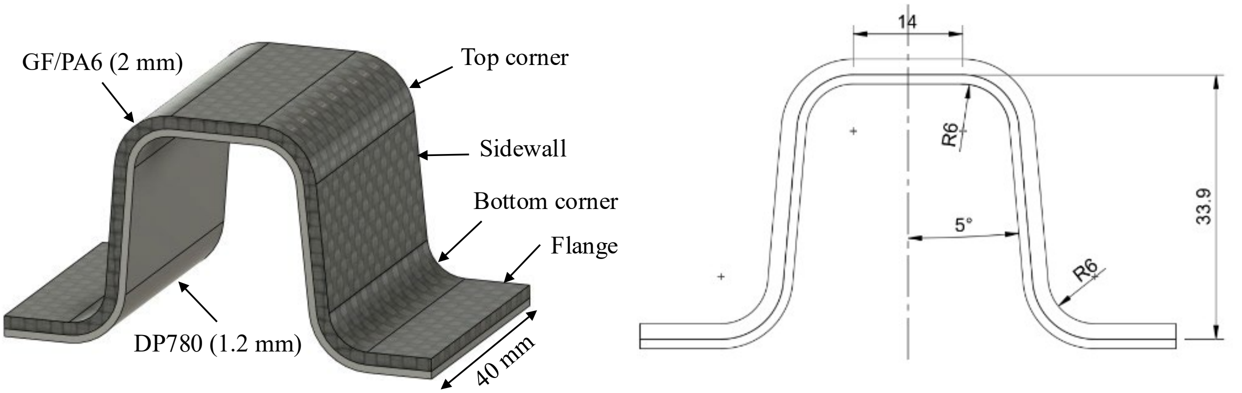
However, the wider adoption of multi-material structures is hindered by manufacturing limitations: conventional heated-tool one-shot thermoforming is energy-intensive, has a slow cycle time (>20 min[6]. Separate forming followed by bonding and fastening can overcome this limitation, but it requires multiple tools, adhesives or fasteners, introducing complexity and additional processing time [7,8].

To address the challenges mentioned above, this work employs a novel one-shot stamping process with single-stamp forming of AHSS-based multi-material structures consisting of dual-phase steel (DP780) and low-cost glass-fibre-reinforced polyamide 6 (GF/PA6). The process achieves a rapid cycle time with stamping and in-die quenching around 30 s using a cold tool and requires no adhesives or curing. The tailored thermal route of the process bridges the temperature gap between the steel and polymer interface, achieving robust interfacial bonding while avoiding polymer degradation.

Materials and Methods

Materials. In the work presented, an advanced high-strength steel (AHSS), dual-phase DP780, was selected as the metallic material, and low-cost glass-fibre polyamide 6 (GF/PA6) thermoplastics laminate was chosen as the FRP material of the multi-material structure.

The component. Figure 1 shows the design and the dimension of the U-shaped demonstrator component to validate the ability of this novel one-shot stamping in forming beam-like multi-material structure. The component is designed with a drawing depth of 33.9 mm, a width of 40 mm, and a draft angle of 5°. The DP780 layer was placed at the bottom with a thickness of 1.2 mm, while a 2 mm thick GF/PA6 laminate was positioned on top.

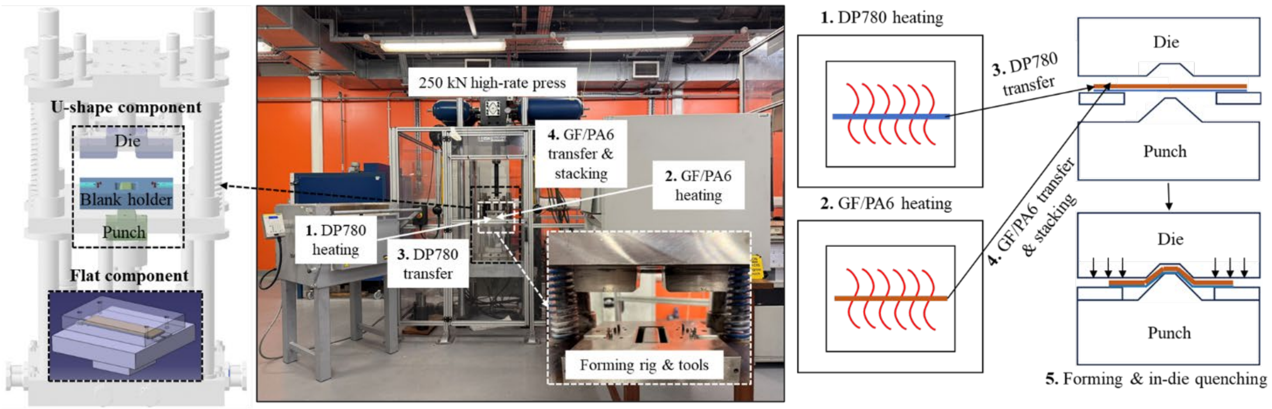


(a) (b)

Fig. 1. (a) Design and (b) the major dimensions (in mm) of the U-shaped demonstrator component.

Stamping equipment and process. Figure 2a shows the design of the stamping rig and the forming tool set mounted onto the rig for one-shot stamping of the demonstrator component. The key elements of the forming tool set include a die, a punch, and a blank holder. The dimensions of the die correspond to the upper surface of the U-shaped component, whereas those of the punch correspond to the lower surface. Figure 2b shows the layout of the heating and forming equipment of one-shot stamping and the forming tool set being assembled onto a high-rate 250 kN hydraulic press. Two furnaces were placed on each side of the machine for heating DP780 and GF/PA6, respectively.

The illustration of the one-shot stamping process is shown in Figure 2c, including the following key steps: first, the two blanks are heated to the targeted forming temperatures (Steps 1 and 2); the heated blanks are then successively transferred to the cold tool, where the GF/PA6 is stacked onto DP780 (Steps 3 and 4); next, the two layers are stamped simultaneously in a single press operation, allowing their shapes to be conformed at the same time, and the newly formed multi-material component is held within the cold tool to rapidly quench to stabilise its geometry and enable effective interfacial adhesion, completing the one-shot process (Step 5).

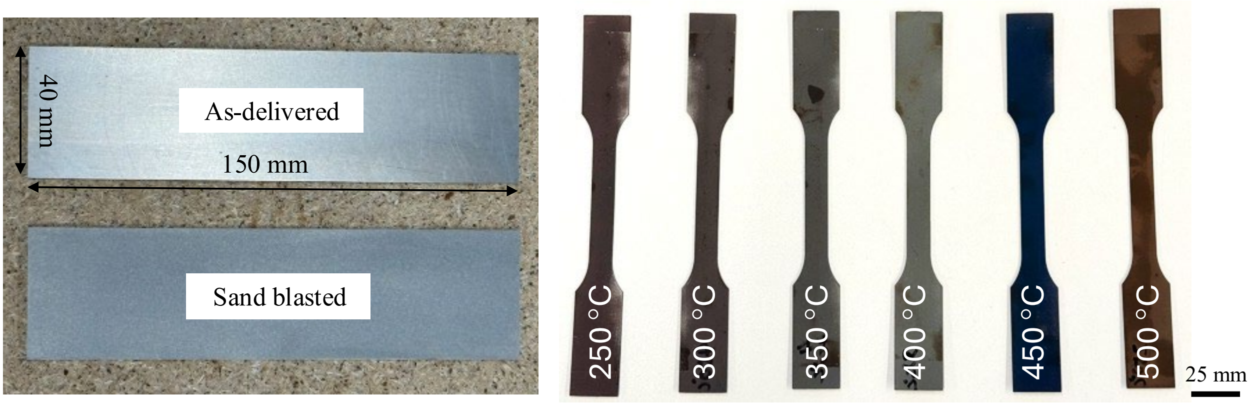


(a) (b) (c)

Fig. 2. (a) Design of the forming rig and tool sets for forming U-shaped and flat components; (b) laboratory equipment layout, with the corresponding one-shot stamping steps indicated; and (c) schematic illustration of the one-shot stamping process.

Pre- and post-stamping tests. Prior to the stamping experiments of the U-shaped component, 150 × 40 mm flat multi-material component were first produced to determine the effects of DP780 surface treatment and forming temperature on the interfacial bonding strength and to identify the optimal forming temperature window. These tests included testing the bonding strength of as-received and sandblasted DP780 surfaces (shown in Figure 3a) and evaluating different DP780 stamping temperatures ranging from 250 °C to 500 °C with respect to bonding strength. The stamping temperature of the GF/PA6 was fixed close to the melting temperature of PA6, i.e. 230 °C. This helps to suppress excessive through-thickness polymer flow at the interface, which could otherwise lead to interfacial polymer depletion and weakened bonding, while still minimising void formation and delamination.

The bonding performance was characterised by double cantilever beam (DCB) tests, with the fracture energy G_C used to quantify the effects of pre-forming sandblasting and forming temperature on interfacial bonding strength. The values of G_C were obtained using the experimental compliance method in accordance with the relevant test protocol [9]. The DCB specimens were water-jet cut from the centre of the flat multi-material components, with a size of 120 × 20 mm. A total pre-crack length of 50 mm was created by inserting ethylene tetrafluoroethylene (ETFE) films with a thickness of 12 µm at the interface. An Instron 3369 uniaxial tester was used for the DCB tests to record the crosshead displacement and load during the tests. During the DCB tests, a camera was used to capture and measure crack growth on the specimens, with distances labelled along the load line prior to testing.



(a) (b)

Fig. 3. (a) Surface appearance of DP780 in the as-received condition and after sandblasting prior to stamping, and (b) surface appearance after heat treatment at different temperatures (sectioned for tensile testing).

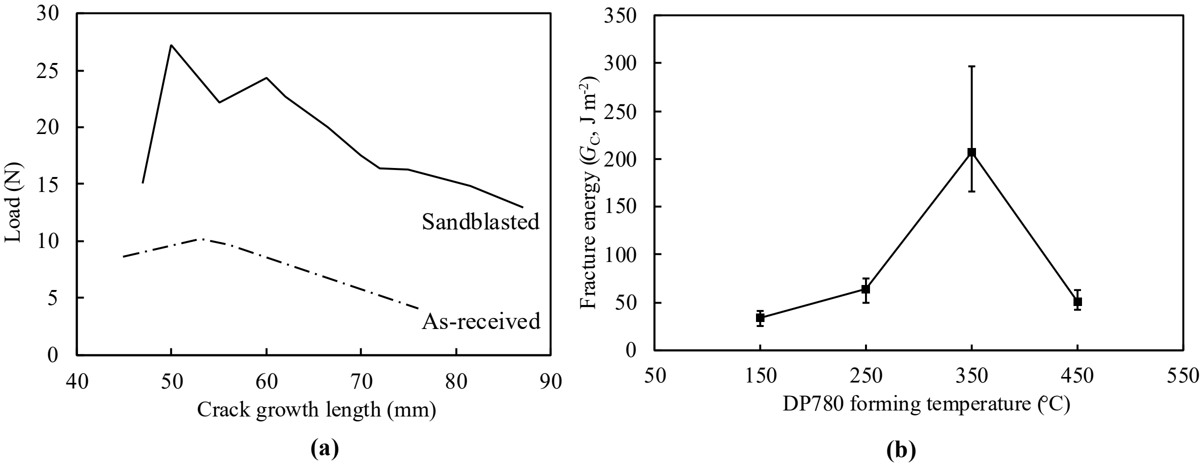
Tensile tests were conducted to investigate the effect of heating temperatures on the post-stamping mechanical properties of DP780. The surface appearance of DP780 specimens treated at different temperatures (for post-stamping tensile testing) is presented in Figure 3b. The surface colours varied due to different levels of oxidation. The tests were performed using an Instron 5584 tester, and the specimens were prepared based on ASTM E8 (Figure 3b). The specimens were water-jet cut from 1.2 mm thick DP780 sheets. Digital image correlation (DIC) was used for real-time measurement of the gauge length and width of the specimen to obtain engineering stress and strain. The crosshead speed was consistently set at 12.5 mm/s throughout the tests.

The micrographs of the post-stamping component were captured using a Leica Microsystems optical microscope. The transverse cross-section of the as-formed component was sectioned and ground using silicon carbide papers from coarse to progressively finer grades for polishing. A minimum material removal of 3 mm from the component edge was ensured to prevent the GF/PA6 microstructure from being affected by polymer squeeze-out near the edge.

Results and Discussion

Figure 4a shows the effect of sandblasting of DP780 on interfacial bonding strength under identical optimal forming condition. It can be seen that sandblasted surfaces significantly increase the debonding load to over 25 N compared with the untreated as-received specimens, which exhibit debonding loads of only around 10 N. This improvement in debonding load is likely attributed to the increase of surface roughness and removal of surface contaminants and oxide layers, which increases the effective bonding area and promotes mechanical interlocking with the molten PA6.

Figure 4b shows the effect of DP780 forming temperature on the fracture energy, G_C. It is observed that G_C increased as the DP780 forming temperature rose from 250 °C to 350 °C, where a maximum was reached. Further increases in the forming temperature resulted in a decrease in G_C, with the value returning to the lowest level at 500 °C. Two factors are likely responsible for this trend. First, higher DP780 temperatures during forming promote a greater extent of polymer squeeze-out, thereby depleting interfacial PA6. Second, surface oxidation of DP780 becomes more severe at higher temperatures, which further reduces interfacial bonding quality.



(a) **(b)**

Fig.4. (a) Effects of surface treatment of DP780 on debonding load and (b) effects of DP780 forming temperatures on the fracture energy G_C.

Figure 5 shows the relationship between forming temperature and the yield strength of DP780 in the range from 250 °C to 450 °C. The yield strength increases with forming temperature, reaching a maximum of approximately 700 MPa at 350 °C, before decreasing at higher temperatures and falling below the as-received level at 500 °C. This trend is in good agreement with the literature, where the strength degradation of DP780 is mainly attributed to martensite tempering, including carbide precipitation and coarsening, and the associated softening of the martensitic phase in the temperature range of 300-500 °C [10].

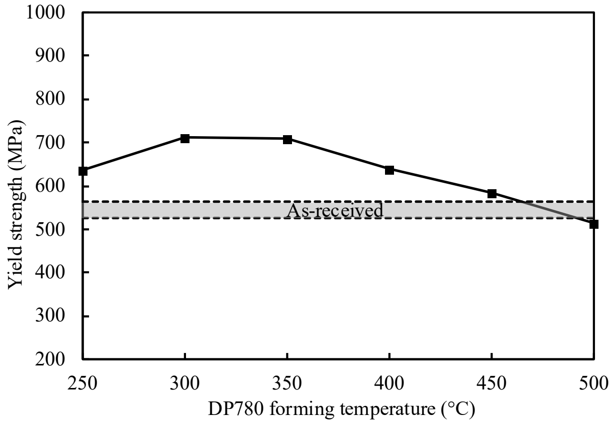


Fig. 5. Effect of forming temperature on the yield stress of DP780.

Combining the results of the DCB and tensile tests, sandblasting of DP780 prior to forming and a forming temperature of 350 °C were preliminarily identified as the optimal processing conditions. The sandblasted surface exhibited a significantly higher debonding load than the as-received condition. In addition, components formed at 350 °C showed the highest interfacial fracture energy (G_C), together with the highest level of post-stamping yield strength and a relatively high tensile strength.

Furthermore, a series of forming experiments was conducted to identify a suitable processing window for the one-shot stamping process. These included improving the consistency of material handling combined with temperature measurements to ensure accurate control of the forming temperatures, fine-tuning the forming temperatures of GF/PA6 and DP780 around 230 °C and 350 °C, respectively, and employing two forming speeds of 100 mm/s and 150 mm/s. Figure 6a shows the micrograph of the as-received GF/PA6, with distinct layering of 0° and 90° glass fibres and PA6 filling the regions between the fibre layers. Figure 6b displays the U-shaped multi-material component produced at a forming speed of 100 mm/s. It can be seen that both delamination within the GF/PA6 and debonding at the GF/PA6-DP780 interface occurred (as indicated by the red arrows in the micrograph), primarily due to non-optimal shear flow within the GF/PA6 laminate at the lower forming rate, which led to excessive squeeze-out of PA6 and, consequently, ineffective adhesion. In contrast, as shown in Figure 6c, the component produced at a forming speed of 150 mm/s exhibited good bonding across the entire GF/PA-DP780 interface together with a defect-free GF/PA6 laminate, with the material distribution remaining nearly undisturbed by the one-shot stamping process compared with the as-received state.

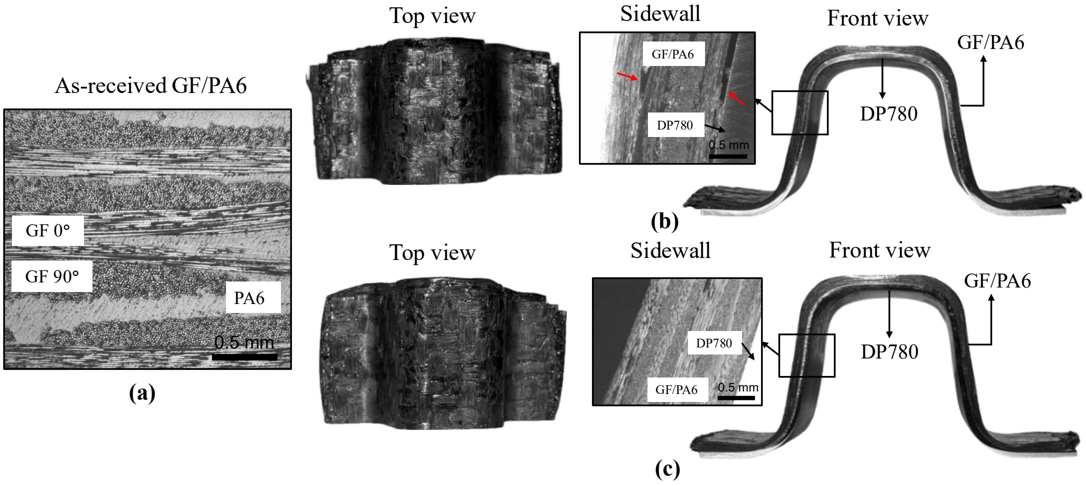


Fig.6. (a) Micrograph of as-received GF/PA6 laminate; and top and front views of the laboratory U-shaped demonstrator components with optical micrographs captured on the on the sidewall of the components produced by (b) 100 mm/s and (c) 150 mm/s forming speeds.

Conclusion

This study investigated the cost-effective one-shot stamping process for manufacturing steel-based multi-material structures consisting of DP780 steel and GF/PA6 laminate. Flat multi-material components were first produced to systematically evaluate the effects of DP780 surface treatment and forming temperature on interfacial bonding quality, using DCB tests. In parallel, tensile tests were conducted to assess the influence of forming temperature on the post-stamping mechanical properties of DP780. Based on the optimised processing window identified from these tests, laboratory U-shaped demonstrator components were manufactured to validate the feasibility of the proposed one-shot stamping process for producing multi-material structures.

The results show that both surface preparation and forming temperature are crucial in achieving robust interfacial bonding while preserving mechanical performance. Sandblasting of DP780 prior to forming significantly increased the debonding load to over 25 N compared with the as-received condition of around 10 N, owing to the removal of surface contaminants and weak oxide layers, as well as increased effective adhesion area and enhanced interlocking with PA6. The interfacial fracture energy, G_C, peaked at a DP780 forming temperature of 350 °C. Tensile testing revealed that the yield strength peaked at approximately 350 °C, indicating a good balance between interfacial bonding and strength at this temperature. Based these findings, sandblasting and a DP780 forming temperature of 350 °C were preliminarily identified as the optimal processing conditions. Following further optimisation of the forming conditions, high-quality U-shaped multi-material components were produced with sound FRP surface finish, minimal polymer squeeze-out, and no observable delamination or porosity, demonstrating the potential of the one-shot stamping process for achieving high-quality, high-performance automotive lightweight manufacturing.

This work demonstrates the capability of the one-shot stamping process to produce multi-material structures with high forming quality and mechanical performance. In the present study, the metal and FRP materials were heated separately using two furnaces to facilitate manual handling during laboratory-scale trials. However, in recent trials, which the two materials were heated in a single furnace with different timing, indicate the potential to employ only one furnace, provided that accurate material transfer and timing control can be achieved. Such an approach is particularly feasible in industrial production environments. Compared with carbon fibre-reinforced polymer composites, the GF/PA6 used in this study offers a significant reduction in material cost while still providing a high level of strength and toughness. Moreover, the results suggest that the proposed one-shot stamping process is applicable to both glass fibre- and carbon fibre-reinforced thermoplastic composites, and can be further extended to alternative material configurations, such as combinations with high-strength aluminium alloys, thereby enabling cost-effective and lightweight solutions for automotive and broader applications.

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