One-Step Process for Press Hardened Steel-Carbon Fibre Reinforced Thermoset Polymer Hybrid Parts

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Abstract

A new one-step process for manufacturing Press Hardened Steel-Carbon Fibre Reinforced (thermoset) Polymer hybrid parts with potential for reduced cycle-time, infrastructure requirements and energy consumption compared to traditional two- and three-step processes is developed. The process combines and optimises the press hardening and Prepreg Compression Moulding technologies, traditionally used in isolation for manufacturing Press Hardened Steel and Carbon Fibre Reinforced Polymer parts respectively, to produce hybrid parts in a one-step, fully-integrated process. Heat required for curing and bonding prepreg to steel is provided by residual heat of the steel part immediately following hot forming and interrupted die-quenching of steel. Thermal conductivity of tool material is investigated to achieve the optimal balance between

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die-quenching rate for martensite formation in steel and temperature maintenance for complete curing and bonding of prepreg. Addition of epoxy adhesive and thickness ratio between steel and prepreg are also investigated. Benchmarking is conducted against parts manufactured by the traditional two-step process, in which the Press Hardened Steel part is formed in isolation before joining with the Carbon Fibre Reinforced Polymer part. No sacrifice of part-quality is found from the new one-step process with no loss of mechanical performance, despite clear economic and environmental advantages.

Key words: hot forming; boron steel; prepreg; composite; adhesive bonding; multi-material construction

1. Introduction

Multi-material construction is becoming increasingly common in automotive body engineering to achieve a suitable combination of lightweighting, crash-safety and cost, as demonstrated by Fig. 1a. Two of the most desirable materials in this sector are Press Hardened Steel (PHS) and Carbon Fibre Reinforced (thermoset) Polymer (CFRP), with PHS representing the highest strength material in the sector and with CFRP, once reserved for niche-market vehicles only, now beginning to emerge in medium-volume production vehicles owing to the development of mass-production technologies. Holmes highlights various applications of CFRP in automotive body engineering, including current applications and proposes applications for the future, and discusses the technical developments taking place to meet such demands, such as prepreg material development, part manufacturing development and environmental development such as reuse of chopped carbon fibres[1]. Industry based case studies validate his claims. Moreover, the attractiveness of PHS and CFRP for lightweight, high-load bearing structural applications can be understood by specific tensile strength values of up to approximately 0.24 and 1.00 MPa.m^3/kg respectively, compared to just 0.12 MPa.m^3/kg of 5000 series aluminium alloys currently in use.

Hybrid parts combine two materials with specific desirable properties in one to optimise multi-material construction and structural performance. Examples of hybrid parts used extensively in automotive body engineering at present are provided by tailored technologies within PHS, including tailor welded blanks, patch-work blanks, tailor rolled blanks, tailored heating, tailored quenching and tailored tempering. Merklein et al. provide a detailed explanation of each established tailored technology, including insights into technical considerations, such as formability, friction, tool coatings and numerical model development to support each technology[2]. As they illustrate, the B-pillar is a common application of PHS tailored technologies, including the tailor welded bank with two different sheet steel blanks (of different chemistry) welded together before press hardening, giving rise to a hybrid part with different mechanical properties in different regions, for optimised load-management and crash-safety. The tailored technologies are demonstrated by extensive application to the 2014 Volvo XC90. Lindberg provides a technical overview of the 2014 Volvo XC90 and explains that the extensive application of PHS and tailored technologies give rise to a direct weight reduction of 22 kg compared to the previous generation (2003) XC90 and a weight reduction of 40 kg compared to what the 2014 XC90 was projected to weigh if PHS and tailored technologies were not used[3]. This is clear evidence of the importance of PHS and tailored technologies and cannot be dismissed. In the same vein and to capitalise further, CFRP is beginning to be incorporated into hybrid parts of high-end medium-volume vehicles. In Fig. 1b, the B-pillar is composed of a CFRP inner bonded to a PHS outer. CFRP presents up to approximately 3.3 and 4.2 times the specific stiffness and specific strength respectively of the highest strength PHS, but PHS presents approximately 1.6 times the absolute stiffness. Given the B-pillar is highly dependent on part-stiffness in side-impact to minimise displacement into the safety-cell, to achieve equivalent part-stiffness from monolithic CFRP would require much greater part-thickness (limiting geometric design-freedom and driver-visibility) and significantly increase cost over the monolithic PHS part, where cost of CFRP is of the order of \$15/kg[4] compared to just \$1/kg of PHS[5]. Owing to the higher cost of CFRP over PHS, despite development of numerous economy-focused out-of-autoclave CFRP part manufacturing technologies, including Liquid Compression Moulding (LCM), Resin Transfer Moulding (RTM), Sheet Moulding Compound (SMC) and Prepreg Compression Moulding (PCM), as used elsewhere in the body structure of Fig. 1b, the PHS-CFRP hybrid part is considered promising for the B-pillar as it achieves a suitable balance between specific stiffness, specific strength, absolute part-stiffness, thickness and cost.

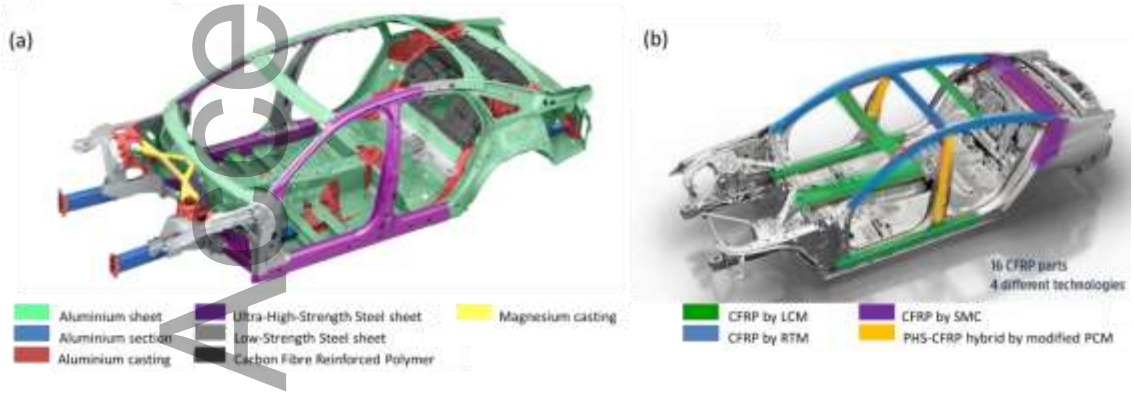


Fig. 1: Multi-material construction in (a) 2018 Audi A8[6] and (b) 2015 BMW 7 Series with PHS-CFRP hybrid parts[7]

PHS-CFRP hybrid parts may be manufactured by a traditional three-step process, in which PHS (step 1) and CFRP (step 2) parts are formed in isolation before bonding (step 3). To reduce cycle-time, infrastructure requirements and energy consumption, novel technologies have been developed in an attempt to integrate the three steps. Wang et al. demonstrated a two-step steel-CFRP hybrid part manufacturing process by RTM, in which the steel part is formed in isolation (step 1) and subsequently, the RTM process for forming the CFRP part is conducted around the steel part, with the steel part in the RTM dies so that the CFRP part is simultaneously formed and bonded to the steel part (step 2)[8]. While the development by Wang et al. is highly commendable, the RTM process is well known for its limitation to low and at most, medium-volume production volumes. Thus, in order to reduce cost further, a similar process to that of Wang et al., but substituting the RTM process for the lower cost PCM process has been developed. Starke explains the modified PCM process, as used by BMW in manufacturing the hybrid B-pillar of Fig. 1b and can be considered the industry benchmark[9]. Additionally, Starke provides a detailed insight into material and manufacturing process development at BMW, where the focus on CFRP technologies, including PHS-CFRP hybrid parts, is made clear. This is clear evidence of the demand for PHS-CFRP hybrid part manufacturing technologies. With increased application of steel-CFRP hybrid parts, new technologies have been developed to improve joint-stability. In his explanation of hybrid part manufacturing technology at BMW, Starke goes on to demonstrate that while adhesive layer thickness of up to 1.5 mm between steel and CFRP reduces specific stiffness and specific strength compared to more conventional thickness of 0.3 mm, the greater thickness compensates for relative movements between steel and CFRP and increases elongation to failure of the hybrid part. This is especially useful during the modified PCM process as the PHS part and CFRP part exhibit different thermal expansion coefficients. From academia, Huang et al. propose a hybrid joining method combining adhesive bonding with plastic deformation[10]. The method is shown to provide increased joint strength compared to conventional joining methods, including mechanical fastening, adhesive bonding and mechanical fastening-adhesive bonding hybrid methods, owing to the mechanical anchor effect of the deformation zone, expansion of adhesive, concentration of adhesive at the edge of the deformation zone and the heating procedure. Because of the necessity for plastic deformation, this joining method is a good candidate to be incorporated into an integrated forming and joining process between steel and CFRP. By all joining methods, adhesive also provides electrical insulation between steel and CFRP and thereby prevents galvanic corrosion of steel stimulated by the higher cathodic potential of carbon fibres. Yang et al. investigated the effects of salt fog on CFRP-steel bonded joints over a cycle of 5000 h and assessed degradation of bond capacity at selected time intervals[11]. Different mechanisms causing strength losses were found and analysed, including galvanic corrosion due to coupling between CFRP and steel.

A new PHS-CFRP hybrid part manufacturing process is proposed in this paper. The press hardening and PCM technologies are fully-integrated in a one-step hot forming, bonding and curing process, as shown by Fig. 2. The novelty underpinning the new process is that during press hardening steel, die-quenching is interrupted and the forming tool is opened at or near to a suitable cure-temperature for prepreg (in the range of 100-300 °C). Prepreg is laid on top of the PHS part, the forming tool is re-closed and the two materials are pressed to cure prepreg and to bond, with heat required for curing and bonding provided by residual heat of the PHS part. The new one-step process has clear potential for reduced cycle-time, infrastructure requirements and energy consumption compared to the traditional two- and three-step processes and thereby, escalate application to high-volume production vehicles with its economic and environmental advantages.

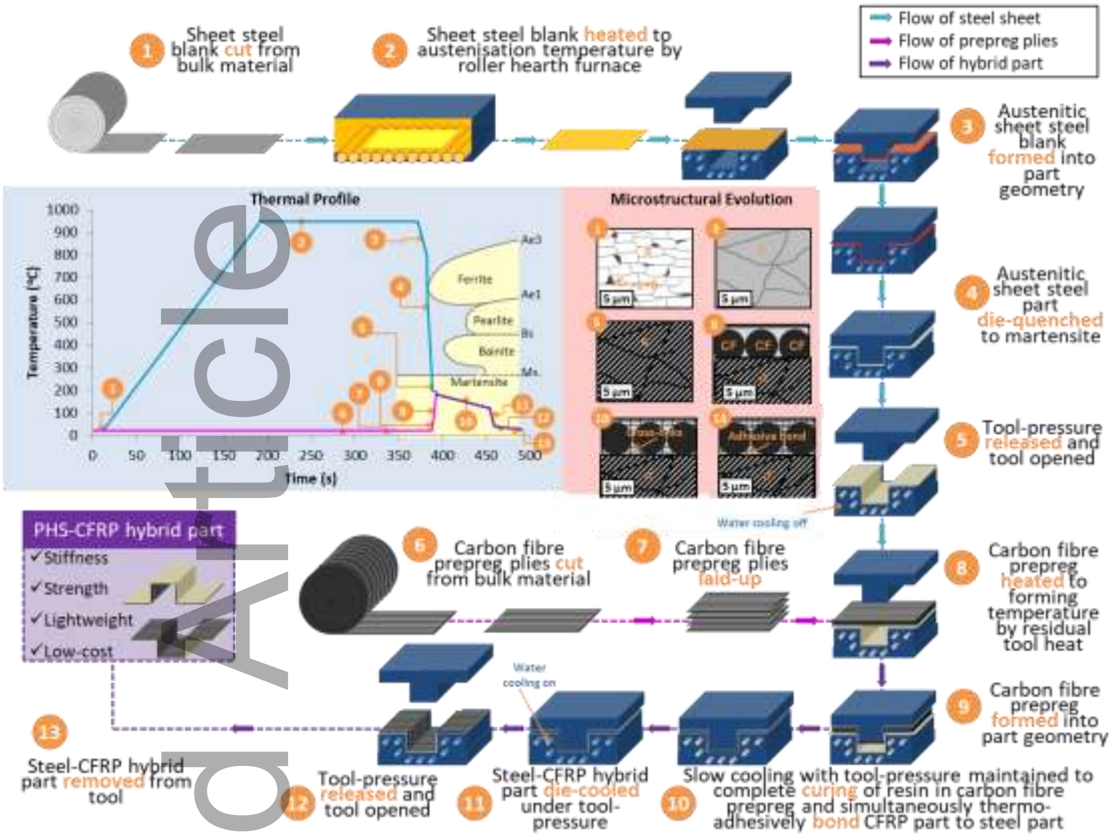


Fig. 2: One-step process for PHS-CFRP hybrid parts

2. Experimental

2.1. Materials

Sheet steel was 1.5 mm gauge aluminised 22MnB5: an aluminium-silicon coated mild-carbon boron-alloyed steel and the most widely used PHS with ultimate tensile strength of the order of 1500 MPa when die-quenched to martensite in the traditional press hardening process. The aluminising coating protects the steel from oxidation at the elevated temperatures and oxidising atmosphere of press hardening. Avoidance of oxide-scale formation is particularly important for subsequent bonding to CFRP in the new one-step process as there is no opportunity for de-scaling. Prepreg was P3252S-10 (T700SC carbon fibre, 5 µm fibre-diameter, 0.67

fibre-volume fraction, impregnated with epoxy resin) of 0.1 mm thickness supplied by Toray. The standard laminate configuration used was $[(0/90)_2/0]$ with thickness of 0.5 mm. Equivalent laminate configurations of $[(0/90)_2/0]_2$, $[(0/90)_2/0]_3$ and $[(0/90)_2/0]_4$ with thickness of 1.0, 1.5 and 2.0 mm respectively were investigated subsequently for the effect of thickness ratio between steel and CFRP. Adhesive was IW2460 Scotch-Weld supplied by 3M; a one-component thermoset epoxy. Adhesive was applied with thickness of 0.2 mm.

2.2. Forming

Forming was conducted with a 5 kN mechanical testing machine (Fig. 3a). Parts of U-bend geometry were formed with a maximum stroke-displacement of 20 mm for evaluation of formability. Flat parts suitable for subsequent flexural testing (ASTM D7264/D7264M – 07) and tensile-shear testing (ASTM D1002 – 99) were produced by flat pressing. Samples were tested in triplicate with mean results presented. Heating of steel blanks was conducted with a box-furnace under nitrogen atmosphere. The thermo-mechanical cycle for press hardening simulated that of a traditional and industrial press hardening line (Fig. 3b), including transfer of steel blanks from furnace to forming tool in approximately 10 s and with die-quenching conducted under the full 5 kN load of the mechanical testing machine. In this new process, die-quenching was interrupted by releasing load and opening the forming tool at a target temperature of 250 °C. This tool-open-temperature was established from preliminary experiments in order to impose minimum disruption to martensite formation, while achieving the desired curing temperature for prepreg. Prepreg laminate (coated with adhesive on the inside surface) was inserted within 10 s and the forming tool was re-closed to 95 % of the complete stroke-displacement. Target forming start temperature for prepreg was 150 °C. Once temperature of prepreg exceeded 200 °C, the final 5 %

of stroke-displacement was completed. Immediately following forming, load was reduced and maintained at 0.1 kN. Temperature was desired to be maintained in the range of 230-180 °C for 300 s to complete curing and bonding. Taylor and Yanagimoto developed a dummy metallic sheet assisted PCM process using the same prepreg material as used here[12]. The above conditions were determined to be optimal for formability, springback and final mechanical properties of CFRP. Thus, the above conditions were used here. Thermocouples were attached to both steel and prepreg. Two tool (die) materials with different thermal conductivities were investigated: TZM molybdenum alloy (120 W/m.K) and Ti6V4 titanium alloy (7 W/m.K). Combined with water-cooling of the forming tool, the different thermal conductivities were investigated for sufficient die-quenching rate of at least 30 °C/s (above the critical cooling rate for martensite formation in the 22MnB5 steel) and for sufficient temperature maintenance in the range of 230-180 °C for 300 s (for complete curing and bonding of prepreg) without use of forced heating. The new one-step process was benchmarked against the traditional two-step process (as used in Fig. 1b) in which the PHS part is formed in isolation before joining with the CFRP part via the PCM process.

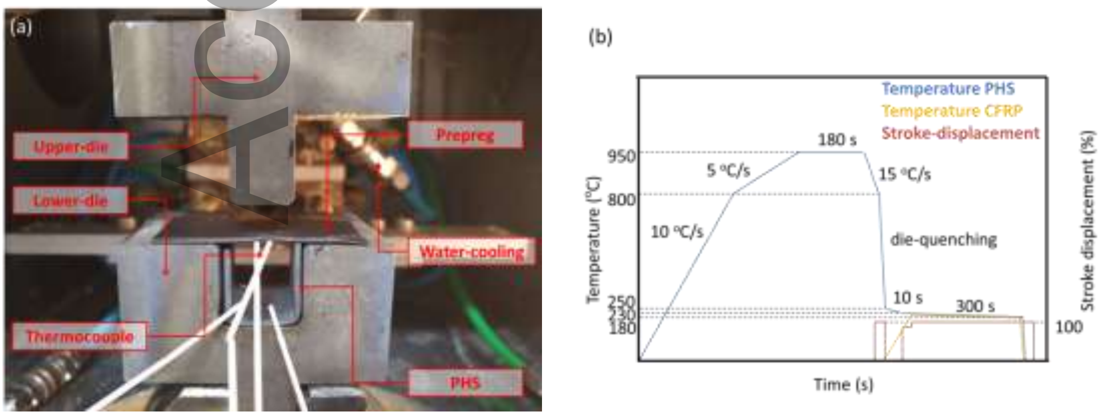


Fig. 3: Experimental (a) 5 kN mechanical testing machine with titanium alloy dies (b) schematic of thermo-mechanical cycle

3. Results & Discussion

3.1. Effect of Tool Material

Molybdenum alloys are common tool materials for press hardening, partly owing to their high thermal conductivities that guarantee a sufficient die-quenching rate for martensite formation. However, in the new one-step hot forming, bonding and curing process proposed here for manufacturing PHS-CFRP hybrid parts, in addition to sufficient die-quenching rate during press hardening of steel, sufficient temperature must be maintained during curing and bonding of prepreg. To minimise infrastructure requirements and energy consumption, it is desirable to achieve the latter without forced heating and with heat required for curing and bonding provided exclusively by residual heat of the steel part immediately following interrupted die-quenching. For this, tool material with low thermal conductivity is preferable. The high thermal conductivity of the molybdenum alloy tool material, combined with water-cooling of the forming tool, provided a die-quenching rate of 421 ^{o}C/s, as shown by Fig. 4a. However, during the 300 s for curing and bonding of prepreg, mean temperature was just 91 ^{o}C. In contrast, the lower thermal conductivity of the titanium alloy tool material, combined with water-cooling of the forming tool, provided a die-quenching rate of 106 ^{o}C/s with a mean temperature of 203 ^{c}C during the 300 s for curing and bonding of prepreg, as shown by Fig. 4b. The titanium alloy tool material (with thermal conductivity of 7 W/m.K versus 120 W/m.K of the molybdenum alloy) thus provides the preferable balance between die-quenching rate and temperature maintenance; and was used for subsequent investigation of the new one-step process.

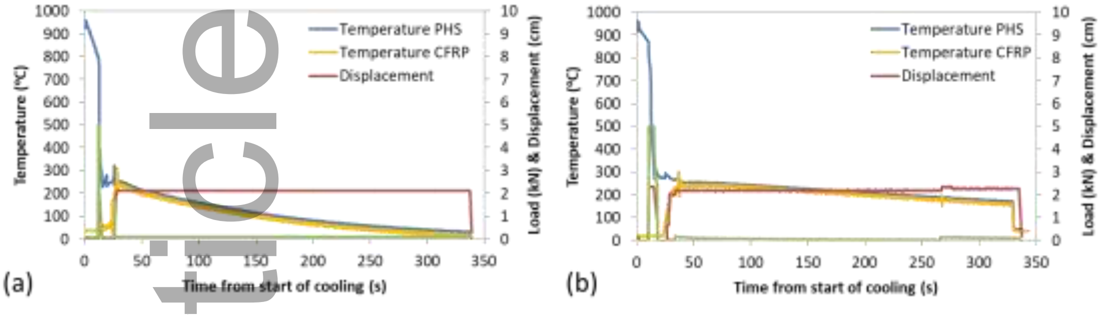
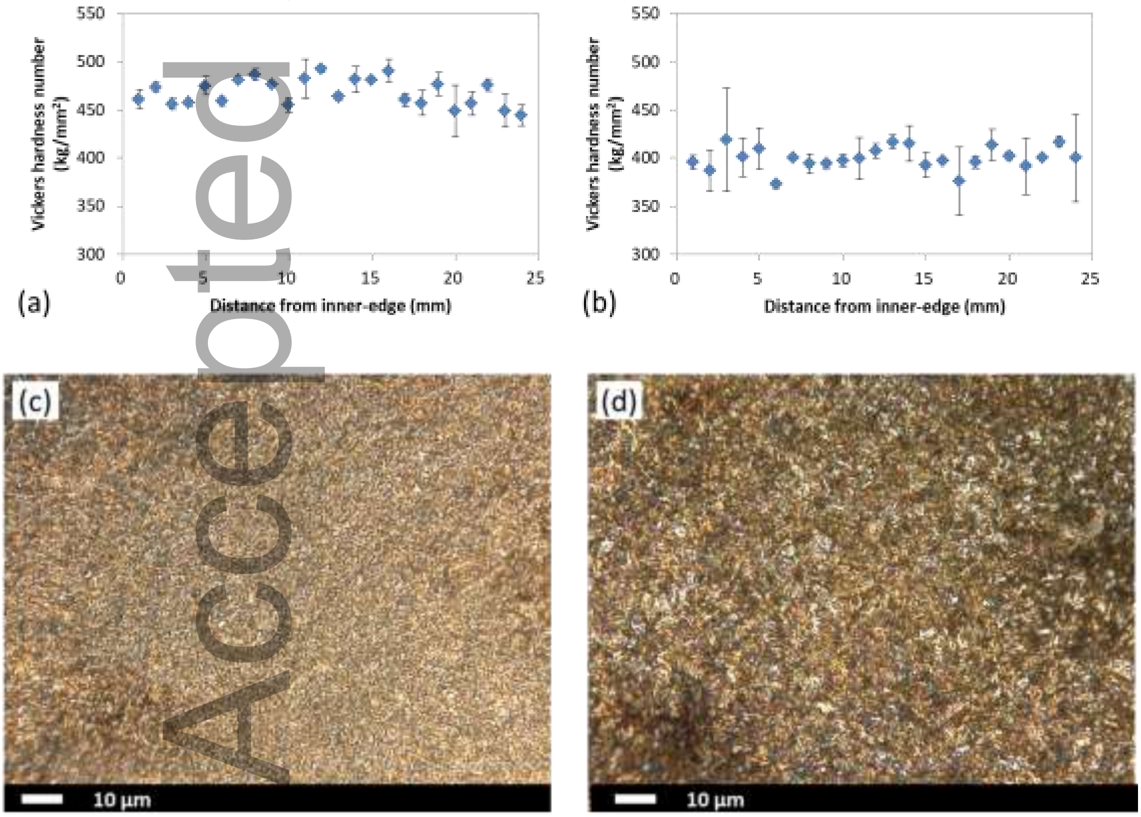


Fig. 4: Thermo-mechanical cycles (a) molybdenum alloy (b) titanium alloy tool material

3.2. Comparison between Two-Step and One-Step Processes

In addition to hybrid parts, monolithic PHS and CFRP parts were subjected to flexural testing to deduce the contribution of each material. Assisted by the hardness (Fig. 5a) of the as-quenched martensitic microstructure (Fig. 5c), via the traditional two-step process (using molybdenum alloy dies), the flexural stress-strain response (Fig. 5e) of PHS was marked by significantly higher flexural stiffness (Fig. 5g) and strength (Fig. 5h) than CFRP. This underlines the importance of PHS, presenting the highest stiffness and strength values in the automotive body engineering sector. The hybrid part presented flexural strength mid-way between those values of the constituting materials, with higher stiffness, strain to failure (Fig. 5i) and energy absorption (Fig. 5j). Via the new one-step process, the flexural stress-strain response (Fig. 5f) of PHS was marked by lower flexural strength. This can be attributed to (auto-) tempering of martensite (Fig. 5d), firstly under the lower die-quenching rate of the titanium alloy dies and secondly, under interrupted die-quenching from 250 °C, giving rise to lower hardness

(Fig. 5b). Incidentally, mean hardness values of 468 and 400 kg/mm^2 via the traditional two-step and new one-step processes respectively, can be estimated to equate to ultimate tensile strength values of 1405 and 1200 MPa respectively. Via the new one-step process, CFRP also presented lower flexural strength. This can be attributed to anisothermal and sub-optimal curing conditions under slow cooling of the forming tool. The hybrid part again presented flexural strength mid-way between those values of the constituting materials, with higher stiffness, strain to failure and energy absorption. Comparing hybrid parts produced via the two processes, overall similar properties were presented, demonstrating no sacrifice of part-quality from the new one-step process despite its clear economic and environmental advantages.



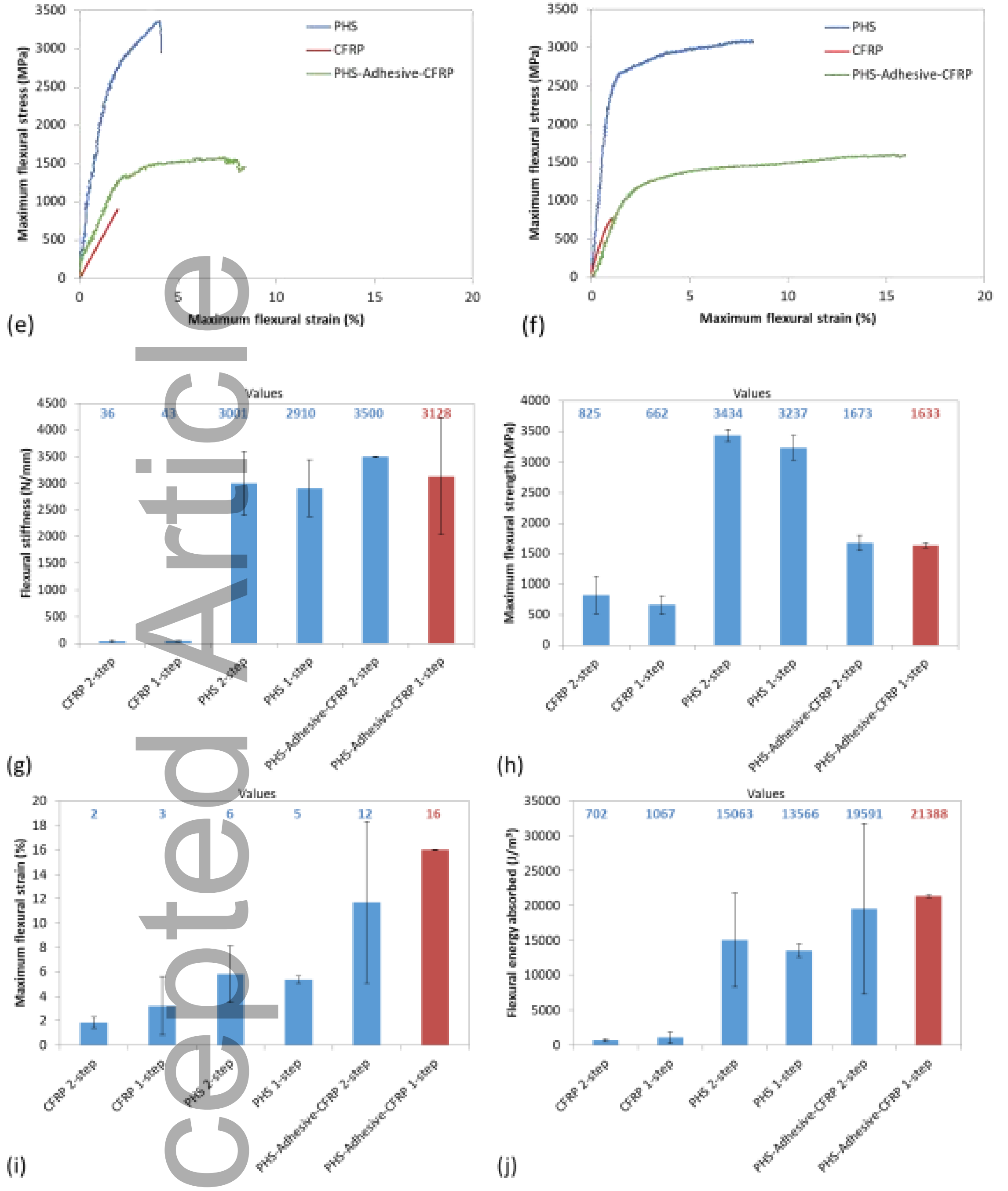
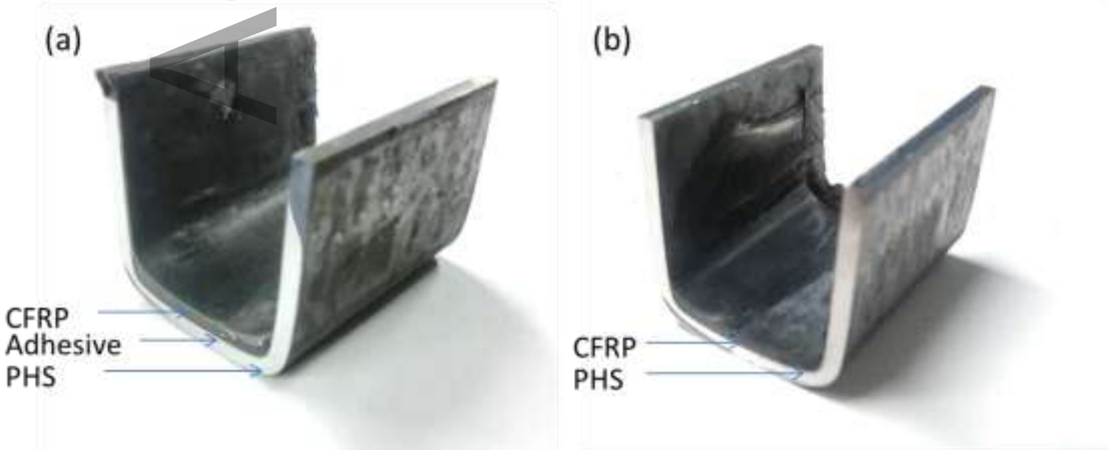


Fig. 5: Two-step and one-step process comparison (a) hardness profile of PHS from two-step process (b) hardness profile of PHS from one-step process (c) micrograph of as-quenched martensite in PHS from two-step process (d) micrograph of tempered martensite in PHS from one-step process (e) representative flexural stress-strain curves from two-step process (f) representative flexural stress-strain curves from one-step process (g) flexural stiffness (h) flexural strength (i) flexural strain (j) flexural energy absorbed

3.3. Effect of Adhesive on Hybrid Parts

Here and in the subsequent section, hybrid parts produced by the new one-step process are evaluated in terms of the effect of adhesive and thickness ratio between steel and CFRP. Adhesive is a common addition between metal and CFRP in hybrid parts in order to provide electrical insulation and prevent galvanic corrosion of the metal stimulated by the higher cathodic potential of carbon fibres. However, adhesive can be expected to impair mechanical properties, particularly stiffness and strength. Thus, parts of U-bend geometry were formed with (Fig. 6a) and without (Fig. 6b) adhesive between PHS and CFRP. Formability, adhesion between materials and surface-quality of CFRP was demonstrated by absence of macroscopic defects. At the interfaces between PHS, adhesive and CFRP (Fig. 6c), the characteristic structure of the aluminising coating was demonstrated, consisting of an aluminium oxide surface-layer (formed during exposure to the oxidising atmosphere of transfer from furnace to forming tool) and numerous layers of solid solution and intermetallic-phases penetrating into the martensitic microstructure of the substrate. Elevated surface roughness is one method by which adhesion can be improved. Following press hardening, Ra (arithmetical average value of all absolute distances of the roughness profile from the centre line) and Rz (average maximum peak to valley of five consecutive sampling lengths within the measuring length) of the as-received steel was raised from 0.1 to 2.7 μm and from 29.1 to 39.4 μm respectively, owing to formation of the aluminium oxide surface layer (Fig. 6e-f). Stable fibre-alignment was maintained in CFRP to the interface, while adhesive uniformly wetted the PHS surface. However, while consistent adhesive thickness was maintained in flat regions of the part (Fig. 6c), adhesive segregated at formed regions of the part (Fig. 6d). Fracture of carbon fibres was also abundant in formed regions.

Flexural stress-strain behaviour of the hybrid part containing adhesive was similar to that of the constituting materials, with the stress-strain curve following a smooth character (Fig. 5f) and with failure mode marked by delamination within CFRP, complete fracture of CFRP and partial de-bonding between PHS and CFRP (Fig. 7a). Without adhesive, flexural stress-strain behaviour was markedly different, characterised by periodic fracturing of CFRP giving rise to a heavily serrated curve (Fig. 7c) and failure mode marked by complete de-bonding from PHS rather than fracture (Fig. 7b). Although addition of adhesive reduces flexural properties (Table 1) owing to the low-stiffness and low-strength character of adhesive, it significantly stabilises flexural deformation behaviour. Stable and predictable deformation behaviour of this character is important in many safety-critical automotive applications to minimise peak-load transfer to connected parts and to vehicle occupants; and also to minimise amplitude and frequency of load-oscillations exerted on vehicle occupants during impact. Corroborating with flexural results, tensile-shear results demonstrate slightly higher bond strength with addition of adhesive (Fig. 7d), while failure mode with adhesive was marked by fracture of CFRP combined with de-bonding (Fig. 7e), but without adhesive, failure mode was marked by exclusive de-bonding (Fig. 7f).



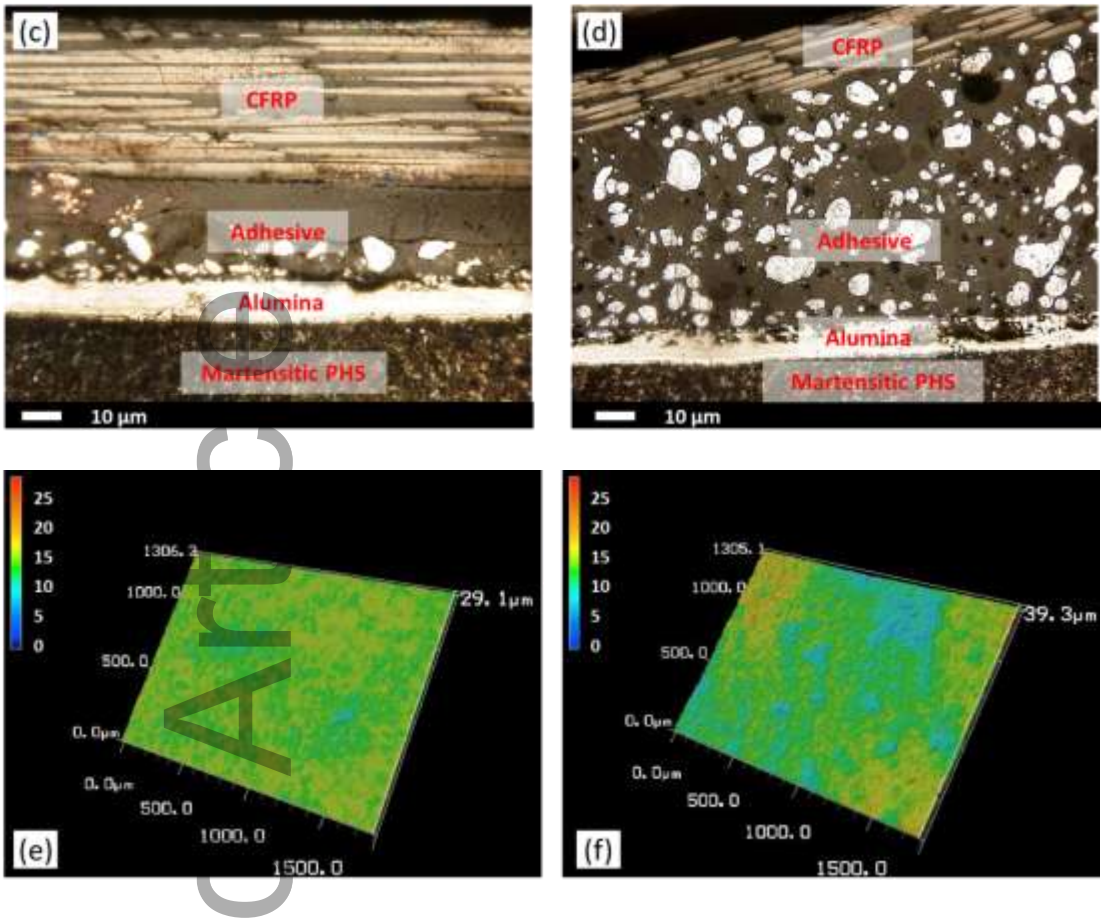
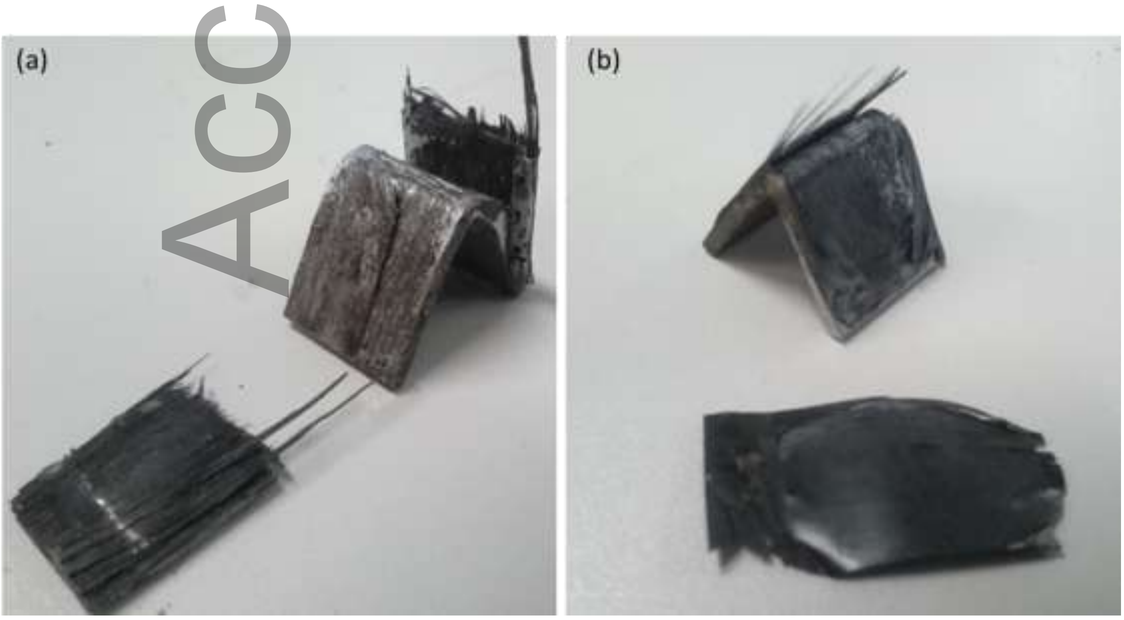


Fig. 6: Hybrid part analysis (a) U-bend part with adhesive (b) U-bend part without adhesive (c) microstructure at interface in flat region of part (d) microstructure at interface in formed region of part (e) Rz surface roughness profile of steel as-received (f) Rz surface roughness profile of steel after press hardening



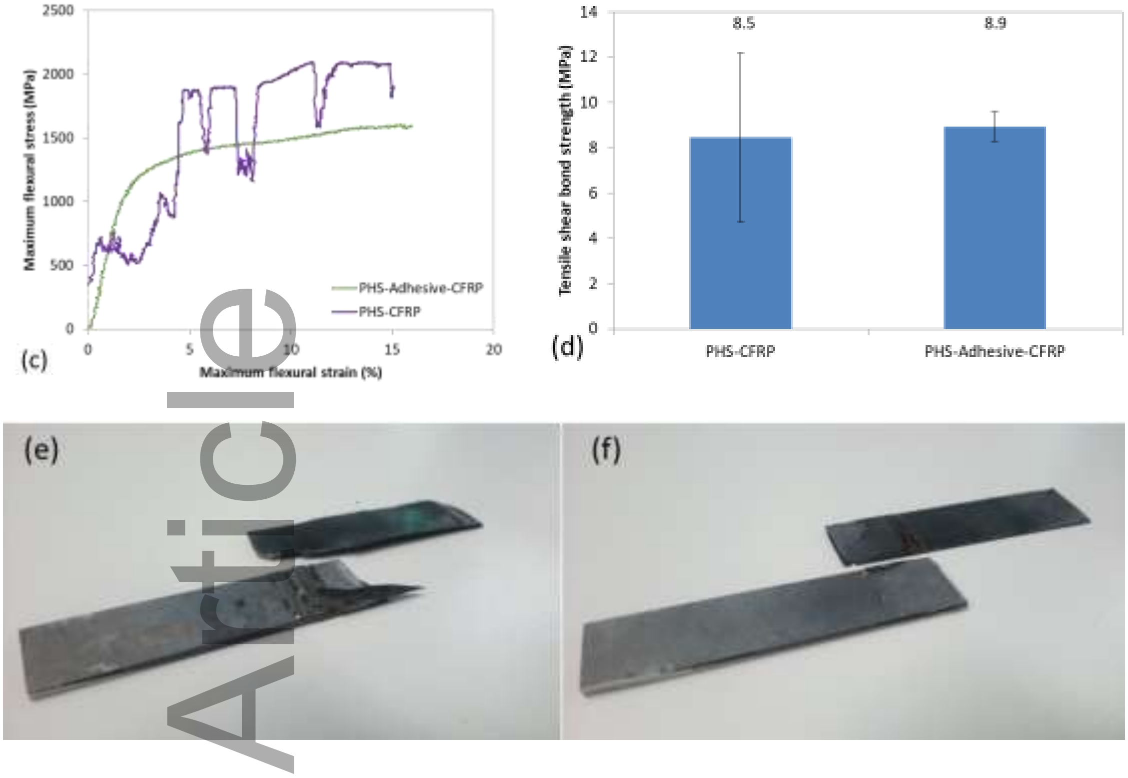


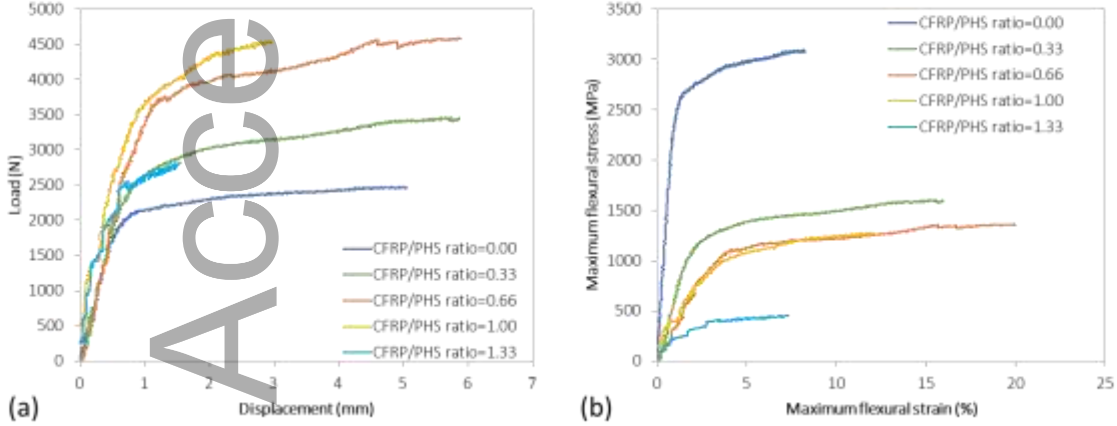
Fig. 7: Hybrid parts with and without adhesive (a) part after flexural testing with adhesive (b) part after flexural testing without adhesive (c) representative flexural stress-strain curves with and without adhesive (d) tensile-shear bond strength (e) failed tensile-shear sample with adhesive (f) failed tensile-shear sample without adhesive

Table 1: Flexural properties of hybrid parts with and without adhesive

	Flexural stiffness (N/mm)	*Maximum flexural strength (MPa)*	*Maximum flexural strain (%)*	*Flexural energy absorbed (J/m^3)*
PHS-Adhesive-CFRP	3128±1097	1633±42	16.0±0.1	21388±185
PHS-CFRP	3566±1729	2015±114	17.5±6.7	33301±6393

3.4. Effect of CFRP/PHS Thickness Ratio

From exclusive PHS (CFRP/PHS thickness ratio = 0.00) to the hybrid part with CFRP thickness of 1.5 mm (CFRP/PHS thickness ratio = 1.00), flexural load-bearing capacity consistently increased (Fig. 8a). This can be understood simply by a greater mass of material to bear load. With increased CFRP/PHS thickness ratio = 1.33, flexural load-bearing capacity surprisingly decreased. With increased CFRP/PHS thickness ratio, maximum flexural stress consistently decreased and with a marked reduction with CFRP/PHS thickness ratio = 1.33 (Fig. 8b). This can be understood simply by increasing thickness with material of lower strength (CFRP) than the base material (PHS). In order to appreciate the value of CFRP in the hybrid part, specific properties must be considered. While specific strength (Fig. 8d) decreased with increased CFRP/PHS thickness ratio, specific stiffness (Fig. 8c) increased with increased CFRP/PHS thickness ratio; and maximum strain to failure (Fig. 8e) and energy absorbed (Fig. 8f) were provided by CFRP/PHS thickness ratio = 0.66.



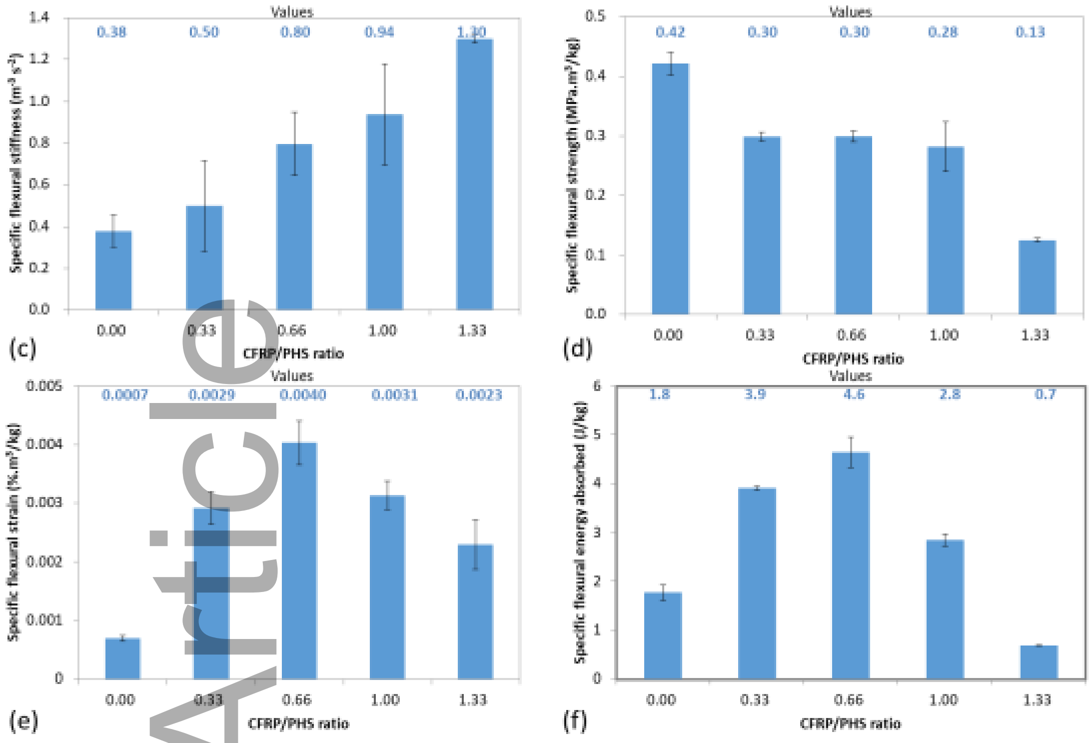


Fig. 8: CFRP/PHS thickness ratio (a) representative flexural load-displacement curves (b) representative flexural stress-strain curves (c) specific flexural stiffness (d) specific flexural strength (e) specific flexural strain (f) specific flexural energy absorbed

4. Conclusions

The new one-step process for manufacturing PHS-CFRP hybrid parts with potential for reduced cycle-time, infrastructure requirements and energy consumption compared to traditional processes was developed. Conclusions include:

- While molybdenum alloys are common tool materials for press hardening, in the new process, lower thermal conductivity of titanium alloy tool material was found to be preferable, providing the optimal balance between die-quenching rate for martensite formation and temperature maintenance for curing and bonding of prepreg.

- Via the new one-step process, PHS exhibited lower flexural strength owing to tempering of martensite during interrupted die-quenching with titanium alloy dies, whereas via the traditional two-step process with molybdenum alloy dies, as-quenched martensite was maintained.
- Via the new one-step process, CFRP also exhibited lower flexural strength, attributed to anisothermal and sub-optimal curing conditions under slow cooling of the forming tool.
- Via both processes, hybrid parts presented flexural strength mid-way between values of the constituting materials, with higher stiffness, strain to failure and energy absorption.
- Via the new one-step process, hybrid parts presented slightly lower flexural stiffness and strength, but strain to failure and energy absorption were higher.
- Comparing hybrid parts produced via the two processes, overall similar properties were presented, demonstrating no sacrifice of part-quality from the new one-step process, despite its clear economic and environmental advantages.
- Addition of adhesive between PHS and CFRP reduced flexural properties, but stabilised flexural deformation behaviour and increased bond strength.
- Optimal CFRP/PHS thickness ratio was 0.66.

Acknowledgments

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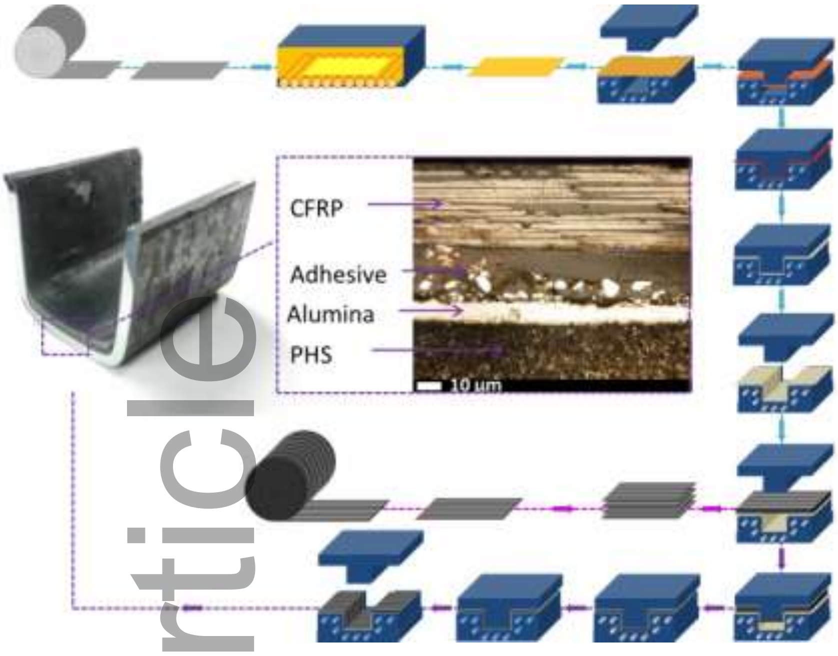
A new one-step process for manufacturing Press Hardened Steel-Carbon Fibre Reinforced thermoset Polymer hybrid parts using residual heat of the steel part immediately following hot forming and interrupted die-quenching for curing and bonding prepreg to steel.


CFRP
Adhesive
Alumina
PHS
10 µm