Key Engineering Materials
ISSN: 1662-9795, Vol. 1051, pp 105-111
doi:10.4028/p-817agE
© 2026 The Author(s). Published by Trans Tech Publications Ltd, Switzerland.

Submitted: 2026-01-18
Revised: 2026-02-17
Accepted: 2026-02-17
Online: 2026-04-17

A Novel One-Shot Forming Process Integrating Hot Form Quench (HFQ) of High-Strength Aluminium for Fibre–Metal Laminate (FML) Panel Parts

Chunyi Gao[1,a], Hao Wu[1,b], Bamber Blackman[2,c] and Nan Li[1,d*]

[1]Dyson School of Design Engineering, Imperial College London, London, UK

[2]Department of Mechanical Engineering, Imperial College London, London, UK

[a]chunyi.gao21@imperial.ac.uk, [b]h.wu@imperial.ac.uk, [c]b.blackman@imperial.ac.uk,
[d*]n.li09@imperial.ac.uk

Keywords: fiber metal laminates, thermoplastic composites, one-shot forming.

Abstract. Fibre metal laminates (FMLs), combining metal alloy sheets with fibre-reinforced polymers (FRPs), offer high specific strength and good fatigue resistance for lightweight structural applications. However, conventional manufacturing routes for thermoplastic FMLs rely on separately forming and bonding or hot pressing, which involve multi-stage forming routes, long heating cycles, high energy consumption and limited industrial scalability. To address these limitations, a novel non-isothermal one-shot forming route integrating hot form quench (HFQ) with FRP stamp forming is proposed in this study. In this process, separately heated metal and FRP blanks are stamped together in cold tools, enabling simultaneous forming and adhesive-free bonding within a single operation. U-bending forming trials were conducted using AA6082 aluminium alloy sheets and carbon fibre-reinforced polyamide 6 (CF/PA6) laminates. The influence of FRP temperature state and aluminium surface condition on forming quality and interfacial bonding performance was systematically examined. Solid-state FRP forming limited excessive polymer flow, resulting in stable bonding but a higher intra-ply void content, whereas molten-state forming promoted polymer redistribution and reduced void content at the expense of bonding performance, leading to local debonding in highly deformed regions. In addition, chromic acid etching of the aluminium surface improved bonding and mitigated debonding after forming and post-form T6 artificial ageing. These results highlight the importance of balancing polymer flow behaviour and aluminium surface condition in non-isothermal one-shot forming, providing a practical and energy-efficient route for manufacturing thermoplastic FML components.

Introduction

The growing demand for higher energy efficiency and lower emissions has increased the need for lightweight structures in transportation. Fibre metal laminates (FMLs), consisting of alternating metal sheets and fibre-reinforced polymer (FRP) layers, represent a hybrid material system that combines a high strength-to-weight ratio with good fatigue and impact resistance [1]. By integrating the load-bearing capacity of metals with the stiffness and damage tolerance of FRPs, FMLs have demonstrated reliable performance in aerospace structures where weight reduction and structural integrity are critical [2]. These attributes have also stimulated interest in extending the application of FMLs to the automotive sector, where high production volumes and strict cost requirements must be satisfied [3].

Existing manufacturing routes for FMLs can be broadly classified into two categories: separately forming and bonding, and one-shot forming. In separately forming routes, the metal and FRP layers are formed independently and subsequently joined through a bonding step. This approach offers greater design flexibility and avoids limiting the formability of the metal by the FRP layer. Typical examples include metal forming followed by adhesive bonding or thermoplastic welding. However, these routes require multiple tools and a multi-stage workflow, which increases tooling cost, energy consumption and overall cycle time [2]. One-shot forming aims to deform the metal and FRP layers simultaneously in a single operation. Hot pressing is a representative example, in which the laminate stack is heated to soften the polymer prior to forming. Nevertheless, heating and cooling the entire laminate and tool set lead to long thermal cycles, high energy demand and reduced tool life, making such processes difficult to scale for high-volume production [4-6]. These limitations underline the challenges in developing cost-effective, energy-efficient and industrially scalable forming routes for FML components.

To address the limitations of conventional manufacturing forming routes of FMLs, a novel non-isothermal one-shot forming strategy was proposed by Li et al [7]. In this adhesive-free process, separately heated metal and FRP sheets are stamped together within a short cycle using cold tools with in-die quenching, which reduces overall cycle time and energy consumption. The material system comprising aluminium alloy AA6082 and carbon fibre-reinforced polyamide 6 (CF/PA6) provides a suitable platform for implementing this forming approach. This concept combines the hot form quench (HFQ) process for AA6082 with the stamp forming process for CF/PA6. In the HFQ process, the AA6082 blank material is heated to its solution heat treatment temperature of approximately 540 °C to achieve sufficient formability for forming. The heated blank is then rapidly transferred to a cold tool for quenching and stamping, enabling good formability and the production of complex geometries [8]. The stamp forming of CF/PA6 follows a similar sequence, involving preheating of the laminate and rapid transfer prior to forming. The similarity between the two forming routes, particularly in terms of preheating, rapid transfer and cold tool forming, facilitates their integration into a single operation. An important factor enabling this integration is the temperature difference between the processing windows of the two materials. The melting temperature of PA6 is well below the HFQ forming temperature of AA6082. When the separately heated blanks are stacked prior to stamping, the hot aluminium surface can locally melt the PA6 at the interface, allowing the polymer to flow and wet the metal surface, thereby forming an adhesive-free bond. As only the metal and FRP layers require heating while the tools remain cold, the process reduces energy demand, shortens the cycle time and provides a feasible route for large-scale manufacturing of thermoplastic FMLs.

Although this novel non-isothermal one-shot forming concept offers a potential route for producing thermoplastic FMLs with reduced energy consumption and shorter cycle time, the deformation and bonding mechanisms involved in such processes remain insufficiently understood. In particular, the influence of the FRP temperature state and aluminium surface condition on forming quality and interfacial bonding performance has not been systematically investigated. To address these gaps, controlled forming trials were conducted using AA6082 and CF/PA6, with forming quality and bonding evaluated through optical microscopy observations under different non-isothermal forming conditions.

Materials and Methods

Materials.

In the forming experiments, the materials included 2 mm thick carbon fibre reinforced PA6 FRP panels in woven and unidirectional (UD) forms, and 1.2 mm thick aluminium alloy AA6082-T6 sheets. The nominal dimensions of both materials are listed in Table 1. To accommodate thermal expansion and ensure proper fitting within the blank holder fixture, approximately 2 mm was trimmed from the blank length prior to forming. The aluminium sheets were tested under both untreated and acid-etched surface conditions. In addition, a lubricant was applied to the blank holder to reduce surface friction between the steel tools and the blanks during forming.

Table 1. Material parameters.

Material	Material grade	Material Details	Length	Width	Thickness
Aluminium	AA6082	T6 temper	120 mm	40 mm	1.2 mm
FRP	CF/PA6	UD and woven Twill 2/2	120 mm	40 mm	2 mm

Forming Set-up.

Non-isothermal forming trials were carried out using a 250 kN hydraulic press equipped with two independent furnaces for separately heating the metal and FRP blanks. Fig. 1 (a) presents an overview of the experimental setup, including the metal furnace, the FRP furnace, and the forming rig mounted on the press. The forming tool consisted of a punch, a matching die and a guided blank holder, as shown in Fig. 1 (b) and (c). The forming configuration corresponded to a U-bending configuration. All tools were maintained at room temperature throughout the experiments.

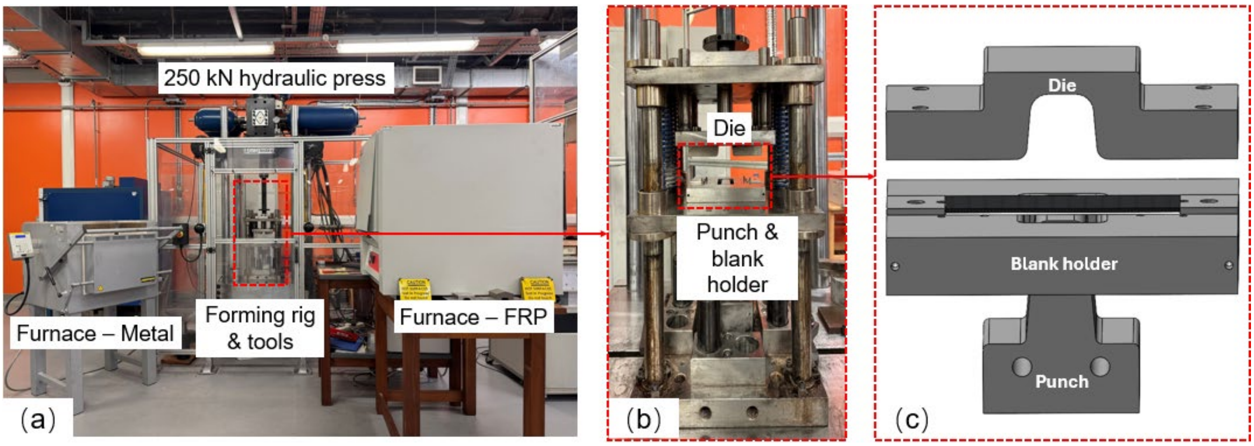

Fig. 1. Experimental forming setup.

The forming process consisted of three stages: separate heating, transfer and stacking, and stamping, as illustrated in Fig. 2. Each heated blank was transferred over a short distance and stacked in the tool immediately prior to forming. The die was driven downward at a constant speed to achieve the U-shaped deformation, followed by a short holding period to ensure quenching of the aluminium sheet and effective interfacial bonding between metal and FRP layers.

No additional adhesive was used; interfacial bonding was achieved through thermally induced viscosity reduction of the PA6 matrix at the metal-FRP interface, followed by quenching that led to re-consolidation of the interface.

After forming, the specimens were subjected to artificial ageing to regain the T6 temper of AA6082. The formed parts were subsequently examined by visual inspection and optical microscopy of cross-sectional samples to evaluate forming quality and bonding performance.

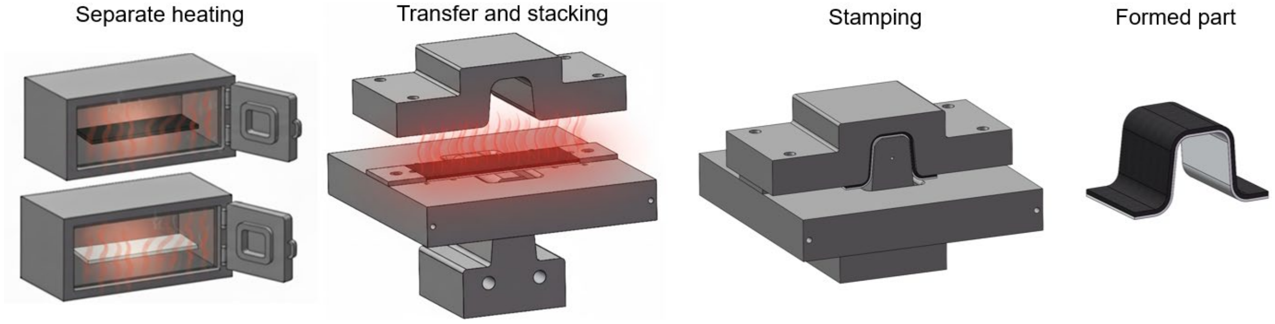

Fig. 2. Forming sequence showing separate heating of the blanks, transfer and stacking, stamping, and the final formed part.

Test Conditions.

The forming trials were designed to examine the influence of key process variables under non-isothermal forming conditions. Both solid-state and molten-state forming of the FRP layer were considered. Solid-state forming was conducted at 215 °C, below the PA6 melting point of 221 °C, whereas molten-state forming was carried out at 235 °C. In this work, the term “solid-state forming” refers to the temperature state of the FRP layer, where the overall temperature across the FRP thickness remains below the polymer melting point before stacking. It is noted that, despite the solid-state classification of the FRP layer, local and transient melting of the PA6 matrix is expected to occur at the metal-FRP interface due to heat transfer from the hot aluminium sheet during stacking and forming.

For all forming conditions, the aluminium alloy was subjected to a solution heat treatment at approximately 535 °C prior to forming, followed by forming at an aluminium temperature of around 420 °C. In addition, the effect of aluminium surface preparation was investigated by comparing untreated and acid-etched AA6082 sheets at a fixed FRP forming temperature of 225 °C, while all other process parameters were kept constant.

Results

Effect of FRP temperature.

The forming results revealed clear differences in forming quality and bonding performance between solid-state and molten-state forming of the CF/PA6 layer. When the CF/PA6 FRP layer was formed in the solid state, the formed parts exhibited good bonding performance. Visual inspection showed no evidence of interfacial debonding between the aluminium and FRP layers. Optical microscopy of cross-sectional samples confirmed that the metal-FRP interface remained continuous, as shown in Fig. 3. In addition, optical micrographs revealed the presence of voids within the FRP layer, particularly in regions associated with polymer flow bands.

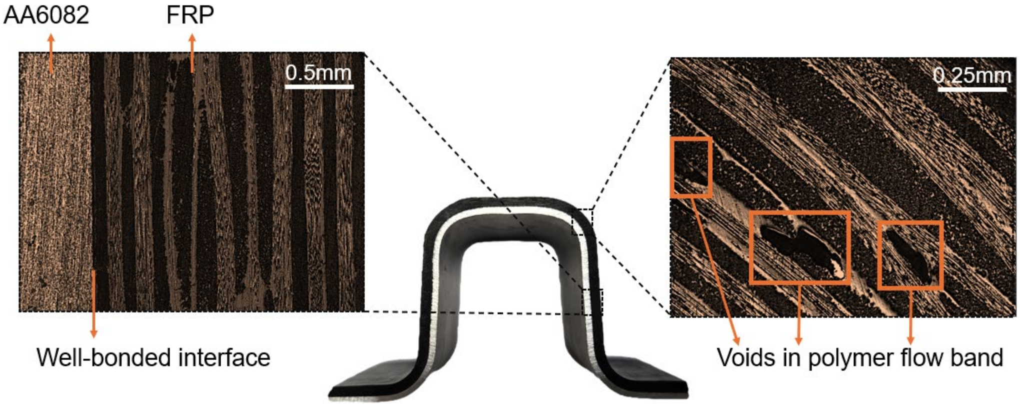

Fig. 3. Formed FML specimen under solid-state FRP forming conditions, with optical micrographs of selected cross-sections.

In contrast, when the CF/PA6 FRP layer was formed in the molten state, a reduction in bonding performance was observed. Local interfacial separation occurred predominantly in the corner regions of the formed parts, as shown in Fig. 4. These regions exhibited distinct separation between the aluminium layer and the adjacent FRP layer. Optical microscopy further showed that the FRP layer contained fewer voids compared with the solid-state forming condition. The polymer matrix penetrated more effectively into the fibre bundles, resulting in a more compact internal structure. Despite the improved intra-ply consolidation, the overall bonding performance of the FML was reduced under molten-state forming conditions.

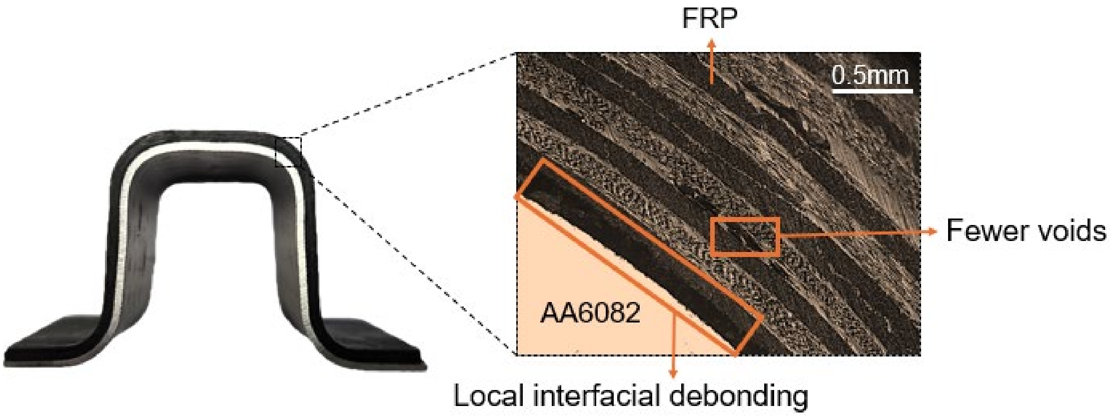

Fig. 4. Formed FML specimen under molten-state FRP forming conditions, with optical micrographs of selected cross-sections.

Effect of aluminium surface condition.

Clear differences in bonding performance were observed between specimens formed using untreated and acid-etched AA6082 sheets, as shown in Fig. 5. For specimens formed with chromic acid etched aluminium, the metal-FRP interface remained largely intact after forming and subsequent artificial ageing. Minor interfacial separation was observed primarily near the corners and flange regions. Despite these local defects, the interface appeared predominantly continuous across the formed parts.

In contrast, specimens formed using untreated aluminium exhibited pronounced interfacial debonding and cracking after artificial ageing. These defects indicate insufficient interfacial bonding strength and a reduced ability of the interface to accommodate the shape mismatch arising from residual stresses introduced during forming and artificial ageing.

Additional insight into the mechanical integrity of the metal-FRP interface was obtained from post-forming double cantilever beam (DCB) tests conducted on FML specimens produced using the same one-shot forming route. All test conditions, including material configuration and processing parameters, were kept identical, with aluminium surface condition being the only variable. The results showed that interfaces formed with chromic acid etched aluminium exhibited a markedly higher interlaminar fracture toughness ($G_{IC} \approx 350$ J m^{-2}) compared with untreated aluminium interfaces (G_{IC} $\approx$ 40 J m^{-2}). In addition, etched specimens displayed stable crack propagation behaviour, whereas untreated interfaces were prone to unstable crack growth and premature delamination. These observations are consistent with the macroscopic interfacial degradation observed after artificial ageing and confirm the critical role of aluminium surface condition in achieving mechanically robust interfacial bonding.

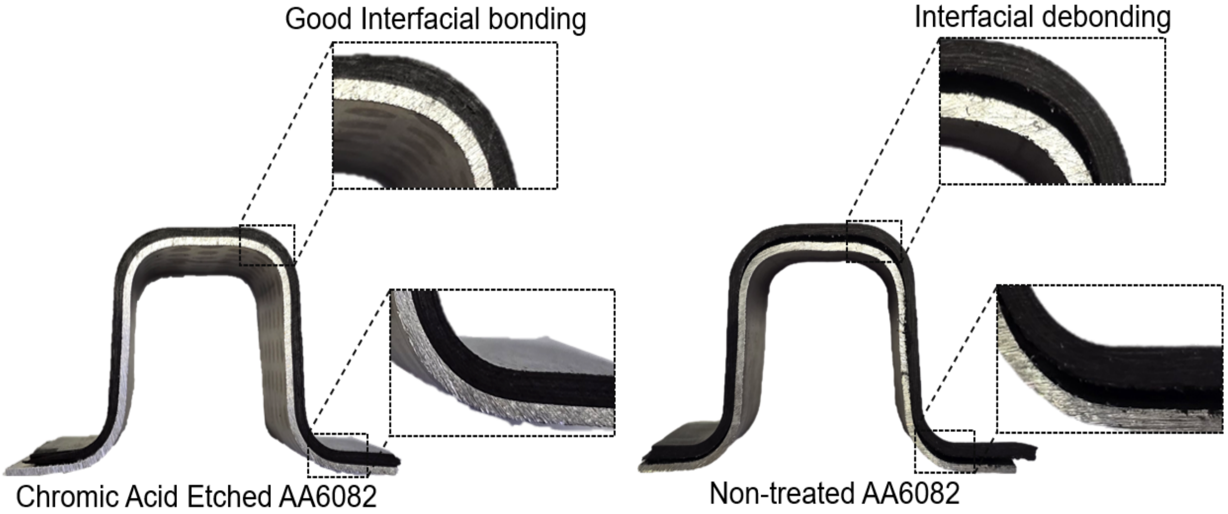

Fig. 5. Macroscopic comparison of formed and aged FML parts produced using chromic acid etched and untreated AA6082 sheets.

Discussion

Influence of FRP temperature.

Under solid-state forming conditions, the viscosity of the PA6 matrix remains high across most of the FRP thickness. Apart from a thin interfacial layer that is locally melted by contact with the hot aluminium surface, the polymer largely remains in a solid or highly viscous state. The high viscosity through the thickness restricts polymer movement in the through-thickness direction and limits redistribution of interfacial PA6 into the FRP interior. As a result, polymer loss from the metal-FRP interface is mainly confined to local squeeze-out at the edges, while a sufficient amount of PA6 is retained at the interface to maintain good bonding performance.

In contrast, under molten-state forming conditions, the PA6 matrix exhibits low viscosity throughout the entire FRP thickness. In this case, the interfacial polymer is not only displaced laterally by squeeze flow but can also migrate into the FRP interior along the thickness direction. The combined in-plane and through-thickness polymer flow leads to depletion of PA6 at the metal-FRP interface, particularly in regions subjected to high pressure and curvature, such as corners and flanges. This depletion reduces the bonding performance.

Optical microscopy observations provide additional insight into this mechanism. The higher void content observed within the FRP layer under solid-state forming conditions indicates limited polymer mobility and restricted through-thickness flow. In contrast, the reduced void content under molten-state forming conditions reflects enhanced polymer redistribution into the fibre architecture. These observations indicate a trade-off between FRP layer consolidation and metal-FRP interfacial bonding governed by the extent of through-thickness polymer flow during non-isothermal forming.

Influence of aluminium surface condition.

The improved bonding performance observed for chromic acid etched aluminium can be attributed to the modified surface condition induced by the etching process. Chromic acid etching thins the native oxide layer and surface contaminants while generating a chemically active and micro-textured aluminium surface [9]. This modified surface promotes improved wetting of the molten PA6 at the interface during stacking and forming, which facilitates more intimate interfacial contact between the polymer and aluminium. As a result, the interface exhibits improved interfacial bonding and is better able to accommodate the deformation imposed during forming, as well as the thermal and residual stresses introduced during artificial ageing.

In contrast, untreated aluminium surfaces provide less favourable conditions for polymer wetting and interfacial conformity. The reduced interfacial bonding strength is insufficient to accommodate the shape mismatch generated during forming and ageing, leading to interfacial cracking and debonding. These observations highlight the critical role of aluminium surface preparation in achieving reliable bonding performance during non-isothermal one-shot forming of thermoplastic FMLs.

Conclusion

A novel non-isothermal one-shot forming route for thermoplastic FMLs based on AA6082 aluminium alloy and CF/PA6 was investigated. The results show that both the temperature state of the FRP layer and the surface condition of the aluminium strongly influence forming quality and interfacial bonding performance.

Solid-state forming of the CF/PA6 layer resulted in improved interfacial bonding, whereas molten-state forming increased the risk of debonding despite enhanced intra-ply consolidation. In addition, chromic acid etching of the aluminium surface significantly improved bonding performance and mitigated interfacial degradation after forming and artificial ageing.

These findings emphasise the importance of controlling polymer flow and aluminium surface condition in non-isothermal one-shot forming. Further optimisation of process control is expected to support the transition towards high-volume industrial manufacturing of thermoplastic FML components.

Acknowledgement

Chunyi Gao acknowledge the PhD Scholarship from Imperial College London. Nan Li and Bamber Blackman would like to thank UKRI Impact Acceleration Accounts within Imperial College London (EPSRC – EP/X52556X/1). For the purpose of open access, the authors have applied a Creative Commons Attribution (CC BY) license to any Author Accepted Manuscript version arising.

References

[1] G. Wu, J.-M. Yang, The mechanical behavior of GLARE laminates for aircraft structures, JOM 57 (2005) 72-79.

[2] Z. Ding, H. Wang, J. Luo, N. Li, A review on forming technologies of fibre metal laminates, Int. J. Lightweight Mater. Manuf. 4 (2021) 110-126.

[3] R.D.F.S. Costa, R.C.M. Sales-Contini, F.J.G. Silva, N. Sebbe, A.M.P. Jesus,A critical review on fiber metal laminates (FML): From manufacturing to sustainable processing, Metals 13 (2023) 638.

[4] B.-A. Behrens, S. Hübner, A. Neumann, Forming sheets of metal and fibre-reinforced plastics to hybrid parts in one deep drawing process, Procedia Eng. 81 (2014) 1608-1613.

[5] L. Mosse, P. Compston, W.J. Cantwell, M. Cardew-Hall, S. Kalyanasundaram, The effect of process temperature on the formability of polypropylene based fibre–metal laminates, Compos. Part A 36 (2005) 1158-1166.

[6] B. Bernd-Arno, H. Sven, G. Nenad, M.-C. Moritz, W. Tim, N. André, Forming and joining of carbon-fiber-reinforced thermoplastics and sheet metal in one step, Procedia Eng. 183 (2017) 227-232.

[7] N. Li, Z. Ding, C. Gao, H. Wang, Method of manufacturing multi-material structures, United Kingdom Patent Appl. P79563GB. (2025).

[8] N. Li, J. Zheng, C. Zhang, K. Zheng, J. Lin, T.A. Dean, Investigation on fast and energy-efficient heat treatments of AA6082 in HFQ processes for automotive applications, MATEC Web Conf. 21 (2015) 05015.

[9] M. Droździel-Jurkiewicz, J. Bieniaś, Evaluation of surface treatment for enhancing adhesion at the metal–composite interface in fibre metal laminates, Materials 15 (2022).