Single point incremental forming of multi-matrix continuously-reinforced composites: A feasibility study

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Abstract. Fibre-reinforced plastics offer remarkable strength-to-weight ratios, making them an excellent choice for lightweight engineering solutions. However, the forming of precursor materials such as preforms or prepregs poses substantial challenges, with defects such as delaminations or fibre misalignments occurring frequently. One approach to de-risk composite parts manufacturing are Multi-Matrix Continuously-Reinforced Composites (MMCRCs), pre-structured with formable and non-formable matrix materials connected by continuous fibre reinforcement. Regions with a matrix of covalent adaptable networks (CANs, aka vitrimers) can be locally formed to the desired shape, while unformable regions with a conventional thermoset matrix restrict undesirable deformations. As targeted local forming operations are required, incremental sheet forming is proposed as a flexible forming process that does not involve expensive moulds. To evaluate the feasibility of incrementally forming MMCRCs, a simple corner geometry is formed using single point incremental forming (SPIF) in this study. The prepared sample with a formable hinge region is attached to a metal dummy sheet with a vacuum bag and heated to forming temperature. Using a specifically developed toolpath strategy, the layup is deformed in a robotic SPIF setup. Albeit revealing challenges in the simultaneous forming of metal and MMCRC sheets, results prove that the proposed approach is promising in allowing the manufacture of high-quality composite parts in decoupled production and forming processes.

Introduction

Fibre composites have become indispensable in many applications, such as aviation, the automotive sector and medical technology. Nevertheless, there are still major challenges in the efficient and cost-effective production of high-quality components with complex and often highly customised geometries. One reason for this are the challenging handling and forming processes associated with flexible preforms or prepregs. Defects such as delaminations, fibre misalignments, and resin-rich regions can occur during layup, forming or consolidation processes, especially in areas with sophisticated, doubly-curved geometric features and processes involving large global deformation [1]. Such defects lead to a high rate of part scrappage, reduced in-service performance, or even premature failures. Therefore, optimising manufacturing efficiency and minimising material waste are essential for broader adoption of composite materials across market segments.

An innovative approach to mitigate these challenges is the development of Multi-Matrix Continuously-Reinforced Composites (MMCRCs). This concept involves integrating both

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formable and non-formable materials within a single composite, connected by continuous reinforcement. Such a configuration allows for a 'flat' pre-structure to be initially produced, followed by the targeted forming of designated formable regions through the application of heat and pressure. While the formable regions adapt to the desired shape, the unformable regions restrict unwanted deformations, with the overall structural integrity being maintained by the continuous reinforcement. This approach not only mitigates defects by limiting excessive deformations but also offers additional advantages, such as reduced layup times and improved logistics as well as potential for improved mechanical performance and repair [2–4].

Key to this approach are the formable regions constructed using covalent adaptable networks (CANs), also known as vitrimers [5]. They have similar mechanical and chemical properties as thermosets but possess reversible chemical side chains that allow reshaping similar to thermoplastics. Their advantages include low processing temperatures (50-200 °C), lower viscosity compared to typical thermoplastics, and compatibility with traditional thermosetting resins. These attributes make vitrimers especially suitable for use in MMCRCs, allowing localised forming with minimal additional cost [2].

However, as fibres within nonformable regions cannot slide freely during forming, the exact fibre length necessary to produce the required final geometry in the formable regions must be known and incorporated during pre-structure preparation. Otherwise, there is a risk of trapping excess fibre length and generating defects such as wrinkles and poor geometric compliance during forming. Furthermore, previous studies highlight the importance of even heating and exact positioning of materials and tools. Consequently, the development of specially designed forming machinery to gradually form the material is suggested, as standard equipment and tools did not always yield satisfactory results [2,4].

A promising solution to realise the localised and gradual forming of MMCRCs could be incremental sheet forming (ISF). In its original form, it is used to form sheet metal without moulds by gradually introducing strains into a circumferentially clamped sheet with a simple standard tool such as a hemispherical tooltip. In single point incremental forming (SPIF), a single tool is moved along the sheet surface by a CNC machine or a robot, locally and progressively deforming the sheet [6]. However, the general deformation mechanisms in the ISF of metals or thermoplastics, elongation and thinning, are impossible for continuous fibres [7]. Therefore, Fiorotto et al. [8] utilised a vacuum bag to affix a woven thermoset prepreg to a metal dummy sheet which was then incrementally formed. This strategy protected the prepreg from direct tool contact and allowed it to slide with respect to the metal sheet while deformed. Compared to thermosets, more researchers applied incremental forming to (continuous) fibre-reinforced thermoplastics (FRTP). The availability of fully impregnated and consolidated organosheets as semi-finished material enables easier material handling, being a good example for the decoupling of material production and forming. For the ISF of FRTP, global heating of the composite is required in addition to employing a metal dummy sheet layup. Most researchers used a hot air chamber and two metal sheets, one above and one below the FRTP, separated by PTFE layers, to perform SPIF [7,9–13].

In this study, to examine the general feasibility of incrementally forming MMCRCs, a simple corner geometry is formed using a hot SPIF setup, combining approaches from previous works on prepreg and organosheet ISF.

Materials and Methods

Sample Preparation. A 90° corner was chosen as a simple target geometry requiring only bending and no in-plane shear deformation. To allow the bending, the flat pre-structure must incorporate the excess fibre length required within the formable vitrimer region, which increases with every ply from the inner towards the outer side of the corner. Thus, a pronounced bead in the shape of a non-buckled wrinkle must be realised on the otherwise flat pre-structure. Therefore, a bespoke mould was manufactured with a continuously splined recess of 13.91 mm width and 5.95 mm height. These values were calculated to exactly capture the required excess length of a 3.5 mm thick sample with a 6.4 mm internal corner radius. The excess length Δ can be calculated using Eq. 1, with A being the highest point of the feature, and B being a shape parameter which can be estimated as 1/8th of the width of the embossed region [2].

$$\Delta = A^2 B/3 \tag{1}$$

A $[0/90_8]_s$ laminate of 3K, 2x2 twill weave dry carbon fibre reinforcement with a cloth weight of 210 g/m² (Pyrofil HT TR 30S 3L), alternating with single 0.3 mm films of vitrimer (Vitrimax^{TM} T100) was laid up. Fibre orientations in the fabric of size 300 mm x 200 mm were either aligned with or transverse to the recess. The vitrimer films had a length of 300 mm and a width of 20 mm, so that the width straddled the recess. After vacuum-bagging, the layup was pressed in a hydraulic hot press at 140 °C with a pressure of 0 bar for 120 minutes (pre-heating), 0.1 bar, 0.2 bar and 0.4 bar for 10 minutes each, and finally 8 bar for 120 minutes. After cooling and removing the pressure, the dry arms of the partially infused preform were vacuum infused with a mixture of Gurit PRIME^{TM} 37 resin and Ampreg^{TM} 3X Extra-Slow hardener, using 100:29 ratio, respectively, mixed for 2 minutes by hand, and degassed for 30 minutes before infusion. After curing for 13 h at 25 °C, 50 °C were maintained for 16 h post cure [2]. Finally, 100 mm x 200 mm samples were cut from the plate, as shown in Fig. 1.

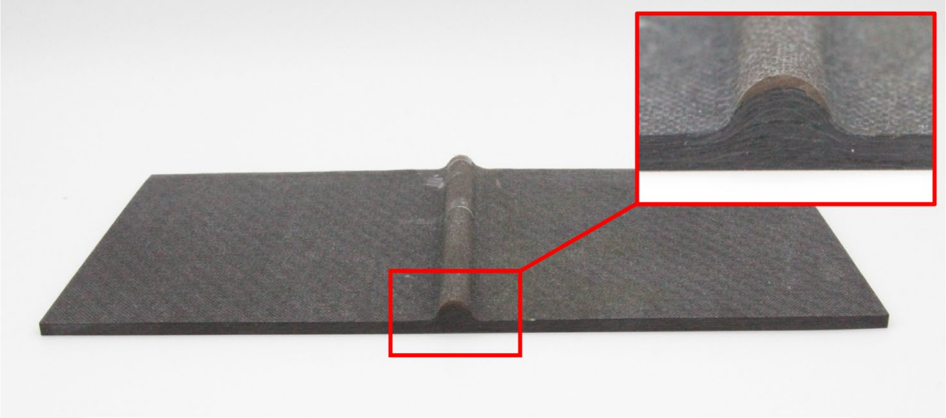

Figure 1 – Flat MMCRC pre-structure, cut to 100 mm x 200 mm, with excess fibre length for bending incorporated in pronounced bead

Forming Setup. To allow single point incremental forming of the prepared MMCRC, a metal dummy sheet is required on the upper side of the sample, protecting it from direct tool contact and maintaining the formed shape also in a heated state. While transferring the deformations, the FRP must be able to slide with respect to the metal sheet, as rigid clamping of its edges would lead to breakage. Due to the pronounced bead of excess fibre length on the lower side of the sample, a vacuum bag attaching the FRP to the metal sheet is most feasible. Therefore, a stack was prepared consisting of an aluminium EN AW-1050A H111 sheet of 1 mm thickness, a PTFE sheet of 0.05 mm thickness, the MMCRC sample, a peel ply, breather fleece and an FEP vacuum bag of 0.025 mm thickness. While the aluminium sheet and the vacuum bag were 350 mm x 350 mm, the other materials were only slightly larger than the FRP. A type K thermocouple was incorporated into the layup to measure the temperature just next to the vitrimer region. The vacuum bag was generously pleated to prevent tearing during the forming process and was sealed around the edge of the aluminium sheet. The vacuum hose connection was realised through a hole in the aluminium sheet. Fig. 2 shows a sectional drawing of the vacuum stack layup and the real stack from below.

The stack was mounted on top of an insulated chamber with the metal sheet facing upwards and the vacuum bag facing downwards towards the outlet of a Leister Mistral 2 premium hot air gun with a power of 3.4 kW. A curved pipe ensured that the hot air jet was directed precisely onto the centre of the stack, where the vitrimer was located. Before tightening the clamps, the vitrimer region was gradually heated to a temperature of 135 °C, allowing the stress-free thermal expansion of the Aluminium. After clamping, while the target temperature was maintained, a 1.2210 steel tool with a hemispherical tip of 20 mm diameter, guided by an ABB IRB 6660-205 industrial robot, was used for SPIF. The tool-sheet contact was lubricated with WEICON Bio-Cut oil. The setup is depicted in Fig. 2 and Fig. 3. After forming, the sheet was cooled to room temperature before the stack was declamped and the vacuum disabled.

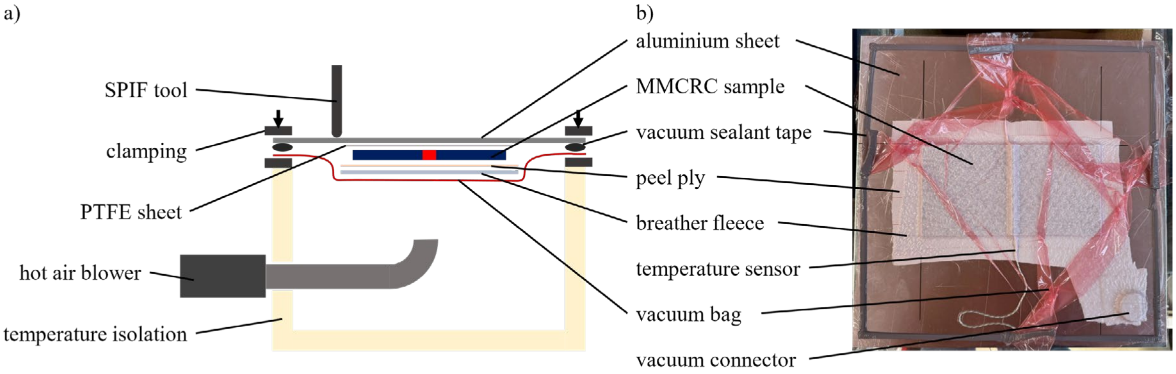

Figure 2 – a) Sectional drawing of the vacuum stack layup clamped on the SPIF setup; b) Vacuum setup, view from bottom side

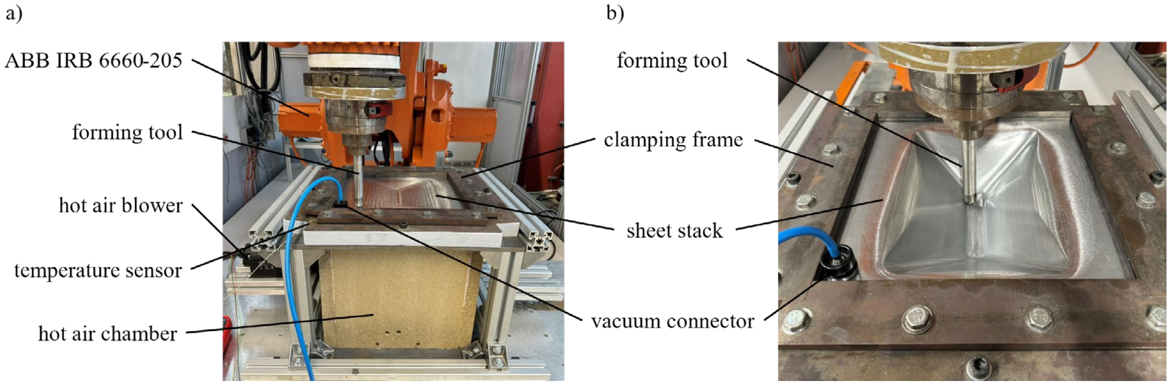

Figure 3 – a) SPIF setup with clamped vacuum stack layup; b) Clamped sheet stack during forming

Toolpath Design. As the metal sheet is firmly clamped on all edges, tapered walls must be added to the simple corner in order to achieve a formable overall target geometry of the SPIF process, which is the frustum depicted in Fig. 4. Thereby, it must be ensured that the intended corner geometry of the MMCRC is part of the overall SPIF geometry while forming limits and expected deformation effects of the metal sheet are taken into account. This includes a global deformation of the metal sheet between the clamping and the locally formed areas as indicated in Fig. 4c). Consequently, the length of the slopes of the bend was extended to ensure plane surfaces for the undeformable arms of the MMCRC. The radius of the corner was chosen to be 20 mm to accommodate the tool with a 10 mm radius.

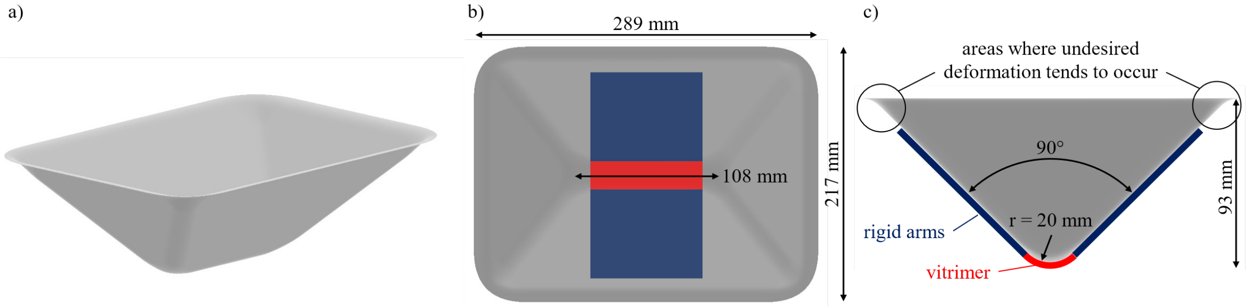

Figure 4 – a) Overall target geometry for SPIF toolpath generation; b) bottom view, c) side view with indicated location of MMCRC sample and measurements

Many widely used SPIF toolpath strategies are based on constant z-increments, in which the target geometry is sliced. The contour of the geometry is then followed by the tool in each z-level or in a spiralling motion, see Fig. 5 a). However, due to the undeformable arms of the sample, the application of those standard SPIF toolpath strategies is impossible, as it would require significant deformation in the rigid parts of the MMCRC. To ensure that the main deformation occurs only in the vitrimer region, several intermediate shapes are generated, gradually increasing the wall angle and, thus, the forming depth by approx. 5 mm per shape. Each intermediate shape is fully formed using a spiralling outside-in approach, moving the tool at a speed of 50 mm/s with a z-gradient of 0.5 mm per revolution. The developed toolpath strategy is visualised in Fig. 5 b).

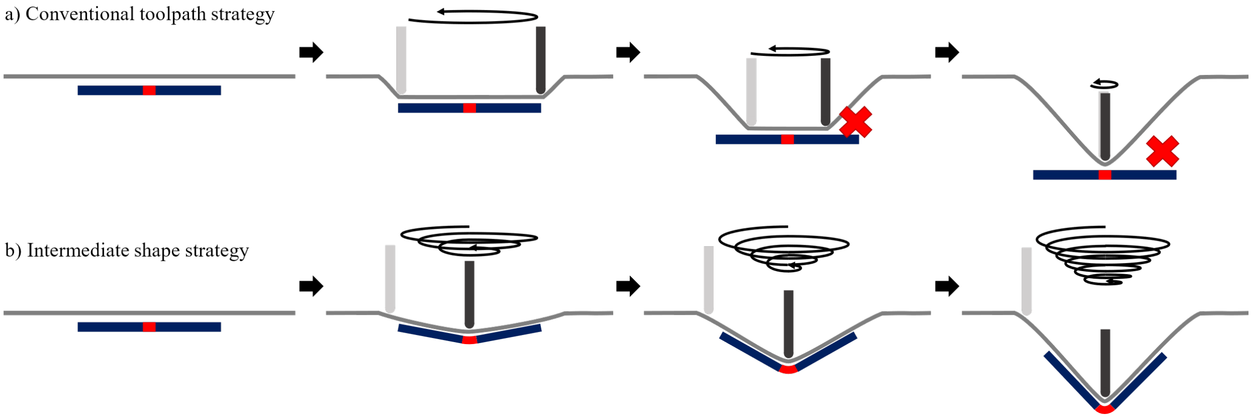

Figure 5 – Comparison of a) conventional contour toolpath strategy, where deformation would be required in the nonformable region of the MMCRC; and b) toolpath strategy, where intermediate shapes with increasing fold angle are formed, promoting the deformation of the vitrimer region

Forming Results

Metal Sheet Forming. In initial experiments, the developed toolpath strategy was tested only on metal sheets to ensure the formability of the geometry. In contrast to a conventional strategy, the tool passes over the same material multiple times, leading to higher accumulative abrasion and a lower metal sheet thickness with each intermediate shape. While the target geometry was successfully formed in the aluminium sheet with a conventional single-shot toolpath, the sheet failed prematurely in the intermediate shape strategy. A typical tear that occurred at the transition between the bottom edge / radius and the wall of the frustum is depicted in Fig. 6 a). In an explorative analysis, influential parameters for enhancing formability were found to be the metal sheet material and thickness, the z-increment for slicing within each intermediate shape, the forming depth increment between intermediate shapes, and the direction of the toolpath spiral. In direct comparison, aluminium 1050A H111 performed better than DC04 steel, as more intermediate shapes could be formed until failure. Furthermore, as expected, higher sheet thickness led to a delayed failure but increased forming forces, presenting a machine limit. A z-increment of 0.5 mm performed better than 1 mm, presumably due to lower forming forces and abrasion. A higher forming depth increment between intermediate shapes means fewer tool passes. Therefore, an increment of 5 mm resulted in a higher overall achievable forming depth of the metal sheet compared to 3 mm. However, further increasing the increment between intermediate shapes would result in a higher wall angle difference between the already deformed wall and the remainder of the intermediate shape. This would put higher stress on the rigid arms of the MMCRC and could lead to breakage while the tool passes over it in the outside-in downwards spiralling motion. Therefore, a forming path starting in the centre was also tested, applying the initial forming force directly in the bend / vitrimer region and spiralling out and upwards within the intermediate shape. However, high forces and global sheet deformation occur, as already the first tool-sheet contact point is loaded with the full forming depth increment. A material flow from the centre of the sheet outwards presumably also contributed to an early failure of this strategy. Thus, the strategy and parameter values reported in the *Materials and Methods* section were chosen to be the best compromise between the formability of the metal dummy sheet, the requirements of the MMCRC, and the capabilities of the SPIF setup. However, despite the optimisation efforts, a premature failure of the metal sheet could not be entirely prevented and occurred in intermediate shape no. 16 of 18. Therefore, when forming the MMCRC samples, the experiment was terminated after the 15th intermediate shape to avoid vacuum leakage and defects. This reduced the resulting final corner angle of the target geometry from 90° to 100.4°.

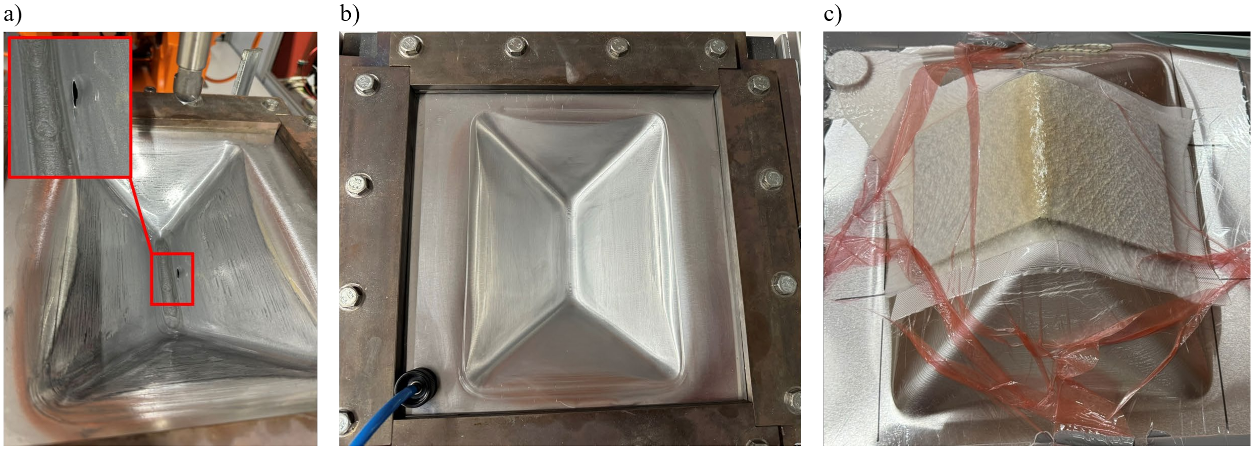

Figure 6 – a) Tear in aluminium sheet after forming intermediate shape no. 16 in initial metal sheet forming trials; b) Clamped sheet stack after successfully forming intermediate shape no. 15 and cleaning the surface from lubricant and abrasion residues; c) Lower side of the sheet stack with intact vacuum setup after removal from the clamping

MMCRC Forming. The successfully formed vacuum stack layup of aluminium sheet and MMCRC sample is shown in Fig. 6 b) and c) from top and bottom view, respectively. After 15 intermediate shapes, the metal sheet and the vacuum bag remained intact, leading to a good conformity of the MMCRC to the metal dummy sheet geometry. The MMCRC could be easily removed from the sheet stack, retaining its mechanical stability and the formed corner angle, which was measured to be 102°. The difference to the nominal target angle of 100.4° can be explained through the elastic springback of the metal sheet and possible path deviations due to the limited stiffness of the forming robot. In future investigations, these could be compensated by incorporating advanced models or simulations predicting these effects during path generation.

As shown in Fig. 7, the inner side of the bend retained a mostly smooth surface with no visible defects in the vitrimer region. However, a wrinkle developed along the width of the sample at the interface between the vitrimer and the epoxy regions on one inner side of the corner, leading to delamination and isolated fibre breakage in the outer laminate layer. This indicates a certain in-plane compressive stress during the forming operations due to the accumulation of excess length between one side of the bend and the thermoset boundary. However, the other epoxy arm remained intact with no apparent defects, suggesting an influence of the outside-in downwards spiralling toolpath and/or of the sample preparation. On the outer side of the corner, as visible in Fig. 7 c) and d), a slight bulge of excess fibre length remained, as the targeted angle of 90° was not reached. In addition, excess vitrimer accumulated on the outer side and the edge of the bend, as it appears to have been squeezed and/or sucked out of the panel. While part of the vitrimer was absorbed by the breather fleece, as visible in Fig. 6 c), a certain flow of the very viscous resin from the vitrimer region into the epoxy arms becomes apparent in Fig. 7 c). This effect is likely to have contributed to the wrinkling and delaminations [2] and should be further investigated, for example by dosing the vitrimer in the embossment region more precisely.

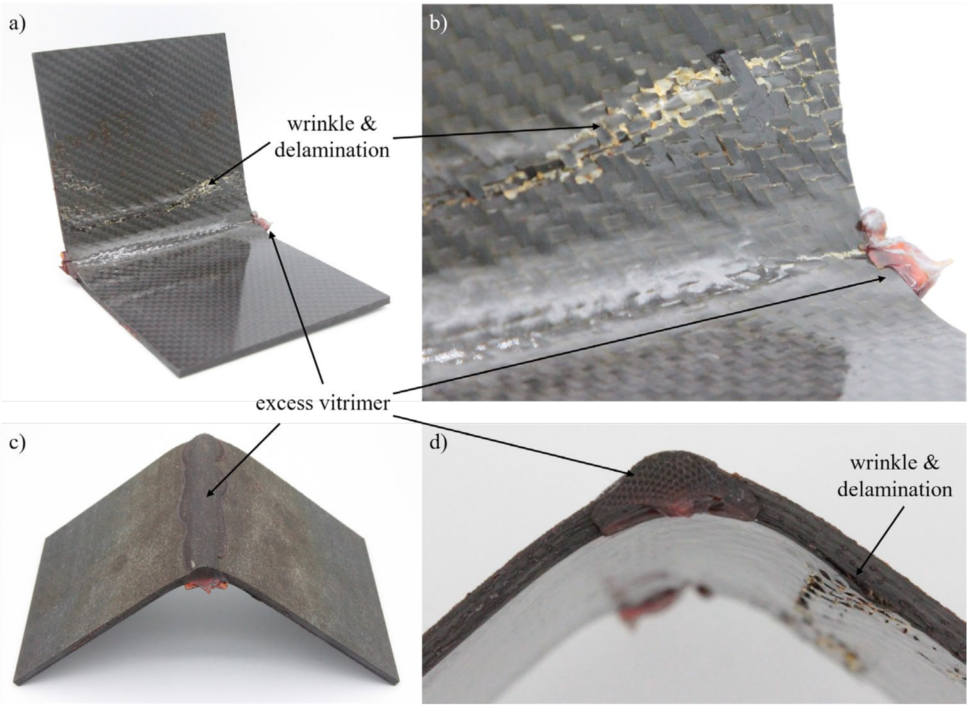

Figure 7 – Formed MMCRC corner from a) side view with b) detailed view of the intact bend and the wrinkling defect in the transition zone between vitrimer and epoxy regions; View on the corner from c) side / top view and d) detailed side view, showing excess vitrimer, 'unused' excess fibre length and delamination defect.

Conclusion and Outlook

Overall, the results of this simple feasibility study show that incremental forming can be an effective method for forming multi-matrix continuously-reinforced composites (MMCRCs). With the aid of intermediate shapes of the final target geometry, toolpaths which ensure that the main deformation is limited to the formable vitrimer domain could be generated. While this is relatively simple for the selected corner geometry requiring bending only, the applicability of this strategy to more complex geometries also involving in-plane shear is generally expected but requires further investigation. The biggest challenge encountered in this study is finding a compromise between metal dummy sheet formability and MMCRC formability. The multiple tool passes required to generate the intermediate shapes lead to premature failure of the metal sheet, which could be prevented by further increasing sheet thickness or optimising parameters such as the forming depth increment of the intermediate shapes. Additionally, multiple metal sheets could be formed into coarsely spaced intermediate shapes, each using a conventional toolpath. These could be then used to form a single MMCRC sample via further, finely spaced intermediate shapes from one coarse shape to another, changing the metal sheet once the next coarse shape is reached. While this leads to a higher number of metal sheets being used, their recyclability, the reduction of waste of resource-intensive fibre composites, and the elimination of the need to produce a conventional mould are expected to have a positive environmental effect and a higher manufacturing efficiency compared to conventional production, especially for small lot sizes. However, the complete elimination of metal support sheets can be a further research goal. Therefore, alternative solutions for clamping and locally heating the vitrimer regions could be found. The latter is expected to also have a positive effect on part quality, as defects such as the observed wrinkle and delamination at the vitrimer-epoxy interface or the resin migration into the epoxy arms could possibly be prevented. To fully understand the reasons and effects of the observed imperfections, internal part quality, such as delaminations and porosities, must be investigated before and after forming as well as in between intermediate shapes, relating them to forming parameters.

To conclude, this study shows promising initial results for the incremental forming of MMCRCs, yet also highlighting the need for further investigations. If a good interplay of precise production of the pre-structure and targeted local forming with the correct paths and parameters is achieved, the combination offers great potential for avoiding forming process-induced defects and simplifying logistics and handling processes in composites production. Furthermore, in spite of a longer cycle time compared to a typical stamping process, the overall lead time for individual parts or small series could be significantly reduced by eliminating the time and effort for mould design and production.

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