Manufacturing of Ceramic Matrix Composites Conical Structures Using Automated Fibre Placement

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ABSTRACT

Automated fibre placement of oxide-based ceramic matrix composites was demonstrated. Tfhis was possible due to the emergence of an aluminium oxide/aluminium oxide tape material format. The material consists of Nextel 610 alumina oxide fibres with a proprietary alumina-based matrix system. Historically, aluminium oxide-based ceramic composites have been created from prepreg formats. In the current work, Automated Fibre Deposition was adapted to create oxide-based ceramic matrix composites using tape material. Key processing variables were investigated, and a cone shaped demonstrator was manufactured. The manufacturing process exhibited control over temperature, pressure and placement, whilst also reducing the material waste from 35% to less than 2%.

RESUME

Le placement automatisé de fibres pour les composites à matrice céramique à base d'oxyde a été démontré, rendu possible grâce à l'émergence du format de matériau en ruban oxyde d'aluminium/oxyde d'aluminium. Ce matériau est composé de fibres d'oxyde d'alumine Nextel 610 associées à un système de matrice à base d'alumine propriétaire. Historiquement, les composites céramiques à base d'oxyde d'aluminium étaient fabriqués à partir de formats de préimprégnés. Dans ce travail, le procédé de dépôt automatisé de fibres a été adapté pour créer des composites à matrice céramique à base d'oxyde à l'aide de matériau en ruban. Les variables clés du procédé ont été étudiées et un démonstrateur en forme de cône a été fabriqué. Le procédé de fabrication a permis un contrôle précis de la température, de la pression et du positionnement, tout en réduisant le gaspillage de matériau de 35 % à moins de 2 %.

KEY WORDS

Ceramic Matrix Composites, Materials manufacturing, Materials performance

MILITARY RELEVANCE

Oxide/Oxide Ceramic Matrix Composites (CMCs) are emerging as alternatives to nickel-based superalloys, offering improved performance in continuous high-temperature operations (1,200 °C) and a relatively low dielectric constant. These properties make them valuable for military applications like aircraft engines and missile systems, where their ability to withstand elevated temperatures enhances performance. Their low dielectric constant and inherent fracture resistance enable effective electromagnetic wave transmission, making Oxide/Oxide CMCs also ideal for high-temperature radar windows, radomes, and advancing hypersonic systems.

1.0 INTRODUCTION

Ceramic matrix composites based on aluminium oxide fibres and an aluminium oxide matrix (ox-ox) are suitable candidate materials to replace nickel-based super alloys in the aerospace and defence sectors. In comparison with their metallic counterparts, ox-ox CMCs provide improved temperature capability, low density and superior oxidation resistance [1]. These properties enable aircraft to operate at higher temperatures with reduced cooling, leading to improved performance and efficiency of aerospace components [2].

The widespread adoption of ox-ox CMCs has been limited due to material inconsistencies and high costs. CMCs are conventionally manufactured using hand layup with pre-preg or using dry fibres and subsequent infusion [3]. These manual manufacturing methods exacerbate the inherent inconsistent nature of ceramics and lead to significant mechanical property variation.

Suppliers have begun creating tape-based ox-ox CMC materials, which contain both the fibre and matrix in a compatible format for automated fibre placement. This new material format enables the benefits of automation that are currently exploited in the polymer composites industry, such as improved manufacturing consistency through reduced manual handling, to be realised in the CMC industry [4]. The current work investigated the compatibility of the new material format with manufacturing equipment conventionally deployed with polymer matrix composite material. The work also investigates the relationship between key processing variables (temperature, deposition speed, deposition force) and the quality of the deposited CMC.

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2.0 BACKGROUND WORK

Prior to the current work, the National Composites Centre (NCC) led a 1-year programme to assess the feasibility of manufacturing tape-based CMCs using Automated fibre placement (AFP) equipment. The programme used a 3M supplied towpreg material and explored the following areas [5]:

- **Compatibility of ox/ox CMCs with AFP** – It was suspected that the ceramic material may lead to increased erosion wear on manufacturing equipment when compared with the conventionally deployed carbon fibre/polymer material. Accordingly, the towpreg material was processed through a Coriolis C1 AFP to manufacture small coupons and to investigate any resulting erosion wear on machine parts. Minor machine modifications were made to prevent significant additional erosion wear on the AFP feed rollers, compaction rollers, cutting blades and cutting anvils. With these minor modifications, the material was deemed compatible with existing AFP machinery.
- **Key Processing Variable Study** – The compaction force, deposition speed and temperature are critical parameters for quality manufacture of organic based composites. An investigation on the impact of these variables upon deposition quality was conducted using the ceramic towpreg. Subsequently, 15 semi-complex coupons were manufactured using different process parameters and the deposition quality was quantified. The study enabled the identification of suitable manufacturing parameters for a semi-complex demonstrator.
- **Semi-Complex Demonstrator** – After the development and optimisation of several process parameters, a 16-ply thick component was manufactured using the Coriolis C1 AFP. Each ply was approximately 0.18 mm thick. Manufacture of the CMC component was then completed by conducting autoclave consolidation and sintering in an atmospheric (oxygenated) furnace. This demonstrator was selected due to its potential use in leading edge applications and was the first recorded European manufacture of an automated ox-ox CMC, as shown in Figure 1. The work demonstrated that use of the AFP process optimised by the NCC led to only 2%wt of waste material. This demonstrates significant material cost saving when compared to manual prepreg methods which produce ~35% waste.

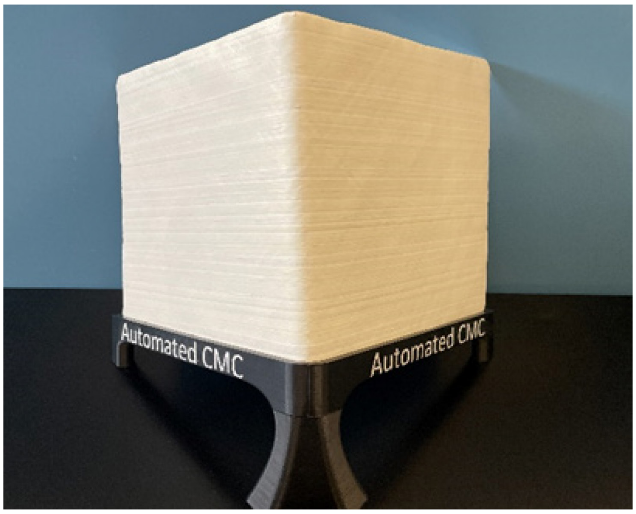

Figure 1: Year 1 demonstrator showing radii capability of AFP-CMC manufacture.

3.0 MATERIALS

During previous work, a specific grade of ox-ox towpreg material was provided by 3M, however, this product has been temporarily discontinued. The emergence of an alternative development slit-tape product from Axiom Materials was therefore used during the current programme. The material uses Nextel 610 fibre within a novel matrix formulation developed by Axiom Materials [6]. The material has a tow width of 6.45 mm and used a 20,000 denier. Once fully processed, the manufacturer reports a continuous operating temperature of 1,000 °C (although subject to atmospheric and loading considerations). The material was provided with no processing conditions; therefore, all processing knowledge was developed within the UK.

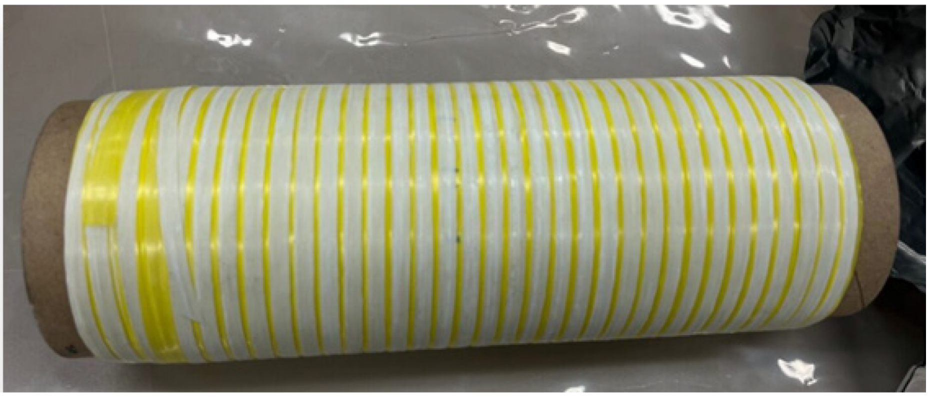

Figure 2: Image of the Axiom slit-tape material.

4.0 MANUFACTURING

4.1 Processing Parameter Trials

A series of trials were conducted to identify suitable processing parameters for manufacturing a prototype technology demonstrator. The trials assessed the deposition of 6 tow wide straight strips of material, as shown in Figure 3.

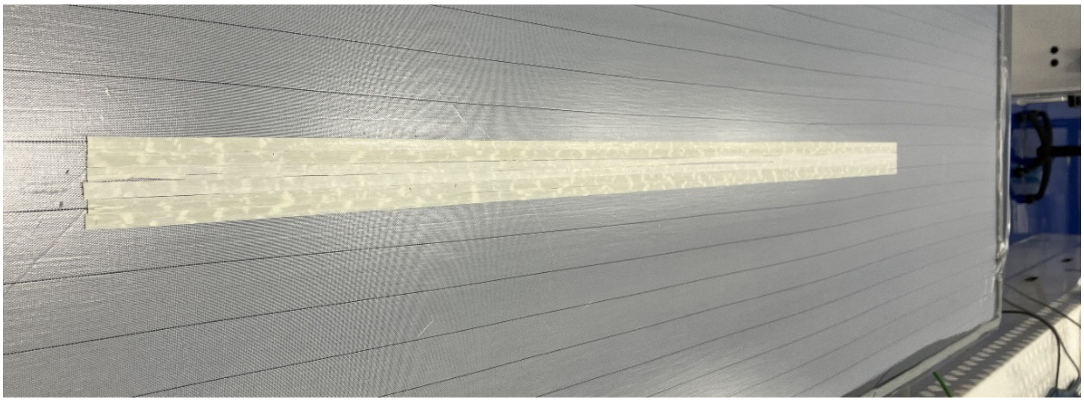

Figure 3: Example of an ox-ox 6 tow strip deposited by AFP to conduct processing parameter trials.

The trials investigated:

- **Heating Technique and Intensity –** Carbon fibre/polymer composites are commonly deployed with AFP and have known properties for the setup of heating sources. They exhibit high thermal conductivities and heat capacities relative to the ceramic materials used in the current research. Therefore, an investigation was conducted to assess the impact of heating type and parameters on the deposition quality of the ceramic tape. It was found that an infrared lamp heating technique did not introduce sufficient heat into the material to enable quality deposition at acceptable speeds. Therefore, the use of a laser heat system was explored. A suitable laser power setting was identified after trialling selected parameters during 'single strip' depositions, as shown in Figure 3.
- **Compaction force** – A suitable compaction force is important to ensure the material tacks to a substrate whilst also ensuring the tape does not snap. Trials using single strips were conducted using several compaction forces to identify a value that provides a consistent successful deposition.
- **Deposition rate** – A high deposition rate is crucial for maintaining commercially viable productivity. However, if the rate is too fast, the material does not spend sufficient time exposed to the heat source to adequately activate tack. An optimal deposition rate was identified following a series of single-strip trials.
- **Steering Trials –** Upon obtaining optimal deposition parameters, a trial to investigate the quality of deposition as a function of steering radius was conducted. The investigation found that the average thickness of the deposited material increased drastically below a particular steering radii. This information aided design for manufacture and subsequent AFP programming for the technology demonstrator.

Figure 4: Photographs of the AFP deposited tape after the steering trials.

4.2 Tooling

A specific tool set was designed and manufactured to support this research (shown in Figure 5). A concave aluminium AFP tool was designed for initial material deposition. The material was then manually transferred to the convex carbon fibre composite tool for autoclave consolidation. The autoclave tool was designed to enable a smooth outer surface for the final component.

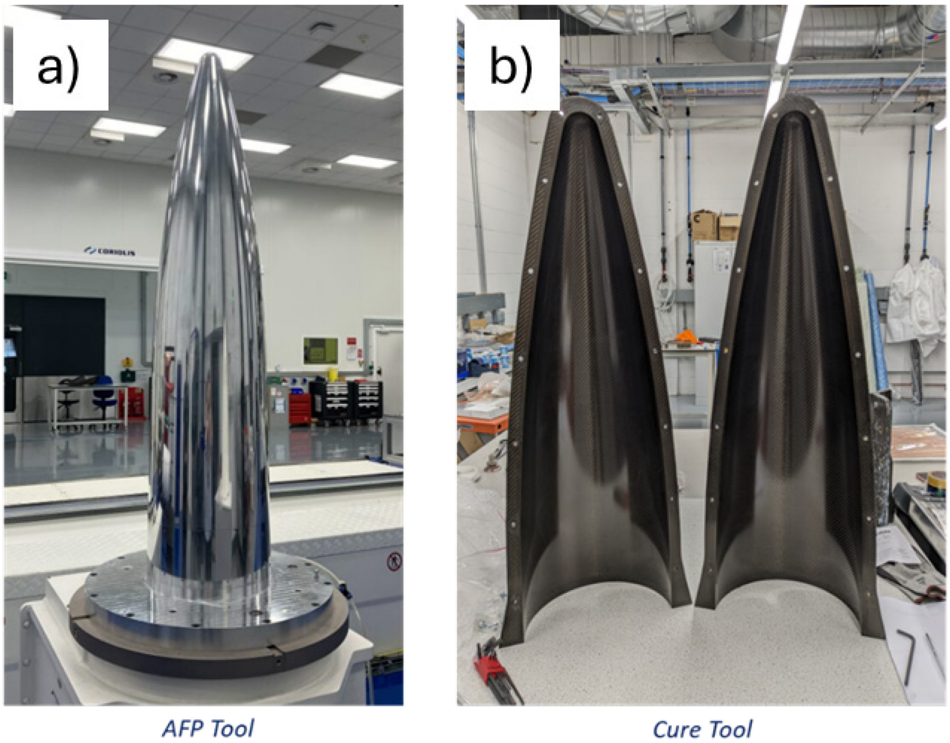

Figure 5: Tools developed for the research: a) AFP deposition tool and b) autoclave consolidation tool.

4.3 Automated Fibre Placement Based Manufacture

Using information from the steering trials, a digital program was written to automate the AFP material deposition, as illustrated in Figure 6(a). When writing the deposition programming, the following factors were considered:

1) Ply Orientation
2) Steering angle
3) Number of tows
4) Number of plies
5) Tool Rotation
6) Layup direction

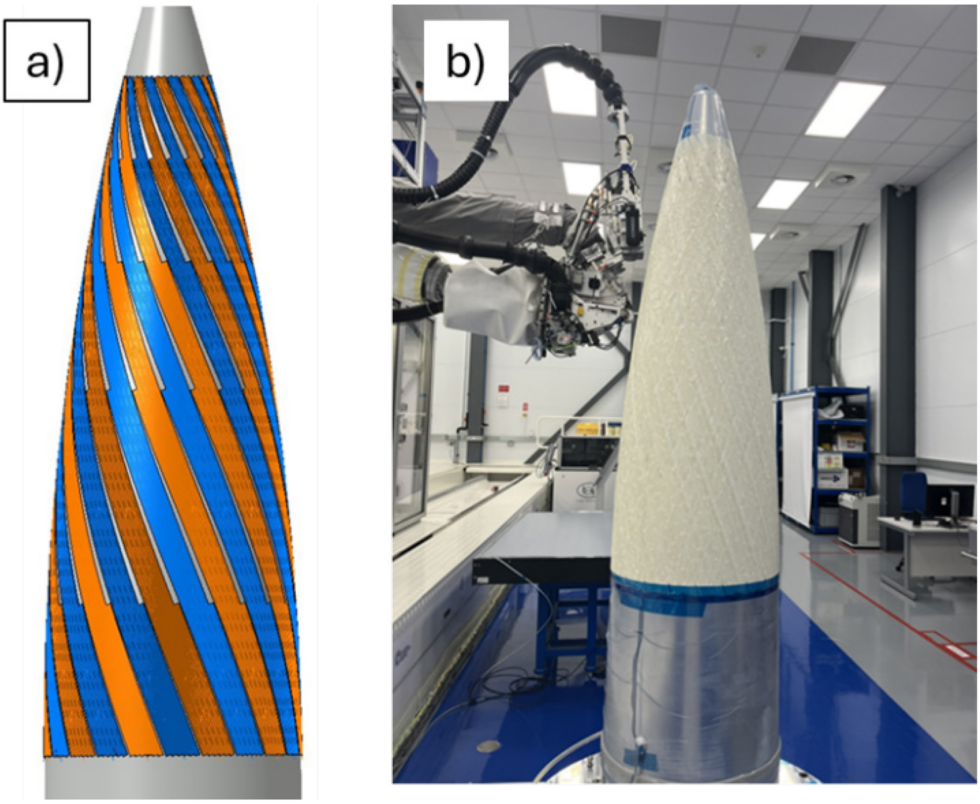

Figure 6: Left, Graphic showing the AFP deposition programme and right, image showing the as- deposited material.

The program enabled successful deposition of the ceramic material onto the AFP tool, as shown in Figure 6(b). However, due to the size of the compaction roller used for the research, the AFP head was unsuitable for depositing materials on the tip of the component. After AFP deposition, the material was manually removed from the tool and placed within the autoclave cure tool, as shown in Figure 5(b). Conventional ox/ox prepreg material (from Axiom) was also manually placed in the component tip area of the autoclave consolidation tool to complete the deposition. The two-part tool was then closed and placed into an autoclave and exposed to heat and pressure. The autoclave process aims to remove organic components from the matrix whilst ensuring consolidation of the material. The component following consolidation is shown in Figure 7. Previous research at the NCC [7] has demonstrated that an autoclave consolidation process can yield a more homogenous porosity distribution and geometry when compared to other consolidation techniques such as infusion and pressing.

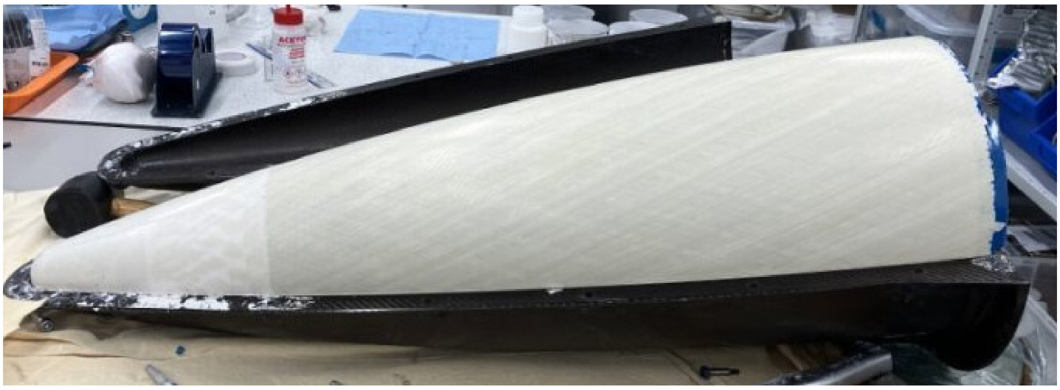

Figure 7: Image of component following autoclave consolidation.

Following consolidation, the component was processed in a furnace under atmospheric conditions. The part was exposed to elevated temperatures for multiple hours. The sintering process removes any residual organic matter and causes ceramic particles to coalesce leading to macro scale material densification. Selecting appropriate sintering parameters is crucial for controlling micro porosity levels, which serve as a toughening mechanism and promote pseudo-ductile (composite) failure behaviour. The component after sintering is shown in Figure 8.

Figure 8: Final component.

4.4 Non-Destructive Testing

Computed Tomography (CT) scanning was conducted to assess the quality of the material following sintering using a voxel size of 100 microns. Example images of the scans are shown in Figure 9. The images show a low degree of macroporosity with an absence of delaminations, indicating good consolidation. However, given the voxel size used in the scans, defects as big as approximately 300 microns may be present but remain.

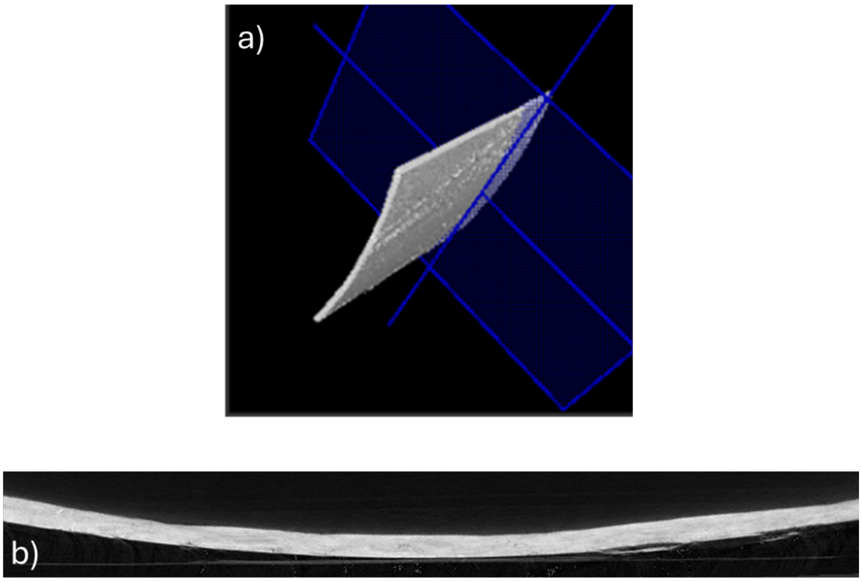

Figure 9: CT scans of the sintered component showing a) the section of the component scanned and b) a scan showing the material cross section.

5.0 RESULTS AND DISCUSSION

The current work used a slit-tape material from Axiom Materials, whilst previous research had used 3M material, which has since been discontinued. Despite the material substitution, trials successfully identified suitable parameters for deposition speed, force and heating, which enabled the AFP of material onto the tooling and thus demonstrated the feasibility of AFP as a viable manufacturing solution for high-temperature hypersonic vehicle components.

Due to restrictions posed by the compaction roller of the AFP head, the material was not able to be automatically deposited to the tip of the cone; instead, this area was covered with manually placed fabric prepreg material. Following consolidation and sintering, this led to a 'first of a kind' hybrid AFP/manual fabric prepreg layup manufacturing technique. This new hybrid approach showcases how the strengths of AFP can be leveraged for manufacturing relatively simple geometries, while more complex features are achieved through hand layup, all within the same component. This new hybrid approach can potentially expand the design possibilities of ox-ox CMCs whilst reducing material waste.

The slit-tape input material supplied by Axiom Materials is still a research material and caused some challenges during manufacture. The as-supplied tape exhibited inconsistencies, including a variation in width, the quantity of matrix, the presence of fibre twists, tows tacked together, and poor-quality fibre splices. These inconsistences can lead to macro sized defects in the resulting CMC and can act as stress concentration sites and lead to brittle failure. This is particularly important for ceramic materials, where even minor defects can cause significant variations in mechanical performance.

These material inconsistencies also lead to significant machine downtime. Tow breakages mid-way through deposition resulted in manual intervention to rectify them, whilst the deposition head frequently jammed due to inconsistent material width exceeding the capability of the machine. The material inconsistencies led to significant machine downtime, with only 6.1% of manufacturing time being spent on productive layup. The NCC has begun working with Axiom to help overcome these challenges in future material iterations.

During sintering, ox-ox CMCs undergo significant densification, which can often lead to warpage. During the current programme, the component observed limited warpage due to the balanced deposition layup and appropriate sintering temperatures. The suitable parameters are also reflected by the CT scans, showing a dense ceramic with relatively few macro-porous regions. This observation indicates that the material will deform in a pseudo-ductile manner. An investigation into the mechanical properties of the material is due in future work.

6.0 SUMMARY

The research demonstrated AFP of oxide-based ceramic matrix composites (CMCs), utilising a new aluminium oxide fibre/aluminium oxide matrix slit-tape material format supplied by Axiom Materials containing Nextel 610 fibres within a proprietary aluminium oxide-based matrix. This work produced a cone shaped demonstrator from the materials using AFP, whilst showing a significant reduction in material waste.

The investigation included identifying optimal processing parameters for deposition, such as the heating method, deposition speed, and deposition force. Bespoke tooling was developed to support the manufacturing process during the AFP and autoclave consolidation steps. Additionally, a hybrid manufacturing technique was demonstrated for the first-time using AFP tape material for simpler geometry sections and fabric-based prepreg laid up manually for more complex features.

Despite some material inconsistencies, such as variations in width, matrix quantity, and fibre quality, the process demonstrated the potential of AFP for producing high-temperature, complex components for hypersonic applications. The findings suggest that AFP could enhance the manufacturing consistency of CMCs, reduce waste, and expand the design possibilities of these advanced materials.

Inconsistencies in materials are currently being improved upon by Axiom Materials in collaboration with NCC.

7.0 REFERENCES

[1] Pirzada, T.J. Oxide Based Ceramic Matrix Composites for High Temperature Aerospace Sealing Applications, Thesis, University of Oxford, 2021. https://ora.ox.ac.uk/objects/uuid:586b9570-0600-42cc-9065-eeea8ec5c88d

[2] Karadimas, G., Salonitis, K., and Georgarakis, K. "Oxide Ceramic Matrix Composite Materials for Aero-Engine Applications: A Literature Review," In M. Shafik and K. Case (Eds.), Advances in Manufacturing Technology XXXIV, IOS Press, 2021. https://dspace.lib.cranfield.ac.uk/server/api/core/bitstreams/62856b45-b7a7-4ae6-9aa1-149904df8767/content

[3] Dawson, D. "Ceramic Matrix Composites: Hot Engine Solution," CW Composites World, 2017. https://www.compositesworld.com/articles/ceramic-matrix-composites-hot-engine-solution

[4] National Composites Centre, "National Composites Centre Manufactures Ceramic Matrix Composites Uisng Automated Fibre Placement in European First," 21 Sep 2022. https://www.nccuk.com/news/ncc-manufactures-cmcs-using-afp-in-european-first/

[5] Nehls, G. (Ed.) "NCC Successfully Demonstrates AFP Manufacture of CMC Parts," Composites World, 21 Sep 2022. https://www.compositesworld.com/news/ncc-successfully-demonstrates-afp-manufacture-of-cmc-parts

[6] Nehls, G. (Ed.) "Axiom Partners with NIAR ATLAS for Oxide-Oxide CMC Research," Composites World, 07 Nov 2022. https://www.compositesworld.com/news/axiom-partners-with-niar-atlas-for-oxide-oxide-cmc-research

[7] Echeverria, I.E., Fishpool, D.T., Rubio Diaz, V., Dorey, R.A, and Yeomans, J.A. "Evaluation of Polymer Matrix Composite Manufacturing Routes for Production of an Oxide/Oxide Ceramic Matrix Composite," Journal of the European Ceramic Society, 42(5) 2420-2428, May 2022. https://www.sciencedirect.com/science/article/pii/S0955221921009535