World Academy of Science, Engineering and Technology
International Journal of Materials and Metallurgical Engineering
Vol:15, No:2, 2021

An Overview on Aluminum Matrix Composites: Liquid State Processing

S. P. Jordan, G. Christian, S. P. Jeffs

Open Science Index, Materials and Metallurgical Engineering Vol:15, No:2, 2021 publications.waset.org/10011835.pdf

***Abstract*—**Modern composite materials are increasingly being chosen in replacement of heavier metallic material systems within many engineering fields including aerospace and automotive industries. The increasing push towards satisfying environmental targets are fuelling new material technologies and manufacturing processes. This paper will introduce materials and manufacturing processes using metal matrix composites along with manufacturing processes optimized at Alvant Ltd., based in Basingstoke in the UK which offers modern, cost effective, selectively reinforced composites for light-weighting applications within engineering. An overview and introduction into modern optimized manufacturing methods capable of producing viable replacements for heavier metallic and lower temperature capable polymer composites are offered. A review of the capabilities and future applications of this viable material is discussed to highlight the potential involved in further optimization of old manufacturing techniques, to fully realize the potential to lightweight material using cost-effective methods.

***Keywords*—**Aluminum matrix composites, light-weighting, hybrid squeeze casting, strategically placed reinforcements.

I. INTRODUCTION

COMPOSITE systems, specifically Metal Matrix Composites (MMC) have been under development since the early 1970's [1], unlike material systems such as metallics and polymers, optimization and research into such systems has taken longer to mature. Current trends reveal MMC materials to be both viable and favoured for its desired engineering application [20], [21]. In many cases MMC's are too expensive to manufacture, or they do not offer the confidence in manufacturing repeatability that is necessary.

As time has progressed, technologies have improved in manufacturing techniques [2] as well as characterization and mechanical testing methods enabling the fundamental understanding of MMCs. Such progression has also facilitated the development of composite systems including graphite, carbon nanotubes and ceramic matrix composites.

Current research and manufacturing of MMCs has reached a point where the optimized manufacturing processes and wealth of supporting knowledge makes these materials a viable choice for light-weighting in place of more traditional options.

Interest in lighter materials is being shown throughout engineering [3], [4], in particular due to tighter restrictions on emissions. For example, many countries worldwide are taking action to reduce aviation emissions due to the large greenhouse gas emissions produced by aircraft [5], where legislation is demanding lower emissions within a few decades. The European Commission has climate objectives to be fulfilled by 2030 and as of 2021 expects airlines to start adhering to their CORSIA (Carbon Offsetting and Reduction Scheme for International Aviation) directive [6]. The most effective method for reaching these targets is to improve fuel efficiency [7], a worthwhile venture for aircraft manufacturers as this will not only assist in meeting the set targets but offer fuel savings, and ultimately cost savings. Light weighting of an aircraft alongside improvements in turbine engine will lead to these large savings in fuel consumption during flight time.

Most modern aircraft and landing gear manufacturers are currently looking at key areas that can be lightened through using alternative materials [7]. Heavy components made of titanium or steel are candidates for light-weighting due to progress in potential replacement materials. Modern manufacturing techniques have improved allowing manufacturing costs of MMCs to be reduced. This improvement has coincided with the drive and investment into light-weighting vehicles, where the trade-off between light-weighting and cost has moved close enough to trigger vehicle manufacturers to seriously look at replacing heavier components with alternative materials such as MMCs.

MMCs have been researched since the early 1970's but are still not as widely adopted as perhaps they should be. Cost has been the main factor hindering rapid uptake of MMC's due to poor understanding and manufacturing methods. High costs were associated with fibre production and particulates. The inevitable thrust towards lighter and more efficient transport methods has increased research into composite systems enabling cheaper materials and manufacturing methods to be developed. Modern techniques involving automated equipment allows for more repeatable, reliable and cost-effective manufacturing that was not available several decades ago.

Aluminium Matrix Composites (AMC) are the most widely used MMC across the aerospace, defence, rail transport and automotive industries [8]. AMCs offer manufacturers the ability to lightweight structures whilst retaining necessary mechanical performance. In addition, AMCs can demonstrate good mechanical properties at elevated and cryogenic temperatures alongside good corrosion and chemical resistance making them an excellent choice in replacing

S.P. Jordan is a Materials and Process Engineer at Alvant Ltd., Prisma Business Park, 3 Berrington Way, Wade Rd, Basingstoke, Hampshire, RG24 8GT, United Kingdom (e-mail: steve.jordan@alvant.com).

G. Christian is the Technical Director with Alvant Ltd., Prisma Business Park, 3 Berrington Way, Wade Rd, Basingstoke, Hampshire, RG24 8GT, United Kingdom (e-mail: g.christian@alvant.com).

Dr.S.P. Jeffs is with the Institute of Structural Materials (ISM) at Swansea University, Bay Campus, Fabian Way, Swansea, SA1 8EN, United Kingdom (e-mail: s.p.jeffs@swansea.ac.uk).

heavier components.

The capability of using reinforcing fibres in specific areas of a component can further reduce costs by limiting the amount of costly fibres within a given component to only what is required to achieve the necessary structural capability. Aircraft manufacturers have increased composite usage recently due to such improvements and MMCs have now got to be considered. Cost has become less of a limiting factor since there are little to no alternatives that can produce the specific strength at temperatures up to 500 °C. Although there are several combinations of MMCs available, AMCs offers the best specific strength alongside properties such as low coefficient of expansion (CTE), high thermal resistance, high specific stiffness and good wear resistance.

Novel manufacturing methods of AMCs presented in this work offer near net or net shaped components containing strategically placed reinforcement rather than employing a general preform shape or particulate filled material. An additional method is under development, placing specific reinforcement in a floating design, capable of being cast in a solid block. This configuration allows net shape machining to take place after casting, using datums or X-ray Computed Tomography (XCT) as a guide. Specific placement of preform or fibre reinforcement allows machining to take place on aluminium regions in order to form the final shape, thus mitigating difficult alumina fibre machining practices.

Traditional manufacturing of AMCs has moved towards particulate reinforced stir cast techniques [9] due to cost and the ability to achieve net shaped components. This work investigates techniques using the more expensive method of unidirectional fibres and woven material following a strategic placement regime, which aims to reduce cost while retaining required mechanical performance for the specific application. Further optimization of casting and machining methods, as well as through robotic placement of fibres [10] and stress analysis to design exact reinforcement needs for each individual component will lead to a desirable and cost-effective product.

II. Manufacturing Processes

Several decades of research and development of MMCs has produced a variety of manufacturing methods. Most are manufactured using one of a few chosen methods such as; liquid infiltration, stir casting, or powder metallurgy. Other methods closely aligned with those above are gas pressure infiltration and mechanically assisted infiltration [11].

Traditional manufacturing methods can be labour intensive and expensive, depending on whether it is high volume or low volume prototyping. Modern manufacturing techniques have led to powder metallurgy methods which produce good homogenous reinforcement distribution resulting in good mechanical properties. This method is continually developing and once optimized will be a good choice for high volume manufacturing [12]. Additionally techniques being developed for these materials include diffusion bonding, friction welding and high energy ball milling [13].

Research in this work was completed using a modified squeeze casting process allowing infiltration into complex preforms and shapes. The optimized forced infiltration due to external pressure was well suited to the preform designs. This paper offers an introduction into research aiming to help push AMC's into further production through manufacturing optimization and introducing new methods of manufacture.

III. Matrix and Reinforcements

Many combinations of matrix and reinforcement have been studied for MMCs. Matrix systems include; aluminium, magnesium, titanium, zinc and copper have been investigated and a collection of reinforcements have been implemented such as; Alumina, silicon carbide, basalt, glass fibre, carbon fibre and even biomaterials such as bamboo fibres. Researchers and manufacturers currently choose the best matrix and reinforcement combination for each individual application as required and arrange the reinforcements using one of the methods shown in Fig. 1.

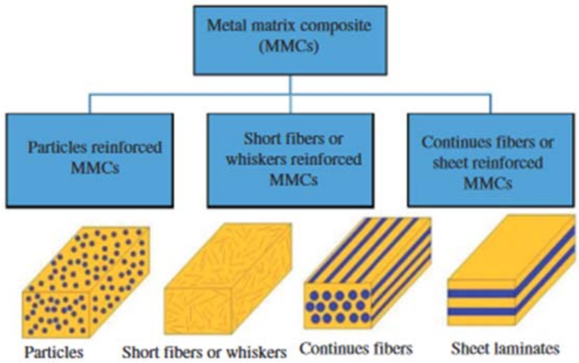

Fig. 1 Methods of reinforcement placement in MMC's [13]

Current interest from manufacturers is largely focused on particulate reinforcement using various reinforcement materials since it has the potential to be a cheaper route of manufacture due to simpler techniques and materials. Silicon carbide is commonly used as a particulate reinforcement in AMCs as it offers a slight increase in stiffness and strength to base aluminium alloys but at a cheaper manufacturing cost. Advantages are shown in manufacturing methods of such arrangements due to the capability of producing near net or net shapes from the stir casting method. Challenges with this method arise when trying to produce an even homogenous distribution of particulates due to wetting factors and mixing techniques. While this method has not yet been perfected it still attracts considerable attention due to potential for success and its cost-effective nature.

This work attempts to show an overview of the ongoing research being conducted to produce cost-effective AMC components envisaged to replace heavier materials like titanium alloys currently used in applications such as links and struts in landing gear. The current requirement for light-weighting leans towards the use of aluminium/alumina due to its low density, good compatibility with both elements being aluminium based and strong interfacial bonding strength between the constituents. Here, an aluminium matrix and alumina reinforcement in the form of unidirectional continuous fibres is presented (Fig. 2). Due to commercial sensitivity, the exact composition and makeup of the composite is not described. The anisotropic properties that arise in unidirectional fibre and woven material often meet, and sometimes supersede the heavier material to be replaced in specific orientations. In addition, small fibres and woven material can be placed directly where needed.

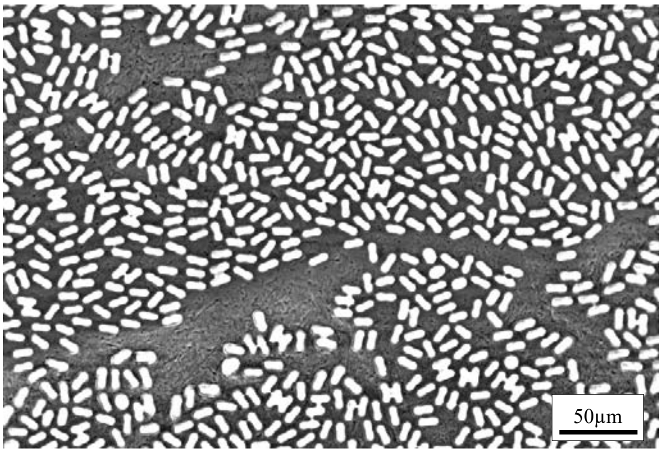

Fig. 2 Unidirectional alumina fibres within an aluminium matrix

The ability to allow strategic placement of fibre reinforcement can lead to cheaper and simpler machining of the final component. Traditional manufacture of preforms and casting processes involves using fibre to fill the entire component, leading to difficult final machining operations using expensive diamond coated materials.

Attempts to produce components employing unidirectional fibre tows or monofilaments have long been expensive and difficult to control exact placement of fibres. Woven material has benefits although loses some directional strength due to the weaving pattern lay-up. Unidirectional fibre AMCs are shown to be strong in a longitudinal direction (parallel to fibre length) with lower strength exhibited in the transverse direction (perpendicular to the fibre length), whereas woven materials reveal a trade-off where the transverse values are increased, to the detriment of the longitudinal direction.

The purpose of this ongoing study is to optimize and further research the use of unidirectional and woven material combined strategically in the form of preforms and placement of exact fibres within the final cast component. The good bonding produced at the interface using aluminium based elements for both matrix and reinforcement is highlighted in Fig. 3. This is especially the case in AMC's when using pure aluminium which allows high modulus and tensile strength in the region of 250 GPa and 800-1000 MPa respectively. The high mechanical strengths are obtained due to the combination of high strength fibers within a ductile matrix creating a strongly bonded interfaced composite. Even higher values are obtained in compression.

Although higher mechanical property values are obtained when compared to cheaper and easier to manufacture methods such as stir casting with particulates, the production of components as described above has traditionally been expensive and difficult. Infiltration and wetting issues must be overcome whilst trying to produce a near-net, or net shape component. Additionally, the cost of machining material that contains ceramic fibres is higher and can push the economic viability of the combined process beyond where it may be considered.

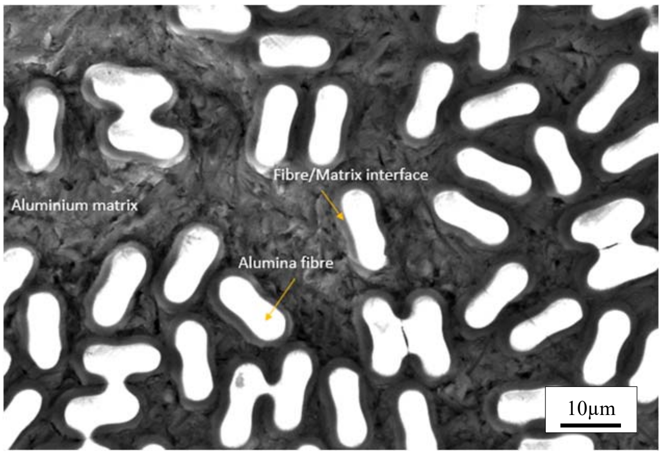

Fig. 3 Bonding at fibre/matrix interface

IV. TRADITIONAL FIBRE PLACEMENT

Full optimization of a process such as fibre lay-up or placement will eventually be managed by automation. Robotics and developing manufacturing software (i.e., Industry 4.0) will revolutionize and reduce the costs involved in these labour-intensive processes. The ability to use computational simulation software to determine optimal fibre locations alongside robotic placement is a common sight in other manufacturing fields such as carbon fibre composites. Optimizing these methods to work with casting and metallic matrices poses more of a challenge, although the potential benefits of these materials means that capabilities are continually advancing.

More primitive technologies are exploited during this work due to financial constraints at the early research stage. Hand lay-up methods alongside simple winding machinery are employed to strategically place fibres where required in the component structure. Although due to commercial sensitivity, manufactured components and preforms are not shown in their entirety; elementary parts of the process are described to help disseminate the processes studied.

A patented method to squeeze the molten matrix material into the preform allows complicated and thick preforms to be used, as infiltration occurs throughout due to hydrostatic pressures applied during casting. To produce "perfect" material, fibre placement needs to be exact, allowing the ideal matrix to fibre ratio to achieve optimum mechanical properties. In reality this is a difficult task due to factors such as broken or twisted fibres, movement of fibres during casting, and the small size of individual fibres.

Fig. 4 shows the unidirectional alumina fibre placement which is applied by a mechanical device controlling tension, speed of placement and travel of the winding placement arm. Overall, fires are shown to be placed reasonably regularly, although aluminium channels and the movement of fibres during infiltration is evident. Increased magnification is shown in Fig. 5 highlighting the excellent infiltration achieved between individual fibres. Further research is being conducted to achieve improved placement of straight fibres, using individual fibres and tows of fires alongside novel fibre constructions and application methods.

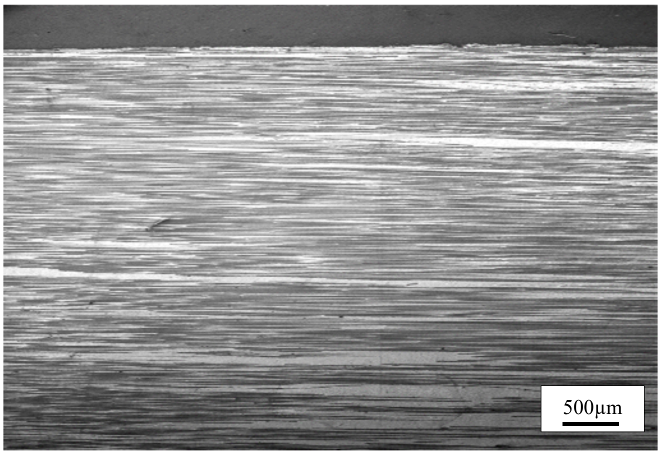

Fig. 4 Alumina fibre placement in the longitudinal direction

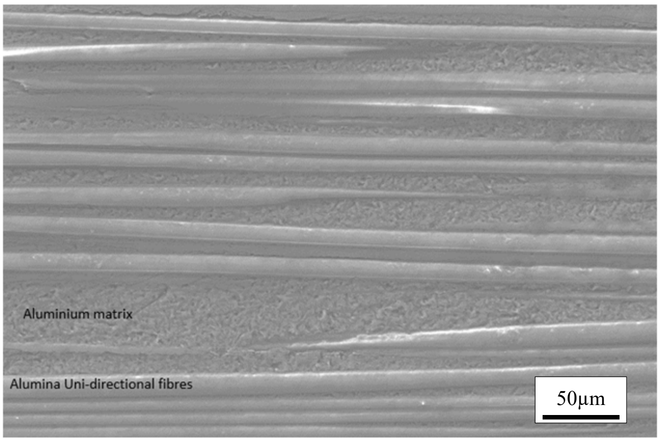

Fig. 5 Infiltration of aluminium between individually placed alumina fibres

The use of binders and glues to assist fibre placement, attempting to keep them in place during infiltration is also under review [14]. Binders such as colloidal silicas and polymer-based glues can be used although these suffer from evaporation at lower temperatures. The ability to hold fibres and preforms in their original shape during preheating and casting proves to be a challenge. Difficulties associated with infiltration and heat loss rule out use of metal moulds. Rapid cooling and flashing can occur during the pressurized infiltration process due to the massive heat sink produced by the moulds.

V. STRATEGIC REINFORCEMENT PLACEMENT

Research work at Alvant Ltd. is concentrating on producing complex components, with the ability to strategically place reinforcement only in areas that require enhanced mechanical properties. Reducing the use of fibre material will help alleviate the problem of cost when looking at light-weighting complex components. In combination with computational simulations, components may be engineered to ensure optimum mechanical capabilities for specific applications and fibre placement is then designed to achieve this. Essentially, components can be designed and optimized in collaboration with the end use rather than generically reinforcing an entire component which results in exacerbated costs.

Many material properties can be optimized and manipulated using this technique not only strength or stiffness. A hybrid material can be manufactured using additional elements as desired for a given application. If, for instance, a component is required to provide increased conductivity alongside the traditional benefits of AMCs then elements such as copper, diamond or graphene can be added to enhance such properties. Research into composites containing more than two elements is underway, with an interest in biomaterials in particular.

At this stage of research, strategic placement of single fibres is the main approach to enhance mechanical properties to enable the replacement of heavier metallic based components for Aerospace and Automotive companies. While in past years MMCs and AMCs have been too expensive for such companies to consider, however, pressure from environment laws have now pushed these companies to seriously consider these advanced materials and the benefits offered from light-weighting in areas such as fuel savings. This interest in turn helps facilitate research, which enables longer term reductions in manufacturing costs.

VI. ENGINEERING APPLICATIONS

Research into components that are suitable to be manufactured using the patented liquid squeeze cast process at Alvant Ltd. is currently restricted by size. Current ideal candidates are links and struts for various applications such as those found in landing gears in the aerospace sector (Fig. 6).

To prove the concept of design using strategically placed reinforcement, initial research has been completed to replace some small link arms and struts for a long-standing landing gear set up. Several components have been chosen to help prove the concept using advanced modelling tools and optimised manufacturing techniques. Solidworks and Ansys Finite element (FE) modelling (Fig. 7) have been implemented to perform stress analysis which can then be used to determine strategic fibre placement and reinforcement.

Simulations highlighted stress accumulation in areas that would be expected. Fig. 8 shows the area around a circular section on a link strut where high stress measurements are shown under compressive loads. Generally, this region would have to be either thickened or redesigned to accommodate this stress level during service or use excessive strength materials. The ability to strategically place fibres in a chosen orientation at a specific location in an AMC component such as that shown in Fig. 9 can help reduce unnecessary reinforcement wastage, reducing both costs and complexity. While this reduction in manufacturing and fibre cost is a vital aspect of strategic fibre placement, further cost reduction comes from final components requiring machining of only pure aluminium rather than particulate or fire reinforced net shape preforms.

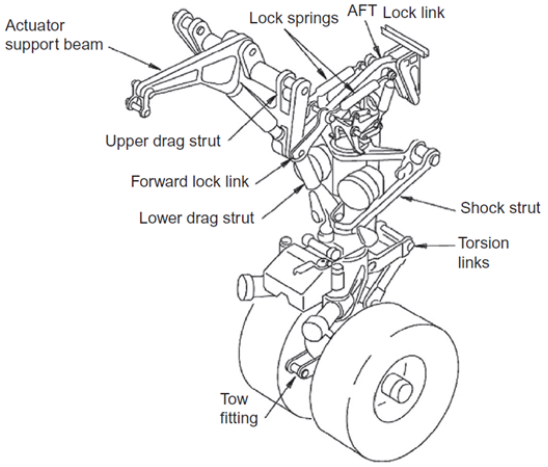

Fig. 6 Possible light-weighting components that could be design-optimized and made from AMC's [15]

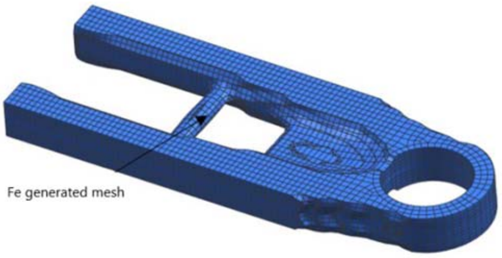

Fig. 7 FE generated mesh design using modelling software

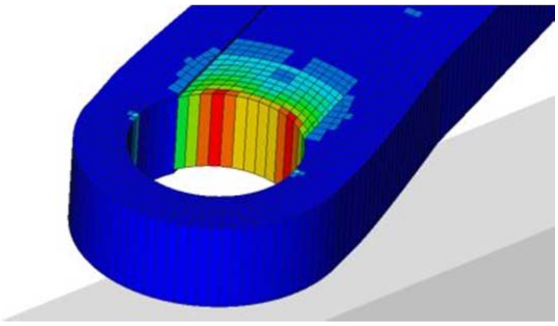

Fig. 8 Stress accumulation around a circular section of a link strut (contour scale bar removed due to commercial sensitivity)

The advantage of producing the component with an aluminium exterior not containing fibre/s allows for an optimal surface finish to be applied post manufacture. For instance, aerospace applications would likely require good corrosion resisting surface [16], whereas automotive components may require a mechanical finish, anodizing, or powder coating. Surface finishes can enhance final components properties and improve characteristics such as electrical insulation, friction, hardness or even wear resistance [17].

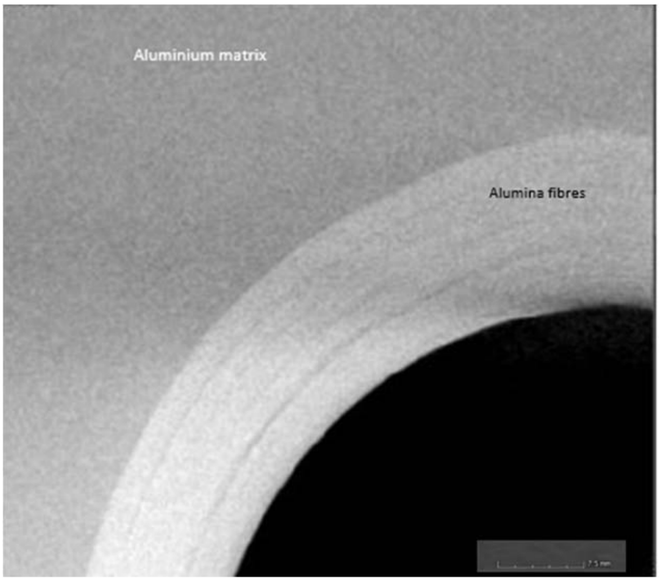

Fig. 9 Strategically placed fibres wound around a circular section to strengthen this area

Current research into preform design and manufacture has the potential to allow directional control of fibres shaped in a mould giving net shape casting capabilities. The ability to produce a net shape preform from a variety of reinforcements will allow complex shapes to be produced. Difficulties in maintaining a structure at high temperature whilst liquid metal is forced through it, has proven complicated to optimize.

Traditional methods for creating a preform for a metal composite rely heavily on the construction of a porous ceramic form, bound with silicon or phosphor. The current work being researched involves the use of different binders and manufacturing methods for preforms. Current binders and methods use inorganic binders that are designed to burn away before casting, this form forces a moulded shape to be created and hold form during casting. Investigations are ongoing to create a solid preform capable of holding form at 700 °C allowing removal of costly moulds. Suspension within a die of a solid bound preform solves problems of infiltration within a mould and potentially enables very complex geometries to be designed and created.

VII. Future Research

By strategically placing fibres and woven material only where required, or in a more optimized fashion, cost savings can be made during manufacture of AMCs. To enable industry uptake of these advanced materials, further investigations into modern technologies and optimization techniques is necessary. One such technology is Non-Destructive Testing (NDT) of final machined components for defects and confirmation of fibre placement.

XCT has allowed 3D material examination without the need to cut it up and inspect [18]. XCT has traditionally been used for medical examination techniques but has recently seen a huge interest in mechanical fields [19]. Final components can scan relatively quickly at high resolution, offering views detailing the component through thickness and in 3D. Post-processing software can then manipulate XCT data sets to analyse and investigate manufactured parts for defects such as porosity and internal damage. Fig. 10 demonstrates a transparent 3D render processed to show porosity through the manufactured part.

Research is underway aiming to exploit the benefits of XCT scanning alongside preform casting to allow machining to be programmed using a combination of computer aided design drawings and XCT co-ordinate measurement systems. The desired output would be to cast a component within a block of aluminium and scan the finished product, allowing exact placement of the final component to be measured exactly. Traditionally, datums would be needed to identify the position of the final component within the cast material. This precise measurement would allow quick and cost-effective final machining of one or more components within a cast block.

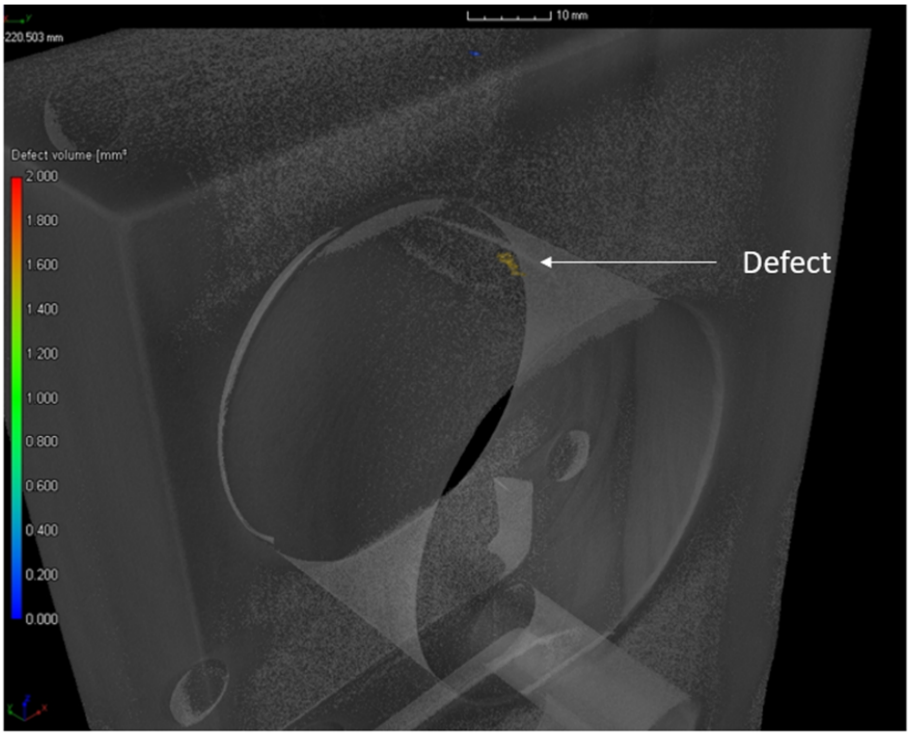

Fig. 10 3D XCT render showing transparent view and small porosity defect in yellow

VIII. SUMMARY

In summary, the current work has highlighted improvements and advances in manufacturing methods of AMC components. Although no final components that have been optimized are presented here, they will follow in further publications. The shift in commercial interest shown for AMCs has advanced research following the realization that light-weighting of vehicles and materials is imperative to meet industry commitments to environmental targets.

ACKNOWLEDGMENT

All research work was undertaken at Alvant Ltd., Basingstoke, United Kingdom.

REFERENCES

[1] G. R. Cappleman, J. F. Watts, and T. W. Clyne, “The interface region in squeeze-infiltrated composites containing δ-alumina fibre in an aluminium matrix,” *J. Mater. Sci.*, vol. 20, no. 6, pp. 2159–2168, 1985, doi: 10.1007/BF01112300.

[2] C. Bulei, M. P. Todor, and I. Kiss, “Metal matrix composites processing techniques using recycled aluminium alloy,” *IOP Conf. Ser. Mater. Sci. Eng.*, vol. 393, no. 1, 2018, doi: 10.1088/1757-899X/393/1/012089.

[3] A. Taub, E. De Moor, A. Luo, D. K. Matlock, J. G. Speer, and U. Vaidya, “Materials for Automotive Lightweighting,” *Annu. Rev. Mater. Res.*, vol. 49, pp. 327–359, 2019, doi: 10.1146/annurev-matsci-070218-010134.

[4] A. A. Gokhale, N. Eswara, P. Biswajit, and B. Editors, *Light Weighting for Defense, Aerospace, and Transportation*. 2019.

[5] A. J. Timmis *et al.*, “Environmental impact assessment of aviation emission reduction through the implementation of composite materials,” *Int. J. Life Cycle Assess.*, vol. 20, no. 2, pp. 233–243, 2015, doi: 10.1007/s11367-014-0824-0.

[6] “CORSIA directive.” (Online) Available: www.ec.europa.eu/clima/policies/transport/aviation_en.

[7] J. Larsson, A. Elofsson, T. Sterner, and J. Åkerman, “International and national climate policies for aviation: a review,” *Clim. Policy*, vol. 19, no. 6, pp. 787–799, 2019, doi: 10.1080/14693062.2018.1562871.

[8] A. K. Sharma, R. Bhandari, A. Aherwar, R. Rimašauskiene, and C. Pinca-Bretotean, “A study of advancement in application opportunities of aluminum metal matrix composites,” *Mater. Today Proc.*, vol. 26, pp. 2419–2424, 2020, doi: 10.1016/j.matpr.2020.02.516.

[9] T. S. Srivatsan, I. A. Ibrahim, F. A. Mohamed, and E. J. Lavernia, “Processing techniques for particulate-reinforced metal aluminium matrix composites,” *J. Mater. Sci.*, vol. 26, no. 22, pp. 5965–5978, 1991,

doi: 10.1007/BF01113872.

[10] T. Aized and B. Shirinzadeh, “Robotic fiber placement process analysis and optimization using response surface method,” *Int. J. Adv. Manuf. Technol.*, vol. 55, no. 1–4, pp. 393–404, 2011, doi: 10.1007/s00170-010-3028-1.

[11] J.Paulo Davim, *Metal Matrix Composites*. 2017.

[12] B. Cantor, F. Dunne, and I. Stone, “Metal and ceramic matrix composites,” *Met. Ceram. Matrix Compos.*, pp. 1–417, 2003, doi: 10.1533/9781845698560.305.

[13] P. S. Sahu and R. Banchhor, “Fabrication methods used to prepare Al metal matrix composites- A review,” *Int. Res. J. Eng. Technol.*, vol. 03, no. 10, pp. 123–132, 2016.

[14] K. Naplocha and K. Granat, “The structure and properties of hybrid preforms for composites,” vol. 22, no. 2, pp. 35–38, 2007.

[15] A. M. M. Aliofkhazraei, *Handbook of materials failure and analysis with case studies from the Aerospace and Automotive Industries*. Elsevier Ltd., 2016.

[16] K. A. El-Aziz, D. Saber, and H. E. D. M. Sallam, “Wear and Corrosion Behavior of Al–Si Matrix Composite Reinforced with Alumina,” *J. Bio-Tribo-Corrosion*, vol. 1, no. 1, pp. 1–10, 2015, doi: 10.1007/s40735-014-0005-5.

[17] B. Group, “Aluminium surface treatments guide.” (Online)Available: www.bwcgroup.co.uk/news/aluminium-surface-treatments-guide. (Accessed: 07-Dec-2020).

[18] M. De Giovanni, J. M. Warnett, M. A. Williams, N. Haribabu, and P. Srirangam, “X-ray tomography investigation of intensive sheared Al-SiC metal matrix composites,” *Mater. Charact.*, vol. 110, pp. 258–263, 2015, doi: 10.1016/j.matchar.2015.11.003.

[19] R. N. Yancey and G. Y. Baaklini, “Computed tomography evaluation of metal-matrix composites for aeropropulsion engine applications,” *ASME 1993 Int. Gas Turbine Aeroengine Congr. Expo. GT 1993*, vol. 2, 1993, doi: 10.1115/93-GT-004.

[20] R. Moona, Girija;Walia , R.S; Rastogi, Vikas;Sharma, “Aluminium metal matrix composites: A retrospective investigation,” Indian J. pure Appl. Phys., vol. 56, pp. 164–175, 2018.

[21] S. T. Mavhungu, E. T. Akinlabi, M. A. Onitiri, and F. M. Varachia, “Aluminum Matrix Composites for Industrial Use: Advances and Trends,” Procedia Manuf., vol. 7, pp. 178–182, 2017, doi: 10.1016/j.promfg.2016.12.045.