

Characterization of Titanium Metal Matrix Composites (Ti-MMC) Made Using Different Manufacturing Routes

Luigi Sanguigno^{a,1}, Marcello Antonio Lepore^a and Angelo Rosario Maligno^a

^a*Institute for Innovation in Sustainable Engineering IISE, University of Derby, Derby, UK*

Abstract. The mechanical and morphological properties of the unidirectional metal matrix composite (MMC) in titanium alloy reinforced with continuous silicon carbide (SiC) fibres are investigated. The lay-up manufacturing process known as the Foil / Fibre (FF) lay-up was compared with the matrix-coated-fibre (CF) method which promises a better final shape of the reinforcing fibre net. Tensile tests were performed to measure mechanical performance of the manufactured MMCs both longitudinally and transversely respect to the direction of SiC fibres. Elastic behaviour of the investigated MMCs was assumed orthotropic and related to mechanical properties and spatial distribution of the MMC constituents: SiC fibres and Titanium (Ti) matrix. This was achieved using micromechanical modelling based on Finite Element (FE) calculations. FE micromechanical modelling was carried out on the Representative Elementary Volume (REV) of the MMC microstructure resolved by non-destructive analysis such as X-Ray tomography. The analysis carried out highlighted and justified mechanical performance difference between composite laminates containing the same amount of SiC reinforcement fibres for unit of volume but made following different manufacturing routes. To compute overall orthotropic behaviour of the MMC laminate, each constituent was assumed as an elastic isotropic heterogeneity during the averaging. This simplify assumption was validated by comparison with experimental data during the mechanical characterization of the investigated MMC composites.

Keywords. Ti-MMC, Sic Fibres, Micromechanics, Finite Elements, X-Ray Scan

1. Introduction

Titanium alloy metal matrix composites (MMCs), reinforced with continuous ceramic fibres, offer attractive combinations of strength, stiffness and elevated temperature performance and are currently being considered for a range of advanced applications, particularly in the aerospace and transport field [1,2].

Several lay-up methods have been ensued for titanium based MMCs [3], the Foil/Fibre (FF) lay-up technique is perhaps the oldest and most established approach to the problem of combining the high strength and stiffness of monofilaments with the high temperature capability of reactive titanium alloys.

¹ Corresponding Author. l.sanguigno@derby.ac.uk

Other methods include the slurry tape casting method, where parallel fibres are coated with a mixture of powder and organic binder to form a pre-cursor tape, the plasma-spray method, where metal is sprayed onto an array of fibres to form mono-layer tapes, the wire-winding method, where alternate layers of silicon carbide fibre and alloy wires are held in place with an organic binder to form a pre-cursor sheet material, finally the matrix-coated fibre (CF) method, where fibre is pre-coated with the matrix alloy by electron beam evaporation to form a matrix pre-cursor material [3].

The mechanical performances of MMC achieved using two different manufacturing processes are investigated here. The Foil/Fibre (FF) lay-up is compared to the matrix-coated fibre (CF) method in which the reinforcing fibres are pre-coated with the metal matrix before being consolidated by diffusion bonding.

The main difference between the two investigated methods is the precursor adopted to create a metallic matrix that binds all the fibres together. Foil/Fibre (FF) lay-up uses thin metallic sheets hence a two-dimensional precursor while the matrix coated fibre (CF) method has a one-dimensional precursor represented by the metallic coating of the fibres. To investigate deeply this difference, mechanical testing, non-destructive measurements, and FE analysis have been carried out on MMC samples made by the FF and CF manufacturing routes using an equal amount of reinforcing fibres. The reinforcement selected for the investigated MMC is silicon carbide (SiC) monofilament, Textron SCS series (140 mm diameter).

The mechanical properties of each MMC samples were characterized through tensile tests along and crosswise to the direction of MMC reinforcing fibres by monitoring simultaneously longitudinal and lateral strain to gather information on the orthotropic elastic behaviour assumed for all investigated MMC samples.

To determine the spatial distribution of constituents within the investigated MMC samples, 3D X-Ray topographies have been carried out obtaining a 3D intensity value maps where constituents are recognizable and computable according with their density value [4]. Finally, Young's modulus and Poisson's coefficient measured for each MMC were compared with estimates calculated by FE micromechanical modelling based on X-Ray detected geometries [5,6].

Experiments and simulations confirm that spatial distribution of diffusion bonding regions mainly affect ultimate strength and yielding so the mechanical performance of MMC laminates made by FF and CF manufacturing processes differ at increasing deformation. The different mechanical behaviour at large deformation has been related to shape of metallic matrix precursor used for each process.

2. Materials and Methods

The specimens consist of MMCs made by foil /fibre (FF) lay-up using as matrix precursor sheets of IMI 834 (Ti-5.8Al-4.0Sn-3.5Zr-0.7Nb-0.5Mo-0.35Si-0.06C) and MMCs produced by matrix-coated fibre (CF) method using a coating of IMI 318 (Ti-6Al-4V) matrix. All MMC samples were reinforced with SM1140+carbon coated SiC fibres, see Figure 1.

Rectangular specimens with fibres in the longitudinal or transvers directions were produced by TISICS LTD having dimensions of 10 mm x 150 mm. Panel thicknesses were six ply and fibre volume fractions were between 0.32 and 0.36. Unreinforced specimens made of monolithic Ti were tested under identical conditions to the MMCs to

quantify mechanical properties of the Ti metal matrix precursor adopted during each investigated manufacturing route.

Mechanical properties of the manufactured MMC samples have been investigated through tensile tests carried out longitudinally (0) and transversely (90) respect to the orientation of fibres within the sample. Specimens made of monolithic matrix precursor (M) were also tested under identical loading conditions.

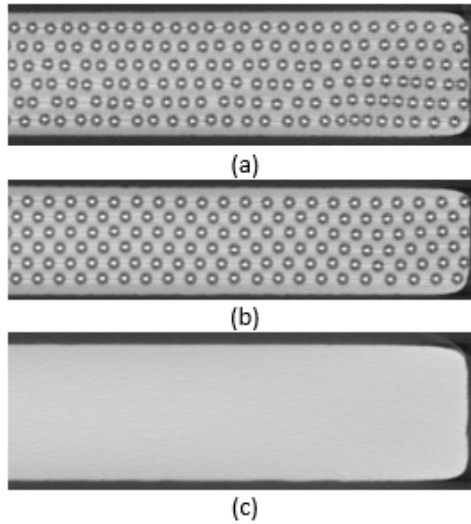


Figure 1. MMC orthogonal section as observed by virtual slicing of X-ray tomography maps; a) MMC by foil/fibre (FF) lay-up; b) MMC by matrix coated fibres (CF) method and c) Monolithic Ti specimen (M).

During all test biaxial extensometers (model MTS 632.85F-14 having gage length 25 mm) were used to monitor longitudinal and lateral strain components simultaneously at imposed strain rate of 5 μm per second, see Figure 2(a). An Instron 5985 testing machine was used to perform all tests according to ASTM and ISO standards.

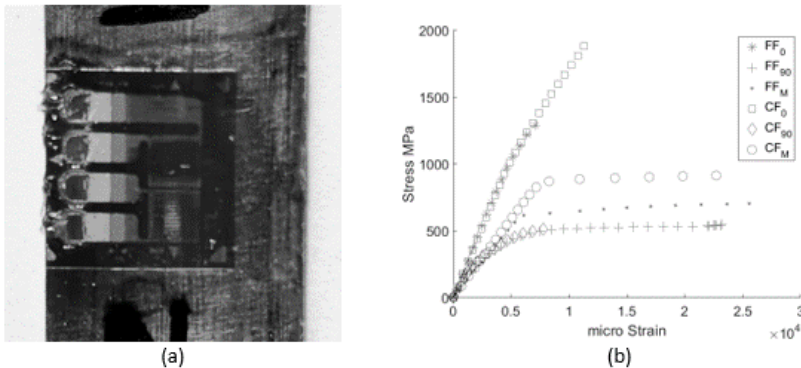


Figure 2. Experimental set-up and measurements: (a) biaxial extensometers; (b) Tensile Tests carried out on MMC samples.

The volume fraction and location of the reinforcing SiC fibres within each MMC sample were measured by Computed Tomography X-Ray inspection.

The result of an X-ray scan measurement is a 3D intensity level map representing the density fluctuations within the scanned volume [4]. The scanned volume results therefore partitioned through voxels or pixels having size depending on the X-ray source minimum spot size, here voxel size is 5 μm . 3D intensity level maps arising from X-Ray Scan measurements required post processing to quantify and locate the SiC fibres within the scanned MMC samples. The results were refined using morphological filters to remove small fluctuations and increase sharpness. After morphological filtering, the SiC fibres were satisfactorily quantified and localized, and finally their relative positions investigated to gather information about the MMC microstructure, see Figure 3.

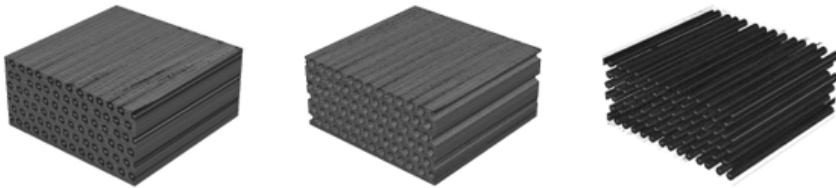


Figure 3. X-Ray Tomography of MMC laminate, measured fibre content for unit of volume.

Fibre packing was investigated by analysing the Delaunay triangularization of all fibres within the normal section of the MMC sample. Thanks to this calculation each fibre was connected to its closest neighbours according to the packing scheme highlighted by virtual slicing of the X-ray 3D map, see Figure 4. Finally, the statistical distribution of relative distances between fibres was analysed to gather reliable fibre packing geometrical descriptors.

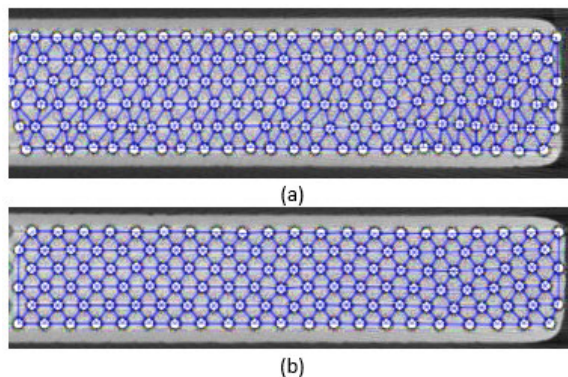


Figure 4. Delaunay's triangularization of fibre detected along the MMC cross-section by X-Ray: a) MMC by foil/fibre lay-up and b) MMC made by matrix coated fibres.

The estimated fibre packing geometrical descriptors were then used to define the microstructure Representative Elementary Volume (REV) of each investigated MMC samples required to model the MMC microstructure through finite element simulations. The MMC REV was modelled using ABAQUS finite element software and discretized using 3D solid bi-linear brick elements. An isotropic mechanical behaviour was assigned

to each microstructure constituent using parameters retrieved from technical data sheet and scientific articles on MMC [5,7]. Periodic boundary conditions were applied to simulate an infinite continuum by mirroring the REV geometry respect to all directions.

To compute the 12 stiffness matrix coefficients required to describe the orthotropic mechanical behaviour of the REV unit volume, 6 independent FE simulations were executed to compute MMC elastic response at given strain loads. During these simulations, a pure strain load is applied to calculate the mechanical response along given directions assumed as reference. 6 simulations are therefore required to characterize the MMC REV stiffness along each strain component, 3 for the linear and 3 for the shear deformations [8]. The FE-Micromechanical analysis also highlights the strain concentration due to the different attitude of the MMC constituents to deform under the uniform applied load, see Figure 5.

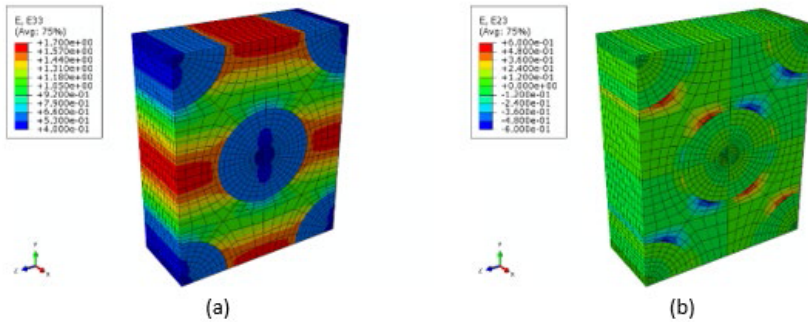


Figure 5. Virtual tensile tests crosswise the reinforcement direction: a) strain and b) shear calculated fields.

3. Results and discussion

Tensile tests show that the elastic coefficients of MMC laminates do not depend on the selected production route if the same quantity of fibres per unit volume is used, see Table 1 and Table 2. Fibre content within each investigated MMC laminate was quantified by X-ray tomographic analysis to be around 65% either for specimens by FF or CF manufacturing methods, see Figure 3.

This percentage agree well with the MMC ultimate strength values experimentally detected during tensile tests along the direction of SiC fibres. Assuming strength of SiC fibres be around 3 GPa, the CF method reproduce expected performances satisfactorily while FF lack of reliability probably since diffusion bonding regions lie in close contact with SiC fibres when Ti foils are used as the metallic matrix precursors.

Moreover, CF method guarantees a more uniform distribution of fibres along the specimen cross section, see Figure 4, avoiding concentration of stress that can promote premature failure of the MMC composite, see Figure 5. During MMC manufacturing, the CF method bind the fibres starting from a better dispersion of the metallic matrix precursor favouring the densification process and bonding of MMC constituents.

However, samples made using CF method are weaker than those made by FF layering when tested crosswise, see Figure 2 (b). In particular, the FF method guarantees a resilience comparable to that of the matrix in terms of yield and max deformation, while the mechanical failure occurs at one fifth of the maximum deformation measured for the metal matrix for samples made with the CF method.

Table 1. Young's modulus values measured by tensile tests longitudinally (0) and transversely (90) with respect to the direction of SiC fibres; Units are in GPa.

MMC	0	90	M
Foil/Fibre	217.8	153.2	108.1
Fibre Coated	213.4	152.0	118.8
Average	215.6	152.6	113.4

Table 2. Poisson's coefficient values measured by tensile tests longitudinally (0) and transversely (90) with respect to the direction of MMC fibres; Units are dimensionless.

MMC	0	90	M
Foil/Fibre	0.2801	0.2032	0.3803
Fibre Coated	0.2968	0.1943	0.3334
Average	0.2884	0.1988	0.3569

This difference of ultimate transverse strength is again correlated to the metal matrix precursor kind. In fact, foils since bi-continuous provide a lateral compliance like that of the Ti matrix to MMC laminates made using FF method. Matrix-coated fibers instead need diffusion bonding to occur also laterally to form the composite promoting defects that greatly compromise the final lateral strength of the MMC laminate made by CF method.

Table 3. MMC mechanical characteristics of MMC predicted by the FE Micromechanical simulations

MMC	E1 GPa	E2 GPa	E3 GPa	V12	V23	V31
Foil/Fibre	216	158	151	0.2835	0.204	0.353
Fibre Coated	216	155	153	0.2887	0.217	0.354

The packing geometry of the fibres also affects mechanical properties that result less transversely isotropic as fibre distribution within laminate crosswise section deviates from the hexagonal packing. Table 3 reports results of the FE micromechanical simulations carried out on representative geometrical models of MMC microstructures detected by X-Ray tomography, see Figure 4 and Figure 5.

Young's moduli calculated along (E1) and transversally (E3) the direction of the SiC fibres well agree with those detected experimentally proofing reliability and accuracy of the proposed analysis method, see Table 2 and table 1. Simulations highlight that laminate made by CF method are laterally isotropic (E2=E3) since fibres result almost hexagonally packed, indeed the X-Ray measured contact angle between fibres is 55 ± 5 degrees, see figure 4 (b) while broader contact distribution and larger overall average are detected for laminate made by FF method, measured contact angle is 65 ± 15 degrees, see figure 4 (a). Contact angle between fibres mainly depend on thickness of precursor foils or coating as well as temperature and applied pressure during densification by diffusion bonding. Variance of fibre contact angle distribution is related to the technique adopted to keep in place fibres during the MMC laminate manufacturing process.

4. Conclusions

By combining X-ray scanning analysis and FE micromechanical modelling, the mechanical properties of the MMC are estimated based on knowledge of spatial distribution and behaviour of each constituent. The estimates agree well with the experimental data collected along and crosswise the direction of fibres within the MMC laminate.

This validates our simplifying hypothesis that mechanical behaviour of MMC laminate is orthotropic due to the heterogeneous distribution of constituents which instead have isotropic characteristics and full adhesion among them. Under these assumptions, MMC stiffness can be robustly designed on the micrometric scale using non-destructive investigation techniques even for complex shape components.

Indeed, X-Ray tomography reveals internal microstructure with high precision since the great density difference of constituents within SiC fibre reinforced metallic elements.

Some MMC details stay unresolved after X-Ray analysis, the carbon coating of SiC fibres and diffusion bonding interfaces between the metal matrix precursors. The carbon coating thickness is quantifiable by the fibre producer data sheet as 5µm while locations and extension of bonding interfaces depends on the chosen MMC manufacturing route.

The spatial distribution of diffusion bonding interfaces is essential to forecast the MMC ultimate strength and failure mode, it can be esteemed simulating manufacturing process, but its extension seems to be limited to few microns as our X-Ray analysis proofs.

Acknowledgements

This research has been fully supported by the EPSRC project “SYstems Science-based design and manufacturing of DYnamic MATerials and Structures - SYSDYMATS”, EP/R032793/1.

References

- [1] M.P. Thomas and M.R. Winstone, Effect of Matrix alloy on longitudinal tensile behaviour of fibre reinforced titanium matrix composite, *Scripta Materialia*, **37** (1997), 1855-1862.
- [2] M.P. Thomas and M.R. Winstone, Transverse tensile behaviour of fibre reinforced titanium metal matrix composites, *Journal of Material Science*, **33** (1998) 5499 – 5508.
- [3] C.M. Ward-Close, L. Chandrasekaran, J.G. Robertson, S.P. Godfrey, D.P. Murgatroyde, Advances in the fabrication of titanium metal matrix composite, *Materials Science and Engineering A263* (1999) 314–318.
- [4] E. Maire, L. Babout, J.-Y. Buffiere, and R. Fougères, Recent results on 3D characterisation of microstructure and damage of metal matrix composites and a metallic foam using X-ray tomography, *Materials Science and Engineering: A*, **319–321** (2001), 216–219.
- [5] M.M. Aghdam, D.J. Smith, M.J. Pavier, Finite element micromechanical modelling of yield and collapse behaviour of metal matrix composites, *Journal of the Mechanics and Physics of Solids*, **48** (2000) 499–528.
- [6] M. A Lepore., L. Sanguigno, A. Zamani, F. Berto, and A.R. Maligno. Non linear fatigue propagation of multiple cracks in an aluminium metal matrix composite (AlMMC) with siliconcarbide fibre reinforcement, *Mat Design Process Comm.*, **2:e119** (2020).
- [7] M. A. Foringer, D. D. Robertson, and S. Mall, A micromechanistic-based approach to fatigue life modeling of titanium-matrix composites, *Composites Part B: Engineering*, **28** (1997), 507–521.
- [8] A. R. Maligno, N. A. Warrior, and A. C. Long, Finite element investigations on the microstructure of fibre-reinforced composites, *Express Polymer Letters*, **2** (2008), 665–676.