Technology-driven design of MMC squeeze cast connecting-rods

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Abstract

Continuous-reinforcement MMC squeeze casting technology is studied to produce connecting rods for racing car engines, aiming to investigate crucial aspects and propose solutions. As a consequence of material peculiarities, the shape of the connecting rod is firstly optimised to make the fibres placement as efficient as possible; then a mould adequate for the production is developed. The design consists in a preliminary kinematics study, devoted to compare the loads acting on conventional and MMC connecting rods; then a 3-D FEM analysis is carried out, enabling the definite dimensioning. The mould is developed for complying to several requirements, i.e. the assessment of adequate fibres positioning and tensioning systems, inert to thermal–mechanical effects; the design of casting sprues, runners and gates able to guarantee easy filling and good wetting; the optimisation of moulding assembling. The production phase implies the set-up of techniques for fibres winding (by means of a suitable coil winder), matrix casting and item de-moulding. The final characterisation, consisting of static tensile proof testing, radiographic and microscopic investigation, allows to assess the soundness of the technology as well as the effectiveness of the precautions implemented to optimise its adoption. © 2002 Elsevier Science Ltd. All rights reserved.

Keywords: Metal matrix composites; Squeeze casting; Connecting rod

1. Introduction

In designing and producing, aerospace industry has always paid attention to weight saving, provided structural efficiency and safety were guaranteed [1,2]. During the last period, an increasing interest towards lightweight structures was also shown by those industrial fields which traditionally cannot afford a design approach too much attentive to this aspect. In particular, the adoption of light and performing materials (typically composites) is becoming a reality in the automotive and racing engines industry, where the outstanding structural efficiency of the components made with these materials positively influences the performances of the overall assembly: a typical case is represented by connecting rods [3,4].

Owing to the peculiar working conditions of connecting rods (prevailing axial forces, high temperature, presence of aggressive chemical agents like fuels and lubricants), metallic matrix composites (MMCs) made of aluminium alloy and silicon carbide (SiC) continuous fibres may find a convenient application [5].

The adoption of different types of reinforcement can induce remarkable changes in shape: discontinuous fibres and whiskers lead to isotropic composites suited for producing conventional connecting rods, while continuous fibres should be placed along the main loading axes [6,7], thus giving ‘8’ dog-bone or ‘0’ winding paths around the connecting-rod small and big ends. The latter solution presents some advantages, in terms of ease-of-production and optimal response to axial loads. However, it may be adopted only if the crank pin can be keyed through crankshaft disassembling. Besides, since this fibres deposition works well only if subjected to tensile loads, the bearing effects due to the contact with pin and gudgeon should be counteracted by means of secondary winding paths.

MMCs improves the mechanical performance of metallic matrices, but maintains their surface characteristics [8]. Since aluminium alloys do not possess a surface hardness able to guarantee the keying tolerance and the roughness needed for friction minimisation, two cemented steel bearings should be provided at the connecting rod’s small and big ends, around which the fibre are wound.

These remarks lead to the geometry shown in Fig. 1; it differs from conventional ones [9–12], allows to satisfy the design requirements, guarantees remarkable weight savings which positively influences both crankshaft and bearings dimensioning, but could imply larger dimensions inside the crankcase, whose size/shape should be modified.

However, the real performances of MMCs mostly depend on the chemical–physical and thermal–mechanical compatibility, which onset at the matrix/reinforcement
interface [13,14]. The production technique, the technological parameters and the forming environment (temperature, pressure, atmosphere) are crucial to get the right integration between the two phases. For this reason they deserve to be deeply investigated.

2. Materials and technologies

The fabrication of MMCs employs non-conventional technologies, devoted to promote wettability and matrix-to-fibres cohesion. They also are aimed to reduce the interfacial failures and the performances decay due to intergranular segregation which happens during matrix solidification [15].

The processes developed during the last years can be divided into two main approaches: the technologies based on infiltration of liquid metal and the solid-state technologies. While the infiltration techniques like liquid pressure forming LPF (Fig. 2a), pressure infiltration casting PIC (Fig. 2b) and squeeze casting SC (Fig. 2c) can be considered a compromise between conventional pressure die casting processes and composite materials technologies (i.e. autoclave moulding), the solid-state techniques like spray deposition SD (Fig. 2d) and diffusion bonding DB (Fig. 2e) basically exploit the diffusive processes, which establish among metals in tight contact when fusion temperature is reached.

Owing to the shape of the connecting-rod, the solid-state processes should be excluded and the choice should be driven towards infiltration processes. Among infiltration technologies, squeeze casting constitutes the most cost-effective solution even tough it deserves a very accurate choice of matrix and reinforcement. As a matter of fact, moulding at high temperatures in free atmosphere leads to surface oxidation and, as a consequence, to the degradation of material characteristics.

During the moulding of the composite, the molecules of the two phases, solidus and liquidus, should interact in order to develop the energy level needed to promote wetting between reinforcement and liquid matrix. Owing to the high temperature, presence of oxygen and co-existence of different elements, not very reactive materials should be used, but able to guarantee a sufficient fibres/matrix compatibility [16–19]. Availability, affordability and reliability of matrix behaviour during casting also constitute important choice parameters. For these reasons, also in view of the possible future mass-production, an optimal solution was decided, consisting of A356 cast aluminium alloy and CVD silicon carbide continuous fibres, inert to aggressive environments, compatible and easily wettable by aluminium-based silicon alloys up to 900°C.

The fibre shown in Fig. 3 has 140 μm diameter, 3000 kgm⁻³ specific weight, 400 GPa stiffness, 3450 Pa strength and consists of a graphite mono-filament core coated through chemical vapour deposition (CVD) by different layers of silicon carbide (SiC). Such a coating performs two main functions, i.e. to mutuate between graphite core and metallic matrix and to protect the fibre during the moulding process [20,21]. During moulding, the fibre is subjected to different load components, which may jeopardise the cohesion between SiC layers and graphite core, making it environmental-reactive and leading to final failure. These components are due to local curvatures, tensioning during winding process, core thermal expansion/contraction, matrix solidification shrinkage (1.2–1.5% for aluminium–silicon cast alloys) and moulding pressure (up to 2000 bar) [22,23]. The contributions of these effects to the overall deformation are respectively equal to 3200 με (20 N winding tension), 1600 με (curvature around Φ 10.5 mm connecting rod small end bearing) and 500 με (matrix volumetric solidification shrinkage from melting to room temperature). The 5300 με total deformation is lower than 8600 με failure strain; the margin of safety equals 38%.

The matrix consists of A386 cast silicon–aluminium alloy. It is characterised by low solidification volumetric shrinkage (1.2%), compatibility with silicon carbide fibres, excellent castability, appreciable ductility and corrosion resistance. The eutectic is at 11.7% silicon and 577°C temperature. The presence of iron in a percentage larger than 0.6% induce alloy embrittlement, which is counteracted by the addition of manganese [24].

Through the formulae reported in Appendix, the preliminary thermal–elastic characteristics of the composite can be evaluated as a function of fibre volume fraction, as reported in Table 1.

The preliminary technological parameters can be guessed as well. In order to improve wettability, both physical (increase of temperature and pressure) and chemical (use of wetting additives) precautions should be exploited. Due to the complexity of the phenomena, a compromise should be found, driven by feasibility and affordability criteria. The increase of temperature and pressure improves cohesion, but a mould able to operate at very high temperature and pressure (up to 2000 bar) could be quite expensive. Notwithstanding, temperatures high enough to induce matrix fluidity with no intergranular segregation should be adopted. Pressure should guarantee wettability and complete infiltration, mainly at high fibre volume fractions. Because even at low fibre volume fractions appreciable
Fig. 2. MMC technologies: (a) liquid pressure forming; (b) pressure infiltration casting; (c) squeeze casting; (d) spray deposition; (e) diffusion bonding.
mechanical properties can be conferred to the composite, it was decided to produce a MMC with 40% fibre volume content. This allowed to use relatively low infiltration temperatures (680–700°C) and pressures (1000 bar) and to limit the adoption of wetting additives to 2% lithium in weight.

3. Structural design

Thanks to the low density of composites, a MMC connecting rod leads to mass reduction and engine improved performances, but to increased production costs. Therefore, such a solution could be conveniently applied only to niche fields, like race engines. For this reason, the connecting rod of a two-strokes, single-cylinder kart engine, was considered, whose basic characteristics and requirements are summarised in Table 2, [25].

The design of the connecting rod was developed according to three main steps: at first a kinematics study was performed to evaluate the acceleration time-history. Then, based on preliminary geometry, the loads were computed by means of a lumped-mass iterative procedure. Such a procedure was necessary, since inertial forces depend on mass, which — in turn — depends on the cross sections geometry. Finally, a FEM analysis was carried out to investigate stress distribution and to optimise overall design. Fig. 4 compares the geometry of steel and MMC connecting rods, the latter still liable to optimisation. The preliminary mass estimation led to 0.130 kg (steel) [25] and 0.088 kg (MMC); 25% mass saving was expected, while both tensile and compressive loads were reduced by no more than 10%, owing to the presence of piston and gudgeon whose mass remained unchanged.

FEM analysis was performed by means of NASTRAN and PATRAN codes [26]. The mesh, exploiting both geometric symmetries, consisted of 3461 HEXA and WEDGE elements (1.25 mm maximum side length). The piston and the gudgeon were modelled as non-structural masses, perfectly rigidly connected to the con-rod bearing.
Table 3
Comparison of steel and MMC connecting rods

|       | Mass (kg) | Variation (%) | Strength (N) | Specific strength (N/kg)/10³ | Variation (%) | Stiffness (N/mm) | Specific stiffness (N/mm/kg)/10³ | Variation (%) |
|-------|-----------|---------------|--------------|-------------------------------|---------------|-----------------|----------------------------------|---------------|
| Steel | 0.130     | –             | 61 780       | 498                           | –             | 21 960          | 192                              | –             |
| MMC   | 0.088     | –32           | 52 570       | 597                           | +20           | 21 870          | 248                              | +29           |

Fig. 4. Comparison between steel and MMC connecting rods geometry.
through rigid link and gap elements. The pure aluminium alloy and the matrix + reinforcement composite were modelled by means of elastic–plastic isotropic and elastic orthotropic material models respectively. Fig. 5 shows the stress distributions due to compressive and tensile expected maximum loads. Stress concentrations apart, the maximum Von Mises equivalent stress never overcame 470 MPa, well below the allowable value measured through ad-hoc characterisation tests performed on MMC specimens.

4. Technological Design

The mould design should satisfy the requirements of feasibility, affordability and manageability of thermal
contraction and solidification shrinkage effects. Other requirements, like ease of handling, should be faced during the industrialisation process. The choice of material was dictated by its mechanical strength and thermal conductivity, the latter becoming a crucial concern when the mould assumes considerable dimensions.

For reducing the capacity requested by the press, the possibility to exploit the force exerted between mould and dolly was abandoned. The infiltration pressure was generated by a piston which forces the liquid metal into the mould. The internal surface of the mould was equal to 3500 mm²; provided a 1000 bar estimated casting pressure, a 350 KN radial force was generated, which should be reacted in some way.

Bolted solutions were discarded, since large-diameter special bolts were necessary, made of high-temperature-resistant costly material. Thermal insulation of connecting devices should have allowed the adoption of conventional bolts, but the overall mould stiffness should have been affected, owing to the low mechanical characteristics of insulating materials.

The solution adopted consisted in an outer cylindrical skirt (Fig. 6), suited to contain the mould and to maintain its two parts in close contact. Owing to the strong radial forces to be reacted, its thickness and thermal mass were considerable and an appropriate material like electrolytic copper had to be chosen to make heating and cooling procedures quicker. Thanks to its thermal conductivity, the heating process could be performed by means of Bunsen burners: so doing the high costs due to electric furnaces could be saved.

Such an arrangement, consisting of casting mould separated from constraining tool, allowed to optimise the heating process: the sole mould was heated up to casting temperature, while the outer skirt, maintained at room temperature, provided the correct cooling rate to obtain the desired grain size.

The accurate conical (10°) fitting between the inner mould and outer skirt guaranteed the seal; this condition was also maintained during the heating process of the sole inner mould.

To complete the mould design, those phenomena occurring during cooling process had to be considered, i.e. contact effects between liquid metal and mould surface, volumetric shrinkage and inter-granular segregation. These aspect led to the design and sizing of mould runners.

Inter-granular segregation phenomena were counteracted by maintaining the thermal gradient as uniform as possible, while the defects due to volumetric shrinkage were limited by using appropriate sprues; finally, casting de-moulding was facilitated by avoiding bends and sharp edges. The runners were designed by accounting for these precautions.

A set-up consisting of several runners, acting as sprues could be adopted in place of an arrangement made of few runners, with over-dimensioned casting mould to counteract shrinkage effects. Solutions exist which infiltrate liquid metal directly into critical areas; alternative solutions adopt a bottom-up infiltration technique for better de-gassing; other solutions provide straight filling from feeding cylinder to the mould. Since the adoption of external runners implies increased size, weight and thermal mass leading to decreased handling capability and thermal promptness, the latter solutions were preferred.

A low-capacity press (100 KN) being available, the infiltration pressure (100 N mm⁻²) could be generated by a ram-cylinder system 15 mm in diameter. The cylinder also acted as a funnel for the ladle, being provided with double countersink to facilitate ram clenching.

The fitting between the ram and cylinder provided a small clearance: the seal was guaranteed by metal infiltration; the ram should be maintained at high temperature, to keep the liquid metal sufficiently fluid. The height of the cylinder (70 mm) guaranteed the co-axiality with the ram and allowed the built-up of an appropriate sprue. The outer diameter of the mould and the thickness of the external skirt were designed in order to confer sufficient strength and stiffness, also considering the low mechanical characteristics of electrolytic copper.

Owing to the strong difference between copper and silicon carbide (CTEs), the bearings around which the fibres were wound-up could not be built-in with the mould. The problem was solved by adopting an idling core, under-constrained to the mould through slotted pin-and-socket joints. So doing, the thermal—elastic strains acting on the fibres were only due to the difference between CTEs of silicon carbide and core material. Such a material should also possess sufficient mechanical characteristics, should be easily workable and not too much affected by thermal—chemical aggression: both alumina-based-ceramics and low-porosity graphite comply to these requirements; the latter was chosen thanks to its lower cost. The core, shown in Fig. 7, consisted of three separate parts, then assembled: two bearings and a spacer, which can be produced by simple machining rather than costly sintering.
5. Production

The production of the connecting-rod was divided into two main phases, i.e., placement of the reinforcement according to design requirements and positioning of the spool into the mould before final casting. The spool was obtained by winding the reinforcement around the graphite core, to be removed once the final item is obtained.

The fibres placement was performed by means of a 2-axes filament winding machine, consisting of a rotating mandrel and a translating feeder, equipped with an automated velocity inversion system. Since both rotational and longitudinal velocities were constant and adjustable, the fibres could be placed at the controlled pitch of 0.35 mm per revolution. The mandrel and the graphite core were connected through a dismountable aluminium support, containing the core and fixed to the mandrel (Fig. 8).

The elongated shape of winding path induced strong tension changes, which caused frequent fibre failures: as a matter of fact, notwithstanding its elevated mechanical characteristics, the fibres show a remarkably brittle behaviour. To avoid this drawback, a low winding velocity (8 revolution per minute) had to be adopted. Besides, to impart a constant tension to the fibres and to damp the inertial effect due to the heavy feeder, an adjustable dry-disk clutch was used.

To maintain the fibres, once wound, well ordered and securely constrained to the graphite core during their

Fig. 7. Graphite core made of two bearings and a spacer.

Fig. 8. Winding arrangement: (a) filament winding machine; (b) support and core (dismounted); (c) support and core (assembled); (d) fibres wound around the core.
Accurate thermal–chemical tests showed that the wettability of the fibres was not affected.

During winding process, serious difficulties had to be faced to guarantee fibres straightness between the connecting-rod’s small and big ends. These troubles were mainly caused by the fibre’s high flexural stiffness, which should be strongly tensioned to assume a straight shape; this often led to failure. Besides, owing to their large diameter and frequent presence of surface defects, the fibres could hardly be wound around the connecting-rod’s small and big ends, characterised by strong curvatures which cause premature failures. Both these problems should be overcome by adopting fibres more compliant in bending and smaller in diameter, able to accommodate stronger curvatures and deserving lower tensioning during deposition.

Once completed the deposition, the core + fibres were removed from the mandrel and positioned into the casting mould (Fig. 9a). The fibre’s free edges were constrained to avoid their unrolling once the cyan-acrylic adhesive was burned off, and finally the mould was closed through a couple of socket head screws and dowel pins.

The mould, the crucible containing the aluminium alloy and the outer skirt were approached to the press (Fig. 9b); the formers were uniformly heated up to 680–700°C by means of propane Bunsen burners. The temperature of outer mould and fused alloy were measured though contact digital pyrometers. A further improvement should consist in the placement of thermocouples into the mould and graphite core.

Once the desired temperature was reached, the alloy was cast into the mould and the fluid level was accurately monitored. It is crucial that this level should be high enough to completely submerge the spool, but not excessive to allow a ram stroke sufficient for maintaining an acceptable degree of perpendicularity once press-loaded.

Finally, the mould was fitted into the skirt and the assembly was placed under-press; the load was applied to induce

Fig. 9. Casting procedure: (a) core + fibres placed into the mould; (b) mould, skirt and press; (c) mould opened with cast inside.

positioning into the mould, a cyan-acrylic adhesive was applied in between the fibres layers. The contact with fused aluminium induced adhesive pyrolysis, leaving negligible residua and allowing satisfactory matrix infiltration.

Fig. 10. X-rays comparison between connecting rods: (a) cast at 680°C, (b) cast at 700°C.
1000 bar pressure into the liquid metal. The loading rate represented a compromise between the need of avoiding turbulent flow (high rate) as well as premature solidification (low rate). The load was maintained for 20 min, then the assembly was cooled down, the mould was extracted from the skirt and opened (Fig. 9c). At the end, sprues and graphite cores were machined away and the connecting rod was machined to the final tolerances.

The connecting rod was subjected to solution heat treatment consisting of oven-heating at 500°C for 12 h. and rapid water quenching, followed by artificial ageing at 220°C for 2 h. and slow oven-cooling [27].

6. Testing

To evaluate the quality of connecting-rod and the soundness of technology, non-destructive radiographic tests were performed, as well as destructive tensile static proof tests and SEM investigations.

Radiographic analysis were devoted to investigate the possible presence of matrix defects and porosity, as well as interface de-cohesion and poor impregnation. To this regard, in Fig. 10 two connecting-rods are compared, cast at different mould temperature, i.e. 680°C (a) and 700°C (b). In (b) (the graphite cores being removed) a uniform x-rays opacity can be noticed (to the exception of small regions close to small and big ends), symptom of good impregnation. By contrast, in (a) porosity is evident close to small and big ends, due to poor infiltration. The rod, close to the small end, shows dark spots, symptom of voids due to matrix early solidification, caused by inadequate mould temperature. The silicon carbide fibres (transparent to x-rays) appear less evident in the mid part of the rod since fused aluminium infiltrated the fibres array, becoming the true matrix of the composite. The reason for this different wettability resides in the different degree of compaction due to tension during fibres placement, higher at small and big ends than along the

![Graph](image-url)
mance of reference steel item (Fig. 11). The tests were performed on a servo-hydraulic testing apparatus at 1 mm/min strain-rate, in compliance with the procedures prescribed by the Standards. The load-elongation curves are reported in Fig. 12. The behaviour of steel item showed a brittle failure occurring at 64 780 N close to the big end bearing. The behaviour of MMC connecting-rod was quite different: the failure occurred at 52 570 N in proximity of the small end, mainly due to fibres poor impregnation, which induced matrix lacking and locally weakened the cross-section. The slope of the curve was lower and the overall behaviour slightly more ductile.

The comparison in terms of specific performances is reported in Table 3. It shows that the specific characteristics of MMC connecting-rod are remarkably higher than those of its steel counterpart, and could be further on improved through technology optimisation.

The analysis of fibres positioning and matrix infiltration was performed through scanning electron microscopy of rod cross sections. Fig. 13a–c, respectively taken at 100, 200 and 500 magnification factors, show the graphite substrates coated by the silicon carbide cladding embedded in the aluminium matrix. Fig. 13a shows a typical MMC defect, that is the in-homogeneous distribution of fibres into the matrix: such a defect, however, influences the behaviour of the composite only locally. At higher magnification factor (200x, Fig. 13b), good infiltration can be noticed, even in case of fibres high degree of compaction. Besides, excellent interfacial adhesion showing no air gaps between fibres surface and matrix denotes the soundness of the technology. The cracks which damage the fibres cross-sections (Fig. 13c) were due to cutting and polishing procedures and not to intrinsic material defects.

7. Conclusion

In conclusion some recommendations can be made, relevant to both design and technological concerns.

Wettability can be improved by increasing temperature/pressure and adding wetting additives. Temperature induces matrix fluidity with no intergranular segregation. Pressure guarantees complete infiltration, mainly at high fibre volume fractions. The increase of temperature and pressure improves cohesion, but the adoption of moulds able to operate at very high temperature and pressure is quite compelling. Because even at relatively low fibre volume fractions (40%) the composite gains appreciable mechanical properties, relatively low infiltration temperature (700°C) and pressure (1000 bar) and the sole use of 2% lithium in weight as wetting additive are recommended.

A low-capacity press can be used, provided the infiltration pressure is generated by a piston forcing the liquid metal into the mould and not by the direct action between mould and dolly. The strong radial forces can be reacted by an outer skirt, realised with electrolytic copper to make

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Fig. 13. Scanning electron microscopy of MMC connecting rod cross-section: (a) 100x; (b) 200x; (c) 500x.

rod. The degree of infiltration could be improved by reducing the value of tensile load.

A batch of five MMC connecting-rods was proof-tested and the average behaviour was compared to the perfor-
heating and cooling procedures quicker. Thanks to its thermal conductivity, heating process can be performed by means of simple Bunsen burners rather than by electric furnaces. The heating process is further-on simplified and optimised: the sole mould is heated up to casting temperature, while the outer skirt, maintained at room temperature, provides the correct cooling rate to obtain the desired grain size.

Owing to the strong difference between CTEs of copper and silicon carbide, the graphite cores around which the fibres are wound-up cannot be built-in with the mould, but under-constrained through slotted pin-and-socket joints. So thermal–elastic strains acting on fibres are only due to the difference between CTEs of silicon carbide and graphite.

Since the elongated shape of winding path induces strong tension changes, causing frequent fibres failures, a low winding velocity (8 rpm) has to be adopted. Besides, to impart a constant tension to the fibres and to damp the inertial effect due to the heavy fibres feeder, an adjustable dry-disk clutch must be used.

To maintain the fibres, once wound, well ordered and securely constrained to the graphite core, a cyan-acrylic adhesive has to be applied in between the fibres layers. The contact with fused aluminium induces adhesive pyrolysis, leaves negligible residua and does not affect wettability.

The comparison of connecting-rods cast at different mould temperature, i.e. 680 and 700°C, shows that the higher temperature allows good infiltration, while the lower leads to voids due to matrix early solidification, caused by inadequate mould temperature. The degree of infiltration also depends on the degree of compaction due to tension during fibres placement. It can be improved by reducing the value of tensile load.

Owing to their large diameter and presence of surface defects, the fibres cannot be wound around pins of small diameter, which cause premature failures. The problem can be overcome by adopting fibres more compliant in bending and smaller in diameter, able to accommodate stronger curvatures and deserving lower tensioning during deposition.

The MMC connecting-rod is 25% lighter than it’s steel counterpart, while both tensile and compressive overall inertial loads are reduced by 10%, owing to the presence of piston and gudgeon, whose mass remains unchanged. The maximum Von Mises equivalent stress never overcomes the values of MMC allowable.

The behaviour of MMC and steel connecting-rods differs in proximity of final failure: the former fails close to small end, owing to possible localised poor impregnation, which induces matrix lacking and cross-section weakening. Such a phenomenon leads to a quasi-ductile overall behaviour, to be compared to brittle failure of steel competitor.

The specific characteristics of MMC connecting-rod are remarkably higher (+20% strength, +29% stiffness) than those of its steel counterpart and could be improved through further optimisation, although the good infiltration, the high degree of compaction and the excellent interfacial adhesion prove the soundness of the technology.

Presently, the affordability of MMC connecting rods is still questionable, mainly owing to their costs, which is notably higher (+200%) than those of high performance forged or machined titanium-alloy items, mainly due to the high cost of reinforcing fibres and low production rates: as a matter of fact, the costs of metal matrix (conventional aluminium alloy), main equipment (press) and tooling (casting mould) are not higher than those needed for conventional metal forging or casting.

For these reasons, once the cost of reinforcement will be reduced exploiting scale-economy effects, and the equipment and tooling will be more efficiently depreciated, thanks to the mass-production, the overall cost of MMC connecting-rods (+30/40% than titanium counterparts) will become convenient, mainly on the basis of a lifecycle, cost benefit analysis.

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Appendix A

The main thermal–elastic characteristics of the composite were preliminarily evaluated through semi-empirical relationships based on the rule of mixtures:

\[ E_L = [(K_0 - 1)V_t + 1]E_m \]

\[ E_T = \frac{1}{1 - \left(1 - \frac{1}{K_0}\right)V_t}E_m \]

\[ \sigma_L = \frac{\sigma_t}{K_0}[(K_0 - 1)V_t + 1] \]

\[ \sigma_T = \sigma_m \]

\[ \nu_{LT} = -\frac{E_L}{E_T} \nu_{TL} \]

\[ \nu_{TL} = V_t\nu_t + (1 - V_t)\nu_m \]

\[ \rho_{MMC} = V_t\rho_t + (1 - V_t)\rho_m \]

\[ \alpha_L = \alpha_t V_t K_0 + \alpha_m (1 - V_t) \]

\[ \alpha_T = \alpha_t V_t + \alpha_m (1 - V_t) \]

\[ + \frac{V_t(1 - V_t)(\nu_t - \nu_m K_0)}{V_t(K_0 - 1) + 1}(\alpha_t - \alpha_m) \]
where: \( V_f \) = fibre volume fraction; \( E_f, \sigma_f \) = fibre Young’s modulus and stress ultimate; \( E_m, \sigma_m \) = matrix Young’s modulus and stress ultimate; \( E_L, \sigma_L \) = composite longitudinal Young’s modulus and stress ultimate; \( E_T, \sigma_T \) = composite transverse Young’s modulus and stress ultimate; \( \nu_f, \nu_m \) = fibre and matrix Poisson’s coefficient; \( \rho_{LT}, \rho_{TL} \) = longitudinal and transverse Poisson’s coefficient; \( K_0 = E_f/E_m; \rho = \rho_{MMC} = \) matrix, fibre and composite density.

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