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Interfacial shear strength behaviour of Ti/SiC metal matrix composites at room and elevated temperature

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Abstract

Synchrotron X-ray strain measurements have been used to follow the distribution of elastic strain, and hence interfacial shear stress, along single SCS-6 and Sigma SM2156 Ti–6Al–4V matrix coated SiC monofilaments sandwiched between Ti–6Al–4V foils during single-fibre-fragmentation testing. The interfacial shear strength behaviours were characteristically different. For the SCS-6 system, the interfacial response was dominated by classical frictional sliding, initiating near the ends and progressing along most of the length of the fragments, in common with previous observations. By contrast, for the SM2156 fibre system, a significant threshold stress was evident which must be exceeded before sliding could occur. As a result, sliding was only found near the ends of the fibre fragments. Upon unloading, reverse frictional sliding was found to take place, initiating from the fibre ends at a shear stress somewhat lower than that for forward sliding. Finite element modelling suggests that this is due to a reduction in the radial fibre clamping stress upon unloading rather than a change in the friction coefficient. For both the systems, the frictional sliding strength fell approximately linearly with increasing temperature towards zero at ~600–700 °C, consistent with a Coulomb friction coefficient of ~0.4 and thermal clamping residual stresses that approach zero at these temperatures. By contrast, the threshold stress required to initiate sliding for SM2156 falls at a slower rate with increasing temperature, such that it would still be significant at these temperatures. Some evidence was found for a decrease in interfacial shear stress with decreasing fragment length.
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1. Introduction

It is well known that the properties of a composite depend not only on the properties of the fibre and matrix, but also on the interface between them [1]. The interface is a critical constituent because it governs how load is transferred between the fibre and the matrix, especially when one or the other has cracked.

While SiC fibre/Ti metal matrix composites have been identified as promising materials for elevated temperature applications [2,3], perhaps surprisingly, most research has focused on characterizing the interface properties at room temperature (RT) [4–12]. Consequently, little is known about how the interfacial shear strength varies at elevated temperatures. The aim of this paper is to provide a more detailed picture of how the interfacial properties of Ti/SiC composites vary with increasing temperature for composites containing SCS-6 and Sigma SM2156 SiC monofilaments.

Push-out [13], transverse tensioned push-out [14] and full fragmentation [11,15,16] testing have been applied previously to measure interface strength. All rely on micromechanics models and simplifying assumptions (e.g., constant radial clamping stresses along the fibre length) in order to back-out the interface properties. In particular, the estimate of the maximum shear stress to initiate sliding is particularly sensitive; indeed, in connection with a maximum stress inferred by FE modelling push-out data for Ti/SCS-6 SiC, Zeng and Peters report that 'the estimated interfacial shear strength (in their case 500 MPa at RT

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and 140 MPa at 530 °C) is somewhat arbitrary, as a maximum stress criterion is problematic if singular stress fields are involved'. In view of such difficulties, the present authors developed a modified version of the single-fibre full-fragmentation test in which the fragmentation process is examined in situ prior to full fragmentation by synchrotron X-ray diffraction [17]. In this way, it is possible to follow the development of elastic fibre strain along the fractured segments [4,17,18]. This technique has the advantage over the classical full-fragmentation test that the interfacial shear stress is calculated directly from the gradient in the measured fibre strain point by point and is thus not dependent on an accurate knowledge of the fibre fracture strength. This is important, because the SCS-6 fibre fracture strength has been previously observed to fall sharply from ~5–6 GPa [17,19] to ~1.2–2 GPa after the initial fibre fracture event [17,18], presumably owing to the introduction of surface flaws. Similarly, the failure strength of free Sigma SiC fibres has also been observed to fall from 3.2 to 1.3 GPa, along with a significant drop in Weibull modulus, when pristine fibres are processed [20]. For SCS-6 fibres, this drop in failure strength is accompanied by a change in failure mode from initiating at the core [19,21] to failures originating from the surface, leading to multiple 'wedge' cracks being observed by X-ray tomography for subsequent fractures [21], in agreement with scanning electron microscope observations [16,22]. A similar transition from high strength core failure to low strength surface initiated failure has been observed for Sigma fibres by Shatwell [23]. This decrease in the failure strength during testing results in fragments that are typically much shorter than one would expect during fragmentation. These would give rise to an unrealistically high estimate of the interfacial frictional shear strength τ_{fric} were the initial free-fibre strength used in a 'blind' full-fragmentation length assessment of τ_{fric}.

Conventional interpretation of the fragmentation test also relies on the assumption that stress transfer takes place purely by frictional sliding under a constant sliding stress [11,24]. This assumption is critically important such that, if this is not so, the interfacial shear strength derived via a simple analysis will be in error. More sophisticated analytical [25] and finite element [26] models have been developed to understand the test better.

The primary aim of this paper is to quantify and compare the interfacial shear stress behaviour of two Ti–6Al–4V matrix/SiC monofilament systems tested at room and elevated temperatures. At elevated temperatures, the thermal residual fibre clamping stresses would be expected to be smaller, possibly easing interfacial sliding. The micromechanical behaviour of the fibre/matrix interface was examined at a much higher spatial resolution than before, thereby enabling the strain gradient to be resolved in more detail, and hence the variation in interfacial shear stress. Furthermore, it was possible to provide some of the first measurements at elevated temperatures. These experiments reveal quite different classical interface behaviours for the different fibre systems and indicate how they might perform in hot applications.

2. Experimental

2.1. Materials

Two Ti–6Al–4V coated fibre systems were studied (see Fig. 1): (i) a SCS-6 fibre with a 3M Corporation Ti–6Al–4V coating (supplied by Rolls-Royce) and (ii) a Sigma SM2156 fibre with a MkII Ti–6Al–4V coating (supplied by QinetiQ).

The SCS-6 monofilament comprises SiC deposited on a 1.5-μm pyrolytic carbon-coated 33-μm C-core, giving an overall filament diameter of ~140 μm. The SCS-6 fibre coating is a complex multi-layered C coating. Ning and Pirouz [27] found the coating to consist of three layers; layer 1 being 1.7-μm thick, creating a smooth surface compared

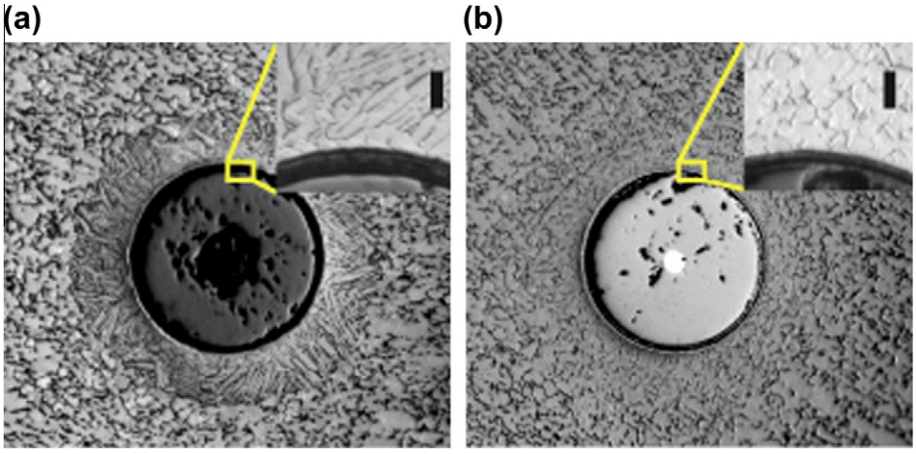

Fig. 1. Micrographs showing cross sections taken from: (a) SCS–6/Ti–6Al–4V (3M coated fibre) and (b) SM2156/Ti–6Al–4V (MkII coated fibre). Both fibres have a diameter ~140 μm; the former with a 33 + 3-μm C-core, the later a 15 μm-W core. The samples were polished to 1 μm using a suspension of colloidal silicon and subsequently etched, using Kroll's etchant, to reveal the microstructure of the metal matrix. Complex 1–2-μm scale coating/matrix reaction zones can be seen in the magnified inserts which include vertical 5-μm scale bars.

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