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Fracture and fatigue crack growth behaviour of PMMC friction stir welded butt joints

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ABSTRACT

The paper is focused on the evaluation of the fracture and Fatigue Crack Growth (FCG) properties of butt joints of particulate metal–matrix composite (PMMC) obtained by friction stir welding (FSW). The materials considered are two aluminum alloy matrix/alumina particle PMMCs (AA6061/Al_2O_3/20p and AA7005/Al_2O_3/10p). Tests were conducted on unwelded and welded PMMCs using CT and Extended CT (ECT) specimen geometries, respectively. The crack growth rate was monitored by means of compliance with a strain gage attached on the back of the specimen. FCG experiments were carried out both at the centre and in the Thermo-Mechanically Altered Zone (TMAZ) at the side of the weld. The comparison between unwelded and welded PMMCs showed that FSW influences fracture toughness and FCG rate in a different fashion depending on the material. In particular, the FSW AA6061/Al_2O_3/20p butt joint exhibited comparable fracture toughness and higher FCG threshold with respect to the unwelded material, while in the case of AA7005/Al_2O_3/10p the behaviour is the opposite. The interpretation of this trend has been carried out by optical analysis of the crack path roughness and its correlation with the FCG rate. The dynamic recrystallization of the aluminum matrix and particle shaping operated by the FSW tool are at the ground of the explanation.

1. Introduction

In the last few decades, particle metal–matrix composites (PMMCs) have come increasingly to the attention not only of the academic community but also of industrial sectors such as automotive (brake discs and drums, brake callipers, pistons), railway (brake discs, callipers and shoes), sporting goods (bicycle frames, golf clubs and rods), shipbuilding (deck panels), aerospace (reinforced Ti-alloys) and electronics (device substrates, packaging). The global metal–matrix composite market is excepted to rise from its estimated 2005 level of 3.6 million kg to 4.9 million kg by 2010, with an average annual growth rate of 6.3% [1].

The interest about PMMCs mainly concerns their lower cost with respect to short or long fibre-reinforced MMCs [2]. Commonly, Al- or Mg-alloys are the matrix materials while high modulus ceramics, such as Al_2O_3 and SiC, are the reinforcement materials in form of particles. The main improvements given by PMMCs with respect to the matrix alone are higher stiffness, mechanical and wear resistance, with a quasi-isotropic mechanical response [2,3].

Since their dual-phase nature, the mechanical strength of PMMCs with respect to the alloy matrix is the result of several factors: (i) type of particles; (ii) size distribution and shape of the particles; (iii) processing technique. The detailed knowledge of standard mechanical properties such as tensile or fatigue strength, but also of fracture toughness and fatigue crack growth (FCG) properties is therefore important to guarantee a reliable in-service durability. The fracture toughness of a

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PMMC is generally lower than the respective matrix alloy due to the constraint on plastic deformation caused by particles. On the other hand, at low FCG rates, the PMMC shows a better performance than the unreinforced alloy due to particle-activated shielding mechanisms such as crack deflection or trapping [4–9]. Furthermore, in cast PMMCs the particles are often located at the grain boundary, leading to a crack tip shielding mechanism known as *egg-shell* [10]. A great influence on FCG properties of PMMCs comes from the *R*-ratio $R = K_{min}/K_{max}$, where K_{min} and K_{max} are the minimum and maximum values of the applied stress intensity factor (SIF) during the fatigue cycle. As in unreinforced alloys, the higher the *R*-ratio the higher FCG rates. This can be interpreted in terms of crack closure [6], which in PMMCs is magnified due to crack surface roughness induced by particles or crack bridging.

A major concern for the industrial application of PMMCs is the joining technology and the resulting strength of the bond. The underlying issue is that reactions between matrix and reinforcement may be promoted by the heating of the pieces typically used to fabricate the joint. Possible outcomes of this reaction are: (i) cracking at matrix-particle interface; (ii) partial dissolution of the reinforcement and (iii) precipitation of third-phases due to matrix reaction with the reinforcement material [11]. For these motivations, solid-state processes like friction welding or diffusion bonding have generally a lower detrimental impact on the strength of PMMC joints than liquid-state processes such as Inert Gas arc welding (TIG or MIG), Laser Beam and Electron Beam Welding (LBW, EBW) [12–17].

Among solid-state techniques, friction stir welding (FSW) is a welding process recently developed and patented by The Welding Institute (TWI) of Cambridge (UK). In FSW, the parts to be joined are tied together while a rotating tool is pressed on them and moved along the seam, as illustrated in the scheme of Fig. 1 [18]. The tool consists of a cylinder (shoulder) with a profiled protrusion of smaller diameter (probe). The rotation of the shoulder generates a high frictional heat, causing softening of the material, which is then stirred by the probe. The overall effect is the extrusion and forging of the material from the leading side to the trailing side of the tool. Nowadays aluminum pieces with thickness ranging from 0.5 to 75 mm can be joined, at speeds up to 35 mm/s, [19]. FSW joints are not symmetric with respect to the seam due to the rotation of the tool; the side of the weld where translation and rotation speeds have the same direction is called advancing side, while the side where they are opposite with each other is the retreating side.

So far, this technique has been employed especially in the naval and aerospace industries thanks to the capability of joining aluminum alloys with higher quality, strength and comparatively low cost with respect to more traditional welding techniques. This technique results in low distortion and high joint strength compared with other welding procedures, and is able to join all aluminum alloys, including those like series 2XXX and 7XXX that are considered as virtually not weldable with classical liquid-state techniques, due to the decrease in strength after re-solidification. Microstructure, mechanical strength and their correlation with FSW process parameters have been extensively studied in the past few years in the case of lightweight (especially Al-based) alloys [19–29].

Nowadays, the extension of FSW to other materials has become a research topic. As a solid-state joining process, FSW can be particularly effective in the case of materials sensitive to re-solidification after liquid-phase welding. This is indeed the case of particulate metal–matrix composites (PMMC), which suffer from poor weldability with traditional processes due to the presence of ceramic particles. So far only few attempts have been made to produce and characterize PMMC FSW joints, [30–35], therefore leaving this field virtually unexplored.

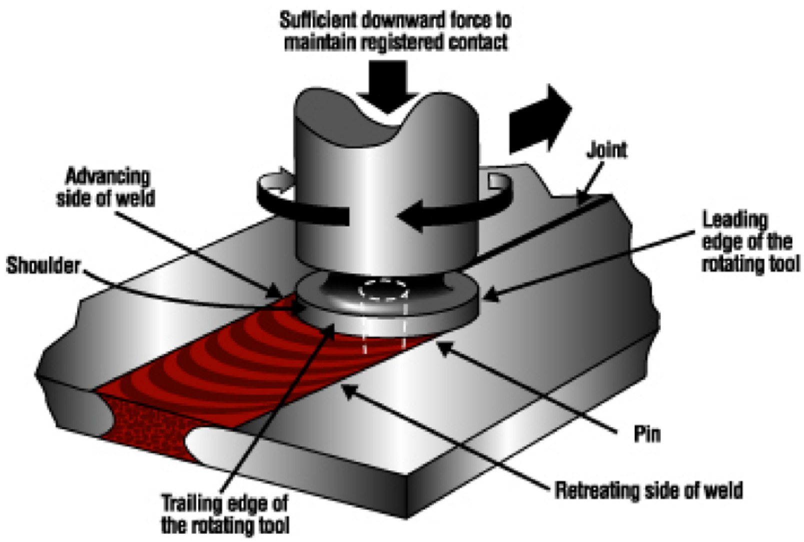

Fig. 1. Outline of the FSW process [18].