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Determination of macroscopic and microscopic residual stresses in friction stir welded metal matrix composites via neutron diffraction

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Abstract—This study presents a new method to determine both the macroscopic and microscopic (including elastic mismatch, thermal misfit and plastic misfit) residual stresses in metal matrix composite (MMC) welds via neutron diffraction. As an illustration, friction stir welded 17 vol.% SiCp/2009Al-T4 plates were investigated. It is shown that the calculation of the thermal misfit plus plastic misfit residual stresses in the metal matrix of the MMC welds is much more accurate by using the absolute unstrained lattice parameter of the SiC powder sample based on the stress equilibrium condition compared with using that of the unreinforced alloy sample. The profiles of the longitudinal (*L*), transverse (*T*) and normal (*N*) components of the total residual stress in the reinforcement are entirely different from those in the matrix. It was found that the profiles and total variations of the *L*, *T* and *N* components of the total residual stress are dominated by those of the macroscopic residual stress in the matrix, and by those of the elastic mismatch residual stress in the reinforcement, revealing a significant load transfer from the matrix to the reinforcement. The maximum total residual stress in the metal matrix of the FSW 17 vol.% SiCp/2009Al-T4 weld could reach up to ~69% of the yield strength of the 2009Al-T4 alloy. Increasing the rotation rate has small effects on the basic profiles of the total residual stress, apart from increasing the width of the profiles.

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1. Introduction

Metal matrix composites (MMCs) possess greater stiffness and strength, improved resistance to fatigue, wear and creep, a lower coefficient of thermal expansion (CTE) and better dimension stability compared to unreinforced metals, which makes MMCs the ideal structural materials for aerospace and defense applications. However, the high manufacturing cost, the poor formability and weldability of MMCs are the major factors that limit the widespread application of MMCs [1].

Friction stir welding (FSW), an innovative solid-state joining technique, is considered to be a promising technique to produce high quality MMC welds. In the early stage of applying FSW to MMCs, due to the poor flow ability of material and the severe tool wear, welding defects were easy to form in the welds, such as the surface defects [2], the matrix voids [3,4], the particle cracks [5], and the impurities resulting from the tool wear [2,6]. In recent years, with the development of new types of welding tools, such as the WC/Co tool coated with diamond [7] and the ultra-hard cermet tool [8], sound MMC welds can be produced via FSW under careful design of the welding parameters [9,10].

As with other welding processes, residual stresses are generated after FSW. Early in FSW development, the residual stress in FSW joints was thought to be very small compared to that in fusion welded joints [11], however, in recent years further research has revealed that the residual stress in FSW joints can be significant [12–20]. For instance, the ratio of the maximum longitudinal (*L*) residual stress to the yield strength of the base material ranges from ~20% to 99% in FSW aluminum alloys [18–20]. Residual stress in the welds is a crucial issue because it significantly affects the weld performance [21–25], such as plastic collapse [21,25], fatigue properties [23,24] and stress corrosion [26]. To guarantee the safety of engineering design, improve the accuracy of life prediction and damage evolution models for highly reliable structures, accurate knowledge of the residual stress in the welds is crucial.

Until now, there have been only limited studies on the residual strain or stress in MMC welds using non-destruc-

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tive measurements [22,27,28]. For instance, Jun et al. [27] measured the residual stress in linear friction welded 25 vol.% SiCp/2124Al plate via neutron diffraction. The unstrained lattice parameters were roughly obtained through the measurements at the corner of the plate, however, because strain-free samples were unavailable [27]. This introduced significant errors because the variations of the unstrained lattice parameter of the 2124Al matrix due to thermal exposure were not taken into account. Other investigators [22,28] measured the residual stress in small samples cut from MMC welds. Due to stress relaxation, the measured residual stresses were found to be small [22,28]. An unexpected profile of the residual stress that was measured using traditional X-ray diffraction was also detected due to uncertain surface effects [22]. No systematic study has been undertaken to investigate the residual stress in MMC welds.

According to their scales and sources, the residual stresses in MMCs are divided into macroscopic and microscopic (including elastic mismatch, thermal misfit and plastic misfit) residual stresses [29]. The macroscopic residual stress has a variation wavelength at the scale of several millimeters or more. The elastic mismatch residual stress, reflecting the load transfer from the matrix to the reinforcement, is the result of the mismatch in elastic constants between the matrix and the reinforcement. The thermal misfit plus plastic misfit residual stresses arise during cooling because of the mismatch in the CTE between the two phases. The plastic misfit residual stress is generated because plastic deformation occurs in the ductile matrix, while only elastic deformation takes place in the stiff reinforcement. The plastic deformation in the matrix can be caused by the macroscopic temperature gradient, the stirring effect of the welding tool and the heterogeneous deformation during the cooling stage of the FSW process due to the mismatch in the CTE between the matrix and the reinforcement. The elastic mismatch, thermal misfit and plastic misfit residual stresses are phase specific and belong to the microscopic residual stress, with a variation wavelength at the scale of several micrometers. Clearly, the residual stress in MMCs is more complex than that in unreinforced metals. Consequently, current methods of determining the residual stress for unreinforced metals have their limitations for MMC welds.

Recently, Cioffi et al. [20] proposed a method to determine the macroscopic residual stress in unreinforced metals based on a genetic algorithm and equilibrium conditions of both stress and bending moments, avoiding measuring the unstrained reference parameter. So far, applying this new method [20] to MMCs remains a great challenge and the process needs further development. The complexities induced by the load transfer from the matrix to the reinforcement and the presence of the thermal misfit plus plastic misfit residual stresses have to be taken into account. To solve these issues, the measurements of the unstrained reference lattice parameters may be unavoidable. Besides, further hypotheses about these methods may be necessary. For instance, the elastic mismatch, thermal misfit and plastic misfit residual stresses may be assumed to be constant across the weld, and then, the problem is virtually the same as exists without reinforcement. In spite of this, the measurements of the unstrained reference lattice parameters for the metal matrix of MMCs are especially difficult [30], because the precipitation state in the matrix is changed due to the non-uniform thermal histories. Such variations of the precipitation state lead to changes in the unstrained reference lattice parameters according to Vegard's law [31]. So far, there is no report of applying these methods to ascertain the macroscopic and phase specific microscopic residual stresses in MMC welds.

To sum up, there is a strong demand to develop a new framework to measure, separate and analyze the macroscopic and phase specific microscopic (including elastic mismatch, thermal misfit and plastic misfit) residual stresses in each phase of MMC welds and such a framework is the main contribution of the present work. The effects of the rotation rate on the residual stress in FSW MMC welds are also assessed. The residual stresses in FSW 17 vol.% SiCp/2009Al-T4 plates are studied as an example.

2. Experiments

2.1. Material and FSW

3.1 mm thick 17 vol.% SiCp/2009Al-T4 composite plates were used in the present work. 2009Al alloy has a nominal composition of Al–4.0Cu–1.4Mg (wt.%) and SiC particles have an average size of 7 μm. The composite was fabricated using the powder metallurgy (PM) technique and subsequently hot rolled into plates at 480 °C. The detailed fabrication and rolling processes have been described in a previous study [22]. The composite plates were heat treated to T4 condition (solution treated at 516 °C for 1 h, water quenched and naturally aged for 7 days).

Composite plates $300 \times 75 \times 3.1\ \mathrm{mm}^3$ in size were welded parallel to the rolling direction, at a welding speed of 100 mm/min with rotational rates of 600 and 1500 rpm. A cermet tool with a shoulder 14 mm in diameter and a cylindrical pin 5 mm in diameter and 2.7 mm in length was adopted. The FSW MMC samples are named R600 (600 rpm) and R1500 (1500 rpm), respectively. The detailed information about FSW of the composites was reported in the previous investigations [8,9,22,32–34]. Optical microscopic (OM) examination was carried out on the transverse section of the welds. The OM specimens were mechanically polished and etched by Keller's reagent.

2.2. Neutron diffraction

Neutron diffraction at the diffractometer STRESS-SPEC of FRM II [35] was used to measure the three principal strains, along the L, transverse (T) and normal (N) directions, across the welds at the middle thickness and the middle weld length (see Fig. 1). The Si monochromator was selected using symmetric (400) reflection yielding a wavelength of $\lambda = 1.7458$ Å for the neutron diffraction. This wavelength enabled simultaneous measurement of the 2009Al (311) and 6H SiC (116) reflections at scattering angles of $2\theta_{\mathrm{Al}} \sim 91°$ and $2\theta_{\mathrm{SiC}} \sim 83°$, respectively.

The states of the residual stress in different samples should be understood for extracting different residual strains. Usually a comb sample, in which the macroscopic residual stress is assumed to be relaxed, is used to determine the unstrained reference lattice parameter d_0 for calculating the macroscopic residual strains in welded samples [36]. In MMCs, the macroscopic residual stress will create additional microscopic residual stress due to the mismatch in stiffness, i.e. the elastic mismatch residual stress. Taking this into account, the elastic mismatch residual stress is therefore also assumed to be relaxed in the comb samples.

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