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Scripta Materialia 52 (2005) 693–697

Scripta MATERIALIA

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Correlation between microstructure and microhardness in a friction stir welded 2024 aluminium alloy

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Received 4 February 2004; received in revised form 4 February 2004; accepted 21 December 2004

Abstract

A 2024-T351 aluminium alloy has been friction stir welded and the microstructures investigated. An inner HAZ hardness minimum was a result of an overaged S phase, whereas an outer minimum was believed to be due to precipitate dissolution. An interjacent HAZ maximum was attributable to the presence of very fine S phase precipitates. The nugget zone contained ~4 μm grains and complex dislocation structures.

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Keywords: Friction stir welding; Aluminium alloys; Precipitation; Hardness; TEM

1. Introduction

Friction stir welding has been well documented in recent times as an economically viable solution to the problem of joining hitherto difficult to weld aluminium alloys (e.g. [1]). In particular it has attracted the attention of the aerospace industry, due to potential weight and cost savings, combined with favorable retention of properties (e.g. [2]).

The details of the process have been described elsewhere (e.g. [3]), and in essence consist of a rotating pin (connected to a shoulder) which is forced into and then translated along the join line. This results in plastic deformation in the vicinity of the pin and significant levels of frictional heating, due to contact between the tool pieces and material. Exceptionally high strain levels (i.e. >40 [4]), experienced in what is termed the 'nugget zone', have been found to result in very fine grain sizes (i.e. <10 μm [5]). Previous work relating microstructure and properties, in a precipitation hardenable 6063 aluminium alloy, has been undertaken by Sato et al. [6] and also by Ortelt et al. [7]—for a 2195 aluminium alloy. The latter authors found differences in the dislocation density within the nugget zone grains (a dynamically recrystallized zone), together with incipient formation of sub-grain boundaries. Interestingly, they also observed a reduction in hardness within the HAZ, at ~15 mm from the centre of the weld nugget.

An understanding of the microstructural 'mechanisms' occurring during and after the welding process is important if resultant weld microstructures and associated mechanical properties are to be optimized. The aim of the present work—which is part of a larger study looking at modeling of the material flow during the process [8]—is to investigate and correlate the various weld microstructures and micro-hardness using transmission

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doi:10.1016/j.scriptamat.2004.12.027

electron microscopy (TEM), scanning electron microscopy (SEM) and electron back-scattered diffraction (EBSD) techniques.

2. Material and experimental methods

The base material used in this study was a 2024-T351 aluminum alloy in the form of 15 mm plate (grain size ~56 μm). Vickers micro-hardness measurements of the base material were found to be ~135H_v, regardless of location. Samples of this plate were tooled down to 10 mm thickness and friction stir welded by EADS CCR (France). The joint was sectioned in the transverse plane, enabling microstructures produced within specific areas of the welded material to be examined. Specimens for TEM studies were prepared by spark eroding discs of 3 mm diameter from the nugget and HAZ regions of the weld. Thin foils were then produced using a twin-jet polisher containing a 30% nitric acid and 70% methanol solution at −30 °C and 12 V, and specimens were then examined using a Phillips CM200 operating at 200 kV. SEM and EBSD specimens were mechanically polished using standard techniques, prior to electropolishing under the same conditions as that of thin-foil preparation. Specimens were then examined in a JEOL JSM-6500F FEG-SEM operating at 20 kV. Orientation maps were obtained from electropolished SEM specimens using the HKL Channel EBSD acquisition system. In order to investigate the variation in mechanical properties, Vickers micro hardness (H_v) measurements were made across the transverse plane using a Matsuzausa MXT 70 micro-hardness tester (100 gf load) at mid thickness.

3. Results and discussion

Fig. 1 shows part of the hardness profile across the transverse plane of the weld on the retreating side (together with the locations used for microscopic examination). Moving out from the edge of the nugget zone (the TMAZ extended out to ~8 mm), the HAZ can be seen to contain an inner and outer minimum, together with an interjacent maximum-located ~12, 27 and 18 mm from the join line respectively. The hardness in the nugget zone can be seen to fluctuate in the range 120–130H_v, which may be due to experimental error when considering the similar variation seen at distances >35 mm from the join line (i.e. approaching the base material (135H_v) towards the edge of the HAZ). Although not investigated, it should be noted that this variation in hardness may be due to the 'onion ring' structure of the nugget zone and associated precipitate distribution (e.g. [9,10]).

Both the central and retreating sides of the nugget zone (locations 1 and 2 in Fig. 1) were found to contain

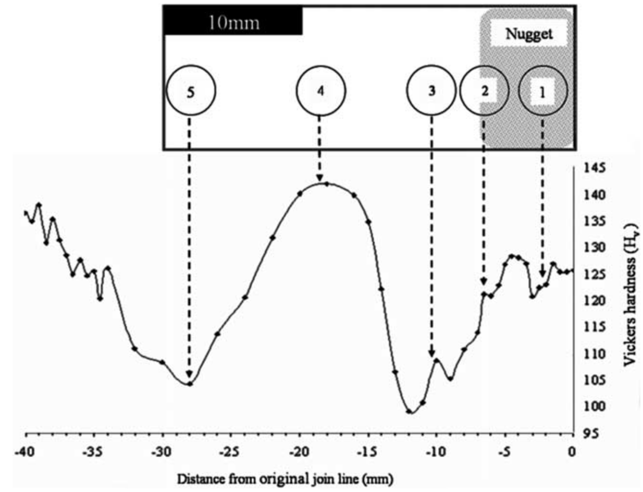

Fig. 1. Schematic of weld transverse plane (retreating side) showing locations used for TEM examination together with their associated hardness values.

a very fine equiaxed grain size (~4 μm), as shown by the bright field TEM image in Fig. 2. EBSD orientation maps gave a slightly higher grain size of ~5 μm (due to low angle grain boundaries (LAGBs) below 2° being omitted) as shown in Fig. 3. This microstructure is typical of that found in the nugget zone (e.g. see [5]), and as generally reported in previous investigations, the presence of a high proportion of high angle grain boundaries (HAGBs) in the nugget zone (e.g. Fig. 3) contributes to hardening through the well known Hall–Petch relationship. A number of these fine grains were found to contain a high dislocation density, whereas others appeared to have rather low densities. In some instances a number of helical dislocation structures were observed within

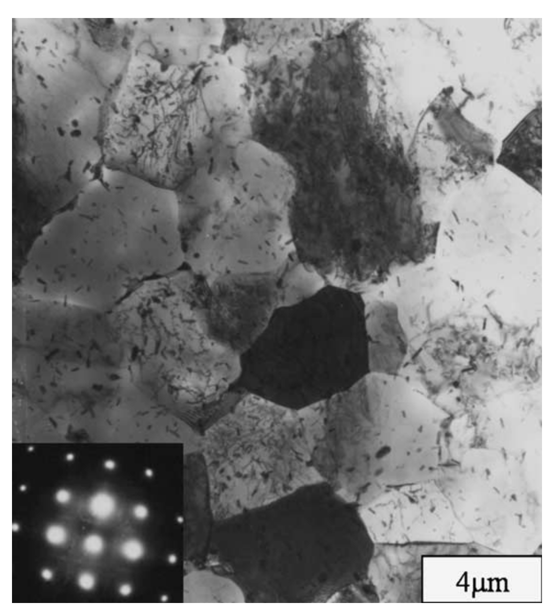

Fig. 2. TEM micrograph of central nugget zone (location 1 in Fig. 1).

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