



Subgrain formation in ultrasonic enhanced friction stir welding of aluminium alloy



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ABSTRACT

Recrystallization fractions in the stirred zone of Al 6061-T6 friction stir welds, prepared with and without ultrasonic vibrations, were evaluated using recrystallization fraction maps. Based on the maps, it was suggested that the microstructure evolution can be described as different dislocation manipulation processes. It was observed that superposition of static load of FSW on residual ultrasonic softening induces subgrain formation. Subgrain formation was substantial at the center of the stirred zone where the ultrasonic impact was the maximum.

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1. Introduction

Current understanding on the microstructure evolution in friction stir welding (FSW) is largely qualitative and inadequate to establish a fundamental science [1]. Recently, ultrasonic vibration enhanced FSW (UVEFSW) has been developed to economically extend the FSW process to harder materials [2]. As compared to FSW, the UVEFSW of aluminium (Al) alloys resulted with lower process load, improved material flow, wider deformation zone, and better weld physical and mechanical properties [2,3]. Besides, the UVEFSWed Al 6061-T6 alloy comprised of better grain refinement, recrystallization, grain orientation, and strain characteristics [3,4]. The above improvements were attributed to the more favourable dislocation dynamics achieved in the UVEFSW. Therefore, UVEFSW has the potential for the economic welding of harder alloys.

In UVEFSW, the FSW process load is superimposed on the ultrasonic effect. Previous studies predicted that the ultrasonic effect is maximum in the weld center and diminished towards the stirred zone extremities (SZE) [3,4]. Superposition of ultrasonic vibrations on static load causes ultrasonic softening [5,6] of material which alters the physical, mechanical and metallurgical properties of the material [7–11]. Ultrasonic softening is described by the reduction in quasi-static stress due to stress superposition, i.e., augmentation of quasi-static load with the

oscillatory stress of ultrasound [12]. In micro-indentation studies of Al-alloy, stress superposition resulted with extensive subgrain formation [7,13]. This was attributed to reduction in dislocation density due to increasing chances of dislocation annihilation. Subgrains facilitate metal deformation by reducing the number of local active slip systems [14]. Withdrawal of ultrasonic vibrations reduces the ultrasonic softening to residual softening [4,12]. Most of the ultrasonic studies considered only the surface frictional effects on the plastic deformation while the volumetric effects were neglected.

Ultrasonic irradiation produces recovered grains in metal [15]. Hence, a workpiece in UVEFSW consists of recovered grains rather than coarse grains before the welding. The higher deformation in UVEFSW was attributed to an enhanced material flow velocity which indicates reduction in flow stress by ultrasonic vibrations [16,17]. Also, the higher deformation would cause internal crystal rotations which alter the subsequent dislocation generation and recrystallization. In this study, the effect of ultrasonic vibrations on the recrystallization of Al-alloy in UVEFSW was evaluated using local recrystallization fraction (RF) maps. The RF maps were derived from electron backscattered diffraction (EBSD) based data on internal average misorientation (IAM) of individual grains.

2. Materials and methods

Single pass welds of 6 mm thick Al 6061-T6 plates were prepared using FSW and UVEFSW processes under identical process

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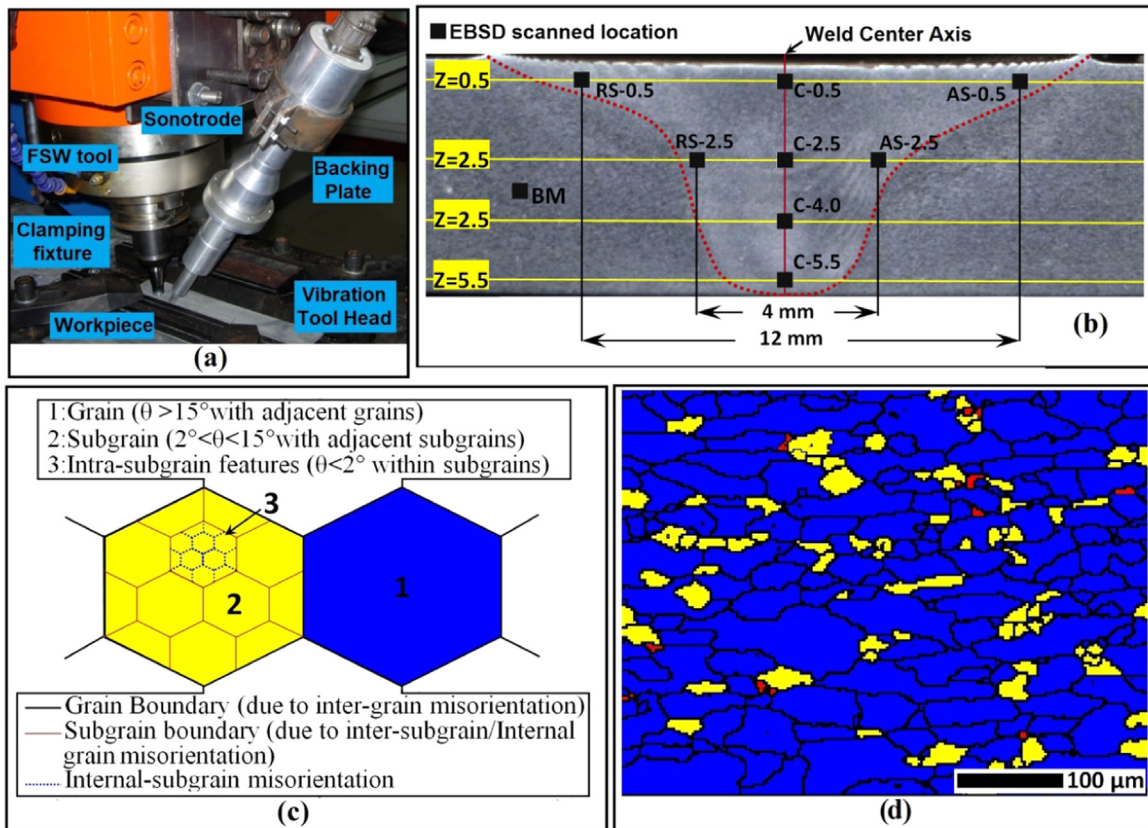


Fig. 1. (a) Photograph of UVeFSW, Schematics of (b) SZ locations scanned by EBSD (c) grain, subgrain and internal subgrain features, (d) RF map of base metal.

parameters (rotation speed 800 rpm, welding speed 320 mm/min, shoulder plunge depth 0.05 mm, and tool tilt angle 2.5°). The FSW machine was position-control type. FSW tool comprised of a concave concentric shoulder (diameter 15 mm) and a threaded pin (diameter ~3.5–6 mm and length ~5.75 mm). Fig. 1a shows the UVeFSW setup. In UVeFSW, ultrasonic vibration was imparted at 45° by the tool head of the sonotrode (fixed to FSW machine) along the weld seam line of workpiece. The tool head was moved 20 mm ahead of the FSW tool. The sonotrode was operated at a frequency, 20 kHz, amplitude, 40 μm , normal load, 300 N and has an output power, 300 W. Details of the UVeFSW is provided elsewhere [18].

Fig. 1b shows the transverse SZ locations selected for EBSD scanning. The locations are at depths $Z=0.5, 2.5, 4.0$ and 5.5 mm along the weld center axis (WCA) and at depths $Z=0.5$ and 2.5 mm on the advancing side (AS) and retreating side (RS) of the SZ extremities (SZE). EBSD scanning was conducted using a scanning electron microscope (ZeissEvoMA 10) equipped with an EBSD (NordlysMax II detector and HKL CHANNEL5 Tango data-processing module). Parameters used for the scanning were step size $0.5 \mu\text{m}$, low-angle boundary (LAB) 2° and high-angle boundary (HAB) 15° . The Tango module generated the RF maps automatically by first constructing the grains on the basis of the pre-established HAB and later by calculating the IAM inside each grain. Subsequently, a grain with IAM $> 2^\circ$ (generally, $\sim 4\text{--}5^\circ$) was classified as deformed grain (DG) while that without LABs and with IAM $< 2^\circ$ was classified as recrystallized grain (RG). A substructured grain (SG) comprised of subgrains with IAM $< 2^\circ$ and inter-subgrain misorientation $> 2^\circ$. Fig. 1c shows the grain, subgrain and inter-subgrain features. Percentages of DG, RG and SG in the RF maps were evaluated on the basis of grain area.

3. Results and discussion

The UVeFSW process is different from other stress superposition processes. Considering the linear kinematics of FSW tool and ultrasonic tool head during welding, the material undergoing UVeFSW can be described to be under an integrated effect of quasi-static load superimposed on residual softening. This is because, at each instance of welding, the moving tool head generates a residual softening which is augmented by the load of the following FSW tool. In UVeFSW, the initial dislocation generation by ultrasonic irradiation increases the dislocation motion. The improved dislocation motion facilitates dislocation consumption which makes deformation of material easier during the action of FSW tool. Subsequently, at the beginning of microstructure evolution, dislocations are regenerated, rearranged or re-consumed depending upon the heat generation, mechanical stress, strain etc. Therefore, in this study, RF analysis has been carried out by assuming the microstructure evolution as a series of dislocation manipulation phenomena. The internal dislocation density of a grain varies directly as its IAM. For example, Fig. 1d shows the RF map of Al 6061-T6 base metal where grains are $\sim 94\%$ recrystallized, $\sim 5\%$ substructured and $< 1\%$ deformed. Accordingly, the base metal has $\sim 93\%$ HAB (represents RG) and $\sim 7\%$ LAB (represents SG) [3].

Figs. 2 and 3 show the RF maps of the locations in WCA and SZE, respectively. Fig. 4 shows the stacking of RG, SG and DG percentages, calculated from Figs. 2 and 3. The RF maps in Fig. 2a show that C-0.5 locations in both FSW and UVeFSW are dominated by SGs. This may be attributed to slower microstructure evolutions due to recurring shoulder effect. The recurring effect arises from the different sizes of the shoulder and the location and allows multiple shoulder rotations on C-0.5 resulting with relatively slower overall dislocation consumption. Fig. 4a shows that the RG:

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