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Gradient micro-structured surface layer on aluminum alloy fabricated by in situ rolling friction stir welding

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ABSTRACT

A gradient micro-structure was formed in the surface layer of 2219 aluminum alloy joint by means of in situ rolling friction stir welding (IRFSW). The micro-structured surface layer is about 200 μm deep, corresponding to a gradient change in microhardness from 86.8 to 59.4 HV in the coarse-grained weld nugget zone (WNZ). Compared with those of the base material, the friction coefficient values are evidently decreased and the wear resistance is obviously enhanced on the surface layer. The corrosion current was relatively low and corrosion potential value was positive with respect to that of the base material. The second-phase particles in the upper surface layer were much more and smaller than those of the base material.

1. Introduction

In most cases, material failures occur on surfaces such as fatigue fracture, fretting fatigue, and wear and corrosion. These failures are very sensitive to the structure and properties of the material surface. To many materials, the low surface hardness and poor wear resistance has restricted their applications in engineering fields [1]. However, optimization of the surface microstructure and properties is an effective approach to enhance the global behavior and service lifetime of materials [2].

Plastic deformation-induced grain refinement in the submicrometer or nanometer regimes has been extensively investigated in various metals and alloys over the past decades, both in bulk forms [3] and in surface layers on bulk materials [4]. Optimizing surface properties by refining grains in surface layers to the nanometer scale (referred to as surface nanocrystallization) provides more promising practical industrial applicability. Surface mechanical attrition treatment (SMAT) is a developed technique that can induce grain refinement into the nanometer regime in the surface layer of bulk materials [5]. The SMAT transforms the original coarse-grains at the surface material into refined-ones [6]. The grains refining mechanisms in SMAT is conducted by the random and repetitive impact of milling balls to the sample's surface. This technique has been successfully applied in achieving surface nanocrystallization (SNC) in a variety of materials including pure metals, alloys and steels [7–10]. Another technique has been developed based on basically the principle of plastic deformation-induced grain refinement is friction sliding [11]. However, these two processes suffer from either low processing efficiencies or limited nano-structured layer thicknesses, or structural inhomogeneity in the surface layer, all of which have hindered the widespread application of surface nanocrystallization technologies [12].

In recent years, surface mechanical grinding treatment (SMGT) is developed to synthesize a gradient nano-micro-structure in the surface layer of bulk metals [12]. The SMGT technique is based on machining-induced plastic deformation and can achieve surface modification by generation of a nano-structured surface layer so that the overall properties and behavior of the materials are significantly improved. This technique requires only simple procedures and can be readily applied to engineering materials [12]. Friction stir processing technique refines the microstructure in the surface layer during which a large plastic strain is generated together with a substantial mass flow accompanied by a large, localized temperature rise [13]. This results in relatively large grain sizes, typically of the order of several hundred nanometers, via dynamic recrystallization [14]. FSP has proved to be a viable tool for enhancing the mechanical properties of materials, however, the major focus has been upon improving the bulk properties of light metals and their alloys [15,16].

A surface enhancement technology, Low Plasticity Burnishing (LPB), is also developed to produce a deep layer of highly compressive residual stress with a minimum amount of cold working, or plastic deformation [17]. It can provide compression in the surface layer of sufficient depth to effectively eliminate the degradation in corrosion/fatigue life attributed to salt pit corrosion [18]. Unlike LPB, conventional roller and ball burnishing utilize a hard wheel

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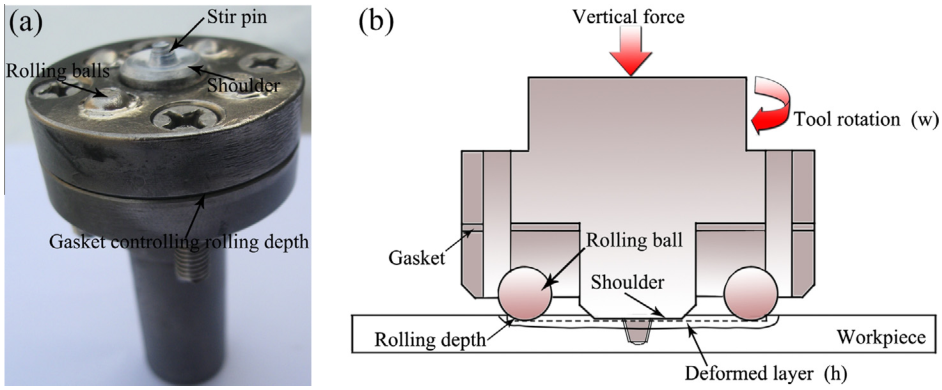

Fig. 1. (a) Photo of in situ rolling friction stir welding tool. (b) Schematic illustrations of the IRFSW set-up and the plastic deformation layer induced by the shoulder and rolling balls.

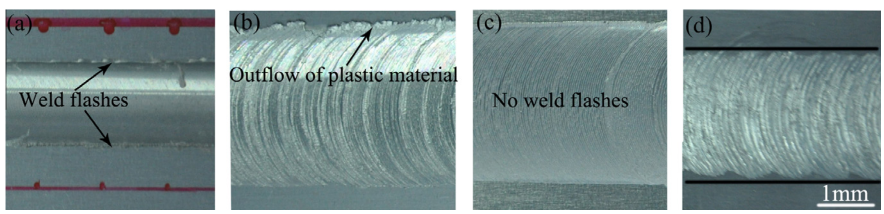

Fig. 2. The surface comparison between IRFSW seam and conventional FSW seam: (a) surface of conventional FSW seam, (b) surface of IRFSW seam with more than 0.05 mm rolling depth, (c) surface of IRFSW seam with 0.05 mm rolling depth, and (d) surface of IRFSW seam with less than 0.05 mm rolling depth.

tool or fixed lubricated ball pressed into the surface of an axisymmetric workpiece with sufficient force to deform the near surface layers, usually in a lathe. Burnishing is performed with multiple passes, often under increasing load, to improve surface finish and to deliberately cold work the surface [18].

In this work, we develop a novel technique, namely in situ friction stir welding (IRFSW), to synthesize a gradient micro-structure in the surface layer of 2219 aluminum alloy joint. We report the processing of the IRFSW, the microstructure and grain refinement mechanism of the surface layer induced by the IRFSW, as well as properties of the micro-structured surface layer in 2219 aluminum alloy joint.

2. Experimental details

The material used is 2219 aluminum alloy (3 mm $\times$ 300 mm $\times$ 100 mm) with chemical compositions of (in wt%): 6.48 Cu, 0.32 Mn, 0.23 Fe, 0.06 Ti, 0.08 V, 0.04 Zn, 0.49 Si, 0.02 Zr and balance Al. Tensile strength and elongation of AA2219 rolled plate is 331 MPa and 11.7%, respectively. As shown in Fig. 1a, four rolling balls 8 mm in diameter are fastened to spherical grooves by brazing, and the rolling tool connects with the shoulder through bolt fastening with a rolling diameter of 26 mm. The rolling depth of rolling balls is controlled by the gasket and the thickness of each gasket is 0.05 mm. The welding tool is fabricated from tool steel and consisted of a shoulder with a diameter of 14 mm and a threaded conical pin 2.6 mm in length. The IRFSW process are finished using an FSW machine (FSW-3LM-003). As schematically illustrated in Fig. 1b, the IRFSW processing involves friction, stirring and rolling. The stir tool gets in touch with the interface of aluminum alloy sheet, rubs against the inner interface, and rolls the bonding surfaces which make the surface of weld seam produce severe plastic deformation in the welding processing. During the IRFSW processing, the rolling balls, shoulder and stir pin rotate at a rotation rate of ω, which slide along the welding line from front to back at a velocity of υ. With a preset penetration depth of the shoulder and rolling balls into the plate, h, a plastic deformation zone is induced underneath the IRFSW tool.

To compare the erosion resistance of the base material and micro-structured surface layer, the samples were exposed to 3.5%NaCl solution at the room temperature. The corrosion current and potential were determined by electrochemical analyzer CHI604C which was comprised of electrochemical cell. It is three electrodes system in which the sheet is used as work electrode, the platinum piece is used as the auxiliary electrode and the saturated calomel electrode is used as reference electrode. In the test, cell current readings are taken during a slow sweep of the potential. The sweep was taken from (−2 to +1) V and the scan rate was 0.01 V/s. Corrosion potential is the thermodynamic parameter

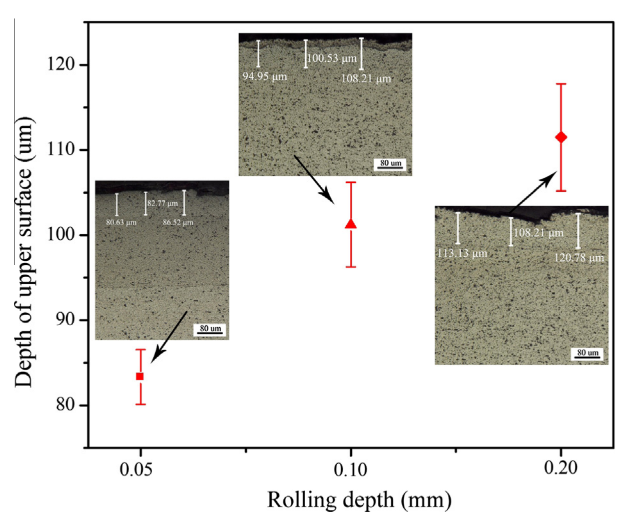

Fig. 3. The variation of depths of upper surface with different rolling depths.