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Impact of cold spraying on microstructure and mechanical properties of optimized friction stir welded AA2024-T3 joint

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ABSTRACT

The tensile properties of friction stir welded AA2024-T3 joints at the rotation speed range of 600–900 rpm and a constant welding speed of 200 mm/min were summarized, finding that the optimized rotation speed is 600 rpm which yield a maximum tensile strength of 420 MPa. Subsequently, an aluminum coating was deposited on the optimized joint surface by cold spraying (CS). The microstructural evolution in the layer near the surface of the coated joint was investigated by a combination of transmission electron microscopy, electron back-scattered diffraction and differential scanning calorimetry. The results show that the CSed joint exhibits significantly enhanced tensile strength, microhardness and fatigue life. This improvement is attributed to refined grains with a higher number of Guinier-Preston-Bagaryatsky (GPB) zones, finer and more S phases, and lower residual stresses due to the heat flow and shot peening effects by the CS on the layer near the surface. CS is shown to be an additional technique to enhance the mechanical properties of FSWed joints whilst providing corrosion protection for them.

1. Introduction

As a promising solid-state joining technique, friction stir welding (FSW) has been applied extensively to join difficult-to-weld light weight components by conventional fusion processes, especially for high-strength aluminum alloys like the 2xxx and 7xxx series [1,2]. However, the intensive frictional heating and mechanical stirring at the stirred zone produced great inhomogeneities in microstructure and mechanical properties across the joint, which obviously caused lower corrosion resistance and mechanical properties than those of the base material (BM) [3–6]. Moreover, the thermal cycle during FSW can result in higher tensile residual stresses in a weld [3]. Their presence is crucial as they significantly affect weld performance [7–9], especially fatigue properties [7,8] and stress corrosion [9]. It is therefore highly significant to find a more efficient method to improve the corrosion performance and mechanical properties of the joints for the further application of FSW technique.

In the past few years, various research efforts have been made to improve either the mechanical properties [10–13] or corrosion resistance [14–19] of the FSWed joints. Enhanced mechanical properties of FSWs could be achieved easily by optimizing welding parameters and tool geometry. Nevertheless, the corrosion resistance of FSWed joints was not significantly modified [20]. With heat treatment (HT), one of the most important methods, the mechanical properties can be effectively improved by adjusting microstructure and releasing residual stresses of the joints [10,11]. However, HT would lead to a high heat input to whole components, and also be limited by the dimensions of components, for example, the large-scale shipbuildings and aircrafte panels [10]. Therefore, many attempts on shot peening have been conducted on the FSWed joints, which displays a significant improvement on mechanical properties of the joints [12,13], but it does not improve microhardness values and is not suitable for processing large-sized materials.

The other big challenge facing in FSW applications is the low corrosion resistance of the weld seam, due to the rotating tool shoulder has damaged the covering pure Al layer [1]. Many studies have shown that the surface coatings could be the best way to protect the weld from the corrosive environment [17–19]. To obtain a good bonding between the protective coating and the weld surface, laser surface melting and micro-arcoxidation etc. have been attempted [17–19]. Although the corrosion resistance were highly improved, an obvious decrease was also widely reported on the mechanical properties of the coated joints caused by the high heat input during the surface coating process. All those reports indicated that it is highly necessary to find an effective

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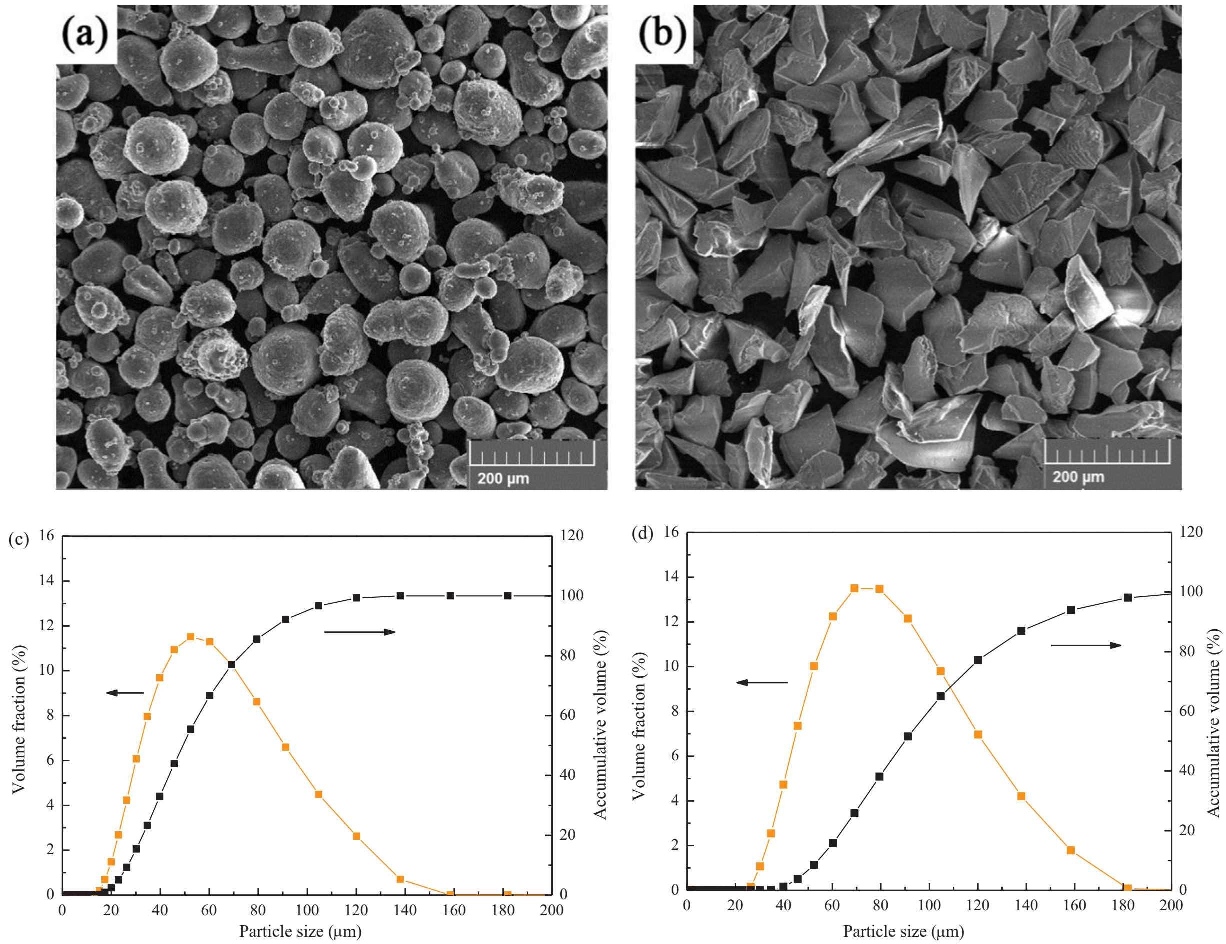

Fig. 1. SEM micrographs and particle size distributions of the powders: (a, c) pure Al powder and (b, d) Al_2O_3 powder.

method to enhance the FSWed joints on both mechanical properties and corrosion resistances.

Cold spraying (CS) as a newly emerging solid-state process, is a powder deposition process characterized by low process temperatures and high-velocity particle impact has received attention [21,22]. Due to these features, the main advantage of CS is that it alleviates the problems associated with high temperature processing of materials, such as oxidation and unfavourable structure changes. Therefore, CSed coatings are used for repair, additive manufacturing and corrosion protection at relatively high deposition rates and low porosity. During CS, the high speed particles accelerated by a gas flow continuously impact the substrate and deform extensively, consequently producing compressive residual stresses in the substrate surface and improving the fatigue performance, similarly to the "shot peening effect (SPE)" [23–25]. It has been shown that the bombardment generated by particles during CS, induces compressive residual stresses near the surface of the substrate, and improves fatigue properties of the substrate [9,26]. Furthermore, the gas is usually preheated to a temperature well below the melting point of the spray material, in order to increase the particle temperature and deformability, similarly to the "heat flow effect (HFE)" [27,28]. In addition, previous results showed that CSed Al-Al_2O_3 coatings on carbon steel and light alloys exhibit excellent corrosion-resistance [29,30]. However, very few studies have been made to evaluate the effect of CSed coating on the microstructure and properties of FSWed joints. In the previous study [31], it is interesting to find that the FSWed joint with a CSed Al coating would exhibit good corrosion resistance and improved mechanical properties. However, in that work [31], the as-FSWed joint was not the optimized one (the tensile strength was only 333 MPa, about 70% of the base metal), one could not clarify the underlying mechanism.

In this study, therefore, the effect of welding parameters (rotation speed) on mechanical properties of FSWed high-strength aluminum alloy joints was demonstrated and then the optimized parameters were chosen for subsequent investigation. The aim is to further enhance the mechanical properties of the FSWed high-strength aluminum alloy joint obtained under the optimized parameters through a CS process and explore the underlying mechanisms via a detailed study of the microstructure and residual stresses before and after coating.

2. Experimental procedure

2.1. Materials and coating preparation

The BM used in the present study is AA2024-T3 alloy sheets. Its heat treatment condition of T3 implies a solution treatment, quenching, pre-deformation and natural aging. The AA2024-T3 sheets with dimensions of 200 × 100 × 3.2 mm were friction stir butt-welded along the rolling direction by a commercial FSW machine (FSW-RL31-010, Beijing FSW Technology Co., Ltd., PR China). The tool rotation speed were 400 rpm, 600 rpm, 800 rpm, and 900 rpm with a constant welding speed of 200 mm/min according to the previous study [32,33]. The welding tool had a shoulder diameter, probe root diameter and probe length of 10 mm, 3.4 mm and 2.9 mm, respectively. The stir tool was tilted 2.5° (Z-axis) and the plunging depth of the tool shoulder was 0.2 mm.

Commercially available Al and Al_2O_3 powders were used in this study. The Al powder was mixed with 20 vol% Al_2O_3. The Al-Al_2O_3 composite powder was CSed onto the FSWed joint surface using a CS system developed in Xi'an Jiaotong University, China. The driving gas