Materials Science & Engineering A 714 (2018) 124–139

Contents lists available at ScienceDirect

Materials Science & Engineering A

journal homepage: www.elsevier.com/locate/msea

Strengthening mechanism in laser-welded 2219 aluminium alloy under the cooperative effects of aging treatment and pulsed electromagnetic loadings

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A R T I C L E I N F O

Keywords:
Strengthening mechanism
Aging treatment
Pulsed electromagnetic loading
Laser-welded 2219 aluminium alloy
Microstructure evolution

A B S T R A C T

Electromagnetic (EM) forming is a high-speed forming technology which uses pulsed EM loadings to form metal sheet parts. A particular advantage of pulsed EM loadings is material strengthening. In the present work, a novel process is proposed to strengthen laser-welded 2219 aluminium alloy. EM uniaxial tension is performed to study the strengthening mechanism in laser-welded 2219 aluminium alloy under the cooperative effects of solid solution-double aging (SS-DA) treatment and pulsed EM loadings. The results indicate that the strength, hardness, and plasticity of the laser-welded joints after SS-DA treatment dramatically improved in comparison to that of as-welded joints. This is due to the elimination of brittle eutectic phases and precipitation of dispersive G.P.(Π) zones, as well as precipitation hardening which dominates the strengthening mechanism. However, under the cooperative effects of SS-DA treatment and pulsed EM loadings, the strength and hardness of the weld joints increase, but the plasticity decreases as the discharge energy increases. The strength and hardness of the laser-welded joints are improved not only because of the appearance of dislocations but also because of the substantial transformative growth of G.P.(Π) zones with a bilayer structure to a thick θ" phase with a multilayer structure which is in close proximity to the dislocations. This demonstrates the combined strengthening mechanism of the strain and intensified precipitation hardening. The significant growth of the precipitates mainly results from the concentration of the solute Cu atoms and the internal energy rise under the effect of the pulsed EM loadings.

1. Introduction

The 2219 aluminium alloy belongs to the wrought Al-Cu family and can be strengthened by solid solution and aging treatments [1]. The chemical composition of the precipitates is close to Al_2Cu, and the common aging precipitation sequence is as follows: supersaturated solid solution (ssss) → G.P. zone → θ" phase → θ' phase → stable θ phase [2,3]. After extensive investigations and discussions [4–8], a more detailed interpretation of the aging precipitation behaviour of Al-Cu alloys after the formation of a solid solution was established as follows: ssss → quenched clusters → G.P.(I) zone → G.P.(Π) zone → θ" phase (independent of G.P.(Π) zone) → θ' phase → stable θ phase [9]. Among them, the G.P.(Π) zone has a bilayer structure and the θ" phase has a multilayer structure. The orientation relationships between these two phases and the α-Al matrix are kept in $(001)_{G.P.(\Pi)/\theta''}\|(001)_{\alpha}$ and $[100]_{G.P.(\Pi)/\theta''}\|[100]_{\alpha}$ on a $\{001\}_{\alpha}$ habit plane [10].

Because of its very good temperature properties, fracture toughness, corrosion resistance, formability, machinability, and weldability, 2219 aluminium alloy is expected to be highly valuable for applications as aerospace materials [11–13]. Therefore, 2219 aluminium alloy is an optimal choice for the manufacture of large metal sheets such as those used in the base of propellant tanks for carrier rockets. The diameters of propellant tanks can approach 10 m; however, to manufacture aluminium alloy sheets of width > 10 m is challenging. Therefore, the welding technology must first be improved to successfully use 2219 aluminium alloy for manufacturing the base of propellant tanks. At present, special welding technologies used for aluminium alloys are friction stir (FSW) [14–16], electron beam (EBW) [17–19], and laser welding (LW) [20–22]. Among these three techniques, LW is the most effective method for ensuring excellent static and dynamic mechanical properties of the weld joints, a narrow heat affected zone (HAZ), and production of low heat stress during the welding of 2219 aluminium alloy sheets.

When laser-welded 2219 aluminium alloy sheets are used, traditional stamping, hydro-bulging, and spinning are applied to manufacture large metal sheet parts. However, the formability and service performance of weld joints obtained by these techniques are low. Therefore, it is of great importance to establish a novel processing

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https://doi.org/10.1016/j.msea.2017.12.081
Received 2 August 2017; Received in revised form 19 December 2017; Accepted 20 December 2017
Available online 22 December 2017
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technology to form large laser-welded sheet parts. Electromagnetic (EM) forming is a high-speed forming technology, which uses pulsed EM loadings to form metal sheet parts. EM forming afford many advantages such as springback reduction and high surface workpiece quality and the fact that it is an environment-friendly process in comparison to other traditional forming processes [23,24]. In addition, EM forming involves a simple force and energy transmission system, and the required large equipment is easy to construct. To accomplish the integral formation of large metal sheet parts, a novel incremental forming process using pulsed EM loadings—electromagnetic incremental forming (EMIF) has been reported [25,26]. Furthermore, the strength of aluminium alloys can be enhanced by pulsed EM loadings, and the ductility and forming limit can be boosted because of the high strain rate and inertia effects [27–30]. Thus, EM forming can effectively overcome the problems typical of laser-welded joints. Therefore, EMIF is an advantageous processing technology for the formation of large metal sheets using laser-welded 2219 aluminium alloy, whether it is from the perspective of precision forming or general improvement in the material's properties.

By a careful analysis of the literature, a novel process route for the manufacture of large metal sheets is proposed as follows: LW → post-weld treatment → EMIF. During the integral process, the strengthening behaviours of the weld joints are fundamental apart from the precision forming. Moreover, it is important to investigate the mechanical properties and microstructure evolution in the laser-welded joints when studying the strengthening mechanism under the cooperative effect of post-weld treatment and pulsed EM loadings.

In the development of the novel process route and determination of the strengthening mechanism, some studies have been particularly important. In regards to the strengthening processes for 2219 aluminium alloy, Elgallad et al. [31] developed an optimum two-step aging treatment (i.e. double aging), which is more effective than one-step aging. GP zones precipitate during the first step, and transform into effective θ'' strengthening precipitates in the second step. Lu et al. [32] found that an increase in the dislocation density of the matrix is related to the pre-deformation and can enhance the strength of the pre-deformed samples by forming a dense rising and smaller θ' phases precipitating dispersively in the α-matrix. According to these studies, precipitation hardening is the most suitable strengthening method for the 2219 aluminium alloy, and it is appropriate to promote strengthening via thermo-mechanical treatment.

The mechanical performance and characteristics of the microstructure of the laser-welded 2××× series aluminium alloys have also been the subject of significant study. Talari and Babu [33] found that compared with the GTA weld, laser-welded 2219 aluminium alloy exhibits higher hardness, ductility, yield, and fatigue strength due to the fine, equiaxed grain morphology and discontinuous eutectic phase distribution. In addition, post-weld aging response and ductility of the laser-welded joints are better than those of the GTA weld joints. Hou and Baeslack [34] revealed that for CO_2 laser-welded 2195 aluminium alloy, post-weld heat treatment can promote the precipitation of T_1, θ', α', and δ' phases in precipitate-segregation zones. However, the distribution of the precipitates in the post-weld heat-treated fusion zone is non-uniform because of solute segregation in the eutectic regions. It is reported that the brittle eutectic phase which results from solute segregation is a common problem for the laser-welded 2××× series aluminium alloys. Consequently, it is necessary for laser-welded 2219 aluminium alloy to ameliorate the eutectic phase by solid solution treatment and to promote precipitation by an aging treatment in order to accomplish superior mechanical properties.

Moreover, the effect of pulsed EM loadings on the formability improvement of aluminium alloys has been previously investigated by Golovashchenko [27] and Thomas et al. [35], who revealed that the EM forming process can improve the formability and ductility of aluminium alloys in comparison to conditional stamping. Li et al. [36] found that differing from the planar slip in the mechanical deformation, the deformation mechanism of 5052 aluminium alloy is dominated by the wavy slip under pulsed EM loadings due to the spatial force. Previous reports have largely focused on the improvement of ductility and the forming limits of aluminium alloys under pulsed EM loadings, but seldom took the strengthening behaviour and mechanism into consideration, which play an important role in the service performance of aluminium alloys.

The aging and thermo-mechanical treatment of 2219 aluminium alloy have been studied extensively. However, the strengthening mechanism in laser-welded 2219 aluminium alloy at different stages of the proposed integral process, along with their mechanical properties and microstructure evolution, are likely to exhibit significant complexity, particularly in relation to the coupling among the thermal, electric, magnetic, and force fields. Meanwhile, the cooperation of post-weld heat treatments and pulsed EM loadings is of great value to the integral manufacture of large sheet metal parts using EMIF. Therefore, it is important to study the cooperative effect of the post-weld heat treatment and pulsed EM loadings on the strengthening mechanism in laser-welded 2219 aluminium alloy.

In the present work, EM uniaxial tension is carried out to analyse the cooperative effects of solid solution-double aging (SS-DA) treatment and pulsed EM loadings on laser-welded 2219 aluminium alloy, by the analysis of the mechanical properties (tensile strength, percentage reduction of area, and microhardness) and observation of its microstructure characteristics (metallography, fracture surface, dislocations, and precipitation). Consequently, this study reveals the strengthening mechanism in laser-welded 2219 aluminium alloy.

2. Materials and experimental methods

2.1. Materials

A 2-mm-thick 2219 aluminium alloy sheet in a full annealing state was used. The nominal chemical composition (wt%) of the alloy is listed in Table 1. Cu is the solute atom in the 2219 aluminium alloy. The microstructure of a 2219-O aluminium alloy sheet comprises elongated grains along the rolling direction with non-uniform grain sizes (Fig. 1).

2.2. Process system

To study the cooperative effects of SS-DA treatment and pulsed EM loadings on the 2219 aluminium alloy, a specifically designed process route using the following sequence, LW-SS-DA-EM uniaxial tension, is proposed. Firstly, specimens were butt-welded by LW and then treated by SS-DA. Finally, EM uniaxial tension is carried out to impose pulsed EM loadings on the specimens. The process route along with three specimen types is illustrated in Fig. 2. The experimental set-up, results, and discussion are all based on these factors.

Table 1
Chemical composition of 2219 aluminium alloy (mass fraction, %).

Element	Al	Cu	Mn	Ti	Zr	Fe	Si	Mg	Zn
Standard	Bal.	5.8–6.8	0.2–0.4	0.02–0.1	0.1–0.25	≤0.3	≤0.2	≤0.2	≤0.1
Actual	Bal.	6.5	0.36	0.06	0.18	0.21	0.05	0.01	0.02

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