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Phase transformation at the interface during joining of an Al–Mg–Li alloy by pulsed current heating

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Atom diffusion mechanisms at the interface during the joining of an Al–Mg–Li alloy by pulsed current heating were analyzed. Transmission electron microscopy results showed that the content of AlLi phase decreased with a symmetric distribution at the interface after joining. Moreover, Al_4Li_9 phase, which does not exist in the Al–Mg–Li alloy, was found growing around the AlLi phases at the interface. Current was found to be the main factor influencing the properties of joints formed by pulsed current heating.

Keywords: Aluminum alloys; Pulsed current heating; Diffusion bonding; Phase transformation

Spark plasma sintering (SPS) or pulsed current heating (PCH), also known as electrodischarge sintering or field-assisted sintering, is a promising technique for powder consolidation [1,2]. The atom diffusion mechanism during PCH is different to that when samples are subjected to traditional combinations of heat and pressure [3]. A complex range of phenomena are involved in PCH, which is influenced by the uneven distribution of temperature, current and electric field [4–7]. Atom diffusion during PCH is mainly influenced by temperature, current and electric field [8,9], and current can enhance the intrinsic growth of Ni–Ti intermetallic compound [10].

Refs. [11,12] are significant in terms of PCH studies. In Ref. [11], it was found that a change in current density plays a dominant role in grain growth, while the effects of Joule heating, the skin effect and the pinch force can be neglected in comparison to the effect of current distribution. Some metals may be nanocrystallized by using high-density pulsed current. However, as reported in Ref. [13], pulsed current and the electric field are two of the most important factors influencing atom diffusion and grain growth, and the Joule heating effect also should be considered when materials are exposed for a long time to PCH.

Lithium-bearing aluminum alloys constitute a group of high-performance wrought aluminum alloys intended for use principally in aircraft and aerospace structures [14,15]. Al–Li alloy 1420 is an Al–Mg–Li product, which was the result of many years of development in Russia, and was employed in the construction of the MIG-29 supersonic aircraft. It has a nominal composition. The reduced solubility of Li in the matrix yields a higher volume fraction of AlLi δ' which contributes to its greater strength [16]. The solute atoms in Al–Li alloy 2090 diffuse according to a vacancy mechanism which promotes the dissolution of Li when an electric field is applied [17].

In this paper, the influences of current on the tensile strengths of joints were studied. The phase transformation of AlLi phase at the interface and its influence on the tensile strengths of joints were also investigated.

Al–Li alloy 1420 was obtained from Southwest Aluminum (Group) Co. Ltd, China. The chemical composition (wt.%) of the alloy is listed in Table 1. The as-received alloy was machined into cylinders 20 mm in diameter × 20 mm high. First, the alloy cylinders were ground with a grinding machine, and then polished with Al_2O_3 grinding papers. Oxidation of the polished surface was removed by treatment with 5% (weight fraction) NaOH solutions at room temperature for

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Table 1. Components of the Li–Al alloy 1420 (wt.%)

Al	Fe	Li	Mg	Zr	Cu	Si	La
91.76	0.05	2.02	5.06	0.083	0.014	0.013	0.011

1 min after treatment with 25% (volume fraction) nitric acid at 343 K for several seconds. The samples were then cleaned with acetone. After being washed with pure water and dried, the samples were joined in a PCH machine (SPS-1050, Japan) at 773, 783, 793, 803, 813 and 823 K in a vacuum (<6 Pa) under 2 MPa of applied pressure and with heating rates of 200 and 60 K min^{-1}.

Tensile strengths were tested using an electro-hydraulic servo-controlled testing system (MTS-810, MTS Company, USA). Electron backscatter diffraction images of joints were obtained by scanning electron microscopy (JSM-5640LV, JEOL Company, Japan). Microstructures of the interface in the joint were examined by transmission electron microscopy (H-600 STEM/EDX PV9100, Hitachi, Japan). The Li contents of the alloys were measured by inductively coupled plasma-atomic emission spectroscopy (ICP-AES) (Optima 4300DV, PV Company, USA). The X-ray diffraction (XRD) patterns of welded Al–Li alloy 1420 were obtained using a D/Max-RB diffractometer (Rigaku Company, Japan).

The tensile strengths of joints joined at different temperatures with different heating rates are shown in Figure 1. The tensile strengths of joints increased with increasing heating temperature when the heating rate was 60 K min^{-1}. When the heating rate was raised to 200 K min^{-1}, however, the tensile strengths of joints increased with increasing heating temperature over the temperature range 773–793 K, and then remained unchanged when the temperature was increased higher than 793 K.

The higher strengths of Al–Li alloy 1420 were due to the distribution and contents of AlLi phase [13,14]. Therefore, the decrease in tensile strength of joints is a result of the segregation and diminution of AlLi phase in the alloys. The AlLi phase content in the alloy can be identified from the Li content in the alloy because Li exists as AlLi phase in Al–Li alloy 1420. As shown in the phase diagram of the Al–Li system [18] (Fig. 2), Li in AlLi lattice dissolves easily from 723 to 833 K. Figure 3 shows the content of Li in the Al–Li alloy 1420 vs. heating temperature for different PCH treatments. Decrease of Li in the alloy was greater at the same heating temperature when heating rate was 200 K min^{-1}, and Li in the alloy decreased dramatically when the heating temperature was higher than 803 K with a heating rate of 200 K min^{-1}. There was an inflexion at 813 K in the content of Li when the heating rate was 60 K min^{-1}. Therefore, AlLi phase content in the alloys changed in a similar fashion to the Li content; this provides a reasonable explanation for the tensile strength trend in Figure 1. However, it is a special phenomenon that the AlLi phase content in the alloy decreased with increasing current, even though the temperature difference of sample from surface to the middle has been reduced by putting the thermal couple on the surface of the sample directly with a smaller sample (20 mm diameter), as shown in Refs. [19,20].

Pulsed currents can enhance the growth of Ni_3Ti intermetallic and promote recrystallization in Al–Li alloy 2091 [10,21], and this enhancement can be promoted by increasing the current: the activation energy of Ni–Ti heated at 923 K with a current density of 2036 A cm^{-2} is 292 kJ mol^{-1}, and the activation energy is 86 kJ mol^{-1} with a current density of 1527 A cm^{-2} at the same heating temperature. Qin et al. [11] have found that although

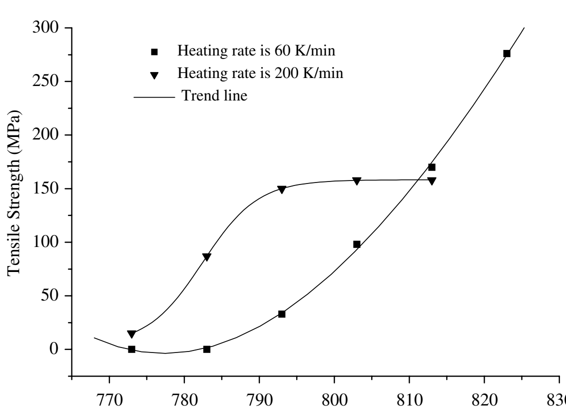

Figure 1. Tensile strengths of the samples welded at different temperatures with different heating rates.

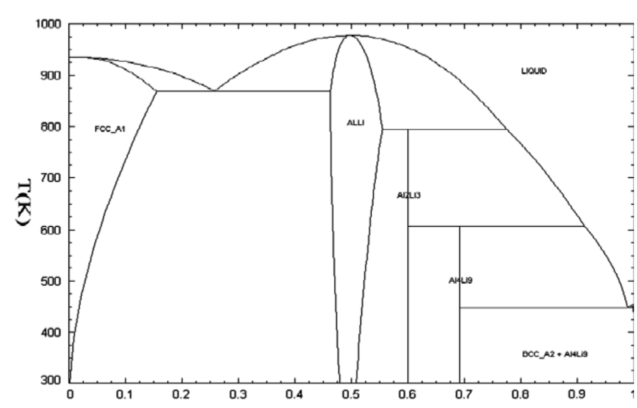

Figure 2. The phase diagram of the Li–Al system.

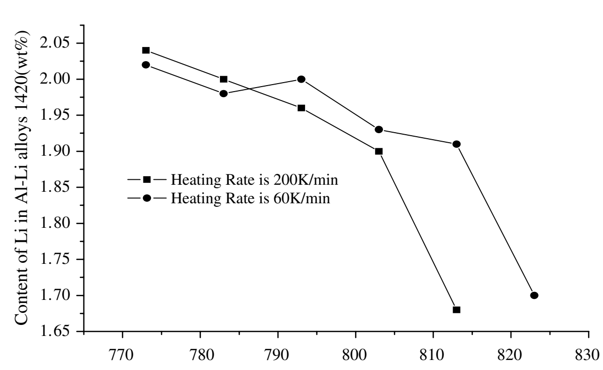

Figure 3. Contents of Li in the Al–Li alloy 1420 after different heat treatments.