Journal of Materials Processing Technology 211 (2011) 1749–1756

Contents lists available at ScienceDirect

Journal of Materials Processing Technology

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

Thixoforming of EN AW-2014 alloy at high solid fraction

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ARTICLE INFO

Article history:
Received 26 January 2011
Received in revised form 14 May 2011
Accepted 21 May 2011
Available online 27 May 2011

Keywords:
Aluminium alloys
Thixoforming

ABSTRACT

EN AW-2014 extruded alloy slugs were thixoformed at 615 °C where the solid fraction is estimated to be 80%. The recrystallization process occurred during heating to the thixoforming temperature, between 550 °C and 600 °C, well above the solidus temperature owing to the pinning of grain boundaries by Al_2Cu precipitates. The equiaxed polygonal grains thus obtained have become increasingly globular upon soaking. Si was enriched in the grain boundaries during soaking while the solid solution matrix was gradually depleted off Cu. The grain boundary composition has moved closer to that of the Al–Cu–Si ternary eutectic with a lower melting point than the binary Al–Cu eutectic, facilitating grain boundary melting. The liquid phase has then penetrated between the grains, forming a more or less continous intergranular network. Microstructural features essential for forming in the semi-solid state were obtained after about 10 min at 615 °C. The subsequent forming process has occurred in the semi-solid state with no evidence of grain deformation. The thixoformed EN AW-2014 part was solutionized at 500 °C for 2 h and was subsequently quenched in water. Artificial ageing at 160 °C has produced hardness values as high as 160 HV after only 8 h. It is concluded that the high strength wrought EN AW-2014 alloy feedstock processed by the RAP route respond to a thixoforming operation in a very favorable fashion.

1. Introduction

With copper as the main alloying addition, aluminium alloys from 2XXX series offer high strength at low specific weight and are reported by Polmear (1996) to be the material of choice for a variety of structural applications in the aircraft industry. Hatch (1984) identifies alloy EN AW-2014 to be one of the most important aircraft alloys both in the form of rolled and extruded products. Typical applications are mentioned in Alumatter (2010) to be heavy-duty forgings, plate and extrusions for aircraft fittings, wheels and major structural components. However, Goncalves et al. (2002) argued that Al–Cu alloys are difficult to hot work, due to their chemical composition and microstructure. It is thus very attractive to form these alloys in the semi-solid state.

Semi-solid forming is claimed by Flemings (1991) to offer to produce intricate parts with a reduced number of processing steps under lower forming pressures. Kirkwood (1994) and Fan (2002) have reviewed the progress of semisolid processing and listed advantages of this innovative near-net forming route over the conventional processes. Loue and Suery (1995) has identified the key feature that permits the semi-solid shaping of alloys to be a non-dendritic microstructure, with globular α-Al grains suspended in a liquid matrix, which may be handled like a solid, but flows readily when sheared. The formability of such a material was claimed by Tzimas and Zavaliangos (2000a) to be exceptional owing to the liquid phase which penetrates between the globular grains. Garat et al. (1998) stated that conventional casting alloys such as A356, A357 are used to produce millions of thixoformed automotive parts every year.

Although components thixoformed from higher performance wrought aluminium alloys are of great technological interest, these alloys are not currently thixoformed due to the unavailability of commercial feedstock as discussed by Liu et al. (2003). Pitts and Atkinson (1998) have stated that thermomechanical processing route to produce wrought aluminium alloy thixoforming feedstock is particularly attractive owing to the commercial availability of aluminium billets with different compositions and extrusion ratios. Tzimas and Zavaliangos (2000b) have compared the degree of spheroidization of alloys produced by spray and magnetohydrodynamic casting and thermomechanical processing and have concluded that the latter results in a microstructure with perfectly equiaxed grains suitable for semisolid processing. Lee and Oh (2002) have used thermomechanically treated EN AW-6061 alloy to obtain thixoformable fine globular microstructures to manufacture steering knuckles for suspension parts of low speed electric vehicles. Birol (2007) has also employed thermomechanical processing to produce EN AW-6061 thixoforming feedstock for semisolid forming. The thixoformability of the cast EN AW-6082 alloy was found by Birol (2008a) to be inferior with respect to that of the extruded counterpart. The latter was in fact shown by Birol (2006,

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doi:10.1016/j.jmatprotec.2011.05.016

Table 1
Chemical composition of the EN AW-2014 alloy used in the present investigation (wt%).

Si	Fe	Cu	Mn	Mg	Zn	Ti	Al
0.603	0.513	4.618	0.932	0.265	0.180	0.030	92.80

2008b) to suffice for the manufacture of sound thixoformed parts. Birol (2009) has shown that thermomechanical processing can also be employed to produce thixoforming feedstock from aluminium casting alloys.

Thermomechanical processing involves the partial melting of a heavily deformed alloy in order to obtain a fine equiaxed microstructure as demonstrated by Young et al. (1983). The transformation of the as-deformed dendritic microstructure to a globular one, relies on the recrystallization process and the penetration of the low-melting point phases through the high-angle boundaries of the recrystallized grains once the temperature increases above the solidus temperature. Of the two variants of the thermo-mechanical processing, the RAP (recrystallisation and partial melting) route, reported by Omar et al. (2004) to be based on warm or cold working (below the recrystallisation temperature), was employed in the present work. Extruded bars of EN AW-2014 alloy were isothermally held in the semi-solid temperature range and subsequently pressed into the die.

2. Experimental procedures

The 154 mm diameter EN AW-2014 alloy billet (Table 1) was produced industrially with a vertical air-slip DC casting unit. It was subsequently heated to 460 °C, extruded into a 40 mm diameter bar (extrusion ratio of approximately 15) and supplied in T4 temper.

Differential scanning calorimetry (DSC) was employed to determine the solidus and liquidus temperatures and thus the solidification interval of the present alloy. 3 mm diameter disc samples, weighing about 30 mg were cut and placed into alumina pans in an argon atmosphere using a SETARAM Labysys Differential Scanning Calorimeter unit. The samples were heated at a rate of 2.5 °C min^{-1} between 450 °C and 700 °C. The heat flow vs. temperature curves obtained by differential scanning calorimetry were used to calculate the change in liquid–solid fractions with temperature. Temperatures for reheating experiments were then estimated from the latter.

Reheating experiments (Fig. 1) were performed in order to identify the optimum heat treatment parameters to achieve thixotropic microstructural features. 40 mm long slugs were sectioned from the as received bar and were reduced to a diameter of 25 mm. A medium frequency induction coil (9.6 kHz, 50 kW) was used to heat these slugs into the semi-solid temperature range. Temperature of the slug was monitored with a K-type thermocouple inserted in a 3 mm diameter hole drilled at the center of the slugs. Measures were taken to achieve rapid heating to the semi-solid range to ensure small recrystallized grains. The average heating rate was approximately 150 °C min^{-1}. Slugs were then soaked in this temperature range for up to 10 min to allow globularization of the grains and then quenched in water.

The thixoforming experiments were carried out with the laboratory press shown in Fig. 2. A pneumatic cylinder was used to provide the forging load (5 ton-f max) and the maximum speed of the ram was 1 m s^{-1}. ⌀25mm × 40 mm slugs machined from the as-received extruded EN AW-2014 bar were heated in situ on the forging press with an induction coil placed right underneath the die manufactured from X33CrMoV32 hot work tool steel. The slugs were rapidly heated to the thixoforming temperature, soaked at this temperature for at least 5 min and then pressed into the die. The heating of the slug was monitored by using two K-type thermocouples, located at a depth of 10 mm from the top of the slug at the center. The quenched samples and the thixoformed parts were sectioned, prepared with standard metallographic practices and were finally etched with Kellers solution before they were examined with an optical microscope.

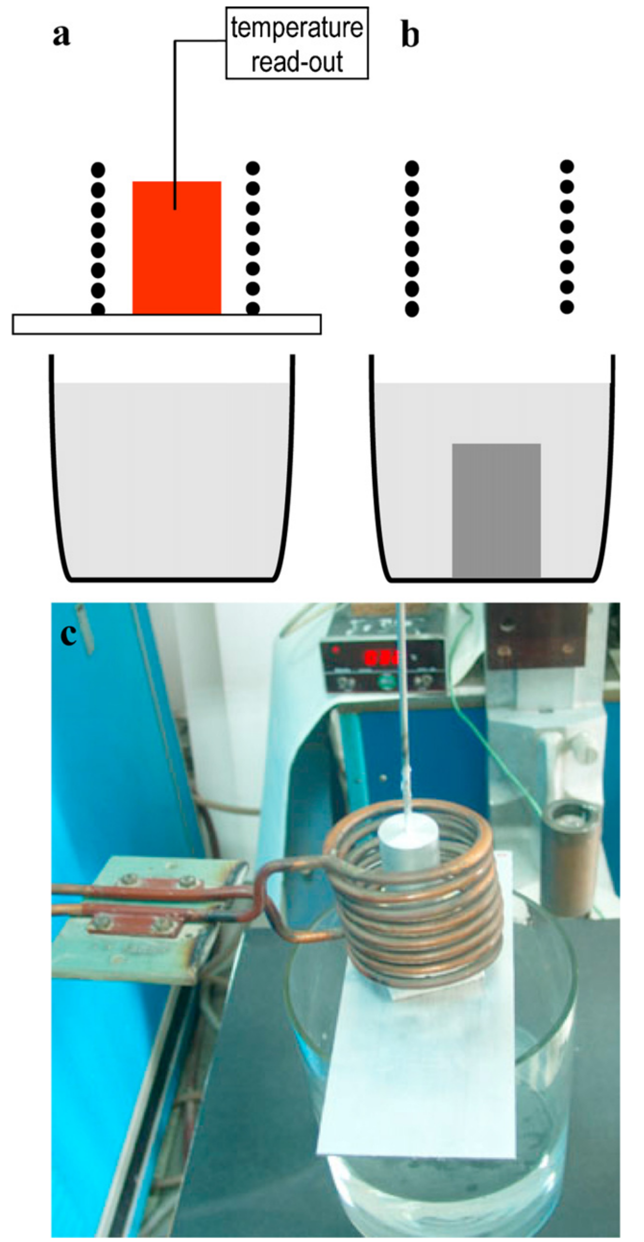

Fig. 1. Sketch of the set up used to perform reheating experiments: (a) heating, (b) water-quenching, and (c) photo of the set-up.

3. Results and discussion

The microstructure of the as-received EN AW-2014 alloy stock is typical of hot extruded aluminium alloys with elongated α-Al grains and intermetallic particles aligned in the extrusion direction (Fig. 3). These features confirm that the deformation introduced during the extrusion process is largely retained with no evidence of recrystallization across the section. Two main constituents were identified in addition to the solid solution aluminium matrix. The quantitative EDS analysis of the light gray particles have revealed only Al and Cu peaks while those of dark gray particles have generated additionally Fe, Mn and Si signals. The EDS results were further