Materials Science & Engineering A 659 (2016) 143–157

Contents lists available at ScienceDirect

Materials Science & Engineering A

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

High-temperature deformation resistance and forming behavior of two-step SIMA-processed 6066 alloy

Chia-Wei Lin, Fei-Yi Hung*, Truan-Sheng Lui, Li-Hui Chen

Department of Materials Science and Engineering, National Cheng Kung University, Tainan 701, Taiwan

ARTICLE INFO

Article history:
Received 15 September 2015
Received in revised form
6 January 2016
Accepted 14 February 2016
Available online 15 February 2016

Keywords:
Aluminum alloys
Semisolid processing
SIMA process
High-temperature formability

ABSTRACT

The aims of this study were to investigate the effects of a modified two-step strain-induced melt activation (SIMA) process on the high temperature formability of 6066 Al alloy, and to understand the compressive and tensile properties of the alloy such processed. For these purposes, the forming test which compressed a cylindrical rod into a screw nut was conducted at 550 °C, while the compressive and tensile tests were conducted at 550 °C and the vicinity. The high-temperature tensile data show that phases on globule boundaries can cause the SIMA-processed alloy to break by integranular fracture, and thus the tensile ductility cannot compete with the alloy in hot-extruded condition to have dynamic recrystallization during tensile deformation. The high-temperature compression test shows that the flow resistance can be decreased by the SIMA process to the level lower than that of the fully annealed alloy. In terms of compressive microstructure, the SIMA-processed alloy is composed of three zones: (1) large deformation zone with flattened structure in specimen center, (2) free deformation zone with globular grain structure near the top and bottom edges, and (3) a transition zone between the above two zones. Finally, the forming test shows that SIMA process can decrease flow resistance by about 25–30%. When a SIMA-processed alloy has sufficient liquid fraction and appropriate globule size, its ability of metal flowing can be significantly increased to have superior high-temperature formability.

1. Introduction

Semi-solid metal processing is a net shape process that combines the advantages of traditional forging and casting. In the process, the alloy is heated to certain temperature in the mushy zone where the solid and liquid phases coexist [1,2]. Strain-induced melt activation (SIMA) process is a common thixotropic semi-solid process which can produce high-spheroidization-degree globules and has many advantages such as simple equipment requirement, stable manufacturing process and low production cost [3–5]. Traditional SIMA process includes the following three steps after casting: hot work, cold work, and heating materials to a mushy zone temperature. Hot work and cold work are to disintegrate the initial dendritic casting structure and to introduce sufficient stored strain energy. Globular grains form through recrystallization, partial melting, penetration of the liquid, and grain growth in the final heating step [2,6–9].

In order to obtain more uniform grain structure, a modified two-step SIMA process is adopted in this research. The modified process, which is depicted schematically in Fig. 1a, differs from traditional SIMA process in (1) employing severe hot extrusion (instead of hot work followed by cold work), and (2) utilizing a salt bath (instead of an air furnace) to increase heating uniformity and heating rate to target temperature for inhibiting excessive grain coarsening and dissolution of second phases.

The microstructure evolution of a cast alloy processed by the modified two-step SIMA process is shown in Fig. 1b, where the black dots in the dendritic structure indicate low-melting-point second phases. In the first step of this modified process, the cast alloy is subjected to severe hot extrusion to develop fine dynamically recrystallized grains. In the second step in which the hot-extruded alloy is heated at a mushy zone temperature in salt bath, low-melting-point phases and part of the eutectic structure start to partially melt and penetrate into certain grain boundaries surrounding fine recrystallized grains [10]. Meanwhile, grain growth occurs and the restriction between neighboring grains disappears to generate spheroidized grains of the lowest surface energy [2,6].

6066 Al alloy, the test material in the present study, is a Si-excess Al–Mg–Si alloy. In general, Si-excess alloys are more brittle and have higher strength compared to Mg-excess. Besides Si and Mg, 6066 Al alloy also contains Cu and Mn. Cu is added to refine precipitates and enhance strength, while adding Mn can inhibit grain growth, increase strength and raise recrystallization temperature [11–14]. 6066 Al alloy thus has higher strength but lower

* Corresponding author.
E-mail address: fyhung@mail.ncku.edu.tw (F.-Y. Hung).

http://dx.doi.org/10.1016/j.msea.2016.02.041
0921-5093/

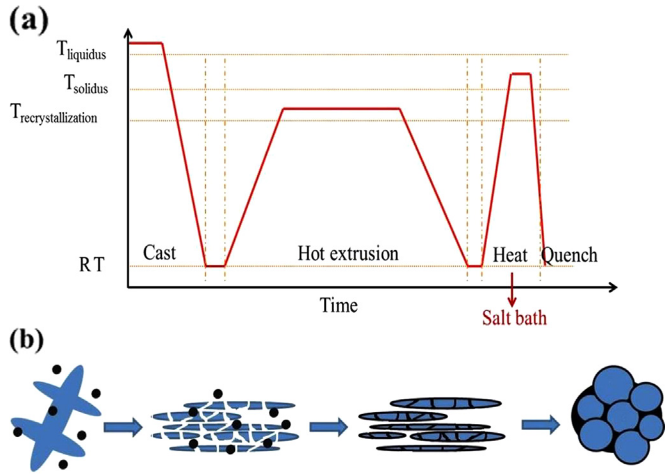

Fig. 1. (a) Process flow of the modified two-step SIMA process; (b) mechanism of grain spheroidization in this process (RT: room temperature).

Table 1
Composition of 6066 Al alloy analyzed using a glow discharge spectrometer.

Element	Mg	Si	Cu	Mn	Fe	Cr	Al
wt%	1.02	1.29	0.98	1.02	0.19	0.18	Bal.

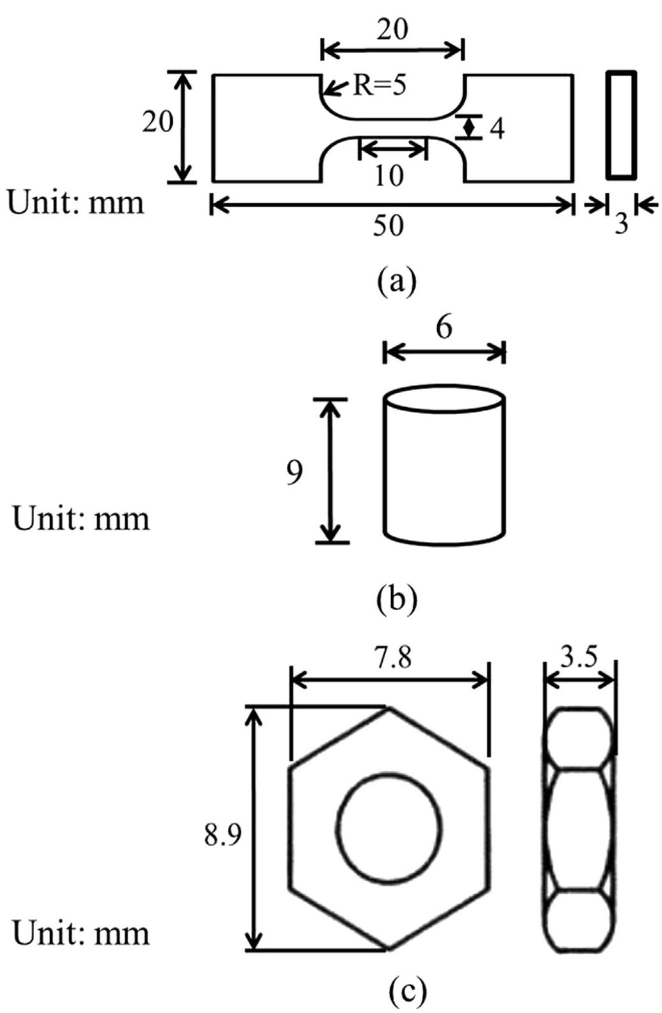

Fig. 2. Dimensions of (a) tensile specimen, (b) compressive and forming specimen, and (c) screw nut for forming test at high temperature.

formability than other 6xxx series alloys. Owing to this reason, it was chosen in this study to explore the effects of the modified two-step SIMA process on its high-temperature formability.

Metal forming of SIMA-processed alloys needs to apply at high temperature [2,3]. In the present study, the forming test was performed at 550 °C to investigate the relationship between ability of metal flowing and the microstructure of the SIMA-processed 6066 Al alloy. Since high-temperature tensile and compression properties can be used to evaluate high-temperature formability but related topics of SIMA-processed alloys are seldom discussed in the literature, a tensile test and a compression test at the temperature range of 500–600 °C were also performed for further exploration in this study.

2. Materials and experimental methods

2.1. Materials preparation and description

The composition of the 6066 Al test alloy is shown in Table 1. The alloy was originally a casting column of 6-inch (15.24 cm) diameter. It was hot extruded in the first step of the two-step SIMA process to a 9-mm-thick sheet with 27:1 extrusion ratio of the area and 3.3 true strain. Hereafter, “F” will be adopted to abbreviate the hot-extruded sheet material. In the second step of the two-step SIMA process, F was held at 620 °C in salt bath. To vary the size of globular grains, four different durations, namely 1, 4, 10 and 30 min, were set in this heat treatment. The specimens of these four different durations will be denoted in the following as S1, S4, S10, and S30, respectively.

In order to examine the microstructure evolution and microstructure characteristic, the following analyses were used: (1) metallography analysis, in which the specimens were polished using SiC papers from #80 to #5000 (80–5000 grits per square inch), Al_2O_3 aqueous suspension (1.0 and 0.3 μm), and SiO_2 polishing suspension (0.04 μm) and etched by Keller's reagent for optical microscopy (OM) observation, (2) phase distribution analysis, in which the polished specimens were analyzed using scanning electron microscope (SEM) and an electron probe X-ray micro-analyzer (EPMA), and (3) micro-hardness analysis, in which nano-indentation test was performed to evaluate the micro distribution of hardness, using a triangular diamond probe with 0.25 nm/s drift velocity and 800-nm depth. The space between adjacent measurement points was 5 μm.

Aluminum alloys are often in fully annealed status for subsequent manufacturing. Therefore, the test alloy in this study was also fully annealed for comparison with SIMA-processed specimens. In the full annealing treatment, F was heated to 420 °C for 2 h, cooled to 220 °C at a cooling rate of 25 °C/min, and then cooled in furnace to room temperature. The fully annealed 6066 alloy will be designated as “O”.

2.2. Mechanical test and forming test

A universal material tester was used for the tensile test, compression test and forming test.

The tensile test was conducted at 500 °C, 550 °C, 600 °C, and room temperature as well, with the initial strain rate set at $1.66 \times 10^{-3}\,s^{-1}$. Room temperature test was to obtain basic reference data. 550 °C was chosen because partial melting and generation of spheroidized grains will occur at this temperature and higher. The other two temperatures were chosen to be higher and lower than 550 °C. Each condition was used for at least three runs. The tensile specimens were in plate form with the dimension shown in Fig. 2a. Each specimen had a 2-mm-diameter circular aperture on each clamping end for pin insertion to prevent