Journal of Alloys and Compounds 487 (2009) 218–224

Contents lists available at ScienceDirect

Journal of Alloys and Compounds

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

Microstructure and mechanical properties of Al–Si–X alloys fabricated by gas atomization and extrusion process

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ARTICLE INFO

Article history:
Received 10 November 2008
Received in revised form 7 July 2009
Accepted 17 July 2009
Available online 25 July 2009

Keywords:
Metals and alloys
Gas atomized powder metallurgy
Crystal structure
Transition element

ABSTRACT

In order to develop good wear resistant and high-strength alloys, $Al_{81}Si_{19}$ alloy was reinforced with transition elements such as Ni and Ce. The solubility of Si in aluminum was amplified, with increasing the Ni and Ce content in the rapidly solidified powders. The extruded bars consist of homogeneously dispersed fine Si particles along with Al_3Ni and Al_3Ce compounds (30–120 nm) in aluminum matrix (grain size below 500 nm). The tensile strength at room temperature for $Al_{81}Si_{19}$, $Al_{78}Si_{19}Ni_2Ce_{0.5}$ and $Al_{76}Si_{19}Ni_4Ce_1$ bars extruded at 400 °C was estimated as 281, 521, and 668 MPa, respectively. In addition, the maximum tensile strength of 730 MPa was attained in $Al_{73}Si_{19}Ni_7Ce_1$ bulk alloy. The uniform dispersion of precipitates (Si, Al_3Ni and Al_3Ce particles) from the supersaturated Al matrix of ternary and quaternary alloys after extrusion was effective for enhanced mechanical properties.

1. Introduction

Al–Si alloys are well known as typical high-strength and lightweight cast materials, which are widely used in automotive and aerospace industries due to their higher strength, good wear resistance and low thermal expansion co-efficient [1]. Currently Al–Si alloys are manufactured by casting and powder metallurgy methods. But, the relatively slower cooling rate, associated with the conventional casting process, produces coarse and segregated primary Si and/or eutectic Si in the Al–Si alloys [2]. Moreover, the wear resistance and mechanical strength of the alloy can be further improved by means of increasing the quantity of Si in the alloy. However, with increasing the Si content, above the eutectic composition (12.6 wt.% Si), primary Si crystals coarsen, which on the other hand results in reduced mechanical properties of the Al–Si alloys. Yet, the distribution and size of the primary silicon particles is more important than the overall silicon content of the alloy. Therefore, many efforts have been made in the microstructural modification of casting Al–Si alloys in order to achieve fine Si particles with the desired shapes and distributions. For example, techniques such as modification [3,4], ternary alloying [5], spray-deposition [6], or rapid solidification processing [7] have been applied to refine the primary Si crystals as well as to achieve their homogeneous distribution in hyper-eutectic Al–Si alloys.

Of all the processes mentioned above, rapid solidification of metallic melts has been known to produce altered constitutional effects such as formation of supersaturated solid solutions, metastable intermetallic phases and even amorphous alloys [8–13]. Besides, the microstructural features (grain size and second phase/intermetallic inclusions) are also refined and the segregation effects are significantly reduced. A number of studies have been reported regarding fabrication of Al–Si alloys employing rapid solidification and hot-extrusion processes [14–16]. The increase in strength and wear resistance was achieved, as a consequence of rapid solidification and/or incorporation of ternary alloying transition elements. For example, it has been reported that nanocrystalline aluminum alloys (Al–Ni–Ln) with a high-strength of above 850 MPa were produced by rapid solidification process through addition of glass-forming Ni and Ln metals [17–20]. It is expected that alloys containing transition metals (TM: Fe, Ni, Cr) can precipitate fine intermetallic compounds from rapidly solidified powder leading to a high-strength as well as increased wear resistance at elevated temperatures.

Hence, in this research Al–Si alloy with the addition of transition elements Ni and Ce was manufactured. Furthermore, the rapid solidification process was used to increase the solubility of Si in Al matrix. The aim of this paper is to present the development of high-strength and good wear resistant aluminum alloy ($Al_{81}Si_{19}$) with the incorporation of glass-forming elements, Ni and Ce.

2. Experimental procedures

The powder produced by high-pressure helium-gas atomization at a dynamic pressure of 9.8 MPa contained homogeneous spherical shape particles with size below 25 μm. It was first cold-pressed into a copper can with a can length of 10 cm, an inner diameter of 20 mm and an outer diameter of 25.3 mm up to the packing density of about 75%, and then degassed at 400 °C for 20 min without any gas. The

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doi:10.1016/j.jallcom.2009.07.108

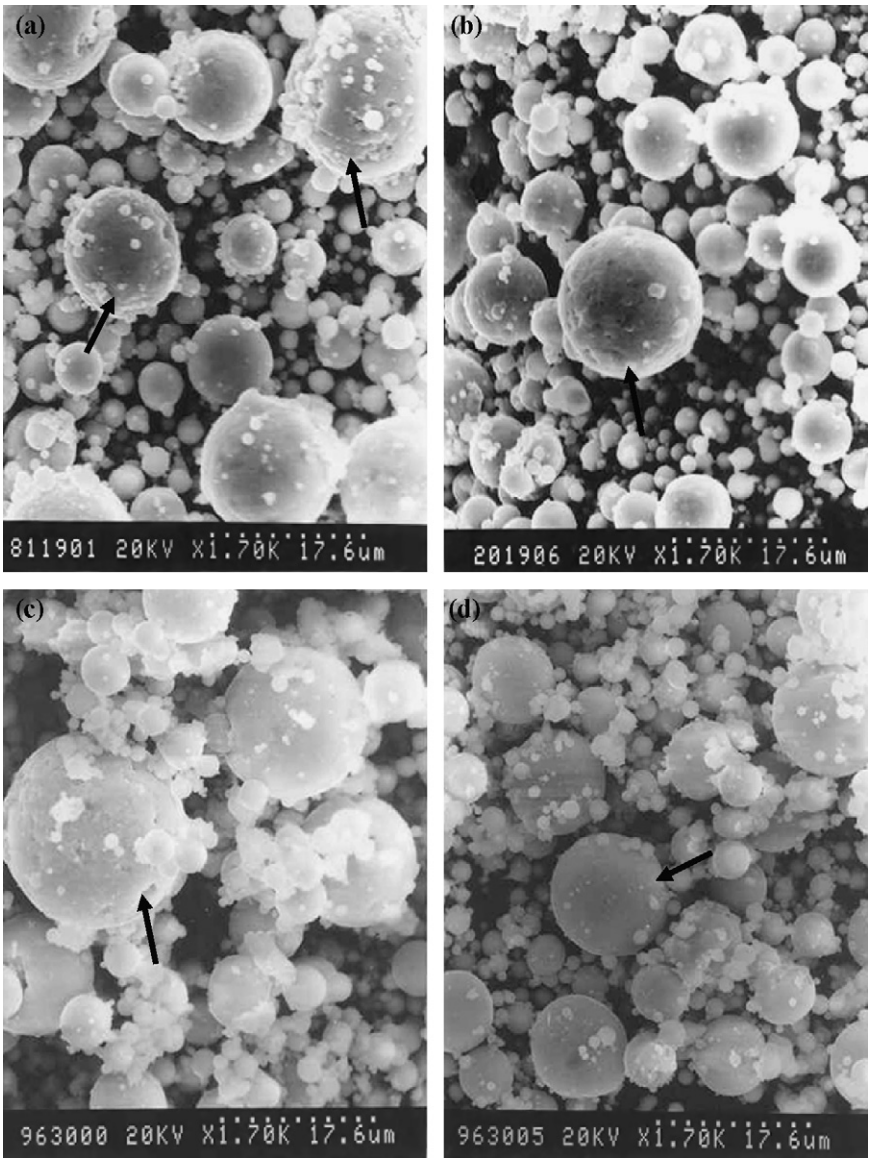

Fig. 1. SEM micrographs of Al–Si and Al–Si–Ni–Ce alloy powders (~25 μm) fabricated by He-gas atomization: (a) $Al_{81}Si_{19}$, (b) $Al_{78.5}Si_{19}Ni_2Ce_{0.5}$, (c) $Al_{76}Si_{19}Ni_4Ce_1$, and (d) $Al_{73}Si_{19}Ni_7Ce_1$.

extrusion was performed at a ram-speed of 2.5 mm/s at 400 °C temperature and the extrusion ratio was 10:1. The size of extruded bar was 100 cm in length and 0.8 cm in diameter.

The size distribution of produced powder was measured with laser light scattering method. The shape of atomized powder was investigated using scanning electron microscopy (SEM). Microstructural analyses of both the solidified powder and the extruded bar were conducted using a SEM and a transmission electron microscope (TEM) equipped with energy dispersive X-ray spectrometers (EDS). Specimens for SEM were prepared by conventional grinding and polishing methods and etched in Keller's reagent. The crystal structures of the phases in the atomized powder and extruded bars were investigated by conventional X-ray diffraction (XRD) method using monochromatic Cu Kα radiation (λ = 0.1542 nm) at 30 kV and 40 mA. Tension specimen with a gauge length of 20 mm and a diameter of 2.5 mm were cut parallel to the extrusion direction. The tensile test of the extruded bars was conducted using an Instron testing machine at a strain rate of 5.0×10^{-4} s^{-1} at room temperature. Vickers hardness measurements were performed with a Shimadzu HMV-2 Vickers hardness tester using a Vickers indenter with a load of 19.6 N applied for 15 s.

3. Results and discussion

3.1. Powder shape and microstructure

The mean size of the powder produced by high-pressure helium-gas atomization was below 10 μm and 90% of the small size particles were below 25 μm. Due to high solidification rate the size of this powder was considerably smaller than that of nitrogen gas atomized powders with an average particle size of 80–100 μm [7]. Fig. 1 shows the SEM morphology of the helium-gas atomized $Al_{81}Si_{19}$, $Al_{78.5}Si_{19}Ni_2Ce_{0.5}$, $Al_{76}Si_{19}Ni_4Ce_1$, and $Al_{73}Si_{19}Ni_7Ce_1$ powders, respectively. It can be seen that most of the solidified powder contains a smooth surface in spherical shape. It should be noted that with the increase of Ni and Ce addition to $Al_{81}Si_{19}$ alloy, the surface of coarse powders remains clean as indicated by arrows. It can be mentioned that, the solid solubility of Si is directly proportional to the content of Ni and Ce, i.e. a higher amount of Ni and Ce affects the increase in solubility of Si. Thus, it prevents the precipitation of primary Si and intermetallic compounds and contributes to the clean surface. In the gas atomization [21] process the smaller particle becomes solid due to faster cooling, whereas larger particle remains either at semi-solid or liquid state owing to the slower cooling rate. Therefore, the fully solidified fine powders are guessed to make bondage with large ones during their flight and consequently powder particles are expected to have many satellites as exhibited in Fig. 1.