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Microstructure and mechanical properties of spray co-deposited Al–8.9 wt.% Si–3.2 wt.% Cu–0.9 wt.% Fe + (Al–3 wt.% Mn–4 wt.% Si)$_p$ composite

L.A. Bereta, C.F. Ferrarini, W.J. Botta F, C.S. Kiminami, C. Bolfarini *

Federal University of São Carlos, Materials Engineering Department, Rod W. Luiz, km 235, PO Box 676, Post Code 13.565-905, São Carlos, Brazil

Abstract

The microstructure and the tensile properties of an spray co-deposited Al–8.9 wt.% Si–3.2 wt.% Cu–0.9 wt.% Fe + (Al–3 wt.% Mn–4 wt.% Si)$_p$ composite was investigated after extrusion and heat treatment. The composition of the AlMnSi$_p$ alloy was selected aiming to improve the formation of α-Al(Fe,Mn)Si instead of β-Al(Fe,Mn)Si intermetallic. The spray formed deposits were extruded at 623 K and heat treated to peak aged (T6) condition. Room temperature tensile tests of the spray formed and extruded/heat treated alloy showed significant increase of elongation to fracture when compared with the values observed for the as-spray formed deposits, >10% and <4%, respectively. This result can be ascribed to the porosity elimination promoted by the extrusion process and to the lower aspect ratio of the silicon and intermetallic particles. Moreover, the spray formed and extruded, T6 heat-treated samples showed significant increase of the ultimate strength without significant loss of the elongation values.

Keywords: Intermetallics; Metals; Powder metallurgy; Casting

1. Introduction

The hypoeutectic Al–Si alloys such as the 380 (Al–7.5–9.5 wt.% Si–2–4 wt.% Cu–∼1 wt.% Fe) series play an important role in the recycling chain of the aluminium alloys and represent the most widely used system for the production of aluminium-based cast parts such as engine blocks/heads and gearboxes [1]. The 380 alloys can be heat treated by ageing if the magnesium content is above 2%, in order to allow the formation of Mg_2Si precipitates, which have a hardening effect. However, their use as structural materials has been limited due to lack of ductility [2] caused by a microstructure composed of plate-like silicon particles and coarse, needle-like intermetallics, embedded in an Al matrix, and therefore there is no meaning in heat treat the 380 alloys in normal casting operation.

The spray forming process refers to the energetic disintegration of molten metal into micron-size droplets by high velocity gas jets. The subsequent deposition of these droplets, which are a mixture of solid, liquid and partially solidified particles, onto a substrate forms a dense deposit. Spray forming presents features of rapid solidification techniques and thus produces fine-grained microstructures, increased solid solubility, non-equilibrium phases and refined intermetallics [3]. These features allow the mechanical processing of hypoeutectic Al–Si alloys, which then are suitable to be used as structural materials. Prior researches aiming to determine the mechanical properties of spray formed Al–Si 380 alloy showed almost 150% increase in elongation when comparing with the values obtained by sand cast processing [4]. However, the absolute value attained (3.74%) was not enough for structural applications yet. This limitation was ascribed to the high porosity levels (4–7%) of the spray formed deposits, which is highly harmful to the mechanical properties [5]. The stress concentration due to the presence of pores is responsible to premature fracture when the material is loaded, impairing both ultimate tensile strength and ductility [6]. Therefore, the application of spray formed Al–Si 380 alloy as structural parts requires further processing such as extrusion to fully densification of the billet [7–9]. During extrusion the most important parameters are the temperature of billet and ram speed [10], whose careful control leads to a material with improved mechanical properties. Co-deposition of particles containing well selected pre-nuclei [11–13] changes the morphology and chemistry of harmful intermetallics, and therefore is another way to improve the mechanical properties.

In the present work we investigated the effect of co-deposition of particles containing AlMnSi-phases on the microstructure and mechanical properties of a widely used, hypoeutectic Al–Si alloy

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* Corresponding author. Fax: +55 16 33611160.
E-mail address: cbolfa@power.ufscar.br (C. Bolfarini).

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with a composition similar to the Al–Si 380 alloy. The spray formed deposits were extruded and heat treated. Moreover, the effect of Mg addition (only 0.3 wt.%) was also evaluated on the response to the heat treatment and on the mechanical properties.

2. Experimental procedure

The composition of the material used in this work, as determined by atomic absorption spectroscopy-AAS, was Al–8.9 wt.% Si–3.2 wt.% Cu–0.9 wt.% Fe–0.2 wt.% Mn–0.04 wt.% Mg and it will be hereinafter referred to as alloy 380. In some heats 0.3 wt.% Mg was added and this modified alloy will be referred to as 380 + Mg. SEM back-scattered electron images (BEI) coupled with EDS were used to distinguish the presence of different phases in the microstructure, which were later more precisely identified with the aid of X-ray diffractometry (XRD). The alloy 380 was co-deposited with particles containing the phase Al–3 wt.% Mn–4 wt.% Si. All the alloys were atomized with nitrogen and deposited onto a copper substrate, positioned 400 mm below the atomization nozzle. Details of the equipment used were described elsewhere [14]. Atomization pressure and temperature were set at 0.6 MPa and about 985 K, respectively. In order to reduce oxidation of the atomized droplets the atomization chamber was filled with inert gas. The deposits were extruded at 623 K and the ram speed was set at 14 mm/min. The reduction ratio was 5:1 in area. The microstructure of the specimens extracted from the extruded rod were analyzed by optical-OM and scanning electron microscopy-SEM. After extrusion, the specimens were heat treated to a T6 condition in two steps: solubilization at 783 K for 8 h followed by water quenching and then ageing at 433 K for 4 or 8 h. The tensile properties of all alloys were determined according to ASTM E8 METRIC standard using an Instron 5500R test machine. Secondary electron images (SEI) were used for fracture surface analysis. For comparison purposes the 380 alloy was tested without heat treatment as well. All mechanical tests were performed at room temperature and for checking reproducibility seven samples were used for each condition. The porosity levels of the alloys were calculated using density values obtained by the Archimedes method.

3. Results and discussion

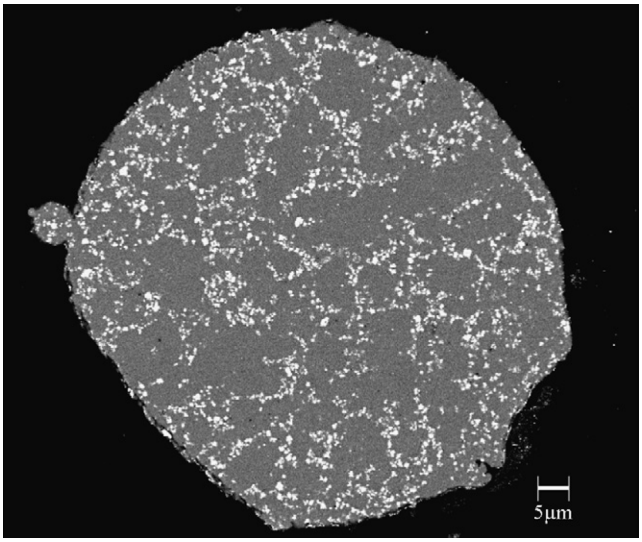

Fig. 1. BEI-SEM microstructure of the powder used for co-deposition.

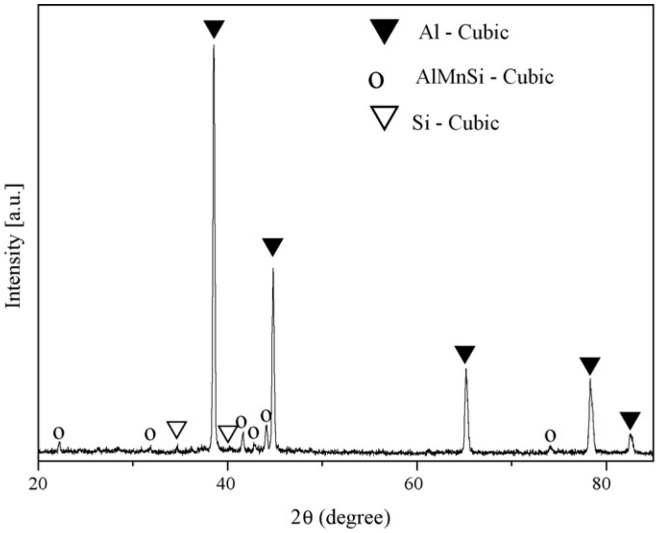

Fig. 2. XRD pattern of the powder used for co-deposition.

Fig. 1 shows the microstructure of the powder particles that were used for co-deposition. It was observed the formation of a homogeneously distributed, round, α-AlMnSi phase embebed in an Al-matrix. XRD diffraction pattern of the powder, Fig. 2, confirms the presence of α-AlMnSi cubic phase, the Al and Si phases. The α-AlMnSi was predicted as a primary phase by the equilibrium diagram, as shown in Fig. 3. It must be pointed out that the phases present in XDR analyses are those predicted in the equilibrium phase's diagram in spite of the rapid solidification that the particles suffered in the atomization chamber (cooling rates estimated to be in the range 10^3 to 10^4 K/s).

The microstructure of the spray formed materials showed significant differences to conventionally cast counterparts. Moreover, the extrusion process reduced considerable the porosity volume levels of the deposits from approximately 4% [4] to ~0.5%. This secondary process increased significantly the elongation to fracture-E_f from almost 4%, as cited in Ref. [4], to 8% (Table 1). In Fig. 4 is possible to recognize an equiaxial, refined α-Al matrix and near-uniform distributed silicon particles having an estimated maximal length of 15 μm. The observed grain structure was homogeneous through the deposit, indicating that a good compromise between heat extraction and deposition

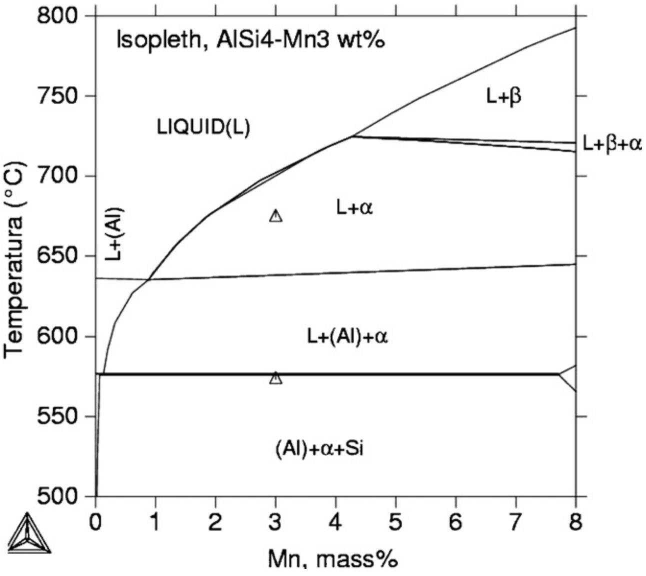

Fig. 3. AlMnSi isopleths calculated at 4 wt.% Si (Cost2000 free database).

Table 1
Mechanical properties and porosity of the spray formed 380 extruded alloys in different conditions

Alloy/condition[a]	UTS (MPa)	YS (MPa)	El (%)	Porosity (%)
380	228.1 ± 9.0	153.0 ± 15.0	8.0 ± 2.1	0.4 ± 0.1
380 as heat-treated 8/8	313.3 ± 23.1	232.6 ± 29.3	9.7 ± 2.5	0.4 ± 0.1
380 + Mg as heat-treated 8/4	341.8 ± 10.5	252.5 ± 6.6	11.0 ± 2.1	0.6 ± 0.1
380 + Al–3 wt.% Mn–4 wt.% Si	234.0 ± 7.0	134.1 ± 6.9	11.2 ± 2.2	0.6 ± 0.1
380 + Al–3 wt.% Mn–4 wt.%Si + Mg as heat-treated 8/4	345 ± 17.1	275.7 ± 10.3	11.0 ± 2.7	0.6 ± 0.1
380 + Al–3 wt.% Mn–4 wt.% Si + Mg as heat-treated 8/8	399 ± 6.0	349 ± 6.6	9.2 ± 1.4	0.6 ± 0.1

[a] 8/8: solubilization 8 h, aging 8 h; 8/4: solubilization 8 h, aging 4 h.

rate was attained during deposit build-up. In addition, the co-deposition process promoted the α-Al(Fe,Mn)Si growth (bright rounded phases in Fig. 4), and simultaneously showed a tendency to decrease the average length of β-AlFeSi (from 5.3 ± 0.8 to 3.9 ± 1.0 μm). These statistical results are for a 90% level of confidence in Student's *t* distribution test. The microstructural changes increased E_f values from 8.0% for the 380 alloy to 11.2% for the co-deposited 380 + Al–3 wt.% Mn–4 wt.% Si alloy (Table 1), a gain of 40%.

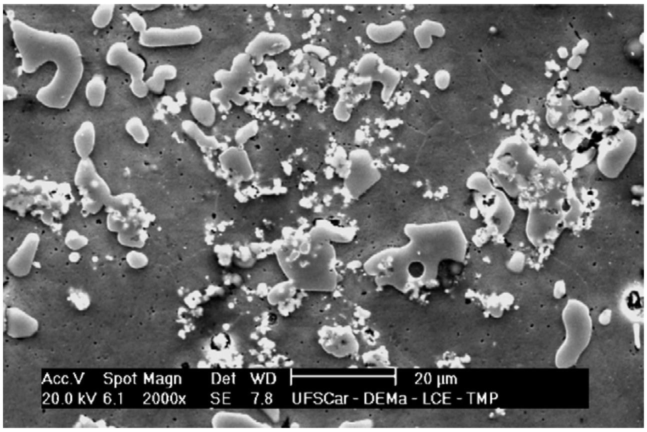

Fig. 5. SEM image of the co-deposited spray formed transverse section (SEI) after heat-treatment.

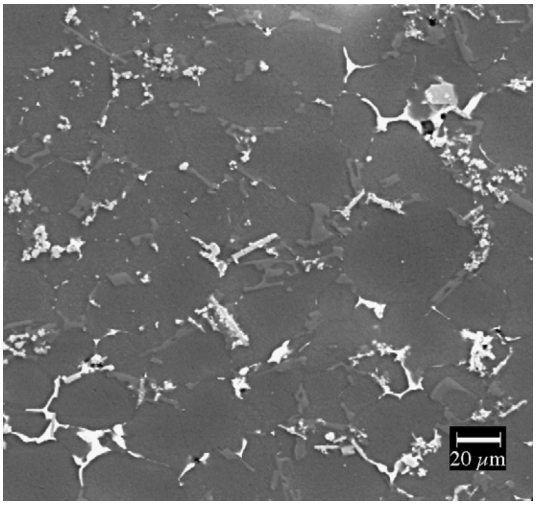

Fig. 4. SEM image of the co-deposited spray formed transverse section (BEI) before heat-treatment.

Heat-treated materials showed higher values for yield-YS and ultimate tensile-UTS strengths as compared with the just extruded material. This behavior was accomplished without significant decrease in E_f as well. The gain in YS and UTS were expected with the heat treatment, however, this should lead to a decrease in the E_f as is well known for precipitation hardening alloys. In order to exply this result it is necessary to consider the influence of the second phases, such as the silicon particles and the intermetallics on the mechanical properties. Generally, the tensile properties of hypoeutectic Al–Si alloys are strongly dependent on porosity levels, heat treatment and the nature, size and morphology of the second phases [15–17]. The porosity levels are very similar, but, there is a significant difference in the aspect ratio of the silicon particles after heat treatment (Figs. 4 and 5). Therefore, it is suggested that the more rounded silicon particles (smaller aspect ratio) in the heat treated condition promote an increase in elongation that compensates the possible decrease caused by the T6 temper. This is accompanied by an increase in the UTS due to the lower levels of stress concentration on the tip of the silicon particles and the minor β-AlFeSi needle-like phase, which delay the fracture process. Examination of the fracture surfaces of the tensile samples of all the alloys reveals fine dimples, a characteristic of ductile fracture, as shown in Fig. 6. It appears that the aluminium matrix flows extensively around the rounded Si-particles retarding the fracture process. The addition of Mg improved further the response to the aging and increased the mechanical properties to very high levels, attaining almost 400 MPa and still maintaining a high value for the E_f. Further TEM studies are necessary to understand this behavior, but it can be suggested that Mg, in addition to the formation of Mg_2Si promotes the formation of

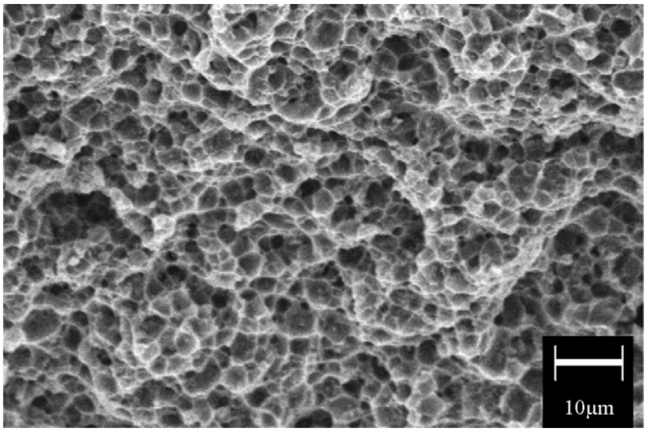

Fig. 6. SEM micrograph showing fine dimples in fracture surface and extensive deformation around Si-particles.

semi-coherent and incoherent Al_2CuMg precipitates, as is the case for other high-strength aluminium alloys [18], which contributes to homogenize the slip process and this way leading to an increase in both the elongation to fracture and the ultimate tensile strength.

4. Conclusions

Room temperature tensile tests of the spray formed and extruded/heat treated 380 alloy showed significant increase of elongation to fracture when compared with the values observed for the as-spray formed deposits, >10% and <4%, respectively. This result can be ascribed to the porosity elimination promoted by the extrusion process and to the lower aspect ratio of the silicon and intermetallic particles. Moreover, the co-deposition of AlMnSi-containing particles and the addition of Mg resulted in significant increase of the ultimate tensile strength without significant lowering the elongation values.

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