Effect of the addition of Mn on the tensile properties of a spray-formed and extruded Al-9Si-4Cu-1Fe alloy

G D Benetti, A M Jorge Jr, C S Kiminami , W J Botta and C Bolfarini 1.
Rod. Washington Luis-km 235-DEMa/UFSCar-CEP 13565905- São Carlos-SP/Brazil
Email1: cbolef@ufscar.br

Abstract. The microstructure and the tensile properties of a spray-formed and extruded Al-9Si-4Cu-1Fe alloy were investigated. Manganese (0.3, 1, 2 in wt%) was added to the alloy to avoid the formation of the needle-like β-AlFeSi intermetallic phases that are highly detrimental to the alloy’s ductility. The deposits were extruded at 623K with a area reduction of 5 to 1. Small faceted dispersoids surrounding the equiaxial α-Al matrix, mainly in the form of silicon particles, were identified by SEM-EDS, as well as the Mn-containing α-Al15(Fe,Mn)3Si2 phase. The presence of the needle-like β-Al(Fe,Mn)Si was scanty, even with the lowest Mn content. The room temperature tensile tests of all the extruded alloys showed a significant increase in elongation to fracture when compared with the values observed for the as-spray formed deposits. This result can be ascribed to the elimination of porosity promoted by the extrusion process and to the smaller grain size of the extruded samples.

1. Introduction
The hypoeutectic Al-Si alloy, A380, is widely employed to produce parts by high pressure die casting (HPDC). It is used extensively in automotive parts such as engine heads, blocks and gear cases. Therefore, their availability for recycling is huge and the standard compositions tolerate higher impurity contents. The main drawback of this alloy is its poor ductility caused by the presence of intermetallics in the microstructure. Due to its low solubility in the α-Al matrix, iron is the main impurity/alloying element promoting the formation of intermetallics with aluminum and silicon. Earlier investigations have demonstrated the detrimental effect of iron-containing intermetallics, which significantly reduce the ductility, as well as the impact energy and fracture toughness [1,2].

The volumetric fraction, morphology and size of enriched iron phases in aluminum cast alloys depend on the alloy’s composition and solidification conditions. These phases may appear as Chinese script, polyhedral, needles (platelets), or angular globules. The size of these phases generally diminishes as faster cooling rates are used [3]. Among the Fe-containing intermetallics, the β-AlFeSi phase is the most undesirable due to its needle-like morphology, which acts as a stress concentrator strongly reducing the ductility of Al-Si alloys.

The use of very high cooling rates to produce finely distributed iron phases, or the addition of trace elements to alter the morphology of the β-nuclei, can counteract the negative effect of iron [1]. Therefore, rapid or near rapid solidification processes are possible routes to influence the formation of intermetallic phases, increasing the solubility of the iron in the aluminum matrix and providing metastable conditions for the formation of less deleterious phases. Among these processes, spray forming is a technique that can be used to produce materials with some characteristics of rapid solidification such as supersaturated solid solutions, homogeneous microstructure containing fine grains and no macrosegregation. Alloying is another possibility to avoid the formation of needle-like intermetallics. When an adequate quantity of manganese is added to the Al-Si alloys, this element combined with the iron forms the intermetallic α-Al15(Fe,Mn)3Si2, removing iron from solution in the Al-matrix and thus hindering the formation of phase β-AlFeSi. However, the deliberate addition of this element can cause thickening of the α-AlFeSi phase and loss of the mechanical properties [4]. The addition of manganese increases the field of formation of the Al15(Fe,Mn)3Si2 phase and changes the growth kinetics of iron intermetallics, allowing for the formation of the α-AlFeSi phase even at low cooling rates.

The main purpose of the present work was to investigate the effect of the addition of manganese (0.3, 1.0, 2.0wt%) on the microstructure and ductility of a widely used, hypoeutectic A380 Al-Si alloy processed by spray forming. The deposits were extruded in order to reduce the porosity .
2. Experimental procedure
The composition of the material used in this work, as determined by Atomic Absorption Spectroscopy/AAS, was Al-bal, 8.9wt%Si, 0.9wt%Fe, 3.2wt%Cu, 0.2wt%Mn, 0.04wt%Mg, 0.13wt%Ni, 0.8wt%Zn, and 0.5wt% others. This material is hereinafter referred to as alloy 380. In order to change the morphology of the intermetallics, 0.1, 0.8 and 1.8 wt% of Mn were added to the alloy in three different heats, each with approximately 3kg, which will be hereinafter referred to as alloy 1, 2 and 3, respectively. All the modified alloys were atomized with nitrogen and deposited onto a copper substrate, positioned 325mm below the atomization nozzle and rotating at 60rpm. Details of the equipment used are described elsewhere [5]. The 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. Specimens were extracted from the extruded rod for microstructural analysis by optical microscopy/OM and by scanning electron microscopy/SEM with energy-dispersive X-ray/EDS microanalysis. The tensile properties were determined according to the ASTM E8 Metric Standard using an Instron 5500R test machine. All the mechanical tests were performed at room temperature and 7 samples were used for each condition. The porosity levels were calculated using density values obtained by the Archimedes method.

3. Results and Discussion
The spray-formed deposits showed 0.3, 1.0 and 2.0wt%Mn and Fe/Mn ratios of 5.0, 1.0 and 0.5 for alloys 1, 2 and 3, respectively. The mean porosity of the deposits (4 ± 2%) was reduced to about 0.4%(± 0.2) after the extrusion process. The microstructures of the spray-formed deposits were composed of near-equiaxial grains of the α-Al phase with an average grain size of 35(± 5), 32(± 5) and 31(± 5)μm for alloys 1, 2 and 3, respectively, and uniform dispersion of the other phases: silicon and the intermetallics. Figure 1 show this microstructure for alloys 1, which are typical for alloys 2 and 3 as well. This microstructure occurs as a direct result of dendrite arm fragmentation during the build-up of the deposit. It has been assumed that during this stage of the process the solid, semisolid and fully liquid droplets impacting the surface of the deposit provide a great amount of nuclei that coarsen due to vigorous agitation and cooling conditions in this solidifying layer, resulting in equiaxial morphology. In addition to this, it is worth pointing out that silicon sometimes assumes a particulate morphology, probably also caused by the impacting droplets breaking the silicon platelets growing in the eutectic, which suffers a further change in its morphology due to the low cooling conditions after solidification, (Fig. 2), which also shows the Al12Cu intermetallic, both identified by EDS. With regard to the silicon particles and the Al12Cu intermetallics, the three alloys showed the same features, as indicated in Fig. 2. In contrast, the morphology of the AlFeSi intermetallics changed strongly from alloy 1 to 3, accompanying the changes in the Fe/Mn ratios from 5 to 0.5. At the Fe/Mn ratio of 5, alloy 1, only the scantly presence of needle-like β-AlFeSi intermetallic is observed (Fig. 3). It should be noted that at this Fe/Mn ratio, the same alloy subjected to conventional solidification techniques showed the β-AlFeSi intermetallic with an aspect ratio higher than 50 [6]. Here, the spray-forming process shows a strong effect on the refinement of these intermetallics, reducing their aspect ratio by a factor of approximately 10, and, in addition, greatly reducing the quantity of these intermetallics, as a consequence of retaining more iron in solution in the matrix.

Increasing the Mn content, which involved lowering the Fe/Mn ratios, caused the β-AlFeSi intermetallic to disappear, forming the α-AlFeSi intermetallic in its place (Fig. 4). Note that the α-AlFeSi intermetallic formed hexagonal blocks instead of the classical Chinese-script morphology typical of casting processes with low cooling rates such as sand casting. This effect was observed previously by Backerud et al. [7], who showed that increasing the cooling rate during solidification caused more silicon and iron to be retained in solution, leading to the formation of primary α-AlFeSi intermetallic(hexagonal blocks) instead of the eutectic growth, which would lead preferentially to the Chinese-script morphology. This result shows that under spray forming conditions it is not necessary to increase the Mn content to avoid the formation of β-AlFeSi intermetallic in order to improve the ductility of the A380 alloy. This is true firstly because there is only little formation of the β-AlFeSi intermetallic with a low aspect ratio, and hence, with a low potential to impair the alloy’s ductility, and secondly because the higher Mn content leads to the formation of an α-AlFeSi intermetallic with a hexagonal block morphology, which probably does not improve the alloy’s ductility.
After extrusion, the three alloys showed partial recrystallization and a strong reduction in porosity (see Figures 5-a,-b, representing alloys 1 and 3, respectively). However, there was no significant change in the size and morphology of silicon particles. Note the very fine recrystallized grains together with elongated grains, which did not attain the necessary deformation energy to recrystallize. This effect was more pronounced in alloy 3, where we can see, qualitatively, a higher fraction area of elongated grains. This effect may be attributed to the lower concentration of alloying elements in the Al-matrix of alloy 3 (due to the formation of the hexagonal α-AlFeSi intermetallics), which could increase the stacking fault energy of the matrix and hence reduce the potential for recrystallization. However, due the obvious difficulties involved in quantitative metallography, this effect was not studied in depth. Independently of this, the grains that recrystallized in both alloys remained very fine. According to Chan et al. [8], this recrystallization behavior can be attributed to the bimodal particle size distribution of the silicon and of the other intermetallics, where the coarse constituent particles (>5 μm) promote the nucleation of recrystallization and the fine dispersoids (<0.3μm) control the grain growth by pinning the grain boundaries.

Table 1 summarizes the results of the mechanical properties evaluated in the tensile tests. The mechanical properties showed a slight improvement in response to increasing Mn content. This was probably a consequence of: i) the higher percentage of the hexagonal phase α-AlFeSi in the microstructure, ii) the fine and homogeneous distribution of this phase in the microstructure, and iii) the higher fraction area of the highly deformed, elongated grains. Nevertheless, it should be noted that the differences were very small. Most important point to note is the elongation value, which was consistently higher than 8%. This value is significantly higher than that presented by the same alloy when conventionally cast, which is lower than 1.5% [9].

![Fig 1: Microstructure of alloy 1 after spray forming.](image1)

![Fig.2: SEM/EDS: Microstructure of alloy 1, showing silicon particles and Al2Cu intermetallic](image2)

![Fig.3: SEM/EDS: β-AlFeSi intermetallic, observed only in the microstructure of alloy 1.](image3)

![Fig.4: SEM/EDS Alloy 2: Morphology of the α-AlFeSi intermetallics formed by higher Mn contents.](image4)
4. Conclusions

The extrusion of the spray-formed deposits led to a significant reduction of the porosity level of alloy 380 and to partial recrystallization, resulting in a material with enhanced ductility, as indicated by the tensile tests. The addition of manganese was effective in avoiding the formation of β-AlFeSi intermetallics, but this change was not effective in further enhancing the ductility of the A380 alloy. The formation of the α-AlFeSi intermetallics in response to the increase in Mn content slightly improved the ultimate tensile and yield strengths. This effect was probably promoted by the presence of the hexagonal α-AlFeSi intermetallics and by the higher fraction area of unrecrystallized grains. Independently of the Mn content, the elongation values of the spray-formed and extruded alloy exceeded 8%, qualifying this recycled alloy for use in structural applications.

5. References

[1] Murali S, Raman K S and Murthy K S S 1995 Mater. Sci. Eng. A 190 165.
[2] Samuel A M and Samuel F H 1996 J. Mater. Sci. 31 5529.
[3] Wang L, Makhlfouf M and Apelian D 1995 Int. Mater. Rev. 40 221.
[4] Murali S, Raman K S and Murth K S S 1994 Mater. Characteristics 33 99.
[5] Pariona M M, Bolfarini C, Santos R J and Kiminami C S 2000 J. Mater. Proc. Tech. 102 221.
[6] Bereta L A, Kiminami C S, Botta W and Bolfarini C 2007 Mat Science and Eng A 449 850.
[7] Backerud L, Chai G and Tamminen J 1990 ( Stockholm: AFS/SK ANALUMINIUM).
[8] Chan N H M and Humphreys F J 1984 Acta Metallurgica 32 2343.
[9] Ferrarini C F, Bolfarini C, Kiminami C S, Botta W J 2004 Mat Science and Eng A 375–377 577

Acknowledgments

The authors gratefully acknowledge CNPq (National Council for Scientific and Technological Development) and FAPESP (State of São Paulo Research Foundation) for their financial support of this Thematic Project.