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Effect of scandium addition on the microstructure, mechanical and wear properties of the spray formed hypereutectic aluminum–silicon alloys

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ABSTRACT

Hypereutectic Al–*x*%Si–0.8Sc alloys ($x=13$, 16, 19 and 22 wt%) were produced by spray forming. The microstructures of all the alloys exhibited very fine silicon phase with average size of about 5–10 μm irrespective of the silicon content of the alloy. Transmission electron microscopy revealed the presence of a nano-scale scandium rich phase, identified as $AlSi_2Sc_2$ (V-phase) uniformly distributed in the alloy. The presence of V-phase resulted in higher matrix hardness (1.34 GPa) in contrast to 1.04 GPa observed in the case of binary Al–Si alloys by nanoindentation. Isothermal heat treatment at 375 °C revealed insignificant coarsening of silicon phase in both binary and ternary alloys. The Al–*x*%Si–0.8Sc alloys exhibited higher flow stress and tensile strength in contrast to their binary alloy counterparts which was attributed to the bi-modal size distribution of the strengthening phases in the form of nano-scale V-phase and sub-micron to 10 μm size silicon particles. The pin-on-disk wear tests exhibited appreciable improvement in the wear performance of the relatively low-silicon content ternary alloys over their binary counterparts while the high-silicon content binary and ternary alloys exhibited no much difference in the wear performance.

1. Introduction

Aluminum–silicon (Al–Si) alloys find their applications in the automotive industry due to their high specific strength and wear resistance. The combination of high thermal conductivity and low coefficient of thermal expansion make these alloys particularly suitable for the internal combustion (IC) engine components such as cylinder block and piston. Sabatino and Arnberg [1] demonstrated that the addition of silicon improves the fluidity of the Al–Si alloys giving them good castability. Moreover, improvement in the tensile strength [2] and tribological performance [3] of Al–Si alloys with increase in the silicon content of these alloys was also observed. Hence, increasing the silicon content to realize better mechanical and tribological properties in Al–Si alloys is of technological interest. However, presence of hard silicon phase which exists in the form of large (more than 100 μm in conventionally cast Al–Si alloys) eutectic and primary silicon crystals in hypoeutectic and hypereutectic Al–Si alloys respectively is not desirable as it adversely affects the mechanical properties of these alloys. The undesirable morphology of the eutectic silicon in the hypoeutectic Al–Si alloys was effectively modified by chemical route typically with the impurity level addition of elements such as sodium [4], strontium [5] and phosphorus [6] by a process known as impurity induced twinning (IIT) mechanism. However, in hypereutectic Al–Si alloys, with the presence of large primary silicon crystals, the modification and refinement by aforementioned chemical routes is not effective. On the contrary, size and morphology of the silicon phase in Al–Si alloys was effectively refined by rapid solidification techniques such as spray forming and powder metallurgy. For instance, Cui et al. [7] demonstrated that the primary silicon phase in Al–Si alloys can be effectively refined by spray forming.

Furthermore, Kim et al. [8] observed that the addition of scandium to the hypoeutectic Al–Si alloys modified the eutectic silicon phase in the Al–Si alloys significantly while similar observation was also reported by Zhang et al. [9]. This phenomenon was attributed to the decreased surface tension of the Al–Si–Sc melt thereby improving the wettability between aluminum and silicon during solidification. However, Kim et al. [10] observed no significant influence of scandium addition on the primary silicon phase of the hypereutectic Al–Si alloys produced by the casting route. Besides modifying the eutectic silicon phase, the addition of

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scandium was also reported to form stable nano-scale intermetallic compound $AlSi_2Sc_2$ (V-phase) which was reported to strengthen the alloy upon heat treatment [11]. However, the influence of V-phase on the mechanical and tribological properties of the Al–Si alloys in general and the hypereutectic Al–Si alloys in particular was not studied. Besides, the effect of scandium addition on rapidly solidified Al–Si alloys was also not explored so far.

In the present study, Al–*x*%Si–0.8Sc hypereutectic alloys were processed by spray forming and the influence of processing route and the scandium addition on the microstructure, mechanical and tribological properties of these alloys was investigated. Moreover, an object oriented finite element modeling tool (OOF2) as described by Langer et al. [12] was used to approximate the microstructural stress distribution as a function of silicon particle size and morphology followed by corroborating with the experimental results.

2. Experimental details

Ternary alloys of Al–*x*%Si–0.8Sc ($x=13$, 16, 19 and 22 wt%) were prepared using master alloys Al–47 wt% Si, Al–2 wt% Sc and pure aluminum (99.7%) in appropriate proportions. The aforementioned alloys were melted in a resistance type furnace 300 °C above their respective melting points. The melts were then allowed to flow through an annular type nozzle where the atomizing gas (N_2) at 14 MPa impinge resulting in a spray of micron-sized melt droplets that were deposited on a copper substrate. The complete details of the spray forming technique were reported elsewhere [13]. The process parameters of the spray forming experiments were given in Table 1. The spray deposits of about 250 mm diameter and 20 mm thickness each were produced.

The density of the spray deposited samples was calculated using liquid displacement method. The representative specimens from the deposits were prepared for microscopic examination following standard metallographic procedures. The samples for microscopic examination were etched using Keller's reagent (2.5% HNO_3, 1.5% HCl, 1% HF and balance is distilled water) for about 15 s for light microscopy and about 60 s for scanning electron microscopy. Samples for transmission electron microscopy were prethinned to 60 μm using emery sheets of progressively finer grid size and then ion milled until the electron transparent area was attained. The porosity of the samples was estimated by calculating the area fraction of the apparent porosity of the low magnification light micrographs using image analysis software.

The bulk hardness of the spray formed samples was measured using Wolpert Wilson Instruments, 402MVD Vickers hardness tester (USA) at a load of 3 kg for a dwell period of 10 s. The Vickers hardness numbers (VHN) were converted to SI units (MPa) using the multiplication factor 9.8. The light micrographs of the samples were captured using Leitz Laborlux 12 ME (Germany) light microscope. The size and morphology distribution of silicon and porosity was calculated using open source tool ImageJ. The scanning electron microscopy (SEM) of the samples was done using FEI Quanta 200 FEG SEM (USA) fitted with lithium-doped silicon energy dispersive X-ray spectrometer (EDS) of AMETEK of Process and Analytical Instruments for the microstructural and wear track characterization. Both secondary electron (SE) mode and back scattered electron (BSE) modes were used to study the wear tracks using SEM. The transmission electron microscopy (TEM) of the Al–22Si–0.8Sc alloy was done using TECNAI $20G^2$ operating at 200 kV.

Table 1
Spray forming process parameters.

Atomization gas	N_2
Gas pressure	14 MPa
Superheat	300 °C
Spray height	400 mm
Gas-to-melt (G/M) ratio	1.5

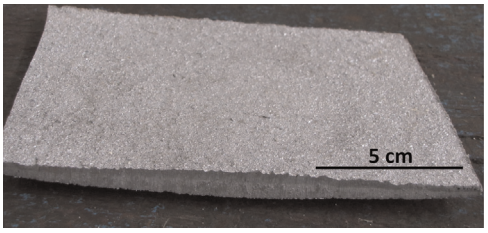

Fig. 1. The representative image of the Al–Si–Sc ternary alloy spray deposit.

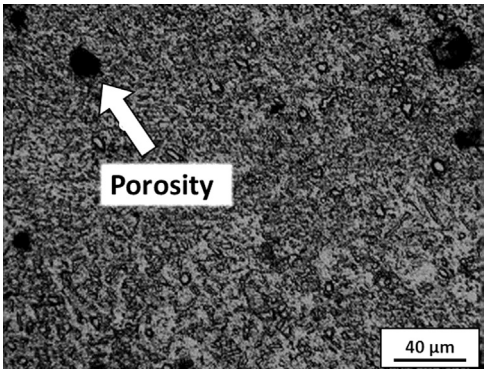

Fig. 2. The representative micrograph of the spray formed Al–Si–Sc alloys showing the presence of gas porosity.

Table 2
Density, porosity and hardness of the as-sprayed deposits.

Alloy	Theoretical density (g/cc)	Measured density (g/cc)	Average apparent porosity (%)	Apparent bulk hardness (MPa)
Al–13Si–0.8Sc	2.64	2.48 (93.9%)	3.58 ± 1.87	639 ± 33
Al–16Si–0.8Sc	2.63	2.50 (95.42%)	3.19 ± 1.56	655 ± 37
Al–19Si–0.8Sc	2.62	2.55 (97.32%)	2.81 ± 1.34	698 ± 49
Al–22Si–0.8Sc	2.60	2.45 (94.23%)	4.21 ± 2.13	735 ± 74

The hardness of the Al–22Si–0.8Sc alloy matrix (without hitting silicon) was determined by nanoindentation using TI 950 Triboindenter, Hysitron Inc. (USA). The indentations were performed at 8 different locations away from the visible silicon particles on the microstructure. A three-sided pyramidal diamond Berkovich tip with a force resolution of 50 nN and displacement resolution of 0.1 nm was used. A trapezoidal loading with a maximum load of 10 mN at a rate of 2000 mNs^{-1} was applied. The spray formed hypereutectic Al–Si binary alloys were also subjected to heat treatment studies and the investigation of mechanical properties for comparison. For the aforementioned TEM, nanoindentation and heat treatment studies, only Al–22Si–0.8Sc alloy was considered as the representative case and the corresponding results were presented and discussed in this work.

The spray deposits were surface milled to get 8 mm thick plates of 100 mm length and 50 mm width plates which were then rolled at 400 °C and 0.5 mm/pass thickness reduction. The tensile tests were performed using INSTRON 30 kN dual column testing machine at a strain rate of 0.00052 s^{-1}. The specimens from each of the spray deposits were isothermally heat treated using tubular