Materials Science and Engineering A xxx (2004) xxx–xxx

MATERIALS SCIENCE & ENGINEERING A

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Microstructure, tensile strength and wear behaviour of Al–Sc alloy

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Received 2 March 2004; received in revised form 8 May 2004

Abstract

A systematic study on the behaviour of commercial pure Al with the addition of scandium (Sc) was carried out and the effects of Sc addition on tensile and wear behaviour were investigated. The Sc addition up to 0.4 wt.% did not show any grain refinement and at higher addition levels, remarkable grain refinement due to the presence of Al_3Sc precipitates during solidification was observed. The SEM, TEM studies showed a uniform distribution of Al_3Sc intermetallics in Al matrix. Sc addition to Al exhibited excellent results of grain refinement as compared to the addition of TiBAl master alloy. A continuous increase in mechanical properties as well as wear resistance behaviour was noticed with the increase of Sc content. Remarkable improvement was observed after homogenization of Sc added Al alloys.

Keywords: Grain refinement; Sliding wear; Homogenization; Microstructure; TEM

1. Introduction

Aluminium based alloys are used for various engineering applications and the as cast commercial pure Al exhibits columnar grain structures under normal solidification rates. The low values of the mechanical properties for columnar-grained structure could be improved by controlling the grain size of the cast alloys. The addition of Al–Ti–B, Al–Ti and Al–Ti–C master alloys to molten aluminium alloys prior to casting is widely practiced to achieve a fine equiaxed grain structure suppressing the columnar grains for improvement of properties. The fine and homogeneous structure in the as cast alloys improves fabricability, yield strength and toughness [1–4]. Most aluminium industries use master alloys of various compositions as grain refiners. The scandium added Al alloys exhibits superior properties than the high strength Al alloys. Mostly, the significant works on Al–Sc master alloys development have been carried out in the Soviet Union [5], due to military demand. In view of having improved properties, the Sc added Al alloys are mostly used for sports, transportation, and aerospace applications [6,7]. In the recent past, several researchers have studied the Al–Sc system due to their unique solidification behaviour where the supersaturated Al–Sc solid solution decomposes via a discontinuous precipitation reaction to form coherent precipitates of stable $L1_2$ (Al_3Sc) phase. The latter having a lattice parameter mismatch of 1.6% with Al can produce a significant ageing response, despite the relatively low solubility of Sc, and hence, a low volume fraction of precipitates [8–10]. The fine precipitates of Al_3Sc provide highest increment of strengthening per at.% of any alloying element when added to Al by reducing the grain size. Even though many researchers have carried out the work on Al–Sc alloys, the characterization of master alloy, mechanical properties and wear studies are not adequately reported. Here, in this paper we report a systematic characterization particularly on the mechanical and tribological properties of Al–Sc alloys.

2. Experimental studies

Aluminium–scandium alloys were prepared through conventional melting and casting route. As cast Al–2Sc master alloys and commercial pure aluminium (CPAl, referred as Al here after) were taken as the starting raw material. All

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0921-5093/$ – see front matter © 2004 Published by Elsevier B.V.
doi:10.1016/j.msea.2004.05.075

Table 1
Composition and properties of various experimental alloys

Alloy	Chemical composition (%)				Tensile strength (MPa)		Bulk hardness (Hv)	
	Si	Fe	Sc	Al	As cast	Homogenized	As cast	Homogenized
CPAl	0.16	0.14	0.16	Balance	90	–	30	–
Al–0.6Sc	0.15	0.14	0.50	Balance	120	147	38	46
Al–1.0Sc	0.15	0.15	0.98	Balance	130	158	45	52
Al–2.0Sc	0.15	0.14	2.00	Balance	138	175	58	64

the alloys were melted in a pit type electrical resistance furnace and the liquid metal was poured in standard permanent moulds and the compositions of the alloys are given in Table 1. A temperature controller of Eurotherm, UK make was used to monitor the furnace temperature with an accuracy of ±1 °C. This was maintained at 720 °C. In order to carry out the grain refinement experiments, 1 kg of Al was melted in a clay bonded graphite crucible. Various quantities of Al–2Sc alloy was added to the Al melt at 720 °C to yield Al–Sc (0.2, 0.6, 1.0). The melt was poured at regular intervals (2, 5, 30, 60 and 120 min into cylindrical graphite mold (25 mm diameter and 100 mm height) surrounded by a fire clay brick with its top open for pouring. The cast bars were sectioned at a height of 25 mm from the bottom, and the section surfaces so obtained were polished and etched. Macrostructures were obtained by etching with standard Poulton's reagent, while etching with Keller's reagent revealed the microstructures of as cast Al–Sc alloys. The

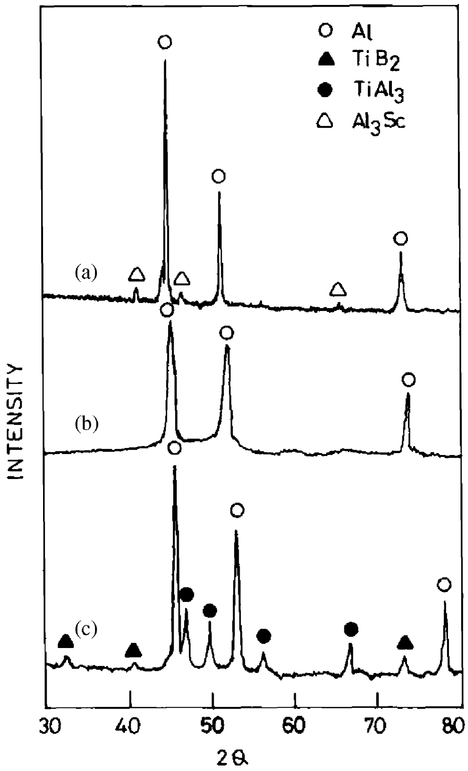

Fig. 1. XRD patterns of (a) Al–2Sc alloy, (b) CPAl and (c) Al–5Ti–1B alloy.

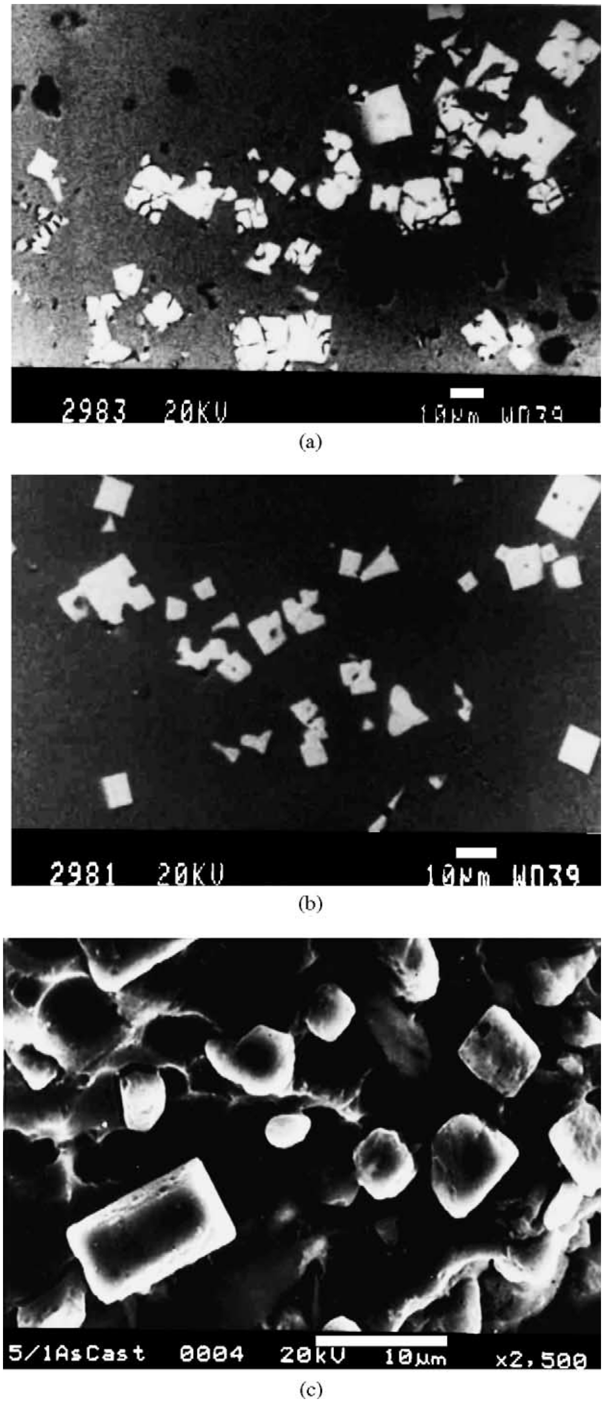

Fig. 2. SEM photomicrographs of (a) Al–2Sc, (b) Al–1Sc and (c) Al–5Ti–1B master alloys.

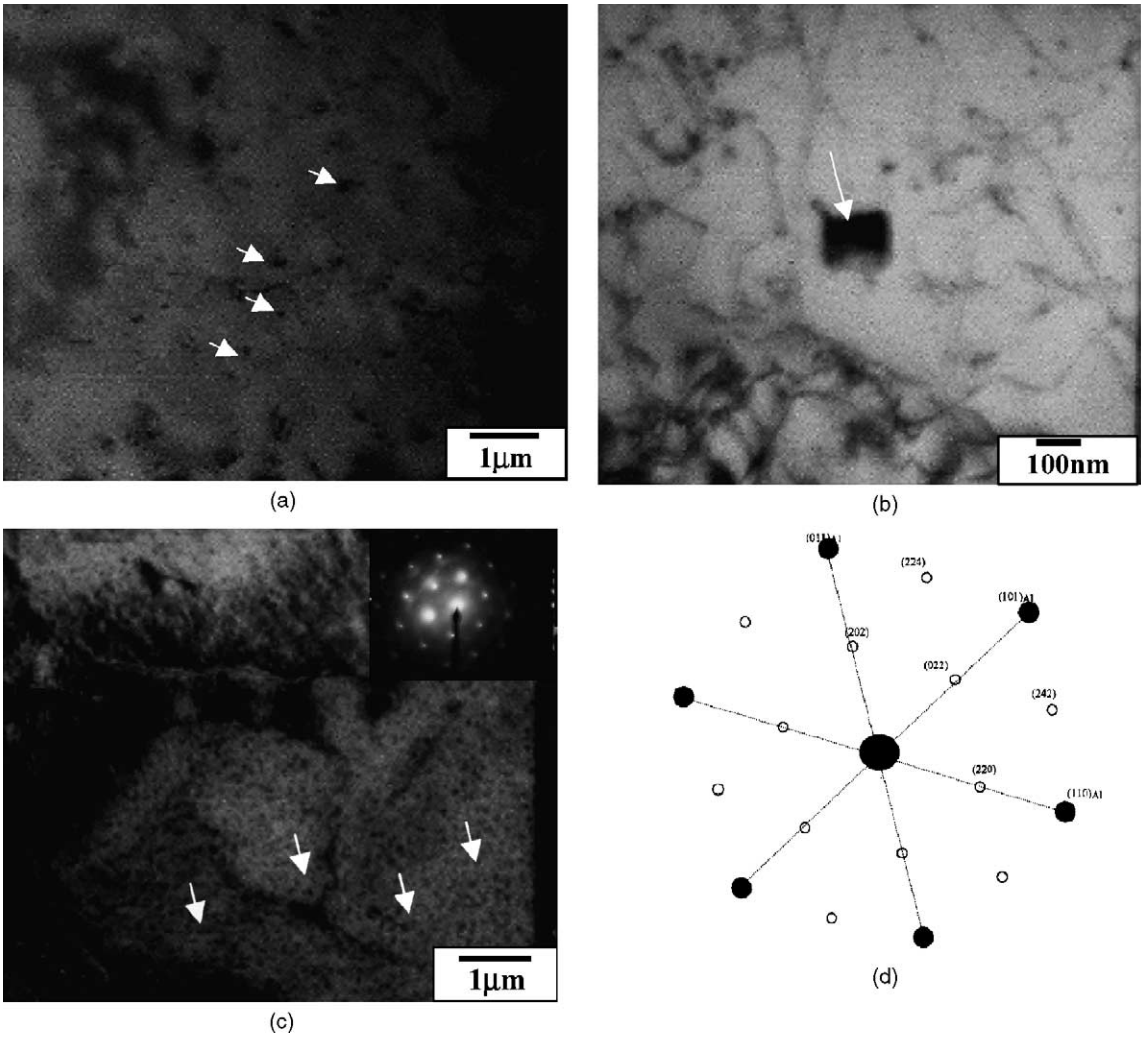

Fig. 3. TEM micrograph of (a) as cast Al–2Sc alloy, (b) enlarged micrograph of (a) (arrows shows the Al_3Sc particles), (c) homogenized Al–2Sc alloy with SAD pattern, and (d) indexing of the SAD pattern (arrow marks shows the fine Al_3Sc particles).

microstructural features were studied using optical microscopy, image analyzer, scanning electron microscope (SEM), transmission electron microscope (TEM). Grain size analysis was carried out by the standard linear intercept method using an image analysis system (Metal Power, India). Scanning electron microscopy studies were carried out using SEM (JSM-840A, JEOL, Japan). TEM studies were carried out using (model CM200, Philips, Netherlands make). X-ray diffraction (XRD) patterns of the Al, Al–Ti–B and Al–Sc alloys were obtained using Siemen's XRD system with Co Kα radiation (D-500, German's make). Dry sliding wear tests were conducted on 8 mm diameter, 40 mm long cylindrical specimens. The counter surface (disc) was made of EN32 steel having a hardness of Rc65. A pin-on-disc machine Ducom (Bangalore, India) was used for carrying out the wear tests at 0.98 N load and the coefficient of friction results were obtained using the Ducom, India software.

3. Results and discussion

The X-ray diffraction studies had shown the presence of Al as the primary phase in the as cast Al–Sc master alloy (Fig. 1a) and with minor peaks of Al_3Sc phase. The former peaks were absent in the CPAl (Fig. 1b) and exhibited only Al peaks. SEM of Al–2Sc and Al–1Sc alloys showed the dispersed Al_3Sc particles in the Al matrix (Fig. 2a and b) and the particle size were observed to be in the range of 5–20 µm. The intermetallics of Al_3Sc were highly faceted and had various shapes e.g., squares, stars and triangles. These shapes in Al_3Sc of Al–Sc alloys and similar alloys were generally referred as cusped cubic morphology. In addition, nanosized precipitates of Al_3Sc could be clearly observed in the Al matrix during TEM studies (Fig. 3a). It could be clearly seen from the Fig. 3a and b that the precipitates were of the order of sub-micron size and randomly distributed in the Al matrix.

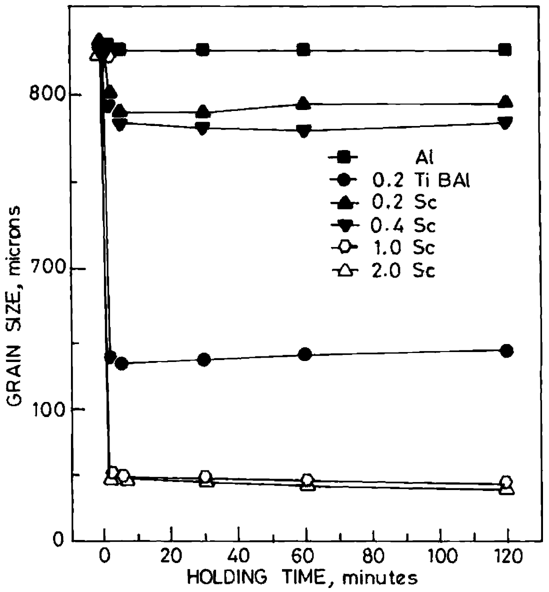

Fig. 4. Grain size analysis of Al, with and without addition of TIBAl and scandium.

The microstructure of Al–5Ti–1B master alloy containing $TiAl_3$ and TiB_2 particles that was used for the grain refining the Al is shown in Fig. 2c. The TiB_2 particles were very fine in size and the energy dispersive X-ray analysis (EDX) results are also clearly demonstrated the presence of $TiAl_3$ and TiB_2 particles. The presence of these phases was also clear from XRD results (Fig. 1c). The grain size analyses of Al with and without addition of Sc and TiBAl obtained from the image analysis of the optical microscope are plotted in Fig. 4. The Al without any addition of grain refiner expectedly showed complete columnar structure for all holding timings. The addition of 0.2 and 0.4 wt.% Sc to molten Al could not modify the columnar grain structures and as such there was no significant amount of grain refinement, expect that a nominal change in the grain size was observed. In the graph (Fig. 4), zero minutes holding time represented that no grain refiner was added to molten Al. Drastic changes in grain refinement were observed when the commercial grain refiner (Al–5Ti–1B of 0.2 wt.%) and Sc more than 0.6% was added to molten Al. During addition of TiBAl to molten Al, complete conversion of columnar to equiaxed grain structure was observed at 2 min holding time. When Al–5Ti–1B master alloy containing wide ranges of $TiAl_3$ particles sizes are added to molten Al as a grain refiner, it was expected that the finer $TiAl_3$ particles would act as nucleating sites due to their higher surface area to volume ratio compared to the coarse particles. At the temperature of grain refinement (720 °C), the $TiAl_3$ particles present in master alloy had a tendency to dissolve in molten Al. This was due to the solubility of Ti in liquid Al at 720 °C is (0.25 wt.%), which was higher than the Ti addition level used for grain refinement (0.05% Ti in the present study). During the dissolution process, the size of the large $TiAl_3$ particles would reduce with increasing the holding time and thus some fine particles were always available for nucleating Al. The presence of TiB_2 particles also helped in improving the grain refining effect of Al–5Ti–1B master alloy [2,4].

Scandium addition (1 wt.%) to molten Al showed better grain refinement results as compared with Al, that was grain refined by adding 0.2 wt.% of TiBAl master alloy. This significant amount of grain refinement was clearly seen in the 2 min sample and the grain refinement effect was maintained

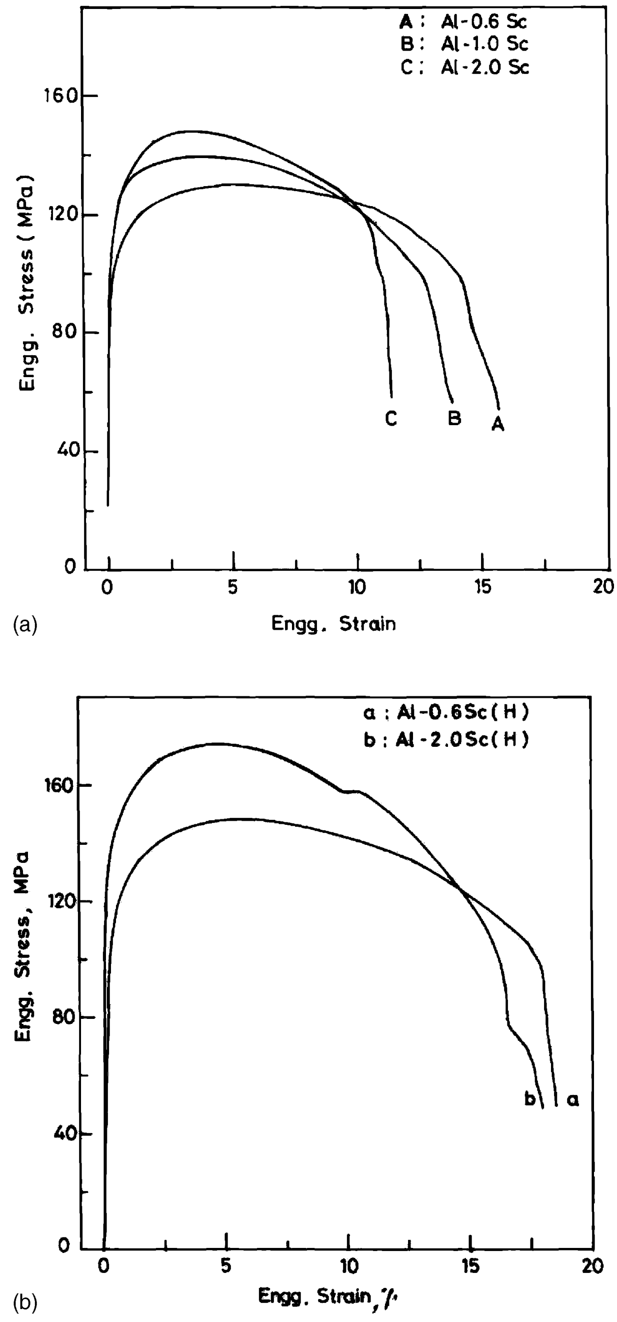

Fig. 5. Tensile strength of various Al–Sc alloys (a) as cast and (b) homogenized.

up to 120 min. This type of grain refiner was mostly referred as ideal grain refiner. Similarly, the addition of 2 wt.% Sc to molten Al showed a drastic change in grain refinement and considered best among all the grain refiners that were referred in this paper. Moreover, grain refining results of 2 wt.% Sc addition to Al matrix are almost similar to 1 wt.% Sc addition levels. It was observed that the 2 wt.% of Sc addition gave marginally better grain refinement results than 1 wt.% of Sc added samples. The present results support the observations reported by Drits et al. and Norman et al. [11,12] that Sc additions in amounts less than the eutectic composition of 0.55 Sc, exhibits a columnar grain structure, whereas increasing the Sc content higher than 0.55 Sc exhibits a fine equiaxed grain structure. The formation of such equiaxed grain structure was due to the formation of intermetallic particles of the $L1_2$ Al_3Sc phase in the Al melt, which acted as nucleating sites during solidification. Also, due to the similarities between the crystal structures of the α-Al and Al_3Sc phases, the heterogeneous nucleation of α-Al might be expected to guide the epitaxial growth of α-Al on the $L1_2$ Al_3Sc particles [11]. In the present investigation Sc addition in different concentrations higher than 0.6 wt.% to molten Al exhibited similar results.

The tensile strength of all the investigated alloys are listed in Table 1. It could be seen from the table that the tensile strength had improved with the increasing amount of Sc in Al. Addition of 2 wt.% of Sc to Al, resulted in a considerable increase in the tensile strength from 90 to 138 MPa. The strength increased from 90 to 120 MPa with the additions of a small quantity (0.6%) of Sc. The increase in Sc addition up to 1.0% exhibited considerable increase in strength, however, similar amount of increment was not noticed when the concentration of Sc was increased from 1 to 2 wt.% (Fig. 5a). It was observed that the alloy that had 0.6 wt.% Sc showed lesser strength as well as lower yield strength compared to the other two compositions viz. 1 and 2 wt.% Sc added Al alloys. In majority of engineering applications, the yield strength was the upper limit for loading and therefore it had a lot of significance. Keeping this in view, the alloy with 2 wt.% of Sc is more attractive.

After the homogenization, all the alloys showed a different trend in mechanical properties and the Sc addition up to 0.6 wt.% showed a significant increase in strength (Fig. 5b). However, the addition of more Sc (2.0%) to Al metal showed a marginal improvement of tensile strength with respect to Al–0.6Sc alloy. The incremental rate of strength was comparatively lower when Sc addition was increased from 0.6 to 2.0 wt.%. The improvement in UTS after homogenization compared to as cast alloy was due to the presence of uniformly distributed fine Al_3Sc particles (Fig. 3c) in the Al matrix. The selected area diffraction (SAD) shown in Fig. 3d is also confirmed the fine precipitates as Al_3Sc. It was observed that the more number of Al_3Sc particles were precipitated from the super solid solution of Al during homogenization and resulted in improved mechanical properties. It was observed that the bulk hardness had increased from 30 Hv for Al to 58 Hv in the Sc added samples. The hardness is further increased to 64 Hv due to homogenization process.

To study the possible phase changes during the heating of Al–2Sc alloy, resistivity measurements were conducted and the results showed that with increasing temperature there was no significant phase change till 400 °C. The resistivity of the samples increased linearly with increasing the temperatures (Fig. 6). The deviations of the resistivity at 160 °C and above 300 °C were possibly due to the dissolution of Al_3Sc

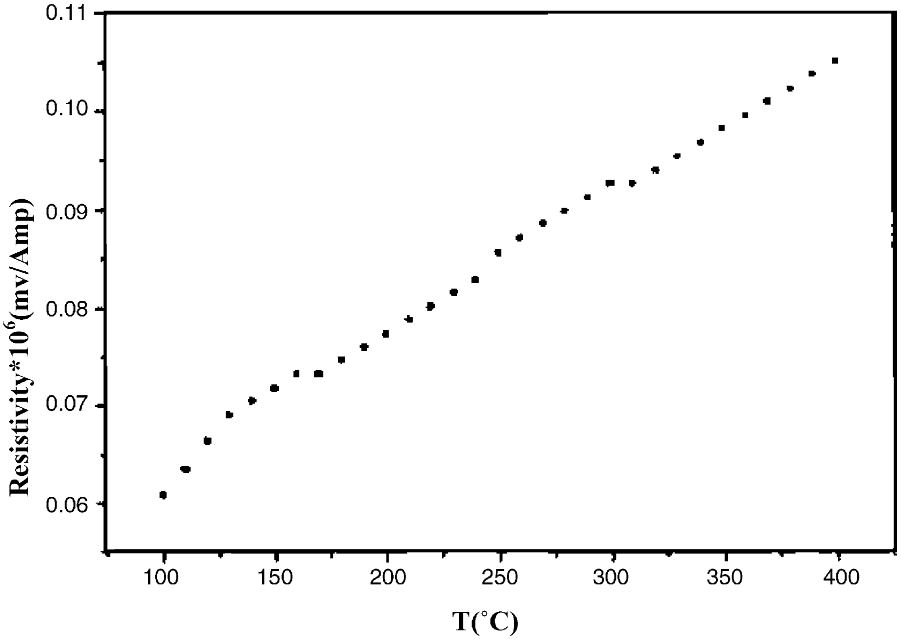

Fig. 6. Resistivity of Al–2Sc alloy.

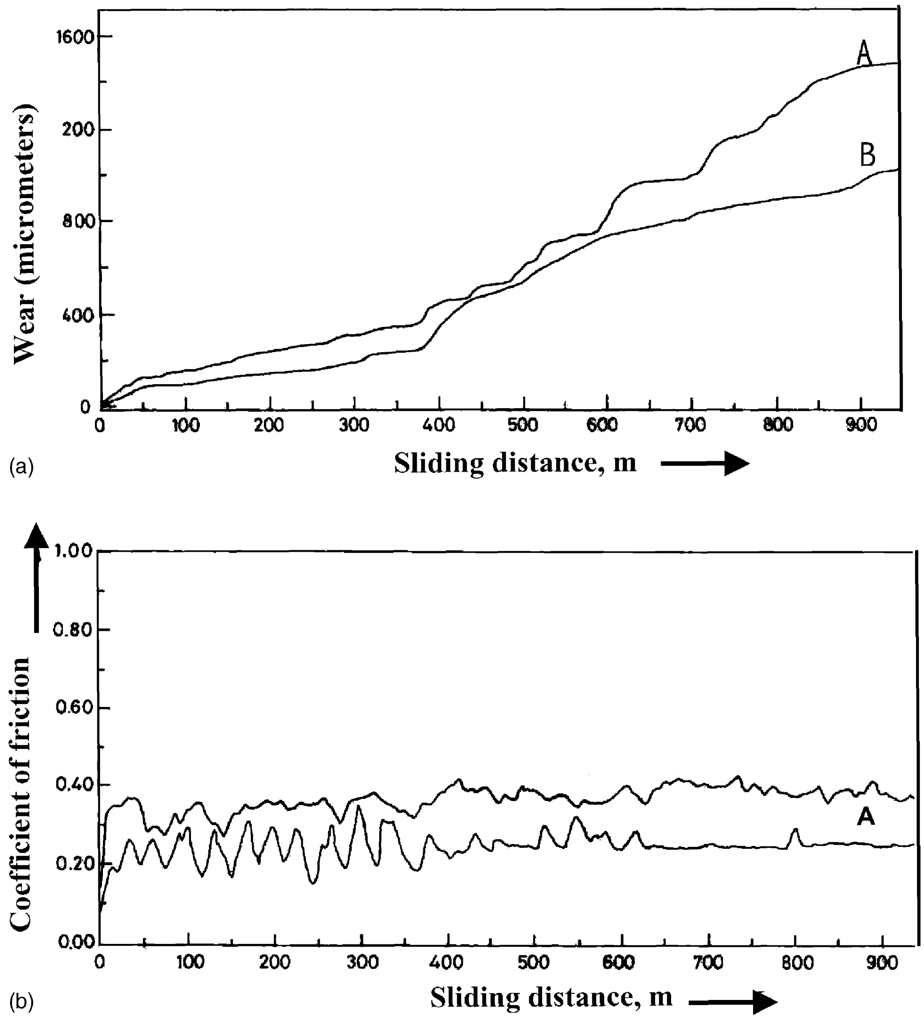

Fig. 7. (a) Wear and (b) coefficient of friction graphs of Al–Sc alloys (A: 1Sc; B: 2Sc).

precipitates and recrystallisation process. Detailed studies to confirm these processes are under investigation.

Dry sliding wear tests were carried out on Al; grain refined with Al–2Sc and Al–5Ti–1B master alloys, at 0.98 N load. These results are shown in Fig. 7a and b. The wear resistance of Sc added Al alloy was better than the Al, refined with the addition of TiBAl. In addition, the wear of both samples increased linearly with sliding time (sliding distance). As the sliding speed was 1 m/s, the sliding distance in meter was same as the sliding time in seconds (Fig. 7a). A fine grained structures observed during grain refinement studies (Section 3) of Sc addition to Al was responsible for higher wear resistance values as compared to the Al alloy that was grain refined with the commercial grain refiner (Al–5Ti–1B). Experiments at different loads would probably demonstrate more systematically the response of grain size on the sliding wear properties. A further work in this direction is in progress. The results on coefficient of friction were different from the wear results. The coefficient of friction for Al alloy that had Ti and B initially showed higher values as compared to the Sc added Al (Fig. 7b). Almost a linear difference in the coefficient of friction could be observed between the two experimental alloys. Sudden increase in coefficient of friction for both the alloys of initial sliding distances was due to the adhesion of the sample to the sliding disc.

4. Conclusions

The following conclusions can be drawn from the present investigation:

A grain size of 40–45 μm in Al was only possible when the Sc addition were higher than 0.6 wt.%. The presence of various shapes of Al_3Sc particles including its fine precipitates was responsible for good grain refining efficiency. The results were much superior to the Al grain refined by the Al–5Ti–1B master alloy. Increasing the Sc content from 0.6 to 2.0 wt.% exhibited a continuous increase in the tensile properties. Homogenization at 460 °C was responsible for further increase in tensile properties probably due to the presence of fine Al_3Sc precipitates and redistribution of Al_3Sc particles that would have been acted as nucleating sites during solidification of Al. Sc added Al exhibited better dry sliding wear resistance values than Al metal that was grain refined with Al–5Ti–1B alloy. A fine-grained structure of Al in the range of 40–45 μm (Sc addition) was responsible for higher wear resistance values as compared to Al alloy that had a grain size of 120–130 μm (TiBAl addition).

Acknowledgements

The authors would like to thank Dr. D. Banerjee, Director, Defence Metallurgical Laboratory, Hyderabad, for providing the Al–Sc master alloy. The invaluable help rendered by Mr. Samar Das, Mr. S.K. Das and Mr. B. Ravi Kumar of National Metallurgical Laboratory, Jamshedpur, for the TEM, SEM and XRD studies, respectively, are sincerely acknowledged. We also would like to thank Prof. S.P. Mehrotra, Director, National Metallurgical Laboratory, Jamshedpur, for his kind permission to publish this paper.

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