International Journal of Thermal Technologies, Vol.2, No.1 (March 2012) ISSN 2277 - 4114

Research Article

Mechanical work feasibility of Al-Fe composite

Sanjay Srivastava[a*]

[a]Materials Science & Metallurgical Engineering, Maulana Azad National Institute of Technology, Bhopal-462051

Accepted 20 March 2012, Available online 21 March 2012

Abstract

In order to produce energy efficient tribological materials for high temperature application, Al-Fe intermetallic composite have been produced by liquid metallurgy methods. The iron content in the composite varies from 6.23 to 11.2 wt%. These composites have been selected for forging studies by selecting the optimum forging parameters. After forging these composite were again selected for annealing studies at choosing various annealing temperature (200, 300, 400 and 500^{0}C for 2 hours). The composite after forging and annealing have been studied under optical and scanning electron microscope, showing the presence of second phase particle, distributed at grain boundaries to the interior of the grain. Further the results of the EDAX and XRD confirm the presence of Fe and FeAl3. Mechanical properties like hardness, strength of the composite are improved with iron alloying in the matrix, however it also has adverse effect on ductility. The forging and annealing on the composite show the same effect.

Key words: *Hardness, Forging, Annealing, EDAX, XRD, SEM*

1. Introduction

Forging is the most primitive method of mechanical working by hammering or pressing. It is widely used for shaping purpose to give a useful shape starting from a bolt to a turbine rotor or it could be wings of aircrafts. Al-Si alloy (L.F.Mondolfo *et al*) pistons are produced by forging operation and widely used. However, a spherical pore undergoes flattening and simultaneous elongation in the direction of lateral flow. Al-Si (E. Rabinowicz e*t al* 1973) alloy is one of the most versatile materials, which is used in plenty of wear related applications in different compositions. In wear related applications strength and hardness is of considerable importance. Unlike Al-Si alloys, Aluminum-iron intermetallic (S.Mohan *et al*, 2002) composites provide two different modes of strengthening; solid solution as well as dispersion hardening due to the formation of different intermetallic, hence, it has an edge over existing Al-Si alloys. In characterization of any material, microstuctural features, presence of different phases and distribution of second phase play a very important role and deciding the suitability of material for a particular application largely depends on their morphology. Forged pistons are made out of eutectic A-S12UN alloys. Similarly, AA 4032 Al-Si alloys are also used to produce forged pistons (W. Hrist *et al* 1957).

In the present work, as-cast Al-Fe intermetallic composites with different composition were developed using liquid metallurgy route and subjected to forge for producing the forged parts of Al-Fe composite. Only two compositions, with 6.23 and 11.2wt. % irons were taken for the study. Annealing behavior is studied in detail at various annealing time and temperature. It has been observed from the studies conducted on as-cast Al-Fe as well as forged and annealed composites that these composites are superior to as-cast, as well as forged Al-Si alloys in respect to mechanical properties and wear properties which shows that it could be a be an alternative material to commercially used Al-Si alloys. But apart from as cast conditions Al-Si alloys are also used in forged condition.

2. Experiment

2.1 Preparation of the composite

Commercially pure aluminum (99.9% purity) and electrolytic iron powder of 300mesh size (99.9% purity) were used for the preparation of Al-Fe composite. Electric muffle furnace was used to fabricate the Al-Fe composite. It is consisted of mixing and casting operation both. The required amount of aluminum was charged and heated to a temperature 250^{o}C above the liquids temperature of the base alloy in electric furnace. After melting the charge, the mixing was commenced at an impeller speed of 2100 rpm. For preparation of different compositions of Al-Fe composite, the required amounts of iron were charged into the turbulent melt during stirring. Mixing was done for a period of 60 second and then melt was poured into the mould placed beneath the furnace using bottom pouring. The mould was put into the ice-brine solution for fast cooling.

2.2 forging and annealing procedure

* Corresponding author's email: s.srivastava.msme@gmail.com

Table 1 Selected parameter of the forging operation

S.No.	Operation	Parameter
1	Dimension	60x25mm
2	Homogenization temperature	450^{o}C
3	Homogenization time	20 hours
4	Operation	Forging
5	Soaking temperature	510^{o}C
6	Soaking time	1.5 hours
7	Direction	Perpendicular to diameter
8	Reduction	50%
9	Quenching media	Water

Table 1a Physical Properties of the Al-Fe Composites

S.No.	Composite	Theoretical density	Experimental Density
1	Al-6.23% Fe	2.96	2.79
2	Al-11.2% Fe	3.28	3.08

Table 1b Mechanical properties of the Al-Fe composite

S.No.	Composite	VHN	UTS (MPa)	0.2%PS (MPa)	% elongation
1	Al-6.23%Fe	163	159	74	27
2	Al-11.2%Fe	179	184	93	17

Table 1 shows the selected parameters for forging. Forging operation was conducted only for two compositions. The forging operation was carried out by pneumatic hammer under constant load. For the forging operation, cylindrical samples of dimension of 60mm x 25mm were chosen. These were homogenized at 4500C for 20 hours. Before forging composites were soaked for 1.5 hours at 5100C. After homogenization and soaking of the composites, 50% reduction was given perpendicular to the horizontal diameter by the pneumatic hammer and immediately quenched in water. To relieve the internal stresses, generated during forging, annealing was done at different combinations of temperatures and time. Annealing was done at different temperatures of 200, 300, 400 and 5000C for 4, 14, 24 hours. After forging and annealing, specimens were prepared for different studies like microstructure; mechanical properties and wear testing and studies were conducted in the same way as in as cast composites

.

Table 2 Hardness of the forged and annealed Al-Fe composites

S.No.	Temperature ^{0}C	Hardness, VHN	
		6.23% Fe	11.2% Fe
1	As-cast	163	179
2	As-forged	197	217
3	200	183	212
4	300	170	197
5	400	166	187
6	500	131	143

2.3 Evaluation of physical and structural properties of as-cast as well as forged and annealed composite

The wet chemical analysis was used to determine the percentage of iron in bulk composite. The density was determined by using Archimedes principle by weighing in water and air. The Vickers hardness were also measured using a micro Vickers hardness tester with a 100g load and a 10s indentation time. A tensile test of the entire composite in as-cast condition as well as in forged and annealed condition were performed in an Instron tensile testing machine at room temperature using standard specimen of 4.5mm diameter and 16mm gauge length. The metallographic specimens were prepared using standard technique and studied under optical as well as SEM for different feature present. X-ray diffraction analysis was carried out for phase analysis.

4. Result and discussion

4.1 As-cast Al-Fe studied

Analysis of iron

The iron was estimated through volumetric analysis. The amount of iron analysed in the casting is tabulated in Table 1. EDAX analysis was used to identify the presence of iron in terms of percentage: present at the grain boundary or within grain. The same result was obtained by EPMA analysis further confirming EDAX results. The phase identification in aluminum base iron containing

Table 3 UTS, proof stress and percentage elongation of Al-Fe composites

S.No.	Temperature (^{0}C)	UTS, MPa		0.2%Proof stress, MPa		% elongation	
		6.23% Fe	11.2% Fe	6.23% Fe	11.2% Fe	6.23% Fe	11.2% Fe
1	As-cast	159	184	14	93	27	17
2	As-forged	220	260	99	127	11	5
3	200	209	239	96	107	13	9
4	300	190	220	82	97	20	15
5	400	170	210	77	96	21	16
6	500	150	177	63	83	31	21

composite were carried out by X-ray diffractometer, that composite contain iron in the Al-Matrix found in two forms (1) as free iron and (ii) in the combined form FeAl3 as intermetallic. The FeAl3 compound form directly from the liquid state through fast cooling.

4.1.2 Density and Mechanical Property of composites

Table 1 a & b represents the composition, density and mechanical properties of the different composites produced. The porosity in chill cast a material was observed to be an inevitable entity and is reported in the table. There is slight increase in the ultimate tensile strength and 0.2% proof strength as iron increase from 6.23 to 11.2 % iron, providing the strengthening effect. It is also found that the presence of iron leads to reduction in the elongation of the composite. The mechanical properties of as cast Al-Fe composite are adversely affected by the presence of iron as large primary or pseudo-primary crystals.

Metallographic Evidence

The entire microstructures of the composite have been studied through optical and SEM microscope. The optical micrographs are shown in Figs 1-2 (a-b). And their SEM micrographs are shown in the Fig 3-4(a). At the lower percentage of iron in the composite are seen as cluster type or needle in shape but at the higher magnification these are clearly seen in spherical from. Intermetallic amount increase with the wt. % iron [10].

4.2 Effect of annealing temperature on 50% deformed composite

After forging composites were annealed at 200, 300, 400 and 5000C for four hours and their structural and mechanical properties were studied in detail.

Structural properties

Microstructures of forged specimens have been studied after annealing at different temperatures under optical as well scanning electron microscope. Figures 5a&b show the optical micrographs of forged specimens of Al-Fe composites with 6.23 and 11.2% iron. Figures 1-4(a-b) in as-cast conditions show the fine network of needle shaped intermetallic of FeAl3 but once specimens are forged, intermetallic are transformed to rhombohedral shape as Figs.5a&b. Further to clarify the structure specimens of Al-Fe composite with 11.2 % iron were also studied under SEM and results are shown in Figs. 6 These figures further confirm the presence of intermetallic in the rhombohedral shape (P.A. Parkhutik *et al*, 1989)

Figures 7a-d and Figs.8a-d show the optical micrographs of Al-Fe composites with 6.23 and 11.2% iron after annealing for 4hhrs at different temperatures of 200, 300, 400 and 5000C on constituent phases. These figures show the presence of large rhombohedral particles, which are unlikely to be FeAl3. FeAl3 is monoclinic in nature and observed as needle shaped particles as in case of as-cast composites. In forged and annealed condition very less particles are observed as needles. Though in case of Al-Fe composites with 6.23% iron, it seems that particles are smaller at higher temperatures but in case of composite with 11.2% iron no remarkable difference is observed. SEM micrographs reveal almost same results even at higher iron percentage of 11.2 as in Figs. 9. But identification of the particles was important which lead to XRD analysis. XRD did phase identification for confirmation. Figure 10 shows the XRD results for Al-11.2%Fe composite. The result shows the presence of FeAl6 (H. Biloni *et al*, 1966) seems that with annealing FeAl3 decomposes to FeAl6 and in case of forged and annealed composites resulting in more and more formation of FeAl6.

Mechanical Properties

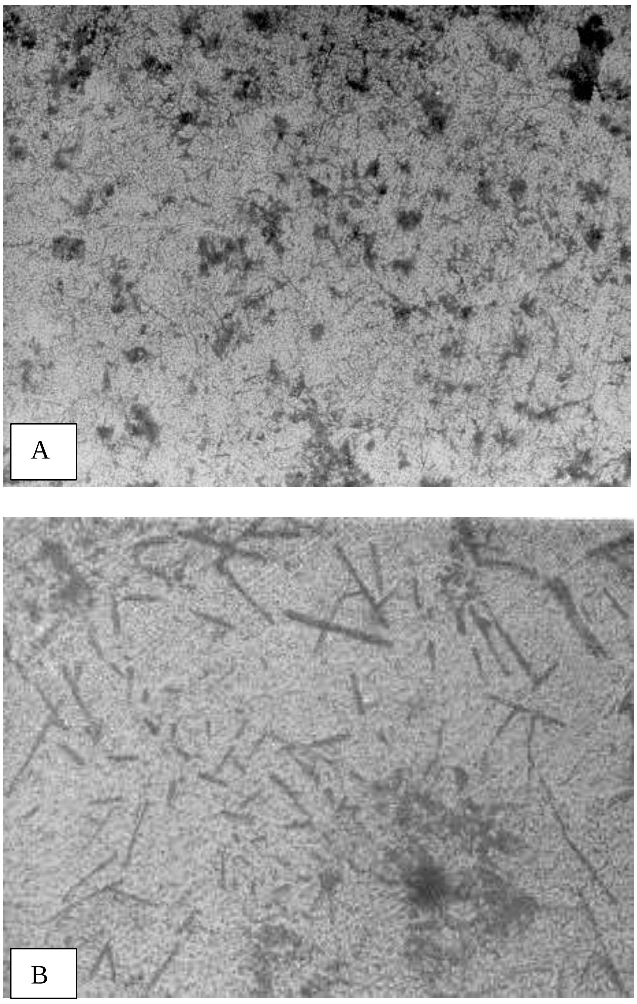
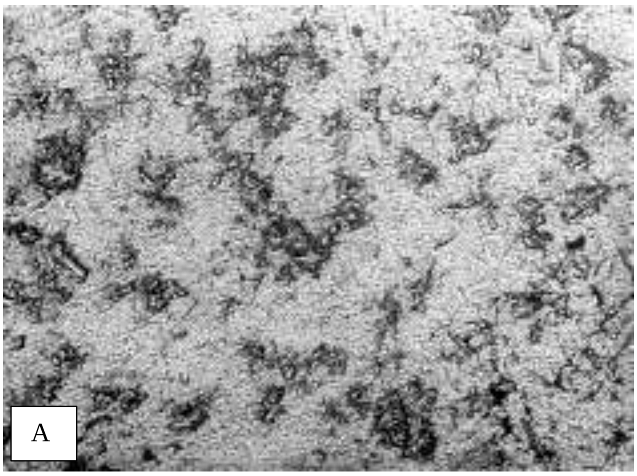


Fig 1a, b Optical micrographs of Al-6.23% Fe composite at different magnifications



Mechanical properties of forged composites annealed at different temperatures for 4 hrs are tabulated in Tables 2 and 3. Table 2 shows that in forged specimens due to strain hardening hardness increases but with annealing stresses are relieved and $FeAl_3$ decomposes to $FeAl_6$ leading to a decrease in overall hardness of the composite as it is more evident from Fig.11 showing variation of hardness with annealing temperature. Table 3 shows the UTS, PS and % elongation of both composites. There is consistent decrease in UTS and PS with annealing

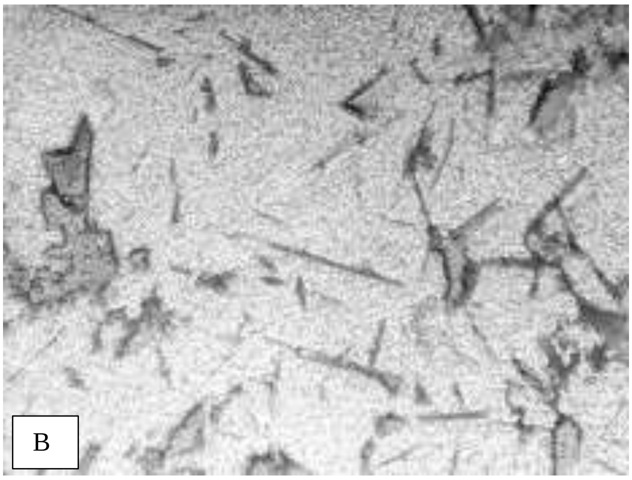


Fig. 2 a, b Optical micrographs of Al-11.2% Fe composite at different magnifications

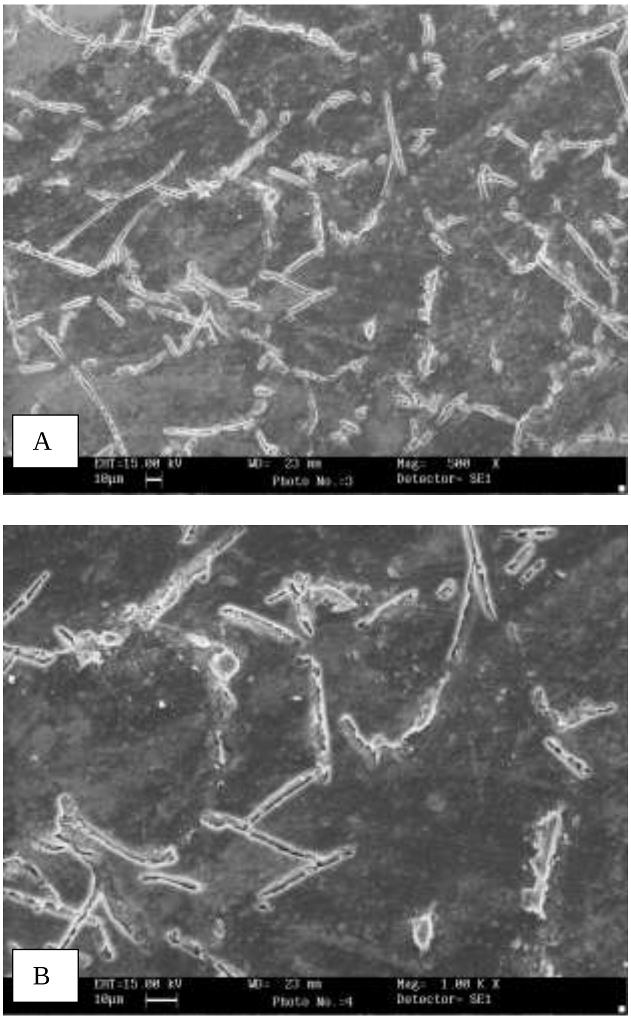


Fig.3a, b SEM micrographs of Al-6.23% Fe composite at different magnification temperature is observed with increasing annealing temperature but % elongation is observed to increase with the increasing amount of FeAl6 and it is more evident from Fig. 12.

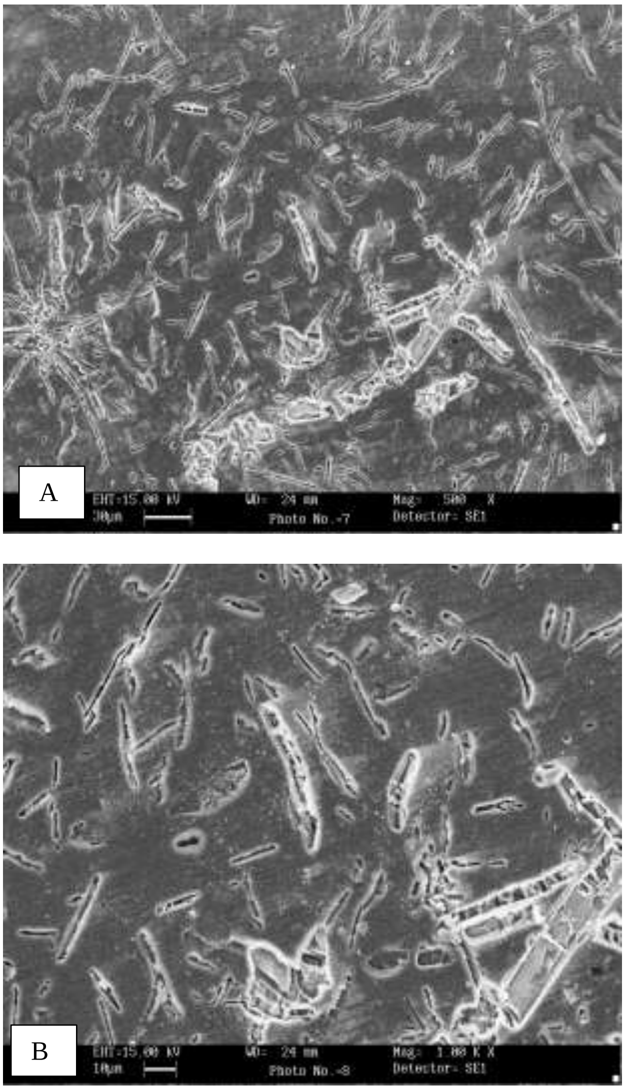
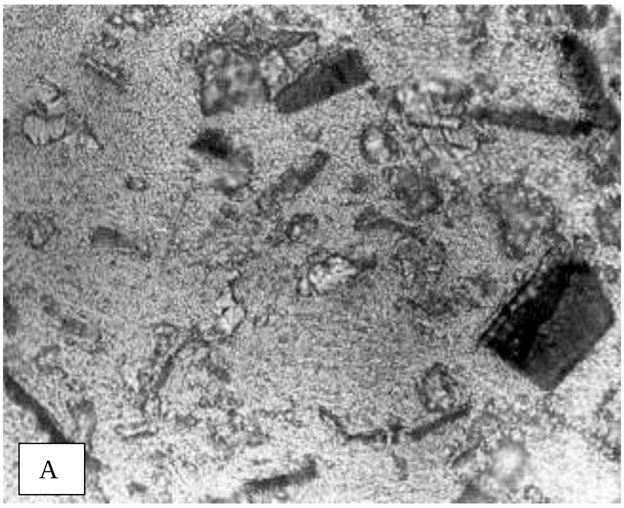


Fig.4a, b SEM micrographs of Al-11.2% Fe composite at different magnification



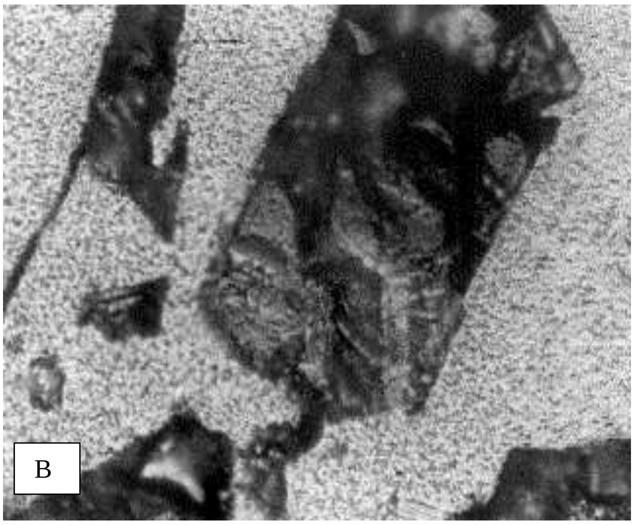


Fig. 5 Forged microstructures of Al-Fe composites with different iron percentage (a) 6.23% and (b) 11.2%

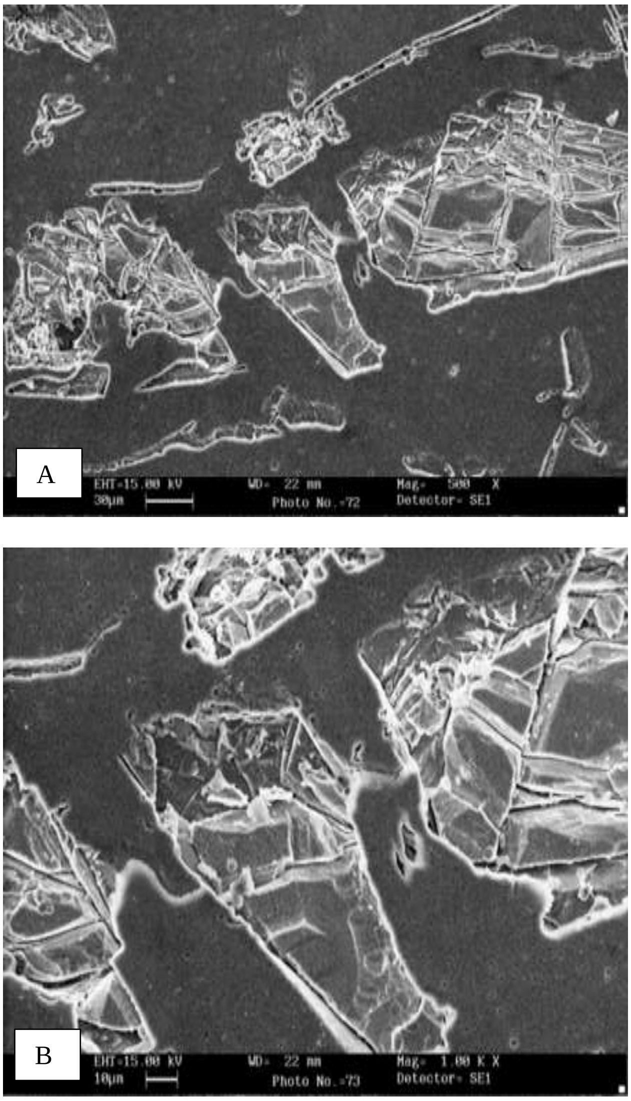
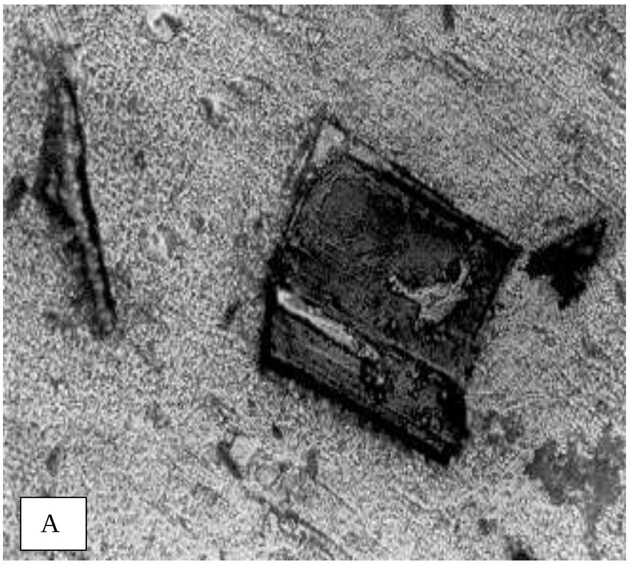
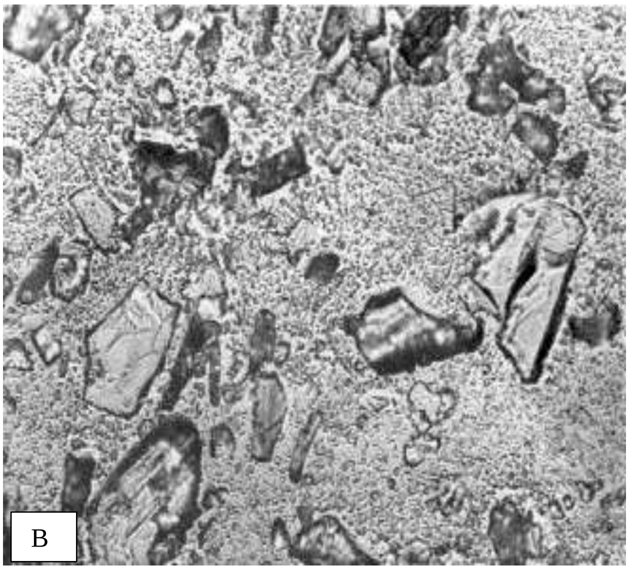
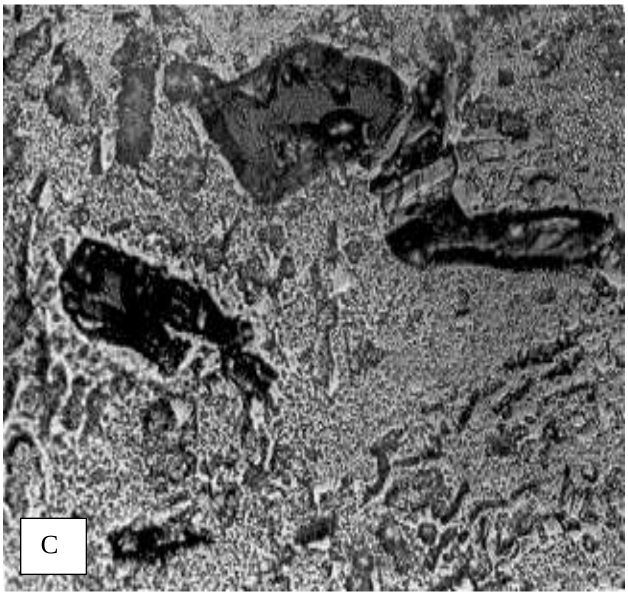
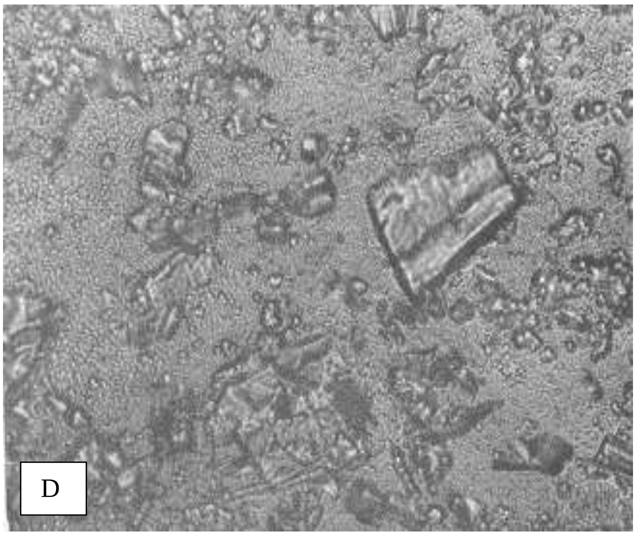


Fig. 6 SEM micrographs of Al-11.2%Fe composites showing the presence of rhombohedral intermetallic at different magnifications

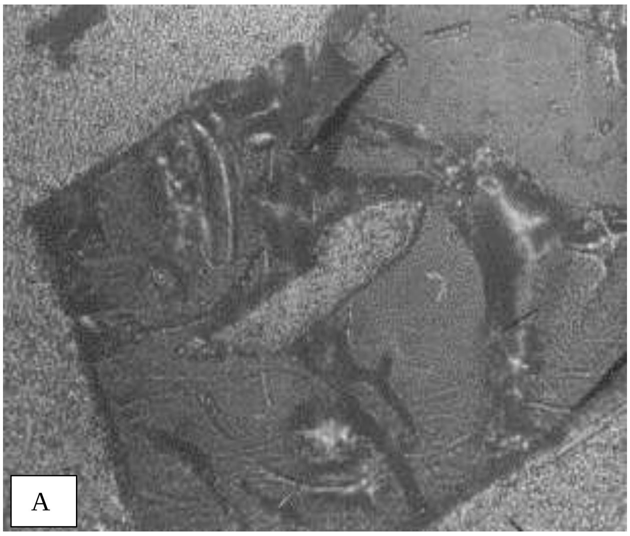


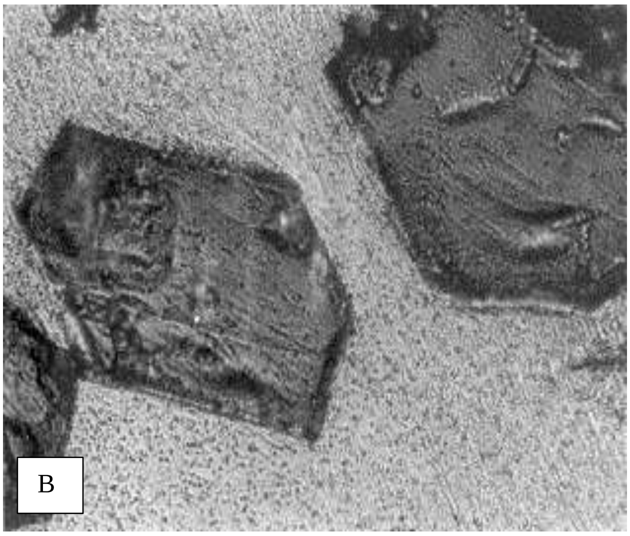


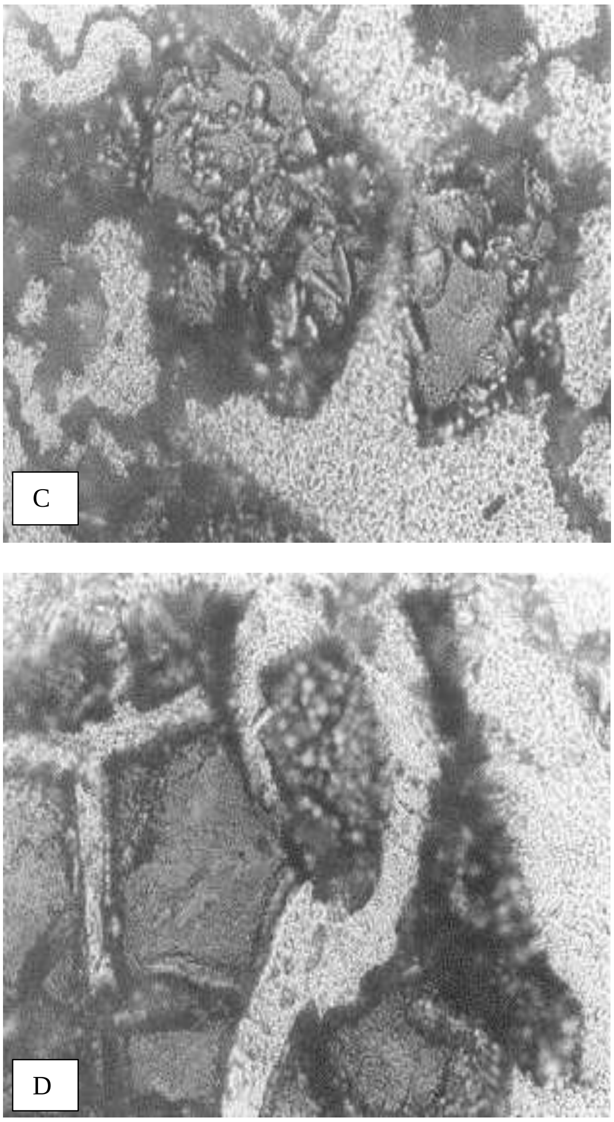




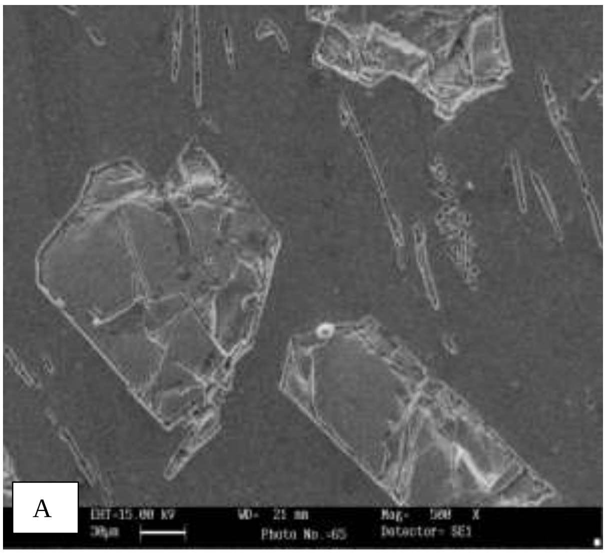
Figs. 7 Optical micrographs of Al-6.23%Fe composite annealed at different temperatures of (a) 200^0C, (b) 300^0C, (c) 400^0C and (d) 500^0C







Figs. 8 Optical micrographs of Al-11.2%Fe composite annealed at different temperatures of (a) 200^0C, (b) 300^0C, (c) 400^0C and (d) 500^0C



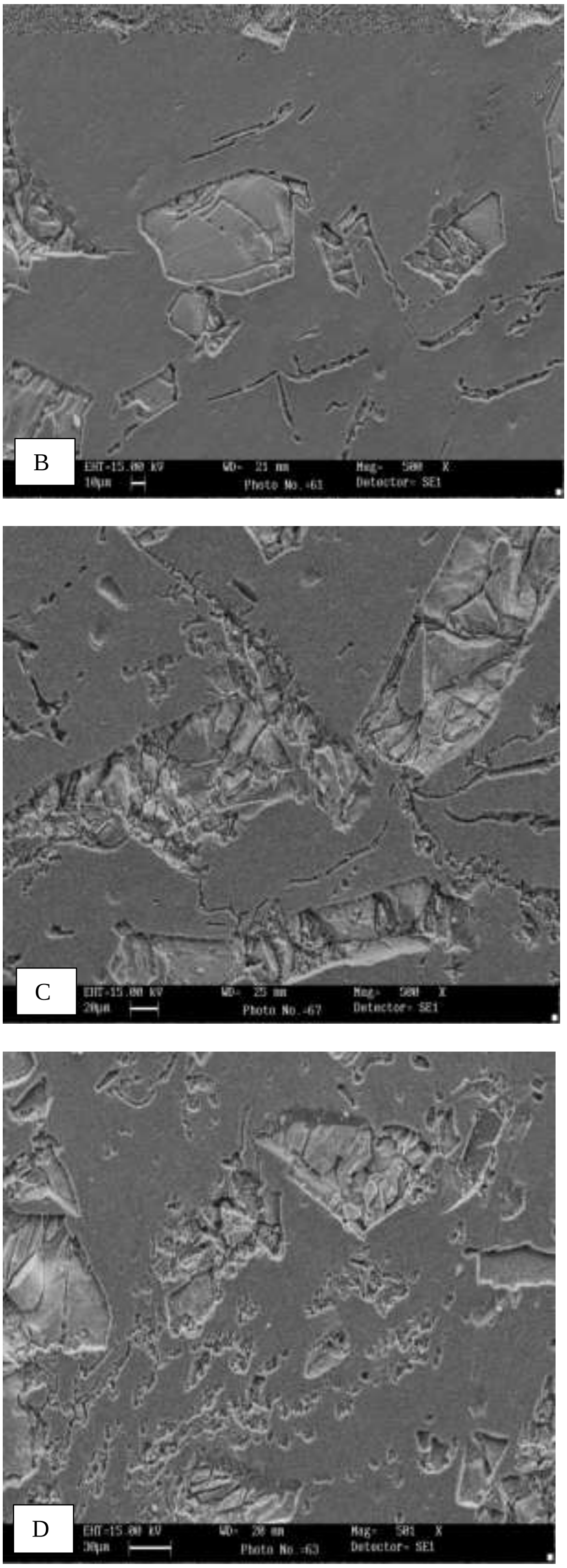
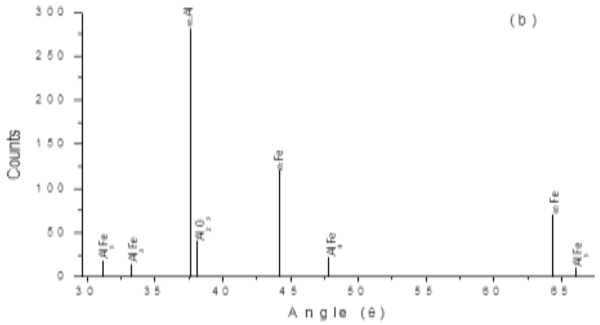


Fig. 9 SEM micrographs of Al-11.2%Fe composite annealed at different temperatures of (a) 200^0C, (b) 300^0C, (c) 400^0C and (d) 500^0C

Friction studies

The character of friction variation with sliding is illustrated in Fig 13. This is graphically representation of result obtained from the friction experiment at a fixed load and sliding velocity. It is evident from the Fig 13the friction coefficient drastically decreases during the running in period. During the steady state period the friction coefficient is being stabilized. The average value of the friction coefficient at normal load is shown in Fig 14. In accordance with the figure the increase of the friction coefficient corresponds to increase the normal load. The increase rate is especially evident for load change from 15 to 30 N.



Figs. 10 XRD of Al-11.2%Fe composites in as-forged and annealed condition showing the peaks of $FeAl_6$ and $FeAl_3$ (a) forged and (b) annealed for 4h at 400^{0}C and $FeAl_3$.

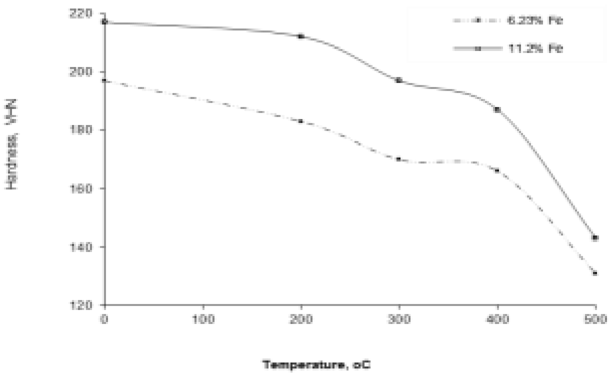


Fig. 11Variation of hardness with temperature of Al-Fe composites annealed for 4h.

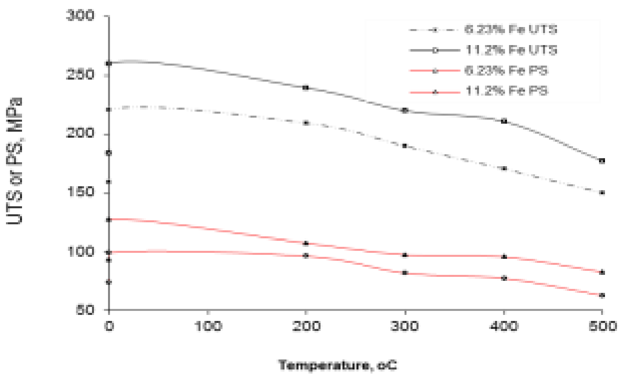


Fig.12Variation of UTS/PS with temperature of Al-Fe composites annealed for 4h.

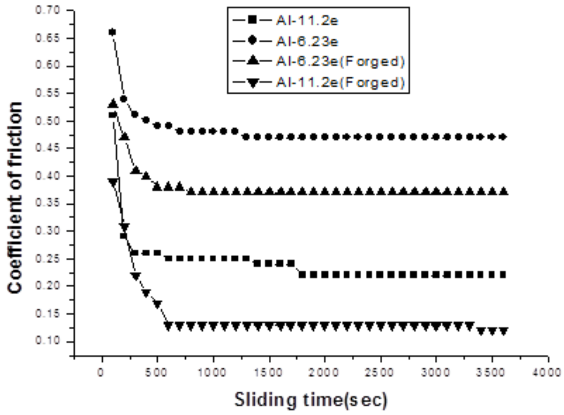


Fig13 Friction coefficient variation of Al-Fe composite during sliding time at fixed specific loads and sliding speeds.

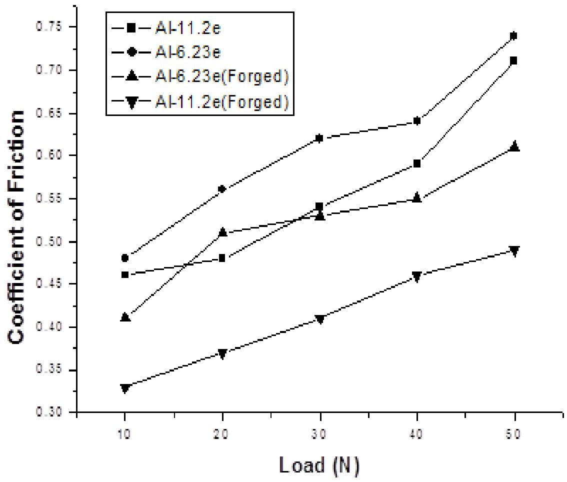
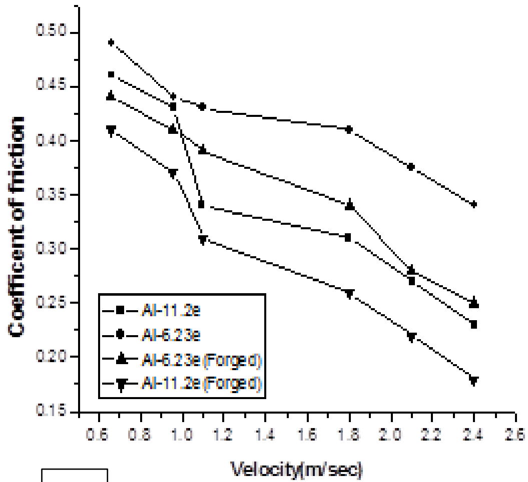


Fig 14 Coefficient of friction vs. applied load for Al-Fe composite



A

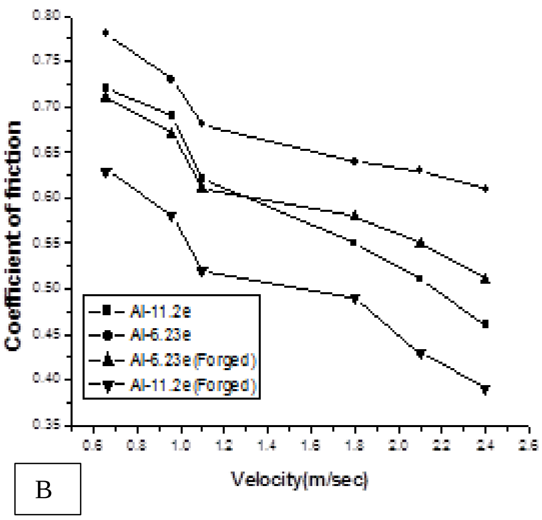


Fig15Friction coefficient vs. sliding speed of Al-Fe composite at different applied loads: (a) 10N (b) 50N

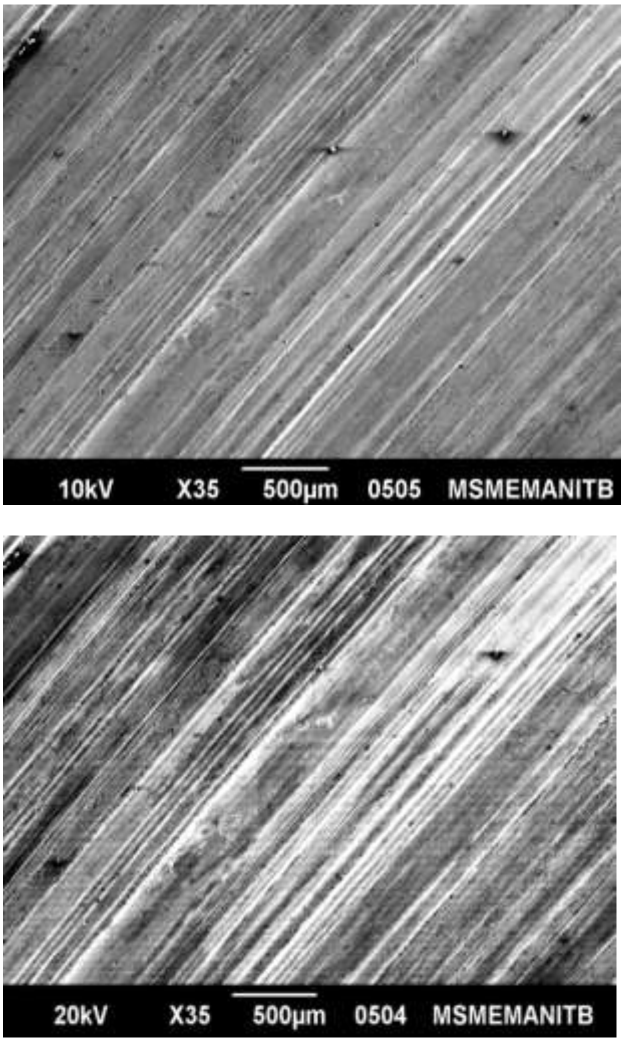


Fig 16 Wear surface of the Al-Fe composite in dry lubricated sliding condition for (a) 20N (b) 50 N of applied load and 0.26 m/s of sliding sp**ee**d

Diagrams in Fig. 15 show the dependence of the steady-state friction coefficient on the sliding speed, for various normal loads in dry sliding conditions. The nature of that dependence, in all the tested composite materials, manifests as decrease of the friction coefficient with increase of the sliding speed. The degree of change is especially prominent in the region of lower values of speeds. Also, in all the tested composite, the friction coefficient increases with increase of the normal load.

The worn surfaces of the samples from the SEM examination are shown in Fig. 21. The worn surfaces of the Al-11.2 wt% Fe samples were noticed to be smoother than those of the Al-11.2%Fe in forged conditions. Generally, the parallel ploughing grooves and scratches can be seen over all the surfaces in the direction of sliding. These grooves and scratches resulted from the ploughing action of asperities on the counter disc of significantly higher hardness.

It can be noticed from the figure that for all the contact loads, the friction coefficient of Al-11.2%Fe in forged condition is found to be low among all the composite. Al-11.2 wt% Fe in forged condition shows the higher hardness and from the metallographic observation FeAl3 is uniformly distributed within the composite. The iron intermetallic has higher hardness and also bears the maximum load. Therefore it acts as lubricant in the materials.

Conclusions

- Iron can be successfully dispersed in aluminum melt by impeller mixing and bottom pouring chill casting technique.
- Forged composite shows higher physical properties as compared to as-cast Al-Fe composite. Due to forging, harder phase like FeAl3 is formed by forging the sample and then cooling immediately.
- From the microstructure, harder phase i.e., FeAl3 and its softer phase i.e.,FeAl6,decomposed due to annealing at different temperature show uniform distribution in the matrix
- Al-Fe composites have superior mechanical properties like UTS, tensile strength, hardness along with superior ductility as compared to almost same compositions range of Al-Si alloys.
- UTS, tensile strength, hardness of the composite decrease with increase the annealing temperature.
- Feasibility study shows that like Al-Si alloys forging Al-Fe composites can make pistons.
- Al-11.2%Fe in forged condition shows the minimum coefficient of friction and Al-6.23% Fe show the higher values.

Reference

L.F.Mondolfo, Structure and Properties of Aluminium Alloys.

E.Rabinowicz(1973)., *Wear* 25, p.375

M.Kawamura., K. Fujita(1983)., *Wear* 89, p.239

S.Mohan and S. Srivastava (2006), Surface Behaviour of As-Cast Al-Fe intermetallic composite, *Tribology Letters*, Vol.22, No.1 April2006

S.Mohan. J. P. Pathak, R.C. Gupta, S. Srivastava (2002), Wear behavior og graphitic aluminium composite sliding under dry conditions.

Aluminum Alloys-contemporary Research and application, Edt. By A. k. Vasudevan, R. D.Doherty, Treatise on material Science and technology, vol.31.

J.A.Nock, Jr. (1947), Division Technical Report, *Alca laboratories.*

J.F. Arhard (1953), Contact and rubbing off flat surface, *J.Appl. Phys*., 24, 981-988,

W. Hrist (1957), In proceeding of the conference on lubrication and wear, *I,ech E*, London 674.

S. Mohan R.C. Gupta and S. Srivastava (2004), Production of Al-Fe composite by Liquid metallurgy for Tribiology Application, *Tribology for Equipment Reliability (ICIT)*, Editor S.K.Swaminathan.

C. Mcl., Adam and J. W. Simon(1983), Influence of microsture on Texture development in an aluminium powder metallurgy alloy, structure/property/Microsture Relationship, *ASM*, Boston33.

P.A.Parkhutik and B.B.Khina (1989), (thermodynamic evaluation of metastable phase in rapidly quenched aluminium-iron alloy), *Respubl*, mezhvuz, "Metllurgiya",Minsk, No.23, 11

H. Biloni, G.F. Bolling (1966), *J. Electrochemical Soc.*1966, vol.1123, pp 7723-78.