Casting and characterisation of Al-1.2Si-Sn alloys

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The aim of this investigation was to disperse tin uniformly and discontinuously in Al-1.2Si alloy matrix and assess the properties of as cast Al-1.2Si-Sn alloy at room temperature. A few compositions of Al-1.2Si-Sn alloys were prepared by impeller mixing and bottom discharge chill casting technique. Microstructure of the as cast alloys was studied under optical microscope. Mechanical properties of the cast products were evaluated at room temperature. Wear characteristics under dry sliding were assessed employing pin-on-disc wear test machine. Uniform and discontinuous dispersion of tin in Al-1.2Si alloy was observed. Tin decreased the strength of Al-1.2Si alloy but enhanced the percentage elongation and wear resistance.

Aluminum is a marginal bearing material, lacking in strength and other required bearing properties. But addition of small quantities of other elements enhances its bearing properties. It has been reported that addition of tin, lead, cadmium, bismuth or indium forms soft low-melting constituent in the alloy which improves the surface quality, enhances wear resistance and reduces frictional forces. On the other hand, nickel, silicon, iron, and manganese produce phases of higher hardness on alloying with aluminum and also impart wear and seizure resistance properties. Common alloying elements such as copper, zinc and magnesium strengthen the aluminum matrix by solid solution and precipitation hardening.

It has been reported that two main categories of Al-Sn alloys have been developed for bearing purpose, viz., low-tin (5.5-7%Sn) and high-tin (20-40% Sn) alloys. Low-tin bearing alloys are of long standing and still widely used in US for high load application such as in aircraft landing gear and in automotive engines. These are usually employed as solid bearing, i.e., without a steel backing, the necessary strength being obtained by alloying combined with heat treatment of a cold worked component. Moreover, small amount of tin in these alloys provides poor antifriction property and insufficient resistance to scoring and seizing but excellent fatigue strength. High-tin (20-40%) alloys were developed to meet the requirement of both strength and surface properties. In practice, a tin content of 20-30% is most widely used, which gives a good compromise between fatigue strength and softness. The alloy that has had the most striking success in Great Britain and rest of Europe is Al-20% Sn, widely used in automotive engines.

However, while casting these alloys tin, solidifies at the grain boundary of aluminum and virtually surrounds the aluminum grains. Such a structure is relatively weak particularly as temperature approaches the melting point of tin, apart from another disadvantage of decreasing ductility. Hence, such alloys are cold rolled, followed by heat treatment to break up the continuous network of tin. The present investigation was aimed to explore the possibilities of using as cast Al-Sn alloys for plain bearings. Attempts were also made to replace copper, which is mostly used in these alloys, by a cheaper hardening element, i.e., silicon. Silicon content of the alloys was kept at 1.2 wt% while the tin content was varied from 10 to 30 wt%. Using impeller mixing and bottom discharge chill-casting, tin was uniformly and discontinuously dispersed in Al-1.2Si alloy. Mechanical properties decreased with tin content while percentage elongation and wear resistance increased.

Experimental Procedure

Experimental materials

To obtain the base alloy of Al-1.2Si, a master alloy of Al-20Si was carefully diluted with commercially pure aluminum. The nominal chemical composition of the base alloy was 1.2 wt% Si, 0.05 wt% Cu, 0.19% Fe and balance Al. Commercial purity tin was added to the base alloy of Al-1.2Si.

Experimental set-up

Modified version of the apparatus (Fig. 1), consists of a cylindrical steel crucible (90 mm inner diameter
and 150 mm long) for melting and holding the metallic charge of 500 g at the required superheat with the help of a surrounding electric resistance furnace. The crucible bottom has a central opening for pouring the mix which is kept closed during melting and mixing by using a stopper rod actuated by a spring loaded lever. To avoid heat losses, open ends of the furnace is closed with cement sheets and the furnace is maintained at controlled temperature by means of a temperature controller and a relay system. The temperature of the melt is continuously monitored with a chromel-alumel thermocouple sheathed in alumina and suspended in the melt. A marine type impeller-mixer is employed which is driven by a variable speed D.C. motor capable of providing rotational speed up to 1450 rpm. The motor is mounted over a disc, which with the help of a chain and pulley system can be raised, lowered and fixed at any desired position. The impeller mixer was specially designed to provide effective mixing of immiscible melts.

The mixer consists of three heat resistant steel bladed impellers mounted at equal spacing of a central shaft. The mixer rotates centrally in a baffled crucible with small clearances between the impellers and the crucible wall. At high speeds of rotation, this design provides very high rates of shear and only axial and radial flow currents are utilised for mixing without any significant vortex formation.

Alloy preparation

Before starting a mixing run, crucible and impellers are coated with asbestos powder slurry and dried well to avoid contamination of iron and other elements in the melt. Measured amounts of commercially pure aluminum and aluminum silicon master alloy for a total weight of 500 g is then charged into the crucible and heated to well above its melting point. The impeller mixer is lowered into the melt (700°C) and rotation provided at required speed. The tin chips about 5 mm in size are charged into the melt through the furnace cover opening (near the central shaft) in required proportion at a rate of 100 g per minute. The drop in the temperature of the melt owing to tin addition is quickly readjusted.

While continuing mixing the melt temperature is brought down by switching off the furnace. The final mixing temperature (630±10°C) which depends on the tin content of the alloy is fixed and mixing continued at this temperature for a definite period of time. The stopper rod is removed and the alloy is poured through the bottom opening provided for the purpose. The above procedure is repeated for various mixing parameters such as time of mixing, temperature and composition of melt. Numerous trial runs were carried out to select the suitable mixing parameters. Basis of selecting final parameters may be elaborated, used in this work are given as.

Start of mixing       = 700°C
Mixing continued and pouring at = (630 ± 10)°C
Speed of rotation  = 900 rpm
Mixing time        = 3-4 min
Alloy composition   = 10-30 wt.% Sn

Metallography of cast ingot

To study the morphology of dispersed phase, i.e., tin in the matrix of Al-1.2Si alloy, the chill cast cylindrical ingots (200 mm length and 25 mm dia) are sectioned in both transverse and longitudinal
directions. These sections are polished by standard metallographic techniques and etched using Kellar's reagent. A Leitz Panphot optical microscope was employed to examine the microstructure of etched section.

**Mechanical properties tests**

Specimen of standard dimensions required for various mechanical tests were machined from the prepared Al-1.2Si-Sn alloy castings. The tensile tests were carried out at room temperature using an Instron Testing Machine. The tests were performed at a cross head speed of 0.5 mm/min using 16 mm gauge length and 4.5 mm diameter specimens. From these tests ultimate tensile strength, 0.2% offset proof stress and percentage elongation were calculated. Compressive test were carried out at room temperature for all compositions of prepared alloy using an Universal Testing Machine with specimens of 10 mm length and 8 mm dia. The stresses at which cracks appeared on the surface of the specimen and the stress for 50% reduction in length were recorded. Vicker's hardness tests were performed on all the specimens using a diamond indenter under a load of 2.5 kg applied for a period of half a minute.

**Wear testing machine**

A modified version of wear test machine previously used by Pathak et al. was employed in the present investigation (Fig. 2). It consists of a heat treated high carbon chromium steel disc connected through a belt and pulley system to a variable speed DC motor capable of rotation speeds up to 1450 rpm. A specimen holder attached to the bottom of a load base pan grips the test pin firmly with its flat end falling against the rotating disc surface. It is loaded normally by means of slotted weights placed at the top of the load base pan centrally through a vertical rod. The arrangement of test specimen on steel disc simulates the actual service conditions since the flat surface of the test specimen in direct contact with the flat surface of the disc is under effective control of the normal applied load. The load base pan can be moved freely up and down as well as forward and backward with the help of a system of guide rods and cross bushes. This facilitates positioning of the test pin on any desired track. To nullify the effect of weight of load base pan, a counter balancing weight device is provided. Most of the parts of this machine are fabricated of gray cast iron to minimise vibrations during working of the machine.

**Wear test procedure**

Cylindrical test pin of 6 mm dia and 30 mm length were machined form the ingot castings. The flat surfaces of both test pin and steel disc were ground to a constant surface finish of approximately 0.40 /-Am. These were thoroughly degreased and dried before commencement of each test. Specimen was initially weighed on a single pan electrical balance (least count 10^-7 kg) which was taken as initial weight. At the end of each wear test, specimen was wiped cleaned of wear particles, degreased and reweighed to get final weight. The difference in initial and final weights of each test pin gave the weight loss from which wear rate was calculated. The latter was studied as a function of sliding distance, normal load, sliding speed and alloy composition. All wear experiments were carried out under non-lubricated condition at room temperature.

**Metallographic examination of wear samples**

It is now fairly established that a metallographic examination of debris and test pin head can yield decisive information about the mechanism of wear damage. Hence, various metallographic examinations were carried out to study the wear behaviour of Al-1.2Si-Sn alloys. The debris collected from the above wear test was examined visually. The colour of
powders and other features like presence of metallic luster was noted. Traces of iron particles were also detected using a magnet and by moving it over the debris. Further, the debris were collected on a white paper and observed under stereographic microscope to record the particle size and shape. The surfaces of the worn test pins were observed under stereo and scanning electron microscopes.

Results and Discussion

Preparation of Al-1.2Si-Sn alloys

The impeller-mixing bottom discharge chill casting technique chosen for the present investigations was found to work quite satisfactorily providing uniform and intimate mixing of the alloy constituents in the solidifying aluminum and rapid cooling of the mix during freezing. The high rate of heat extraction during mould freezing was fast enough to trap molten droplets of tin between the solidifying primary phase dendrites as a homogeneous dispersion. The mixing and pouring temperature (630±10)°C and rotation speed of 900 rpm for a period of 3 to 4 min were found to be the suitable mixing conditions for the alloy under investigations. Castings prepared under such conditions showed uniform and fine cast structures, Figs 3a and 3b. Both transverse and longitudinal sections of the castings showed similar structures and there was no significant difference between the structures at the top and bottom sections of the castings. A higher mixing temperature led to excessive dross formation and developed a relatively coarser structure. Mixing time less than 2 min led to relatively thicker pockets of tin in as cast structure, whereas longer mixing time did not produce any significant improvement in refinement of the above structure. With increase in speed of mixing dendrites of primary phase were progressively refined due to stirring action in the mixing crucible and enhanced rate of heat extraction during freezing caused by vigorous turbulence in the progressively solidifying melt. Figs. 3a and 3b show the optical micrographs of Al-1.2Si-20Sn and Al-1.2Si-30Sn alloys respectively. It can be seen that more or less rounded aluminum rich α-dendrites (light area) are crystallized and tin solidifies in the inter-dendritic regions either as very small globules or patches (black areas). The rounded morphology of the primary aluminum rich α-dendrites may be due to breaking of α-dendrite arms during mixing in the steel crucible and prevalence of turbulence while freezing of liquid in metallic mould.

Table 1—As cast mechanical properties of Al-1.2Si-Sn alloys

<table>
<thead>
<tr>
<th>Wt. % Sn in alloy</th>
<th>UTS (MPa)</th>
<th>0.2% Tensile proof stress (MPa)</th>
<th>Elongation (%)</th>
<th>Stress for crack appearance-compression (MPa)</th>
<th>Stress for 50% reduction compression (MPa)</th>
<th>Hardness (HV)</th>
</tr>
</thead>
<tbody>
<tr>
<td>10</td>
<td>88.06</td>
<td>53.44</td>
<td>8.45</td>
<td>32.82</td>
<td>39.00</td>
<td>35.50</td>
</tr>
<tr>
<td>15</td>
<td>81.50</td>
<td>50.00</td>
<td>10.30</td>
<td>28.45</td>
<td>36.20</td>
<td>32.88</td>
</tr>
<tr>
<td>20</td>
<td>77.00</td>
<td>46.37</td>
<td>14.50</td>
<td>27.05</td>
<td>33.82</td>
<td>30.00</td>
</tr>
<tr>
<td>25</td>
<td>75.00</td>
<td>42.44</td>
<td>17.87</td>
<td>26.26</td>
<td>32.22</td>
<td>28.90</td>
</tr>
<tr>
<td>30</td>
<td>73.50</td>
<td>39.30</td>
<td>20.90</td>
<td>25.07</td>
<td>31.43</td>
<td>26.50</td>
</tr>
</tbody>
</table>
Mechanical properties of Al-1.2Si-Sn alloys

The mechanical properties of as cast samples of prepared compositions are shown in Table 1, as a function of tin content. It can be observed that hardness and strength properties decline whereas, percent elongation improves progressively with increasing tin content. The decrease in hardness and strength properties with increase in tin content is attributed to the fact that tin is a soft and ductile element, it deforms in preference to relatively strong and less plastic matrix (Al-1.2Si) and thus accommodates heavy strain rates. This reduces the stress concentration in the matrix and makes it more deformable. Moreover, tin does not work harden during straining as it recrystallizes below room temperature. Further, the special casting technique employed in this investigation does not allow the development of a continuous network of tin compared to conventional chill casting techniques. The uniform and discontinuous distribution of tin does not embrittle the alloy. All these reasons may account for the increase in room temperature ductility of these alloys with increasing tin content in as cast condition.

Wear characteristics

The first phase of experimental work on wear was to evaluate changes in weight loss with increasing sliding distance, Fig. 4 shows representative results for such evaluation. Similar weight loss versus sliding distance curves were plotted for all alloy compositions. It is observed from all these plots that initially there is a short period of running-in wear, followed by steady state wear during which weight loss and sliding distance vary linearly. This result is similar to wear characteristics of metallic materials reported earlier. In the present investigation, the linear trend of the curves was found to be achieved after a sliding distance of 360-480 m. Hence, a sliding distance of 540 m was selected to study the effect of load and sliding speed on wear. Fig. 5 shows the results obtained for three representative Al-1.2Si-Sn alloys as a function of applied load. It is noticed that, two characteristic regions of wear (Zone I & Zone II) separated by a transition zone are invariably present for all alloy compositions studied. In zone I, the plots are found to be nearly linear and in the transition zone there is drop in wear rate. The transition is found to occur at the same load levels for all compositions. Such patterns of wear rate variation with applied load has also been reported in case of leaded aluminum bearing alloys. Fig. 6 shows variation of wear rate.

Fig. 4—Effect of sliding distance on weight loss of Al-1.2Si-Sn alloys.

Fig. 5—Effect of applied load on wear rate of Al-1.2Si-Sn alloys.

Fig. 6—Effect of sliding speed on wear rate of Al-1.2Si-Sn alloys.
with sliding speed at normal load of 2.0 kg for three representative compositions of Al-1.2Si-Sn alloys. Wear rate initially decreases with increasing sliding speed up to certain limit beyond which there is a rise in wear rate. Similar patterns showing wear rate variation with sliding speed have also been reported in case of leaded aluminum bearing alloys\textsuperscript{3-5} and 60/40 brass\textsuperscript{11}. It is apparent form the Fig. 7 that the wear rate decreased with increasing tin content in Al-1.2Si-Sn alloy under imposed condition of applied load and sliding speed.

Modes of wear

On the basis of observation made from present investigation, it may be envisaged that at beginning of the wear run, asperities of the steel disc impress the relatively hard and strong matrix of the bearing alloy deeper, causing extrusion and smearing of tin over the surface of the test pin. In course of test run tin gradually build-up over the pin surface and some of it is transferred to the steel disc and smeared over the track. Later, uniform film of smeared tin is formed over the entire surface of the pin causing wear to reduce. Some of the tin from the mating surface is swept and it accumulates at the edge of the track. This depleted tin is replaced by further extrusion of tin form the pin surface and is transferred and spreaded over the mating surfaces. Thus, after the running-in wear, there is linear relationship between the wear rate and sliding distance. As sliding generates frictional heat, oxidation of the mating surfaces occur which produces oxides of tin, aluminum and other constituents. Once oxide layer is formed, spalling and fracture of it takes place. However in Zone I all the surface oxides may not be completely destroyed and hence contribute to lower wear through decreased contact between pin and disc surfaces. The drop in the rate of wear in the transition zone is due to the fact that as the applied load increases, tin and or its oxides are smeared over the pin surface which works as a solid lubricant. But as load exceeds a certain value, i.e., the transition load (3 kg), a significant increase in wear rate is observed primarily due to the fact that true area of contact becomes such a large fraction of

Fig. 7—Effect of tin content on wear rate of Al-1.2Si-Sn alloys.

Fig. 8—Stereo micrographs of wear debris of Al-1.2Si-20Sn alloy under 0.8 m/s sliding speed (a) 1.0 kg applied load, (b) 3.0 kg applied load and (c) 4.0 kg applied load.
the apparent contract area that loose wear particle once formed is not able to get away without producing further particles, a self-accelerating process. At this load a gross damage occurs to the pin material and wear takes place largely by adhesion.

When the applied load is kept constant and the sliding speed progressively increased, it is observed that wear rate initially decreases and then increases at a high rate. The decreasing trend may be due to the fact that increasing sliding speed enhances the temperature of the mating surface and thereby promoting formation of protective tin or its oxide films, hence there is less material transfer from the pin to the disc surface. However, when the sliding speed exceeds a certain value, the pin sliding surface becomes quite soft, which is enough to promote local yielding and welding of the latter with the steel disc surface and therefore the wear rate increases.

When the tin content is varied keeping applied load and sliding speed constant, the smearing of tin and or its oxide which works as lubricant layer, becomes more and more uniform with increasing tin content in the alloys and thus the wear rate decreases.

**Metallographic examination**

The visual examination of test pin and wear track indicated that during mild wear, fine black powder was generated between the mating surfaces, which was gradually swept by the pin to form a heap on the edges of wear track. This black powder (Fig. 8a) consists of tin and oxides of tin, aluminium and other constituents. These fine particles appear lumpy due to their flocculating tendency. At lower loads, oxide debris were found dominating and their fineness along with flocculating tendency (Fig. 8b) decreased as amount of load increased. However, at higher speed metallic powders were more dominating than oxides in the debris (Fig. 8c). This was further confirmed as

![Fig. 9](image-url)  
**Fig. 9**—Stereo micrograph of wear of pin surface of Al-1.2Si-20Sn alloy under 1.0 m/s sliding speed (a) at 1.0 kg applied load, (b) at 2.0 kg applied load, (c) at 3.0 kg applied load and (d) at 4.0 kg applied load.

![Fig. 10](image-url)  
**Fig. 10**—Scanning electron micrographs of worn pin surface of Al-1.2Si-20Sn alloy (a) at sliding speed of 0.2 m/s, (b) at sliding speed of 0.6 m/s and (c) at sliding speed of 1.0 m/s.
these debris were coarser and their flocculating tendency was poorer. The wear debris show a transition from oxidative to metallic wear with increasing applied load.

Fig. 11—Scanning electron micrographs of worn pin surfaces of Al-1.2Si-Sn alloys under 2 kg load and 1.0 m/s sliding speed (a) Al-1.2Si-10Sn alloy, (b) Al-1.2Si-20Sn alloy and (c) Al-1.2Si-30Sn alloy.

Further, at low loads under running in wear, surface of the test pin exhibited a progressive build-up of tin (light contrast) spreaded over the entire surface area (Fig. 9a), of the specimen. Degree of ploughing, cracking and spalling of the surface layers increases (Figs 9a-c) as the amount of load increases. However, a massive damage to the surface can be distinctly observed in Zone II as evident form Fig. 9d. This also shows spreading and folding of the test pin edges due to severe plastic deformation.

With increase in sliding speed under constant load, wear rate initially decreases, attains a minimum and then increases. Scanning electron micrographs of worn pin face (Figs 10a-c) corroborates this result obtained under increasing sliding speed. It may be noted that with increase in sliding speed, smearing of tin or its oxides becomes more prominent. Debris generated under various speeds also approve the decreasing or increasing trend of wear rate. At 0.2 m/s sliding speed, debris generated are mostly composed of fine oxide particles with a few metallic particles. But when the speed is increased above 0.8 m/s metallic wear is dominant. This can be clearly adjudged also by the flocculating tendency of the debris as well as distortion and spalling of the oxide layer from the matrix phase. Increase in the uniform distribution of tin and or its oxide films over the test pin surface can be seen in Figs 11a-c with increasing tin content in the Al-1.2Si-Sn alloys.

Conclusions

The results obtained during the present investigation clearly indicate that through impeller mixing bottom discharge chill casting technique, it is possible to disperse tin up to 30 wt% uniformly and discontinuously in Al-1.2Si base alloy. This is remarkably different compared to continuous network type dispersion reported in the literature. The ultimate tensile strength, tensile proof stress, compressive stresses and hardness of Al-1.2Si-Sn alloys decrease with increasing tin content, but percentage elongation of as cast alloy increases with increase in tin. With varying load under constant sliding speed two characteristic zones of wear, separated by a transition zone was found. With increase in sliding speed under constant applied load wear rate initially decreases, it attains a minimum value and then increases with speed. Increase of tin in Al-1.2Si-Sn alloy decreases wear rate. Thus, it may be comprehensively stated that tin acts as an effective solid lubricant for Al-1.2Si alloy.
References