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EFFECTS OF TIN ON HARDNESS, WEAR RATE AND COEFFICIENT OF FRICTION OF CAST CU-NI-SN ALLOYS

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Abstract

An investigation was carried out to understand the effects of Sn on hardness, wear rate and the coefficient of friction of spinodal Cu-Ni-Sn alloys. Alloys of appropriate compositions were melted in a crucible furnace under argon atmosphere and cast into sand moulds. Solution heat treated and aged specimens were tested for hardness, wear rate and the coefficient of friction. It was found that the hardness increases when the Sn content increases from 4% to 8% in the solution heat treated conditions. The peak aging time is found to decrease with an increase in the Sn content. Further, the coefficient of friction is independent of hardness whereas the wear rate decreases linearly with hardness irrespective of Sn content.

Keywords: Cu-Ni-Sn alloy, Coefficient of friction, Spinodal decomposition, Wear rate, Heat treatment.

1. Introduction

The strength of materials can be enhanced by using various common techniques such as grain size refinement, strain hardening, solid solution hardening, quench hardening, dispersion strengthening and precipitation hardening [1]. Spinodal hardening is an emerging technique by which the strength of bronze alloys can also be enhanced [2-5]. It refers to a process in which a supersaturated solid solution decomposes into solute-rich and solute-depleted regions when it is aged at a suitable temperature [6]. As a result, a modulated structure forms within the solid and subsequent aging results in the formation of an ordered structure [6-8]. The strain field around the modulated structure produced by spinodal decomposition along with the ordered structure impedes the dislocation motion and thereby causes hardening to occur [5]. During the aging process, it has been

Nomenclatures

Cu	Copper
DO_{22}	Microstructure of ordering reaction
DO_3	Microstructure of grain boundary precipitates
HR_C	Rockwell Hardness in C scale
Ni	Nickel
R_a	Roughness average value
Sn	Tin
wt.%	Weight Percentage
Greek Symbols	
α	Alpha phase
μ	Coefficient of friction

reported that the strength of the alloy increases up to three times depending on (i) alloy composition (ii) amount of cold work prior to aging and (iii) aging temperature [4].

A number of studies were conducted on spinodal bronze (Cu-Ni-Sn) alloys to assess the microstructures and the mechanical properties, but a limited studies were conducted to determine the wear behavior as these alloys are potential candidates likely to be used in high performance wear applications [9, 10]. Deyong et al. have reported the effect of Sn content on the hardness of Cu-Ni-Sn alloys while keeping Ni fixed at 10 wt. % [11]. Zhang et al. [9, 10] have studied the wear behavior of Cu-15Ni-8Sn spinodal alloy in relation to the hardness whereas Singh et al. [12] have investigated the wear behavior of Cu-15Ni-8Sn alloy with respect to the type of debris that formed during wear testing. Further, Deyong et al. [11] have used both rapid and normal cooling method to prepare their alloys. They have specified melt-spinning as the technique to obtain extremely high cooling rate while they have not stated how they made the normal cooling rate alloys.

Since Cu-Ni-Sn alloys are likely candidates to be used in bearings, wear plates etc., in critical applications, it is necessary to evaluate the wear behavior with respect to various alloy compositions, aging temperature and time. Since casting is the most economical manufacturing process, an investigation with reference to a specific casting method is highly warranted. This will lead to wide application for these alloys. Therefore, in this present study, the effects of Sn on hardness, wear rate and the coefficient of friction of Cu-Ni-Sn alloys while keeping Ni content constant is discussed. Additional information sought in this work is the contributing effect of Sn to the spinodal process when it is increased from a low to a high concentration. Further, green sand casting method has been used to make the specimens for this study.

2. Experimental Procedures

The sand mould was prepared by using metal pattern. Cu-Ni-Sn alloys of compositions Cu-6Ni-4Sn, Cu-6Ni-6Sn and Cu-6Ni-8Sn were melted in a graphite crucible using a muffle type melting furnace under inert argon atmosphere. The molten metal was poured at 1250°C into the sand molds. The cast specimens were of the size diameter 0.016 m × 0.15 m lengths. After the casting process, the chemical compositions of the castings were analyzed using spectrometer. The spectroscopy results are reported in Table 1. The alloy compositions were found to be within a variation of ± 0.2 wt. % from the nominal composition.

Table 1. Spectroscopy Results of the Alloy Compositions.

Element	Cu-6Ni-4Sn	Cu-6Ni-6Sn	Cu-6Ni-8Sn
Ni	6.2	6.2	6.2
Sn	3.9	5.8	8.0
Cu	Balance	Balance	Balance

The cast specimens were homogenized at 820°C for 10 hours and cooled in the furnace itself. Solution heat-treatment was performed for 1 hour at 820°C and rapidly quenched in water in order to maintain the α phase (solid solution of Sn and Ni in Cu) in the supersaturated condition. Solution heat treated specimens were then aged for 1 to 5 hours at 350±5°C and water quenched. All the above heat treatment procedures were performed under inert nitrogen atmosphere. Test specimens were prepared from as cast, homogenized, solution treated and aged conditions for various measurements.

The Mitutoyo make (USA) hardness tester was used to measure the micro-hardness of the specimens at various locations and an average value was calculated from several readings.

The specimens required for friction and wear tests were machined to a size of diameter 0.01m × 0.035 m lengths. The Ducom make (Bangalore, India) pin-on-disc tribometer was used to conduct the test in dry sliding condition in air. The counter-part rotating disc was made from EN31 alloy steel stock and hardened to 63 HR_C with surface roughness of Ra 0.15 μm. Table 2 shows the fixed parameters used for conducting the tests.

Table 2. Friction and Wear Testing Parameters.

Test Parameters	Unit	Test Values
Speed	rpm	636
Velocity	m/s	3
Track Radius	m	0.045
Time	s	600
Sliding Distance	m	1800
Load Applied	N	20

Following were determined using the data obtained from the data acquisition system available in the tribometer: (i) height loss, μm versus time, sec (ii) coefficient of friction versus time, sec and (iii) frictional force versus time, sec. The wear rate expressed as m^3/m (volume loss per meter sliding distance).

Carl-Zeiss Inverted Metallurgical Microscope (Germany) with a CCD camera attachment was used for the microscopic study. Standard metallographic procedure was used for the specimen preparation and etched.

3. Results and Discussion

A typical as-cast dendritic microstructure of Cu-6Ni-8Sn alloy is shown in Fig. 1. The dendritic structure was fully eliminated by the homogenization and the solution heat treatments as shown in Fig. 2.

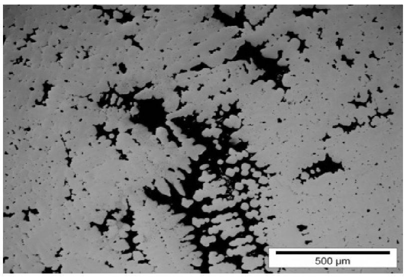

Fig. 1. Typical As-Cast Microstructure of Cu-6Ni-8Sn Alloy.

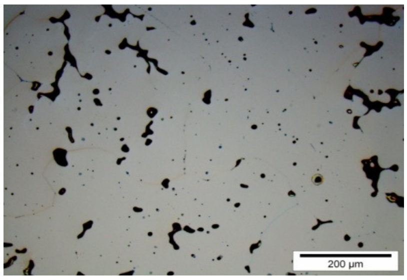

Fig.2 Typical homogenized and Solution Heat Treated Microstructure of Cu-6Ni-8Sn Alloy.

As reported previously, the spinodal decomposition (modulated structure) and an ordering reaction (DO_{22} structure) takes place during the aging process [4, 6-8]. The modulated and the ordered structures are very fine and cannot be resolved by the optical microscopy [9].

Figure 3 shows the microstructure of Cu-6Ni-8Sn alloy aged for 3 hours. When the specimen is over-aged, precipitates started to form along the grain boundaries, an observation in agreement with that of Zhang et al. in the case of Cu-15Ni-8Sn alloy [9]. It has been reported that the grain boundary precipitates are equilibrium α and γ (DO_3) phases [4, 6, 7, 9] and completely fills the structure upon prolonged aging [9]. We have aged our specimens for a short period and therefore Fig. 3 does not show complete filling with equilibrium phases. Further, Zhang et al. [9] have noted that equilibrium precipitates form within one hour of aging whereas it took three hours in our case and the difference in this behavior is attributed to the difference in the Ni content.

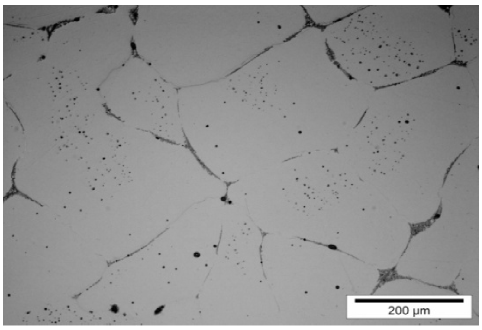

Fig. 3. Microstructure of 3 Hours Aged Cu-6Ni-8Sn Alloy Showing Grain Boundary Precipitates.

Figure 4 shows the variation in the hardness of Cu-6Ni-xSn alloys as a function of aging time. As the aging progresses, the hardness increases, reaches a maximum and decreases as can be noted in Fig. 4. The variation in the hardness is attributed to the change in microstructure of the specimen during aging. The formation of modulated and ordered meta-stable (DO_{22}) structures increases the hardness to a maximum value during the aging process and subsequently, the formation of grain boundary precipitates (equilibrium α and γ (DO_3)) reduces the hardness [4, 6, 7, 9].The trend observed in this study is in agreement with that of Zhang et al. [9] for Cu-15Ni-8Sn alloy and Deyong et al. [11]. Therefore, it can be concluded that the hardness of a given alloy is dependent on the aging time.

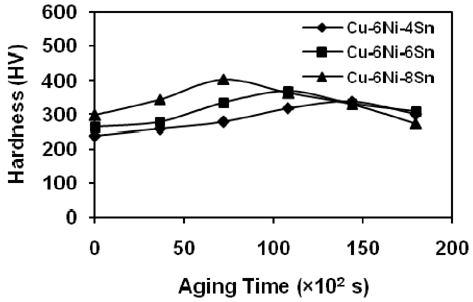

Fig. 4. Variation of Hardness with Aging Time.

Figure 5 shows the variation of peak hardness with Sn content of this study. Included in the figure are the data of Deyong et al. [11] taken from their results pertaining to (i) rapid solidification by melting spinning (Data -1) and (ii) conventional ingot casting (Data-2) for aging at 400°C of various alloys having 6, 8, 10, 12 wt. percentages of Sn with fixed Ni content of 10 wt. %. It is observed from the plot that in all the three cases the peak hardness increases with Sn content. The behavior observed in this study is in agreement with Deyong et al. data 1 and 2. Also it is to be noted that the magnitude of the peak hardness observed is marginally different from each other and this difference is attributed to the difference in Ni content and aging temperature. Therefore, it is concluded from the results that an increase in Sn content increases the peak hardness of the alloy.

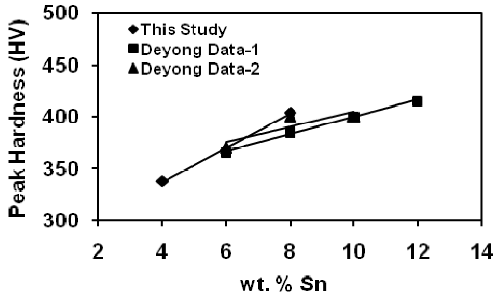

Fig. 5. Variation of Peak Hardness with Sn Content.

The variation of the peak aging time is plotted against the Sn content in Fig. 6 along with the data of Deyong et al. taken from their results. It is observed from Fig. 6 that the peak aging time decreases when Sn content increases in all the three cases. It is observed for a particular wt. % Sn alloy, the peak aging time marginally varies between this study and that of Deyong et al. This variation may be due to the variation in the Ni content between these two studies (this study-6% Ni and Deyong-10% Ni). So we may conclude from this result that an increase in Sn content reduces the peak aging time of the alloy. However, it is not clear from the studies whether rapid solidification contributes to a decrease in the peak aging time or not. Hence, a further study to assess the effect of cooling rate on the aging time is necessary.

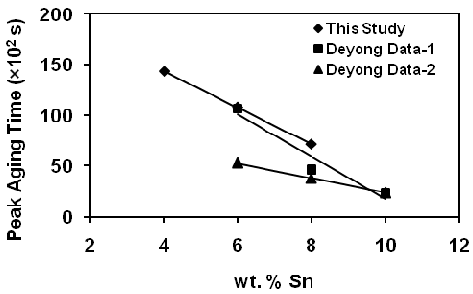

Fig. 6. Variation of Peak Aging Time with Sn Content.

In order to know the effect of Sn on the hardening process, it is necessary to look at two different aspects of strengthening mechanisms: (i) solid solution hardening due to dissolved Sn solutes in the matrix, (ii) spinodal hardening due to the formation of modulated structure along with ordering reaction. As a way to deduce the contribution by Case (i) from the experimental values, we have plotted the hardness against the Sn content in the solution treated condition as shown in Fig. 7. It can be seen from the figure that the hardness increases with the Sn content, thereby illustrating its contributing effect to the solution hardening aspect. Next, we have also plotted the experimental values pertaining to aging treatment in the same figure (Fig. 7) in order to assess the Sn contribution to the spinodal hardening, Case (ii). In the Case (ii) also, the peak hardness increases with the Sn content. An important point to be noted is that the trend lines for both cases are almost parallel and therefore, it can be inferred that there is no incremental contribution due to spinodal hardening by increasing the Sn content from 4 to 8 wt%.

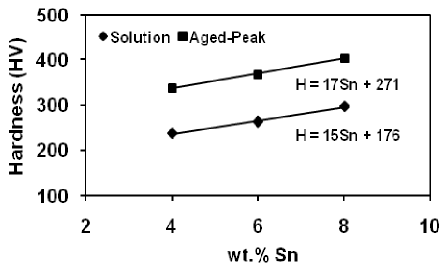

Fig. 7. Variation of Hardness with Sn Content (This Study).

Figure 8 shows the same type of trend lines corresponding to Cases (i) and (ii) for the data of Delong et al. in the case of rapidly solidified ribbons of Cu-Ni-Sn alloys and these lines are also parallel to each other. Based on the results of this study and the data of Delong et al., it can be concluded that (i) Sn induces spinodal hardening when its content is around 4 wt. %, (ii) further increase in the

Sn content does not contribute significantly to the increase in hardness due spinodal/order hardening and (iii) Sn contributes significantly to the increase in hardness due solution hardening effect.

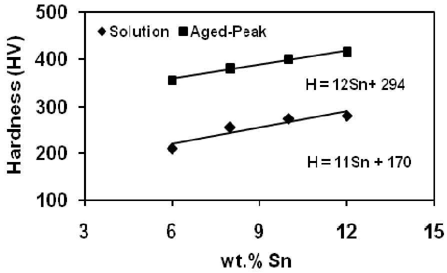

Fig. 8. Variation of Hardness with Sn Content (Deyong Data-1).

Frictional force versus time plot (Fig. 9) of Cu-6Ni-8Sn alloy shows that the frictional force remains constant after a short period of time. The frictional force initially increases rapidly due to uneven contact between specimen and counterpart mating surface. Once perfect contact is achieved, the frictional force remains constant.

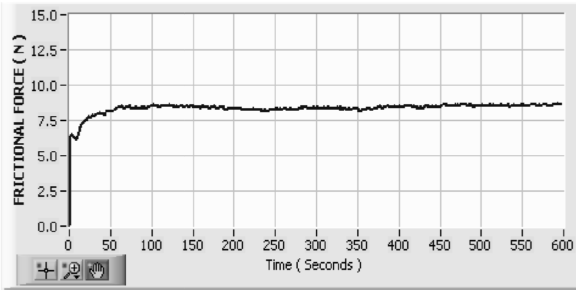

Fig. 9. Frictional Force vs. Time Plot.

A typical plot of coefficient of friction (μ) versus time for Cu-6Ni-8Sn alloy is shown in Fig. 10. The plot shows both transient period and single steady-state regime. The effect of work-hardening and/or accumulation of debris may be the reasons for the transient behavior [12]. The COF value is constant and is equal to around 0.43 as shown in Fig. 10.

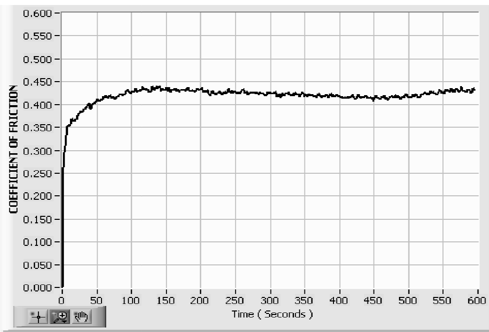

Fig. 10. Coefficient of Friction vs. Time Plot.

Figure 11 shows the variation of COF with hardness of Cu-6Ni-xSn alloys. The value of COF is found to be around 0.43 with marginal variation. Hardness of the alloy does not affect the COF value. An observation of this study is in agreement with that of Zhang et al. [9, 10] and Singh et al. [12]. It is also to be noted that the COF value differ from each author (Singh:0.3 and Zhang:0.7), which may be due to use of different counter face materials and its hardness, surface finish, working atmosphere etc. Hence, we may conclude from the results that COF value is not affected by the hardness of the alloy. The present study, in line with the previous research findings in this regard, indicates that there is no need for aging treatment for Cu-Ni-Sn alloys, if COF is the only factor to be maintained /specified.

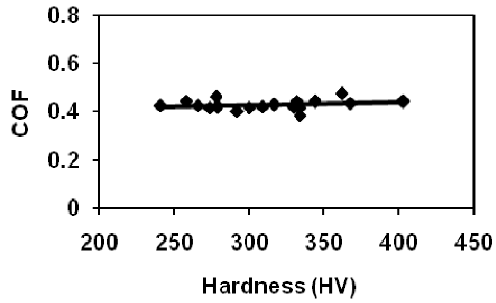

Fig. 11. Variation of COF with Hardness.

Wear versus time plot (Fig. 12) of Cu-6Ni-8Sn alloy shows that the wear linearly increases with sliding time. This behavior is in agreement with that of Singh et al. [12].

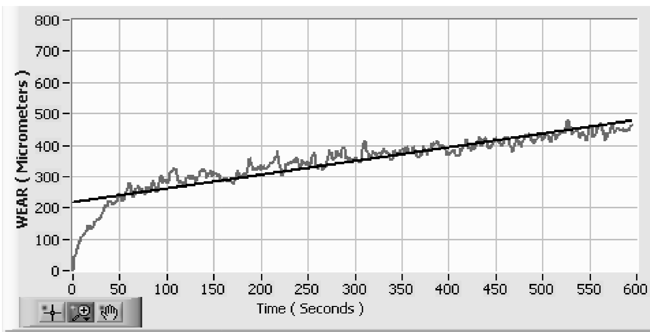

Fig. 12. A Typical Wear vs. Time Plot of Cu-6Ni-8Sn Alloy.

Figure 13 shows the variation of wear rate with aging time of Cu-6Ni-xSn alloys. It is observed from the figure that the wear rate varies with both aging time and alloy compositions. The variation in wear rate corresponds to hardness of the alloy, which varies with aging time. The behavior observed in this study is consistent with that of Zhang. Therefore, it is concluded from the result that the addition of Sn content reduces wear rate by increasing the hardness and wear rate varies with aging time in the case of Cu-Ni-Sn alloy system.

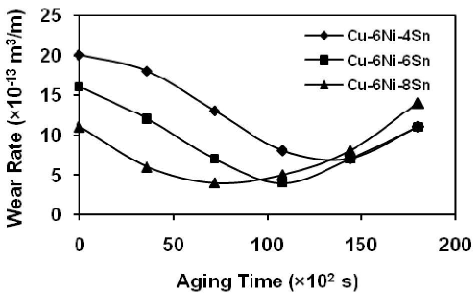

Fig. 13. Variation of Wear Rate with Aging Time.

Figure 14 shows a set of wear rate data obtained under solution heat treated and various aging conditions of the Cu-6Ni-xSn alloys that has been plotted against hardness. The trend line shows that the wear rate decreases with hardness of the alloy and follows the adhesion theory of wear proposed by Archard [13].

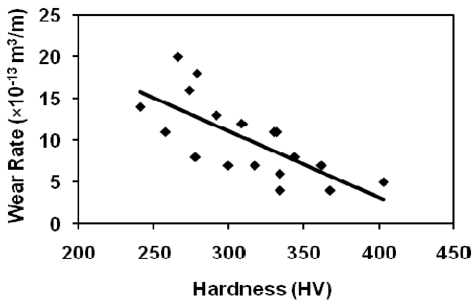

Fig. 14. Variation of Wear Rate with Hardness.

4. Conclusions

Following conclusions were made based on the results of this study: Sn induces spinodal decomposition of supersaturated solid solution during aging when it is present in the amount of around 4wt. % in the sand cast specimens of Cu-Ni-Sn alloys; further increase of Sn content from 4 upto 8wt. % does not contribute significantly to the spinodal/order hardening; Sn contributes significantly to the solution hardening; the peak aging time decreases with increase in Sn content; the coefficient of friction is independent of hardness and remains around a value of 0.43; the wear rate decreases linearly with hardness irrespective of Sn content.

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