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Structure and Properties of the Al-Sn-Cu Bearing Alloy under Different Cold Rolling Conditions

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Abstract: This study was focused on the investigation of the effect of cold rolling reduction mechanism at rates of 24%, 40%, 56% and 72% on the structure, microhardness (Hv), TEC (Thermal expansion coefficient) and electrical resistivity of the Al-20wt.%Sn-1wt.%Cu bearing alloy. The results showed that the structure and properties of the Al-Sn-Cu alloy have been strongly affected by the cold rolling mechanism. The crystallite size of Al-matrix decreased continuously with increasing cold rolling reduction till 56% then slightly increased at 72% reduction. Microhardness of the alloy increased continually with cold rolling deformation till 56% due to strain hardening followed by a reduction at 72% due to the natural softening. The TEC curves of the cold rolled samples showed the lowest TEC obtained for 56% cold rolling reduction at 230 °C. Electrical resistivity increased continuously with increasing cold rolling reduction.

Key words: Bearing alloys, microstructure, TEC (Thermal expansion coefficient), microhardness, electrical resistivity.

1. Introduction

Due to their good antifriction properties [1-3] and improvement of mechanical properties with additional alloying elements [4], engineering applications of the Al-Sn alloys have been increased. These alloys are usually related to plain bearing materials, internal combustion engine pistons, cylinder liners [1, 3, 5] and also as advanced lead-free materials [6].

Tin as an alloying element with aluminum casting alloys has the purpose of reducing friction in bearing and bushing applications [7], because tin phase in these alloys melts at a very low temperature (227.7 °C) and can exude under emergency conditions to provide short-term lubrication to rubbing surfaces if such bearings/bushings severely overheat in service [7].

On the other hand, Cu has been traditionally added in bearing alloys to provide solid solution strengthening of the Al matrix which improved its resistance to fatigue failure. The combination of the two elements additions producing alloys appropriate for bearing applications [8, 9].

Production of aluminum alloys generally involves with casting scalping homogenizing and hot rolling until the desired dimensions are obtained. Further processing such as cold rolling and annealing are applied to get both desired mechanical and physical properties [10]. Most automotive piston engines are currently running at service temperatures of up to 350 °C, with diesel engines running even hotter. Therefore, thermal stresses can be generated from the thermal expansion misfit between matrix and intermetallic during the cooling or heating and promote microstructure damage processes, such as particle cracking [11, 12].

However, few documents dealt with the relation between Hv and TEC for cold rolled Al-Sn-Cu alloys. The aim of this work is to investigate the influence of cold rolling on the microstructure, mechanical and thermal properties of Al-20wt.%Sn-1wt.%Cu ternary bearing alloy.

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2. Experimental Procedures

The used material in this investigation is the Al-20wt.%Sn-1wt.%Cu ternary alloy. It was obtained by the Diesel Motors Military factories of Egypt. Table 1 shows the chemical composition of this alloy. The as-received sample has a rod form of 12.5 mm thickness. It was cold rolled at room temperature for various extends of thickness reduction as following 24%, 40%, 56% and 72%. After deformation, the samples were cut into specimens of 40 mm long and 10 mm wide. X-ray diffraction technique with Cu-Kα radiation was used to identify the structure of the deformed samples. TEC (Thermal expansion coefficient) of the alloy samples was calculated by heating the samples in the range of 25 to 600 °C at constant rate of 10 °C/min using dilatometer (Linseis-76) [13]. The melting reaction was determined using Shimadzu DSC-50 (Differential scanning calorimetry) in the temperature range between 25 to 600 °C at a heating rate of 10 °C/min. Environmental Scanning Electron Microscope (FEI-S) was used for microstructure analyses of the alloy samples after polishing and etching in a solution of 5% HF in dilute water. Microhardness (Hv) measurements were carried out using a Vickers micro-hardness tester with a load of 1.96 N/mm^2 at 5 s. Electrical resistivity measurement was carried out using Hioki 3522-50LCR Hitester (Bridge) at room temperature.

3. Results and Discussion

3.1 X-Ray Diffraction

The structural evolution during cold rolling process of the Al-20Sn-1Cu cold rolled alloy samples is shown in Fig. 1. The pattern for the as-received sample is taken as a reference condition, where the

Table 1 Chemical composition in wt.% of the Al-20Sn-1Cu alloy.

Al	Total others	Ti	Mn	Si	Fe	Ni	Cu	Sn
Balance	0.5%	-	0.1%	0.7%	0.7%	-	0.7 – 1.3%	17.5 – 22.5%

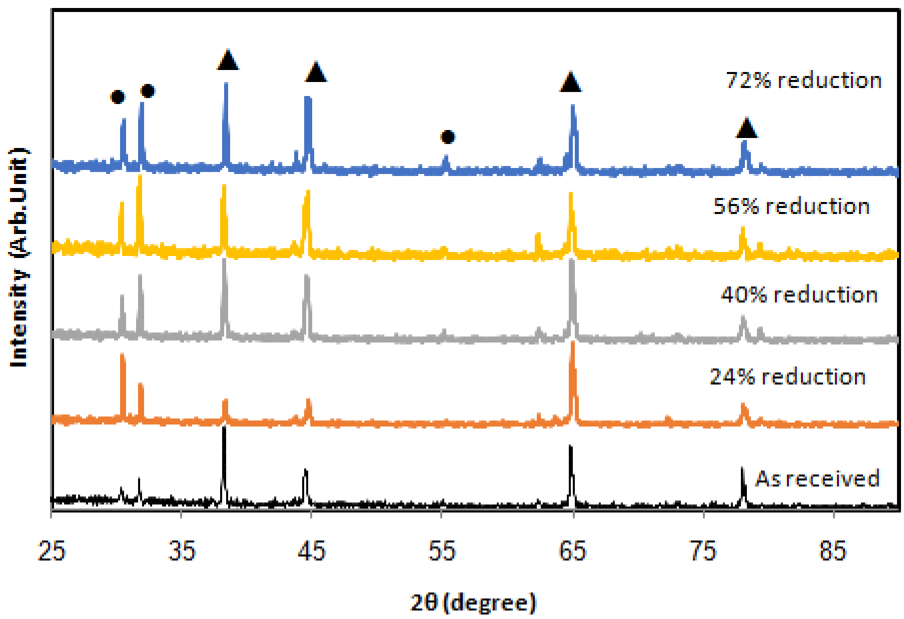

Fig. 1 XRD (X-ray diffraction) patterns of the Al-20Sn-1Cu alloy under the cold rolling conditions.

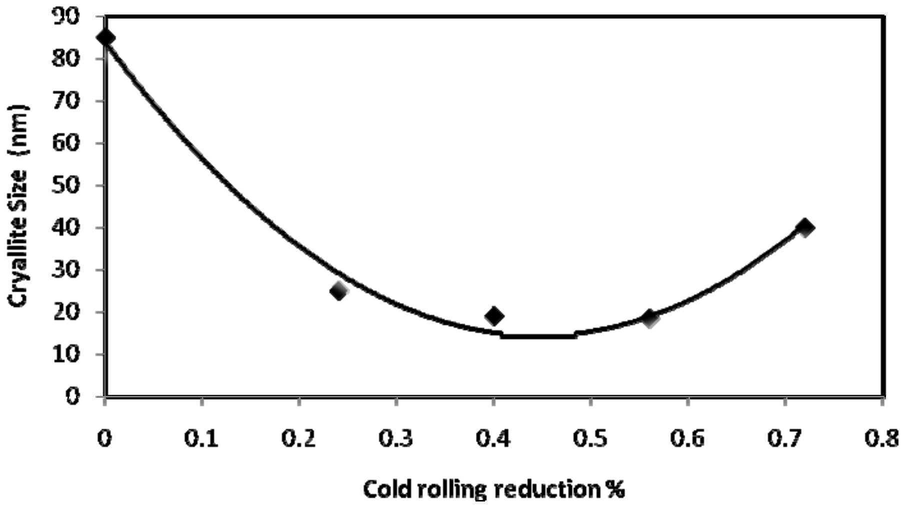

Fig. 2 Crystal size of the Al matrix of the Al-20Sn-1Cu alloy versus cold rolling reduction.

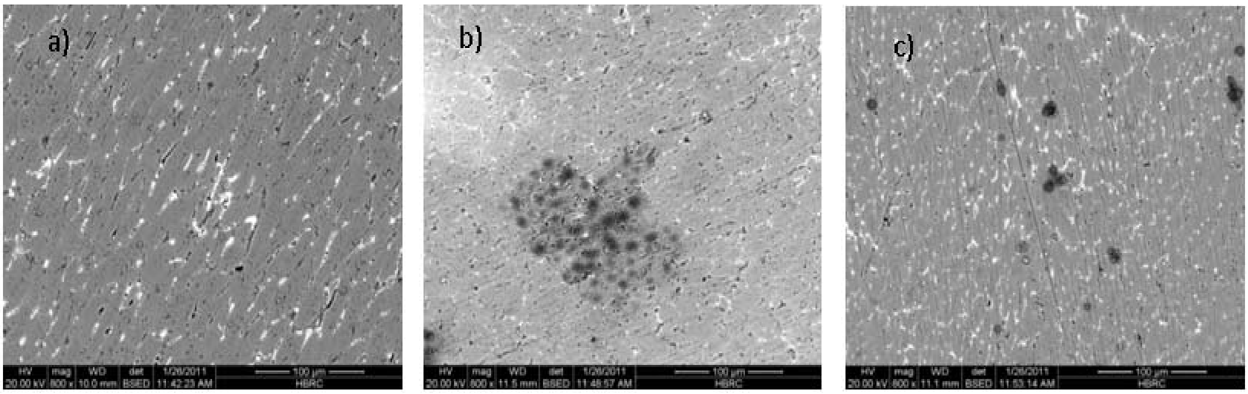

Fig. 3 SEM of the Al-20Sn-1Cu alloy at (a) as-received, (b) cold rolled to 56% and (c) cold rolled to 72% reduction.

diffraction peaks of initial components appear as the cubic Al-matrix phase, tetragonal Sn as a secondary phase, while the cu atoms was dissolved in Al-matrix and form orthorhombic $Al_9Cu_{11.5}$ intermetallic compound. The intensities of diffraction peaks of Sn are lower than that of Al diffraction peaks because of its small amounts in overall composition. The effect of cold rolling is restricted only on the lattice strain and crystallite size [14]. The crystallite size of Al-matrix decreased continuously with increasing cold rolling reduction till 56% then slightly increased at 72% reduction as shown in Fig. 2. Actually, cold rolling process may cause an increase in dislocation density then caused the lattice to be strained. Such an array of dislocations gives rise to a substantial strain energy stored in the lattice.

3.2 Microstructure

Fig. 3 shows the SEM (Scanning electron microscopy) images of the Al-20Sn-1Cu alloy as a function of amount of cold rolling reduction (as-received, 56% and 72%). For the as-received alloy sample as shown in Fig. 3a, the microstructure indicates a continuous tin-rich eutectic occurring as isolated films or pools in addition to spheroidising $Al_9Cu_{11.5}$ intermetallic compound. For the alloy sample rolled to 56% reduction as shown in Fig. 3b, there is some agglomeration of coarse $Al_9Cu_{11.5}$, while for 72% reduction by cold rolling (Fig. 3c), the $Al_9Cu_{11.5}$ particles are broken into small interconnected particles. It appears that as a result of extensive cold rolling, the dislocation density continuously increases while the second phase decreases, developing a final microstructure in micro scale.

3.3 Microhardness

The evolution of microhardness measurements as a function of the amount of cold rolling were carried out at room temperature as shown in Fig. 4. The Vickers microhardness, Hv increases continually with increasing amounts of cold rolling reduction until maximum value of 73 N/mm^2 at 56% reduction then decreases to 67 N/mm^2 at 72% reduction in opposite manner with the crystallite size of Al matrix of the Al-20Sn-1Cu alloy. This can be explained by the fact that, cold rolling breaks down the Al-Cu compound and increases the rate of distribution $Al_9Cu_{11.5}$. The higher dislocation the greater density is created by cold rolling and will occur via drive force to diffuse the solute atoms and with creating more nucleation sites [15]. Sn atoms are larger size than Al atoms and they may collect Cu atoms around them to reduce the strain energy [16]. Hence, the number of Cu atoms available to the G-B zone formation is reduced, and then a decrease in the age hardening at 72% cold rolling reduction is happened.

3.4 Thermal Properties

To clarify the phases of the Al-20Sn-1Cu alloy, the DSC curve of the alloy is shown in Fig. 5. It is clearly seen that there are two endothermic peaks at 230 °C and 639 °C regarding to the melting point of Sn and Al metals respectively. It is believed that the interatomic distance of metals and alloys increases as temperature increase, which may cause the thermal expansion phenomenon. Whereas, there are sudden changes with changing temperature in Al and Sn melts resultant a decrease in the nearest interatomic distances with increasing temperature [17].

The thermal expansion coefficient as a function of temperature for cold rolled samples is shown in Fig. 6. It is clear that TEC of the starting sample is higher than those of the cold rolled samples within the entire temperature range. Additionally, TEC at 56% cold rolling sample has the lowest value compared with the others. From the curve, a sudden thermal contraction is observed especially for 56% and 72% reduction (with less extent) than other cold rolled samples. At temperature higher than 230 °C, the TEC behavior of all rolled samples increase with increasing temperature.

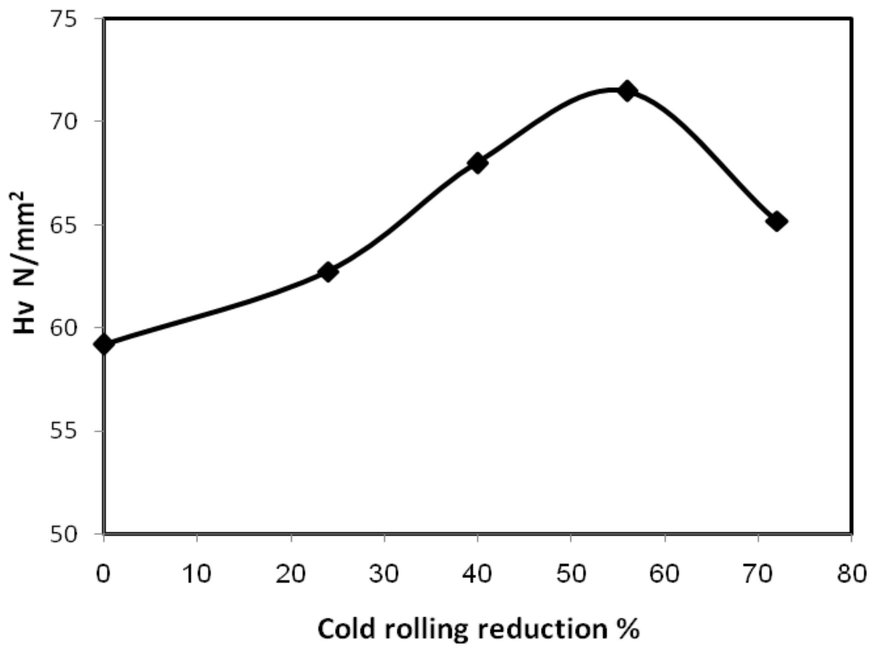

Fig. 4 Variation of microhardness (Hv) of the Al-20Sn-1Cu alloy with cold rolling reduction.

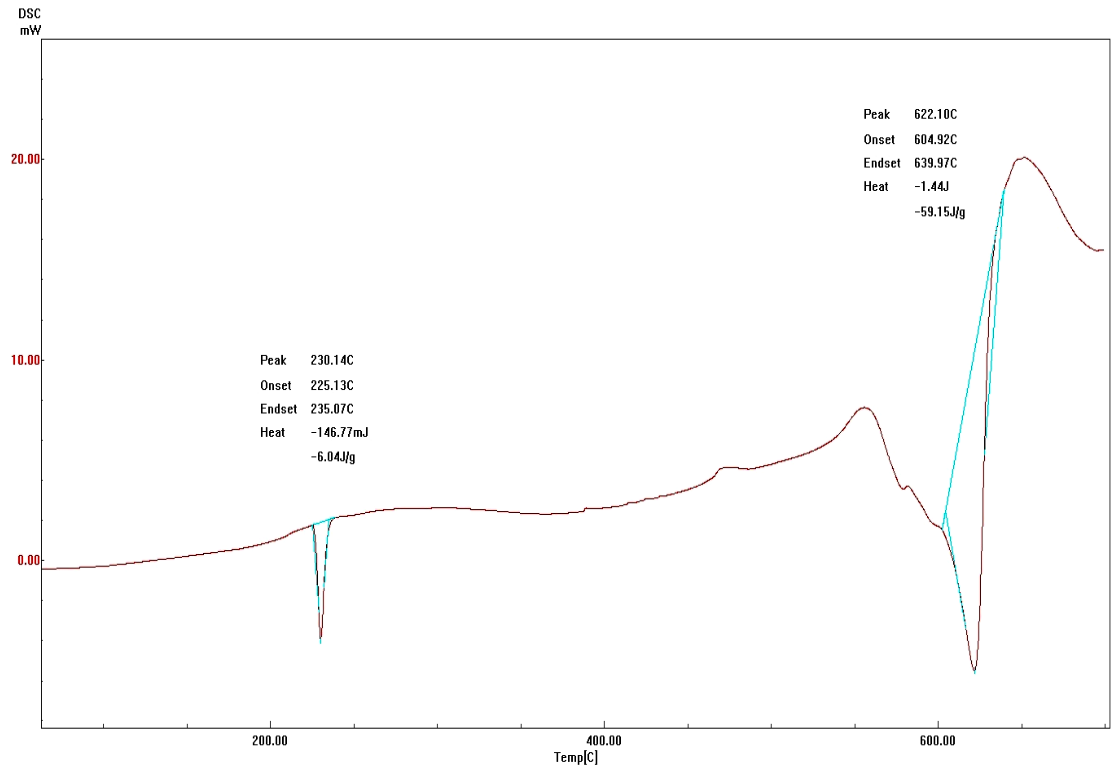

Fig. 5 DSC curve of the Al-20Sn-1Cu alloy.

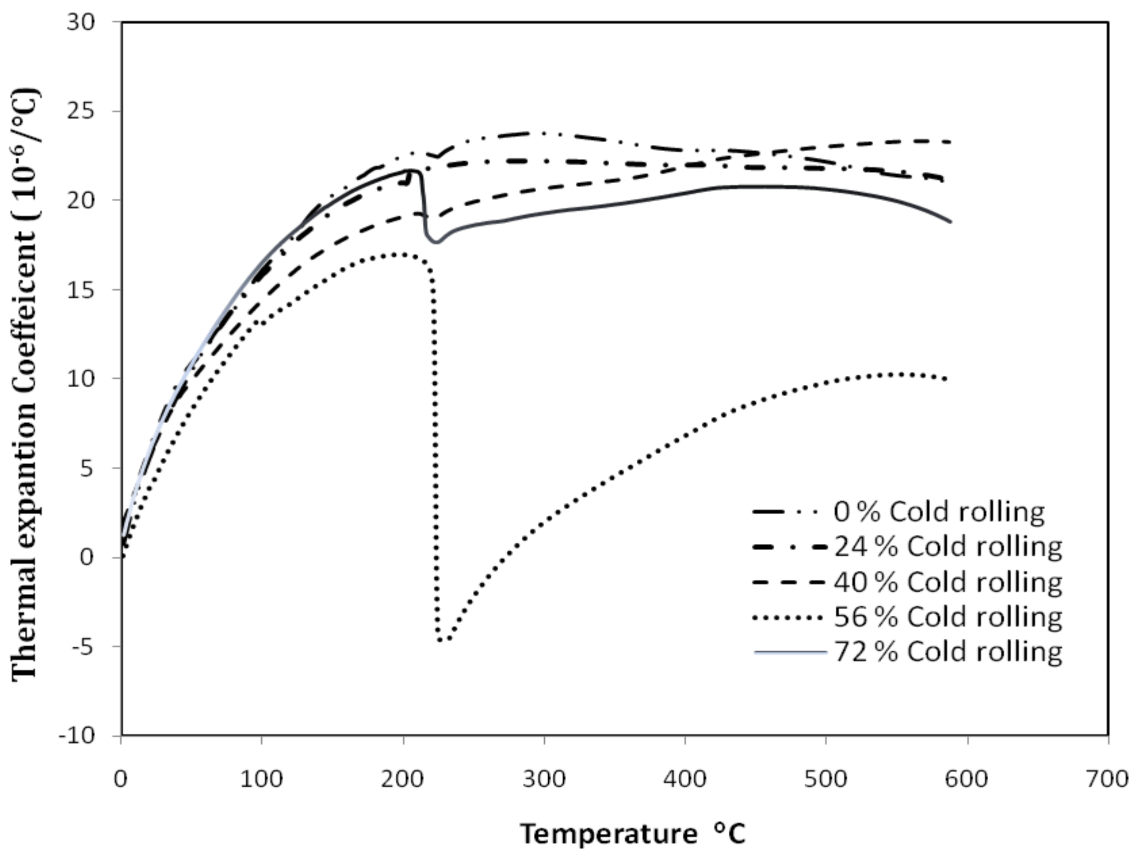

Fig. 6 Thermal expansion coefficient versus temperature of the Al-20Sn-1Cu cold rolling alloy samples.

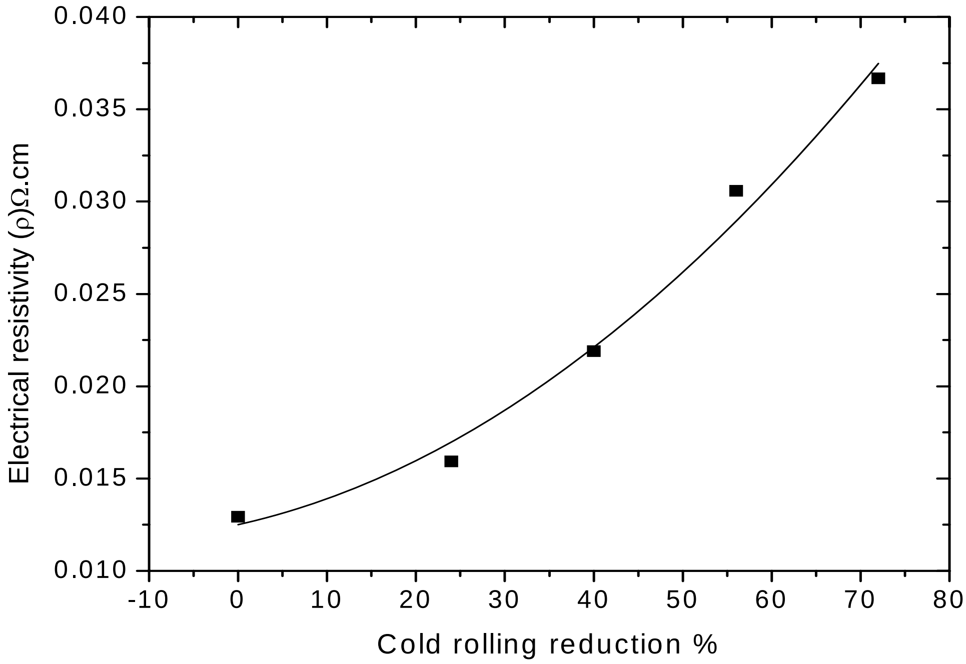

Fig. 7 Electrical resistivity of the Al-20Sn-1Cu alloy versus cold rolling reduction.

For most face - centered cubic or hexagonal close-packed structures metals, the TEC is related inversely to the melting temperature according to the equation of Hidner and Souder [18], $\alpha = 0.02/T_m$, where α is the linear TEC at room temperature and T_m (K) is the melting point of the metallic element. However, the TEC of the Al_2Cu and Sn phases are different, so that the change of temperature can produce a thermal misfit strain. Thus, the development of internal residual thermal stresses cause cracks [11, 12]. Then the largest amounts of Sn atoms tendency towards porosity and hot tearing due to the effect of alloy shrinkage. Moreover, the increase of the rate of solid solution of $Al_9Cu_{11.5}$ phase does have a slight thermal expansion anisotropy effect [11]. Then, the expectations of increase TEC with increasing temperature above 230 °C for all rolled samples is due to possibility of existing more internal stresses absorption by$Al_9Cu_{11.5}$ phase [11].

3.4 Electrical Resistivity

The electrical resistivity (ρ) increases continuously with increasing cold rolling reduction as shown in Fig. 7. This increase can be attributed to the increase of dislocation density and lattice strain induced as a result of cold rolling mechanism. However, distortion of the lattice structure hinders the passage of electrons which reflected as the increase of electrical resistivity [19].

4. Conclusions

The structure and properties of the Al-Sn-Cu bearing alloy were studied and analyzed under different cold rolling conditions and it was revealed that:

The microhardness (Hv) increased with increasing cold rolling reduction till 56% and then decreased at 72% which attributed to maximum age hardening followed by the natural softening, i.e. 56% is the highest hardening samples on micro-scale, which can be attributed to the behavior of crystallite size of Al matrix.

The thermal expansion coefficient curves (TEC) indicate the lowest expansion at 56% cold rolling reduction with increase of the rate of forming solid solution of $Al_9Cu_{11.5}$ phase.

The microstructure could explain TEC properties and the micro-hardness in 56% and 72% cold rolling reduction. It can be concluded that the 56% cold rolling reduction has the best conditions through hardness, thermal expansion and micro-structure.

On the other hand, cold rolling has a negative effect on electrical conductivity the Al-Sn-Cu alloy.

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References

[1] Yuan, G., Zhang, X., Lou, Y. and Li, Z. 2003. "Tribological Characteristics of New Series of Al-Sn-Si Alloys." *Trans nonferrous Met Soc China* 13 (4): 774-80.

[2] Abis, S., Barucca, G. and Mengucci, P. 1994. "Electron Microscope Characterization of Al-Sn Metal-Metal Matric Composites." *J Alloys Compd.* 215 (11): 309-14.

[3] Abis, S. and Onofrio, G. 1989. "New Bearing Aluminium-Based Alloys." In *Proceedings of Advanced Materials*. Milano (Italy), 511-3.

[4] Schouwenaars, R., Torres, J. A., Jacobo, V. H. and Ortiz, A. 2007. "Tailoring the Mechanical Properties of Al-Sn Alloys for Tribological Application." *Mater Sci Forum.* 317: 539-43.

[5] Kotadia, H. R., Das, A., Doernberg, E. and Schmid-Fetzer, R. 2011. "A Comparative Study of Ternary Al-Sn-Cu Immiscible Alloys Prepared by Conventional Casting and Casting under High-Intensity Ultrasonic Irradiation." *Mater Chem. Phys.* 131: 241-9.

[6] Kitajima, M. and Shono, T. 2005. "Development of Sn-Zn-Al Lead-Free Solder Alloys." *Fujitsu Sci Technol J.* 41 (2): 225-35.

[7] Apelian, D. 2009. "Aluminium Cast Alloys: Enabling Tools for Improved Performance." North American Die Casting Association Wheeling, IIIinois.

[8] Kotadia, H., Doernberg, E., Patel, J., Fan, Z. and Schmid-Fetzer, R. 2009. "Solidification of Al-Sn-Cu Based Immiscible Alloys under Intense Shearing." *Metall Mater Trans A* 40A: 2201-1.

[9] Kong, C. J., Brown, P. D., Harris, S. J. and McCartney, D. G. 2005. "The Microstructures of a Thermally Sprayed and Heat Treated Al-20wt.%Sn-3wt.%Si Alloy." *Mater Sci Eng A* 403: 205-14.

[10] Sezek, S. and Aksakal, B. 2009. "Deformation and Temperature Behaviour during Cold, Warm and Hot Flat Rolling of AA5454-O Alloy." *Mater Design* 30: 3450-9.

[11] Chen, C. L. and Thomson, R. 2010. "Study on Thermal Expansion of Intermetallics in Multicomponent Al-Si Alloys by High Temperature X-Ray Diffraction." *Intermetallics* 18: 1750-7.

[12] Zou, Y., Xu, Z., Gao, Y., Gu, H. and Zeng, J. 2007. "Investigation on Friction and Thermal Expansion Coefficients of Al-Sn Bearing Alloys." *Key Eng Mater.* 353-358: 3063-6.

[13] Abdulagatov, I. M., Murlieva, Z. K., Palchaev, D. K., Kazbekoy, K. K. and Maangalov, M. M. 2007. "Thermal Expansion and Kinetic Coefficients of Crystals." *J Phys Chem Solids* 68: 1713-20.

[14] Hammam, M, Saad, A. F., Gouda, E. S., El Gendy, Y. and Abd El, A. H. 2010. "Structure and Properties of Sn-Zn Lead Free Solder Alloy with Heat Treatment." *Engineering Journal* 2 (3):172-8.

[15] Benal, M. M. and Shivanand, H. K. 2006. "Influence of Heat Treatment on the Coefficient of Thermal Expansion of Al (6061) Based Hybrid Composites." *Mater Sci Eng A* 435-436: 745-9.

[16] Kimura, H. and Hasiguti, R. R. 1961. "Interaction of Vacancies with Sn Atoms and the Rate of G-P Zone Formation in an Al-Sn-Cu Alloy." *Acta Metall Mater* 9: 1076-8.

[17] Cheng, S., Bian, X., Wangand W. and Qin, X. 2005. "Effect of Copper Aluminum and Tin Addition on Thermal Contraction of Indium Melt Clusters." *Physica B* 366: 67-73.

[18] Zinelis, S., Tsetsekou, A. and Papadopoulos, T. 2003. "Thermal Expansion and Microstructural Analysis of Experimental Metal-Ceramic Titanium Alloys." *The Journal of Prosthetic Dentistry* 90: 332-8.

[19] Cetinarslan, S. C. 2009. "Effect of Cold Plastic Deformation on Electrical Conductivity of Various Materials." *Mater Design* 30: 671-3.