16th International Research/Expert Conference
”Trends in the Development of Machinery and Associated Technology”
TMT 2012, Dubai, UAE, 10-12 September 2012

THE INFLUENCE OF DEFORMATION DEGREE ON THE ANNEAL HARDENING EFFECT IN A CAST Cu-4at%Au ALLOY

Ivana I. Marković, Svetlana D. Nestorović, Dragoslav M. Gusković, Ljubica S. Ivanić
University of Belgrade, Technical Faculty in Bor
VJ 12, Bor
Serbia

ABSTRACT
Investigations were carried out on the cast samples of Cu-4at%Au alloy, as well as pure copper samples, for the sake of comparison. Cast samples of copper and alloy were subjected to the same thermomechanical procedure. The thermomechanical procedure included: the homogenized annealing at 850 ^{0}C for 24 h, prefinal cold rolling, solution annealing at 500 ^{0}C for 45 minutes, final cold rolling with a final reduction of 20 % and 60 %. After that isochronal annealing up to the recrystallization temperature was performed. The influence of deformation degree during the thermomechanical procedure on the anneal hardening effect (strengthening) in a cast Cu-4at%Au alloy has been investigated for the hardness, microhardness and electrical conductivity measurements. The study has shown that anneal hardening effect appeared in the cast Cu-4at%Au alloy in the temperature range of 60-350 ^{0}C followed by an increase in the hardness, microhardness and electrical conductivity. The amount of strengthening increases with increasing deformation degree of prior cold rolling.
Keywords: anneal hardening effect, copper, Cu-4Au alloy

1. INTRODUCTION
Pure copper (Cu) is among the most commercially important metals because of its ease manufacture and numerous applications because of its excellent electrical and thermal conductivity and resistance to corrosion [1]. But pure Cu has some distinct shortcomings such as low hardness and low strength. The development of Cu based alloys with high tensile strength and hardness is of primary importance. The mechanical strength of Cu based alloys can be increased significantly with standard procedures by age hardening or by introducing dispersed particles in its matrix [2]. But little studied phenomenon of so called anneal hardening is appeared when a single phase copper alloys were annealed at temperatures below the recrystallization temperature after cold working (low temperature annealing), and can be utilized for improving properties [3]. Anneal hardening is a genuine hardening mechanism and three general trends characterizing it:

a) The strengthening which accompanies annealing increases with increasing degree of prior cold work.
b) The strengthening due to annealing increases with increasing substitutional element concentration.
c) The strengthening due to annealing is a decreasing function of the plastic strain at which the strength is measured [4, 5].

Anneal hardening effect was investigated in several binary copper based alloys: Cu-Al, Cu-Zn, Cu-Al, Cu-Ga, Cu-Ni, Cu-Rh, Cu-Zn, Cu-Sb, Cu-Sn [3-11]. But only Vitek and Warlimont [5] have conformed hardening of cold deformed single phase Cu-Au alloy after low temperature annealing by measuring of spring bending limit. A comparative investigation on the influence of prior deformation degree on hardness, microhardness and electrical conductivity of Cu-4at%Au alloys (designated as Cu-4Au in the following text) during annealing was carried out.

2. EXPERIMENTAL

Oxygen free copper (OFHC) and pure gold were used as starting materials. Still mold was previously preheated to 300 ^{0}C. Ingots of pure Cu and Cu-4Au alloy were produced by melting and casting (ingot metallurgy-IM) in a laboratory electro resistant furnace. After ingot cutting the initial shape of the specimen was plate-like with dimensions of 30 mm×10 mm×5 mm. After prefinal cold rolling to the thickness of 5 and 2.5 mm samples were solution treated at 500 ^{0}C for 45 minutes under hydrogen atmosphere, and then rapidly quenched into ice water. After that final cold rolling with 60 % and 20 % deformation degree on the final thickness of 2 mm was performed. Samples were subsequently annealed isochronally for 30 minutes in the temperature range of 60 ^{0}C to 350 ^{0}C. Vickers hardness, Vickers microhardness and electrical conductivity were measured after each step of TMT. Hardness measurements, expressed in $dN{\cdot}mm^{-2}$, were made using a Vickers hardness tester (VEB Laipcig) with a load of 5 kg and a dwell time of 15 s. Microhardness measurements, expressed in $kg{\cdot}f{\cdot}mm^{-2}$, were made using a Vickers microhardness tester (PMT-3) with a load of 100 g and a dwell time of 15 s. The electrical conductivity, expressed in MSm^{-1}, was measured using "Sigmatest" conductomer. At least five measurements of hardness, microhardness and electrical conductivity were performed on each sample.

3. RESULTS AND DISCUSSION

Due to the large number of data only the most important results are shown. To determine an appropriate annealing temperature for the alloy, the samples were isochronally annealed in the temperature range of 60 ^{0}C to 350 ^{0}C. Fig. 1 shows the isochronal annealed curves of the Cu and Cu-4Au alloy samples cold rolled with 20 % and 60 % deformation degree, and then annealed in the temperature range of 60 ^{0}C to 350 ^{0}C for 30 minutes.

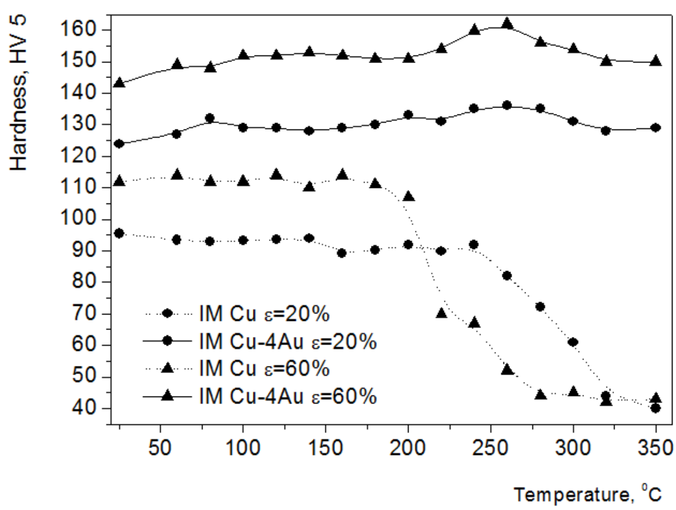

Figure 1. Variation of hardness of cold rolled IM Cu and Cu–4Au alloy with annealing temperature

It can be seen that the Cu-4Au alloy exhibited an apparent anneal hardenability in the temperature range of 60-350 ^{0}C where the hardness values increase for both applied deformation degrees. The maximum hardness increase of about 12 and 20 HV was achieved in alloy samples (ε = 20 % and 60 % reductions). With increasing degree of deformation curves have moved towards greater values of hardness. Previous data are confirmed by the literature facts [3-8] that the amount of strengthening, which accompanies anneal hardening, increases with increasing the amount of cold work as a result of a larger number of defects, the more intensive partial dislocations recombination and interactions of solute atoms with lattice defects during the annealing.

After annealing above 200-250 ^{0}C, cold deformed Cu samples hardness drops significantly as a result of the formation and growth of a new undeformed grain, i.e. the recovery and recrystallization occurrence. Increasing deformation degree from 20 % to 60 % leads to decrease of recrystallization temperature from 250 ^{0}C to 200 ^{0}C.

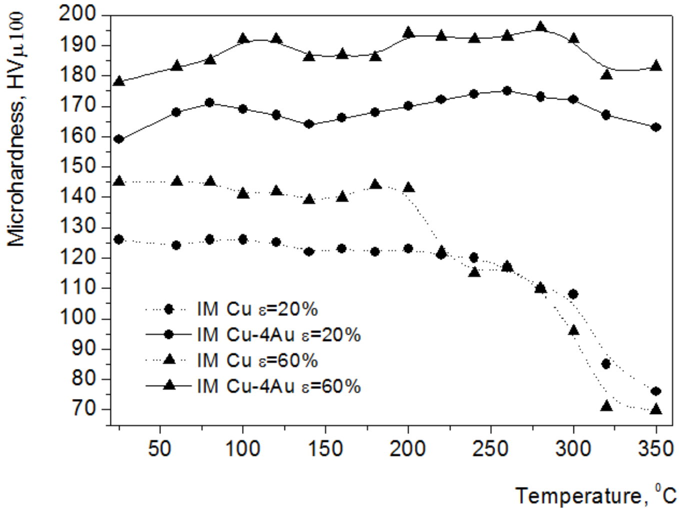

Figure 2. Variation of microhardness of cold rolled IM Cu and Cu–4Au alloy with annealing temperature

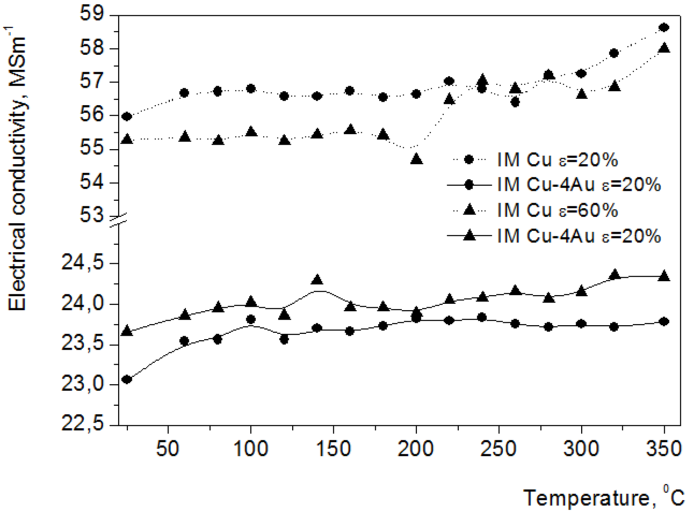

Figure 3. Variation of electrical conductivity of cold rolled IM Cu and Cu–4Au alloy with annealing temperature

Fig. 2 shows variation of microhardness of cold rolled Cu and Cu–4Au alloy with annealing temperature. It can be seen that in the temperature range of 60–350 ^{0}C, at the Cu–4Au alloys, the microhardness values increase for both applied deformation degrees. The microhardness values of Cu-4Au alloy finally deformed with 20 % increase from 159 $HV_{\mu 100}$ to 175 $HV_{\mu 100}$ after annealing at 260

^{0}C and then slowly decrease. The microhardness values of Cu-4Au alloy finally deformed with 60 % increase from 178 $HV_{\mu100}$ to 196 $HV_{\mu100}$ after annealing at 280 ^{0}C and then slowly decrease. Anneal hardening effect appeared in the Cu-4Au alloy as a result of solute (gold) segregation to dislocations, analogous to the formation of Cottrel atmospheres in interstitial solid solutions, which results in strengthening and hardness and microhardness increases [3-5].

Fig. 3 shows variation of electrical conductivity of cold rolled Cu and Cu–4Au alloy with annealing temperature. The electrical conductivity of Cu-4Au alloy slowly increases with annealing in the temperature range where anneal hardening effect appears, due to segregation of gold atoms to dislocations. Electrical conductivity of Cu-4Au alloys cold rolled with 20 % and 60 % were found to be 23.06 MSm^{-1} and 23.66 MSm^{-1}, respectively. After annealing at 260 ^{0}C for 30 minutes, it increased to 23.83 MSm^{-1} and 24.16 MSm^{-1}, respectively.

4. CONCLUSION

Annealing in the temperature range between 60 and 350 ^{0}C after cold rolling was developed to optimize the combination of strength and electrical conductivity of Cu-4Au alloys due to anneal hardening effect. The strengthening and electrical conductivity increase with increasing the degree of the prior cold working and the maximum of hardness, microhardness and electrical conductivity were established after cold rolling with 60 % of deformation.

5. ACKNOWLEDGEMENT

The research results were developed under the Project TR 34003 "Conquering the Production of Cu-Au, Cu-Ag, Cu-Pt, Cu-Pd, Cu-Rh Cast Alloys of Improved Properties by Applaying the Anneal Hardening Mechanisms" for which the funds were provided by the Ministry of Education and Science of the Republic of Serbia.

6. REFERENCES

[1] Jovanović M T., Rajković V.: High Electrical Conductivity Cu-Based Alloys. Part I, Metalurgija-Journal of Metallurgy, 15 (2) (2009)125-133.

[2] Kexing S., Jiairdong X., Baohong T., Ping L., Qrming D.: Influence of Annealing Treatment on Properties and Microstructures of Alumina Dispersion Strengthened Copper Alloy, The Transactions of Nonferrous Metals Society of China, 15 (1) (2005) 139-143.

[3] Izumi O., Yoshiki T.: Secular Change after Cold-Working and Anneal-Hardening of α Brass, Journal of the Japan Institute of Metals, 22 (1958) 158-167.

[4] Bader M., Eldis GT., Warlimont H.: The Mechanisms of Anneal Hardening in Cu–Al Alloys, Metallurgical Transactions A, 7 (1976) 249–255.

[5] Vitek JM., Warlimont H.: The Mechanism of Anneal Hardening in Dilute Copper Alloys, Metallurgical Transactions A, 10 (1979) 1889–1892.

[6] Nestorovic S., Markovic I., Markovic D., Ivanic Lj.: Influence of Thermo Cyclic Treatment on the Anneal Hardening Effect of a Cast CuAl and CuZn Alloys, Proceedings of the International Research/Expert Conference "Trends in the Development of Machinery and Associated Technology" TMT 2011, Prague, Czech Republic, 2011, pp. 153-156.

[7] Nestorović S., Marković D.: Anneal Hardening Effect in Sintered Copper Alloys Dependence on Alloying Elements and Deformation, Proceedings of the 14th International Research/Expert Conference "Trends in the Development of Machinery and Associated Technology" TMT 2010, Mediterranean Cruise, 2010, pp173-176.

[8] Nestorović S., Rangelov I., Ivanić Lj.: Influence of Thermomechanical Treatment on the Anneal Hardening Mechanism of a Cast Copper-Silver Alloy, Proceedings of the 11th International Research/Expert Conference: "Trends in the Development of Machinery and Associated Technology", Hammamet, Tunisia, 2007, p 259-262.

[9] Varschavsky A., Donoso E.: Modeling the Kinetics of Solute Segregation to Partial Dislocations for Isothermal Microcalorimetric Evaluations, Journal of Thermal Analysis, 50 (1997) 533-545.

[10] Varschavsky A., Donoso E.: Kinetics of Solute Flow to Partial Dislocation in Cu-3.4 at.% Sb, Journal of Thermal Analysis and Calorimetry, 57 (1999) 607-622.

[11] Varschavsky A., Donoso E.: A Calorimetric Investigation on the Kinetics of Solute Segregation to Partial Dislocations in Cu-3.34at%Sn, Materials Science and Engineering A, 251 (1998) 208-215.