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Heat Treatments Effect on the Mechanical Properties of Industrial Drawn Copper Wires

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Abstract. In this present investigation, the mechanical properties of industrial drawn copper wires have been studied by creep tests, tensile tests and hardness Vickers. The effect of prior heat treatments at 500°C for different time on the drawn wires behavior was the main goal of this investigation. We have found that these heat treatments influenced the creep behavior of drawn wires and recorded shape curves. The creep tests were applied under ambient atmosphere at 240 °C. The creep duration before rupture decreased with the prior heat treatment time. The creep tests results were confirmed by tensile tests. A relationship between the hardness and the ultimate tensile strength of this industrial material has been established. Optical and scanning electron microscopy observations have been also used. Cross section observations of the wire after tensile or creep-rupture tests have shown that the mechanism of rupture was mainly controlled by the void formation.

Introduction

In materiel science, creep is the tendency of a solid material to slowly more or deform permanently under the influence of stresses. In general, creep occurs in three stages: primary, secondary and tertiary stage. Primary stage occurs at the beginning of the tests, and creep is most transiently; however, in secondary stage the rate of creep becomes roughly steady and it is called steady state creep. Finally, in tertiary stage, the creep rate increases until fracture of the material.

Moreover, mechanism of creep depends on some parameters. For example, Ducki [1] studied the effect of heat treatments on the structure and creep resistance of austenic Fe-Ni alloy. He has found that the origin of the lower creep resistance was the precipitation of secondary phase particles precipitated on grain boundaries which induce intergranular cracks. In addition, Xian and Ellyin[2] also considered that plastic deformation prior creep testing has effect on the material.

The wide application of copper in general has resulted in extensive characterization and analysis of its structure and properties. For example, Rajan and Petkie [3], studied a microstructure and anisotropy in wire drawn copper by using EBSD technique. However, Schamp et al [4], studied a recrystallisation at ambient temperature of heavily deformed ETP copper wire. Baudin et al. [5] investigated the crystallographic texture and microstructure of an electrolytic tough pitch copper by EBSD after cold wire drawing and after primary recrystallization.

However, very limited information is available about creep behavior of cold worked copper by wiredrawing technique. For example, Schwope et al. [6], studied creep properties of several types of commercial coppers. In their investigation, data were presented showing the effect of cold work on the short time creep strengths of various types of commercial copper under several conditions. Ayensu et al [7], investigated creep mechanism of hard-drawn copper wires which were tested at temperatures of 300, 400 and 500 °C under uniaxial stresses of 7.08, 14.16 and 21.24 MPa. From activation energy values, they deduced that the creep mechanism is governed by grain boundary sliding. In this investigation, an industrial copper wire made by wiredrawing process was mainly studied by creep tests, tensile tests and hardness Vickers . In addition, the effects of heat treatments on drawn copper wire were investigated in order to determine the behavior of this materiel during these tests.

Experimental Materials

The material used in this study is an industrial copper electric wire of composition 99.9Cu, 0.001Bi, 0.002Sb, 0.002As, 0.005Fe, 0.002Fe, 0.002Ni, 0.005Pb, 0.002Sn, 0.004S, 0.004Zn and 0.073 others elements. This material is submitted to successive reduction by cold wiredrawing process from ε = 14.24 to 92 %. In this study, a reduced material to ε = 85.94 % was chosen for this investigation. We notice that the ratio of wire drawing is (Eq.1):

$$\varepsilon = \frac{S_0 - S}{S_0}\% \quad (1)$$

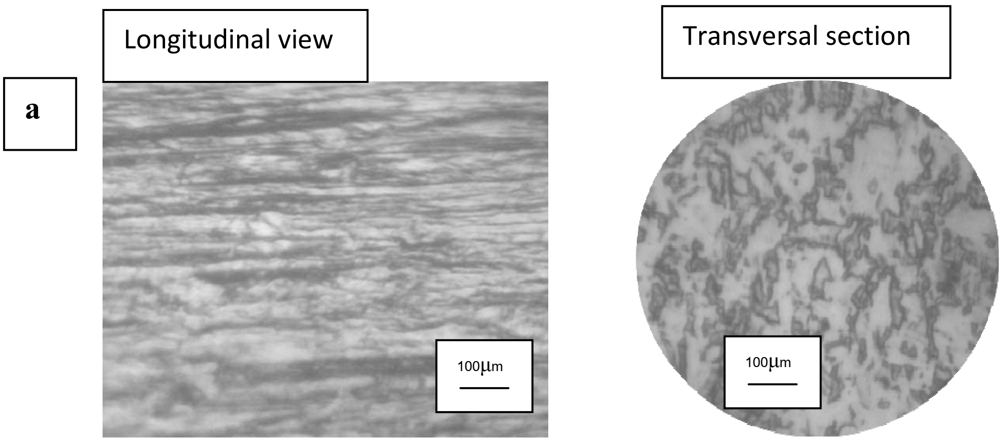
with S and So the final and initial section respectively.

Creep tests were conducted in creep machine test using samples having gauge lengths of 100 mm and a diameter section of 1.8 mmm. The creep specimens were tested at 240 °C using constant stress 138 MPa and under ambient atmosphere. All of the tests were continued until fracture and a double creep test performed for each type of specimen. The strain-time readings were continuously recorded by PC-based data acquisition system. Error in the measurement of displacement is 50 µm.

The tensile test of the copper wire was realized at room temperature with a strain rate of 2 mm/min on the universal testing machine INSTRON4SOS. Samples had gauge length 20 mm and a diameter section of 1.8mm. A total of five repeated tensile tests were made for each sample. Each datum of the hardness was the average of five repeated measured hardness and the test load is 100 g. For microstructural observations, polished specimens were etched by HNO_3 reagent for 2 to 3 seconds. Optical microscopy (OM) observations of the wire were made along a longitudinal view, and transversal section. Cross section observations by Scanning Electron Microscopy (SEM) were conducted on wire after creep rupture and tensile tests. In order to investigate the prior-heat treatments effect on the mechanical behavior of the material, the drawn copper wire was heat treated at 500°C for 2, 15, 60, and 120 min.

Results and Discussion

Microstructural evolution . Figure 1 presents the microstructural evolution of the drawn copper wire after isothermal heat treatment at 500 °C. The structure of drawn-wire after a series of section reduction, is characterized by a regular orientation of the grains along longitudinal section « texture » (Fig.1a). In addition, the state of hard-drawn wire is unstable from a thermodynamic point of view. Heating of this type of material brings about a process of regeneration and recrystallization. In comparison to the drawn copper (Fig.1a), this heat treatment regenerates new grains in material by primary recrystallization reaction (Fig.1b). This last microstructure gives the material a longer time to fracture.



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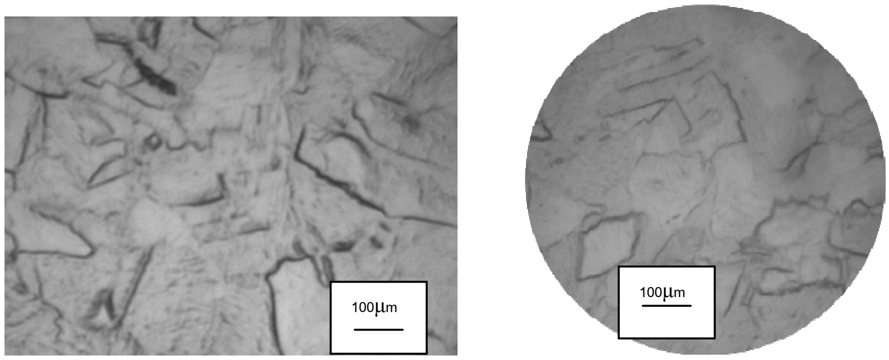


Fig. 1 Microstructural evolution of (a) drawn copper reduced to ε=85.94% and (b) followed by an isothermal heat treatment at 500°C.

Creep tests

Figure 2 shows the creep curves of drawn copper (curve d) and heat treated at 500°C of drawn copper (curves a-c). From these curves, the three stages of creep occur in all samples but their lengths vary from a sample to another, i.e, it depends on prior heat treatments. For example, the heat treated material for 2 min exhibits a long steady state and a high time of fracture. In contrast, the un-annealed drawn copper has the lowest time of fracture. It can be deduced that the heat treatment at 500°C for 2 min is the appropriate one. In contrast to our results, Schwope et al [8] investigated several commercial copper and they reported that cold work increases the creep strength of copper.

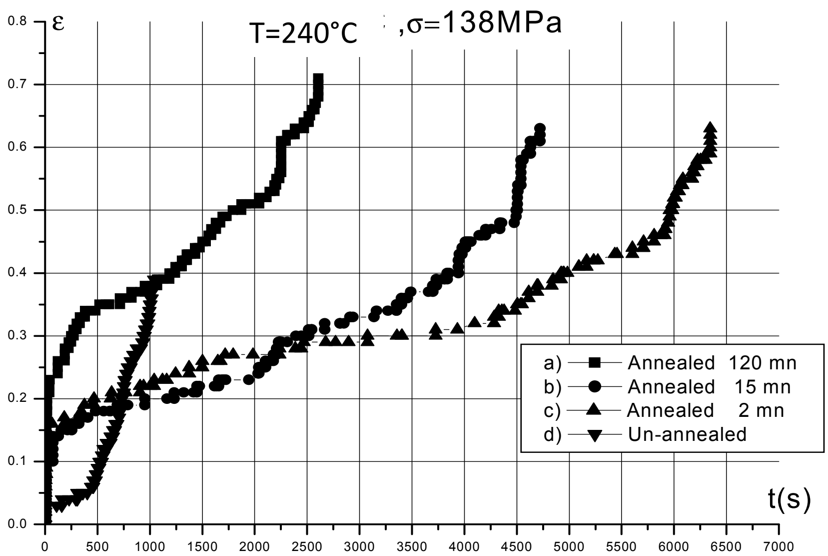


Fig. 2 Creep curves of drawn copper wire at constant temperature and stress.

Observation of all fractured samples revealed a cup and cone morphology. In general, the specimens often fail finally with a "cup and cone" geometry as indicated by Roylance [9]. By using high magnification of fractured section of the drawn copper (Fig. 3), high density of voids is concentrated in interior of the cross-section. However, Wilshire and Battenbough [10] have found that cavities form preferentially near specimen surfaces of polycristalline copper during creep fracture. The numbers of cavities and cracks decrease from the surface to the centre even at fracture, suggesting that cavities nucleate preferentially at small oxide particles created by oxygen ingress along grain boundaries during creep exosure. In our case, crack growth occurs by the coalescence of micro-pores with each other induces the fracture of the material at the necking zone.

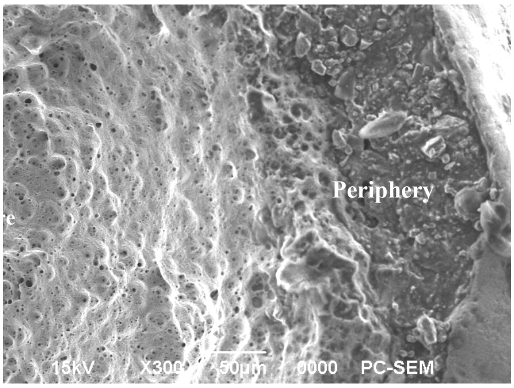


Fig. 3 SEM observation of the cross-section of the fractured drawn copper by creep test.

In our recent study of the creep behavior of an industrial aluminium drawn wire[11], where uni-axial tension creep testing was used to characterize the general creep behaviour. The same phenomenon of fracture is also observed in this material.

Tensile tests

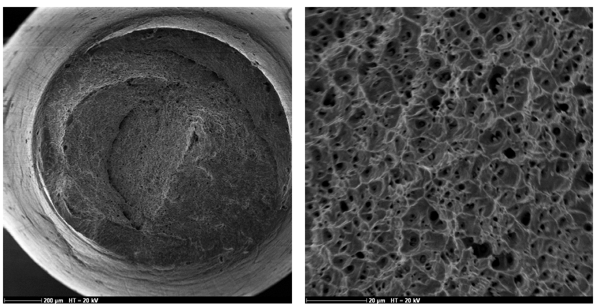
We noticed that the same category of specimens tested by creep tests have been also characterized by tensile tests at room temperature. Identical behavior which has been observed by creep tests is also exhibited during tensile tests. i.e. the heat treated drawn copper for 2 min exhibits the maximum elongation. This last result has been also found by creep test. However, the drawn copper has the highest strength but the lowest elongation in comparison to the rest of samples. From performing the tensile tests, the following properties have been determined and gathered in Table1. Referring to Engineering Materials [12] the yield stresses for copper is 60 MPa, compared to the 380, 085MPa value that was experimentally obtained for drawn copper and between 39 and 52MPa for annealed drawn copper. However the ultimate tensile stress of drawn copper is very close to the theoretical value, which is 400MPa for copper.

Table 1 Mechanical parameters of drawn copper annealed at 500°C.

	Yield Strength [MPa]	σ_{max} [Mpa]	Max Elong. %	Break Elong. %
Un-annealed	380	448	3	8
Annealed 2mn	52	244	64	79
Annealed 15mn	40	232	49	61
Annealed 1h	40	231	42	65
Annealed 2h	47	241	48	62

By examining the fracture morphology by SEM after tensile tests (Fig.5), the fracture surface revealed a cup and cone morphology with necking around the periphery of the fracture which corresponds to the failure mode of most ductile metals. After fracture, the cross-section of drawn wire (Fig.5a) is bigger than the heat treated drawn wire (Fig.5b). In addition, the low ductility of unheated deformed material can be explained by the high number of voids in comparison to the heat treated material.

a



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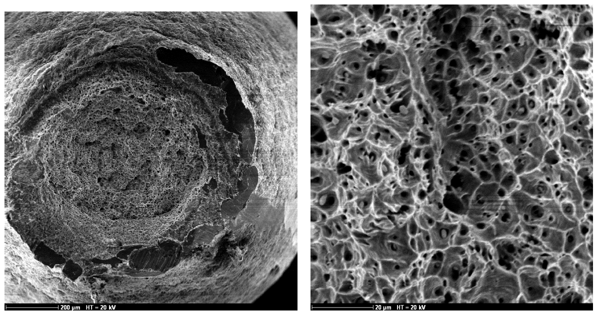

Fig. 5 Fractured surfaces after tensile tests of drawn copper wire (a) un-annealed sample and (b) annealed sample at 500°C for 60 min.

Conclusions

As a conclusion, the combination of different techniques gives more details about mechanical behavior of the matetial. The main results can be summarized as follows:

- The results revealed that the creep behaviour; the creep life of the material, strongly depends on the prior-heat treatments .i.e, the heat treatment of drawn copper wire at 500°C for 2 min induces finer grains which increases the creep life and produce the long elongation during tensile test.
- The origin of the fracture by creep or tensile tests is due to the formation of microspores at the necking zone.
- Mathematical formulation of the relationship between hardness and ultimate tensile strength of the drawn copper has been established which indicates the same variation.

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