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Effect of deformation and oxygen content on mechanical properties of different copper wires

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Abstract. Investigations were done at dip-forming, contirod and SCR copper wire rods. These continuously cast and hot rolled copper wire rods (8 mm in diameter) were cold drawn in two drawing programmes (soft and hard drawn) to various diameters without any intermediate annealing. The results of influence of deformation and oxygen content on the flow stress, tensile elongation and number of twist to failure are given. Strength and strain hardening rates of hard-drawn wires always were higher than the soft-drawn wires. Oxygen effect on the ductility of copper wires measured with the tensile elongation and the number of twist to failure is not clear at large drawing prestrains.

Keywords. Copper wire rod; cold deformability; flow stress; tensile elongation; twist to failure.

1. Introduction

In the recent past, new processes have been developed to produce copper wire rods. Hot rolling process of copper wire bars and continuous cast billets could be exchanged for the combined processes of continuous casting and rolling in the same heat. These direct strand reduction processes consume lower energy because the continuity between continuous casting and hot rolling of the cast strand takes advantage of the high temperature of the strand for the rolling process. The important spin off was: the capability for continuous operation for long periods of time to eliminate costs associated with frequent start-ups, shutdowns, and frequent maintenance (Golovin 1977). Recently, most of the world's copper wire rods are being produced by continuous casting and rolling process, for example, southwire continuous rod process (SCR), contirod process, dip-forming process and the others (Golovin 1977; Yoshida and Tanaka 1987) (SCR and contirod are tough-pitch copper (Coffer 1972; Buch *et al* 1984; Fink *et al* 1984), dip-forming produced oxygen free copper (Vatrušin *et al* 1982; Kipka and Behrend 1983)).

It is known that different conditions of casting and rolling processes influence the state of material and finally the subsequent finishing properties of wires. Therefore, it is necessary to study the correlation between the state of material and the cold deformability of copper wire rods containing varying oxygen content produced by different processes (Lundquist and Carlen 1956; Gusković *et al* 1983; Kozyrev 1983; Smets and Mortier 1984; Aoyama *et al* 1987; Gusković *et al* 1992a, b; Ivanov *et al* 1992). Regardless of the production process, oxygen content is an important factor affecting copper rod quality and downstream wire breaks.

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Table 1. Chemical analyses of copper wire rods (in ppm).

Sample no.	O	Pb	As	Sb	Zn	Fe	Ag	Se	S	Origin of material
1	25	5	3	3	/	8	15	17	40	Dip
2	20	7	3	1	/	10	15	17	40	Dip
3	155	1	1	1	/	1	8	0·5	3	Cont.
4	250	2	2	1	3	5	12	1	6	SCR
5	300	2	1	1	3	5	12	1	6	SCR
6	350	2	1	1	3	5	12	1	4	SCR
7	700	2	1	1	3	5	11	1	6	SCR

2. Experimental

Seven copper wire rods (about 8 mm in diameter), containing varying amounts of oxygen and other trace elements, were prepared (table 1). Wire nos. 1 and 2 were produced by dip-forming process, no. 3 by contirod process and others by SCR process. Wire no. 1 was continuously cast to about 16 mm diameter and hot rolled to 8 mm diameter, no. 2 was continuously cast to about 20 mm diameter and hot-rolled to 8 mm diameter. Sample no. 3 was continuously cast to rectangular cross-section (120 mm × 50 mm) and hot-rolled to 8 mm diameter. Wire nos. 4–7 were continuously cast to a trapezium cross-section (115/90 mm × 55 mm) and hot-rolled to 8 mm diameter. All of these hot-rolled copper wire rods were cold drawn to various diameters without any intermediate annealing. In the first drawing programme, a high reduction per pass (hard drawn—about 37% reduction) was used to get the wires of about 1 mm diameter (total true strain 4·16 or 98·4% total reduction of cross-section) in 10 passes. The programme was stopped at this strain level because of the wire breaks, which occurred very often during further drawing operations. In the second drawing programme, a low reduction per pass (soft drawn—about 20% reduction per pass) was used to get wires about 0·1 mm diameter (total true strain 8·76 or 99·98% total reduction of cross-section) in 39 passes. The first drawing machine was a bull block, worked with dry lubricant. The second machine was slip-stepped cone-drawing machine worked with wet lubricant. To determine the mechanical properties of the hot-rolled and drawn wires, samples were taken after each part of experiment for test specimens, which were prepared according to DIN German standards. Six tests were performed after each drawing operation and the properties were determined as an average of these four test results (without min and max values).

3. Results and discussion

The flow curves of different materials were obtained as the envelope of tensile yield stress versus wire-drawing true strain curves. Any point on the flow curve can be considered to be the yield stress for a metal strained in tension by the amount shown on the curve. Load-extension curves, obtained from tensile testing machine, were used to determine 0·2% offset yield strengths. Plastic deformation begins when the elastic limit is exceeded. As the plastic deformation of the specimen increases, the metal becomes stronger (strain hardening), so that the load required to extend the specimen increases

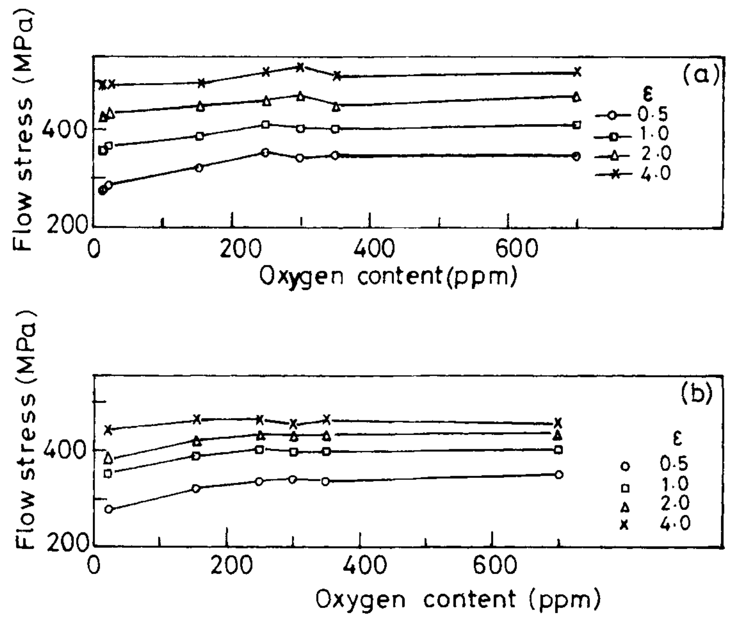

Figure 1. Effect of oxygen content on the flow stress at constant drawing strains (**a**) hard-drawn wires and (**b**) soft-drawn wires.

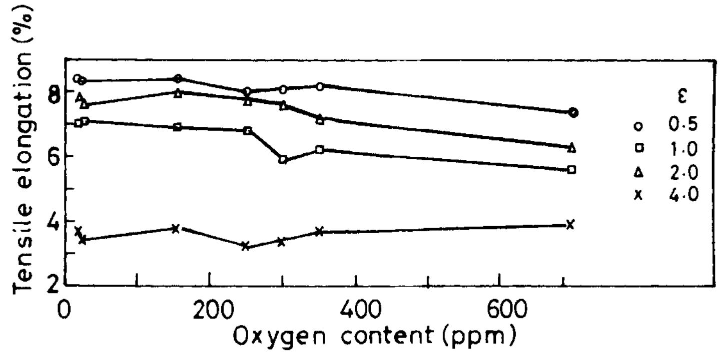

Figure 2. Effect of oxygen content of copper wires on the tensile elongation (soft drawn wires).

with further straining. The averages of the yield strengths of six tensile tests after each drawing operation, were plotted against the true strain, which is the amount of deformation introduced by wire drawing.

The effect of oxygen content on flow stress for the drawn wires is given in figure 1 at constant drawing strains. For oxygen contents of 250 to 700 ppm the flow stresses at constant strains were approximately the same. An increase in the flow stresses was observed with increasing oxygen only in low-oxygen contents, about $O < 250$ ppm, for hard- and soft-drawn wires. This increase in flow stress, with increasing oxygen content of copper, slowly decreased with increasing strain (i.e. the difference in the flow stresses with increasing oxygen at low oxygen levels was large when strain was low, but at large strains, the differences in the flow stresses with increasing oxygen content decreased).

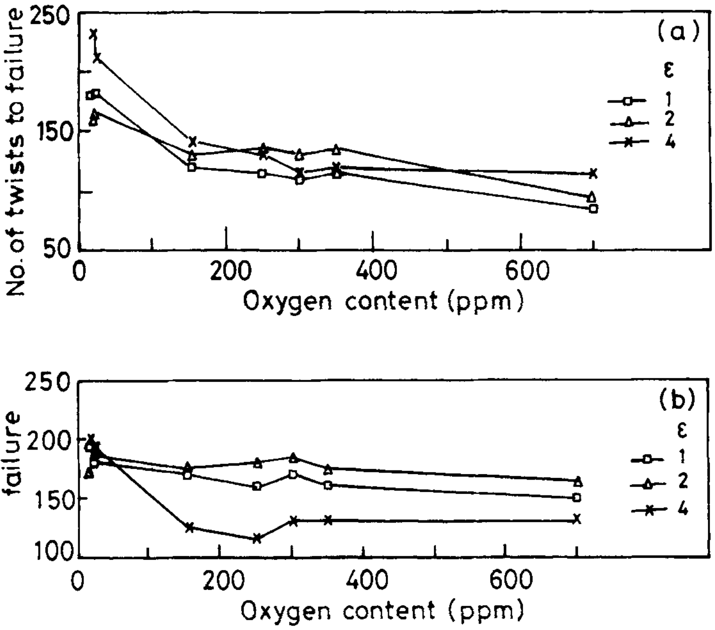

Figure 3. Effect of oxygen content of the copper wires on the number of twist to failure (**a**) hard-drawn wires and (**b**) soft-drawn wires.

The effect of oxygen content of copper wires on the tensile elongations is given in figure 2 at constant drawing prestrains in soft-drawn conditions. Elongation generally decreased with increasing drawing prestrain for all of the studied wires. Elongation values also decreased with increasing the oxygen content of copper up to the drawing prestrain of 2. The effect of oxygen content on the tensile elongation values is not clear at larger drawing prestrains, $\varepsilon > 2$, as seen in figure 2. One can say that no definite effect of oxygen on the tensile elongation was found at very high strains.

The torsion test is useful in many engineering applications and also in theoretical studies of plastic flow(Dieter 1988). The effect of oxygen content on the number of twists to failure is given in figure 3, at constant drawing prestrains for hard- and soft-drawn wires. The number of twists to failure generally decreased with increasing oxygen content of the wires at constant drawing prestrains for hard- and soft-drawn wires. A larger decrease in the number of twists to failure was measured between oxygen-free wires and tough-pitch copper wires compared with that for tough pitch coppers with increasing oxygen content from 150 ppm to 700 ppm, as seen in figure 3. The number of twists to failure for hard-drawn wires, with oxygen content from 150 ppm to 400 ppm, has no clear difference between the examined wires. At very large strains, $\varepsilon = 4$, the effect of oxygen content on the number of twists to failure for soft-drawn wires is not clear, as seen in figure 3b. In the twist to failure test the strain distribution decreased from a maximum at the rod surface to zero at the rod axis. This high surface strain suggests that the test will be very sensitive to the presence of any surface defects, such as oxide inclusion and oxide particle agglomeration. The number of twists to failure values sometimes are different for rods with the same oxygen content (Su 1982).

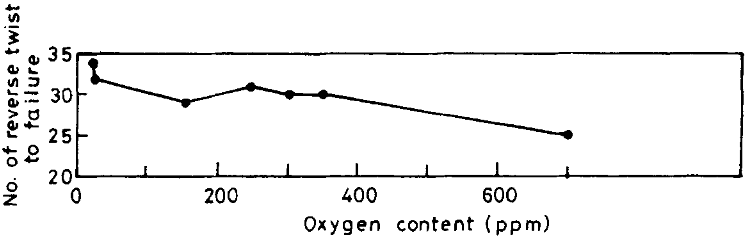

Figure 4. Effect of oxygen content on the number of reversed twists to failure.

A reverse torsion test was developed as an indicator of quality and performance for copper rod, which is similar to unidirectional torsion test, with the exception that the specimen is twisted in one direction (25 turns), the instrument then stops and reverses and the specimen is twisted to failure. All copper rods of 8 mm diameter were subjected to this reverse torsion test to evaluate wire ductility and possible drawability, and the results are given in figure 4 as a function of oxygen content. A decrease in the number of reversed twists to failure was observed in the material with increasing oxygen. This is not in full correlation with the test results of Chia (Chia *et al* 1976), probably due to the fine and uniform distribution of the Cu_2O particles in this tough pitch copper rod under investigation.

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