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Anisotropy effects on the tensile and fatigue behaviour of an oxide dispersion strengthened copper alloy

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ABSTRACT

In this study, the mechanical behaviour of the GlidCop® AL-15, an oxide dispersion-strengthened (ODS) copper, is investigated. As the extrusion process leads to a morphological and crystallographic texture, specimens are loaded in a parallel or transverse direction to the extrusion direction.

Higher monotonic mechanical strength is observed when the loading axis is parallel to the extrusion direction. Under cyclic loading, the material is more prone to cyclic hardening-softening behaviour and exhibits higher fatigue resistance in the extrusion direction than in the transverse one.

1. Introduction

GlidCop® AL-15 an oxide dispersion-strengthened (ODS) copper developed to increase significantly the mechanical strength of basic copper especially at high temperature [1–4]. GlidCop® AL-15 is produced by the internal oxidation method [5,6] that consists of:

- Water atomization of Cu–Al alloy melted in an electrical furnace;
- drying and sieving to collect powder with an average particle size of 100 μm;
- oxidation in air flow for 60 min at 900 °C;
- reduction in hydrogen flow for 60 min at 800 °C.

The reduced powder is poured into a copper can and pre-compacted at 500 MPa. The can is then pre-heated in an argon atmosphere for 60 min at 900 °C and extruded [7,8].

Internal oxidation is a diffusion-controlled process, time required for a complete internal oxidation is one of the key parameters of ODS copper production. Depending on the specimen size, this time must be kept as short as possible to avoid a coarsening of the alumina particles which leads to reduction of the strengthening effect [9]. The internal oxidation process is not sufficient for a complete densification. The consolidation into fully dense shapes is normally obtained by extrusion and can be completed by cold rolling to produce wire, rod, strip tube or plate products [7]. The internal oxidation process provides a microstructure containing a very uniform distribution of fine aluminium oxide particles aimed at strengthening the ductile copper matrix. The degree of strengthening is a function of the size, shape, spacing, hardness, distribution and coherency of the second-phase particle with the matrix [10]. The fine particles are hard and thermally stable even at temperatures approaching the melting point of the copper matrix. They do not coarsen but become less effective as barriers to the motion of dislocations [11]. The fine dispersion of the aluminium oxide particles in the copper matrix also moderates or prevents recrystallization, and this effect depends on particles of appropriate size and distribution [12].

GlidCop® AL-15 can be used as a potential high conductivity–high strength material, since the electrical and thermal conductivity of the matrix should not be strongly affected by the addition of a small amount of dispersoid particles incoherent with the metallic matrix. ODS copper alloys are usually employed at high temperatures for resistance welding electrodes in the automotive industry, relay blades, lead wires, electrical conductors, synchrotron units heat absorbers and slits where vacuum integrity below 10^{-10} torr is required and in nuclear reactors [5,6]. ODS copper alloys are used as heat sink material for the diverter, limiter and first-wall plasma-facing components of the International Thermonuclear Experimental Reactor (ITER)

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Table 1
Chemical composition of GlidCop® AL-15.

Grade designation		Copper		Aluminium oxide	
UNS	SCM	Wt.%	Vol.%	Wt.%	Vol.%
C15715	AL-15	99.7	99.3	0.3	0.7

[7,8,13–15]. They also constitute excellent liners for the hot sections of high-heat-flux engines, such as combustion chambers of rocket engines for launching space payloads [16]. GlidCop-type ODS alloys appear to be the only copper alloys with good strength above 650 °C [17]. However, it has been reported that the ductility and low cycle fatigue properties of ODS copper alloys are weak at elevated temperatures [17].

Many studies have been carried out on the preparation methods, recrystallization, microstructure, influence of irradiation and tensile properties of GlidCop. The anisotropy of the microstructure is due to the manufacturing process. Limited attention has been paid to the effect of anisotropy on mechanical properties, mainly for tensile and toughness properties [18,19].

The purpose of the present work is to evidence the effect of anisotropy of an extruded rod of GlidCop® AL-15 on monotonic and cyclic behaviour at room temperature and at 300 °C. In the first part, the material and the experimental procedures are described. Then, metallurgical investigations for the characterization of the GlidCop® AL-15 microstructure are reported. Finally, results coming from tensile and reversed fatigue tests are presented, associated to microstructural investigations conducted on the fracture surfaces. These investigations help to explain the origin and the mechanisms of this mechanical anisotropy.

2. Material and experimental procedures

For applications that require lower free oxygen contents such as applications in which the material will be exposed under vacuum to elevated temperatures, special low oxygen ("LOX") grade is mandatory.

The material used in the present investigation was a low oxygen grade aluminium oxide (Al_2O_3) dispersion-strengthened copper alloy (C15715), hereafter referred to by the trade name GlidCop® AL-15. This alloy was purchased in the form of a 13 cm diameter extruded rod from the manufacturer OMG Americas (formerly SCM Metal Products, Inc., Research Triangle Park, NC, USA).

Table 1 gives the vendor-reported chemical composition and the volume fraction of the particles.

For the metallographic investigation, the material was mechanically polished using progressively finer grades of silicon carbide paper (220–4000) with water as lubricant, then with diamond paste (3–0.25 μm) with DP-red form Struers as lubricant and then electro-polished with electrolyte D solution from Struers under a voltage of 24 V. Finally, the microstructure was revealed using an etching solution composed of 25 mL NH_4OH (28%) + 5 mL H_2O_2 (30%).

In addition to basic optical microscopy observations, the microstructure was investigated by scanning electron microscopy (SEM). A FEI QUANTA 400 microscope operating at 20 kV and equipped with the electron back scattered diffraction (EBSD) system of Oxford Instruments was used. Diffraction patterns were collected and the data were post processed with the HKL/Oxford Channel 5 software. The microstructure was also imaged by transmission electron microscopy (TEM) using a Tecnai G2 20 TEM operating at 200 kV.

For mechanical testing, cylindrical rods were first extracted in two different directions with respect to the extrusion direction: parallel (ED) or transversal (TD) to the extrusion direction. Then,

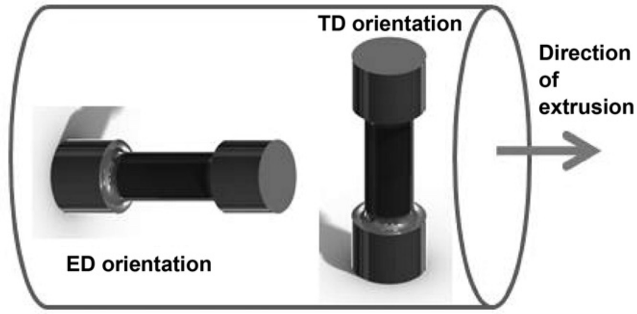

Fig. 1. Orientation of the specimens in respect to the extrusion direction of the rod of GlidCop® AL-15.

tensile and fatigue specimens, 10 mm in diameter and 15 mm in gauge length, were machined from the rods (Fig. 1).

Before testing, the specimens were polished using the same procedure as described previously in order to avoid early crack initiation.

Tensile and fatigue tests were carried out on a servo-hydraulic machine. Tensile tests were carried out at room temperature at a constant strain rate of $2 \times 10^{-3}\ s^{-1}$. Low cycle fatigue (LCF) tests were performed at room temperature and at 300 °C under axial total strain control $\Delta\varepsilon_t = 0.6\%$, $\Delta\varepsilon_t = 0.8\%$ and $\Delta\varepsilon_t = 1\%$. A fully push-pull mode ($R_\varepsilon = -1$), a triangular waveform, a constant strain rate of $4 \times 10^{-3}\ s^{-1}$ were employed. The temperature was monitored and measured by a thermocouple in the gauge length of the specimen. The fatigue life N_f was defined as the necessary number of cycles for a 25% drop in the tensile stress taking as a reference the stabilized hysteresis loop.

3. Results and analysis

3.1. Metallographic characterization and microstructure

The microstructure of the material, observed on surfaces parallel or perpendicular to the direction of extrusion, is shown in Fig. 2a and b, respectively.

As a consequence of the process, the material exhibited a morphologic texture with grains elongated in the extrusion direction. The grain size of GlidCop® AL-15 ranges between 5 and 15 μm in a plane parallel to the extrusion direction and between 0.3 and 0.9 μm in a plane perpendicular to the extrusion direction. The statistical distribution obtained by EBSD (Fig. 3) shows that the grain size of GlidCop® AL-15 in a plane perpendicular to the extrusion direction is rather homogeneous with a value of 0.4 μm for 75% of the grains.

Crystallographic texture was determined by indexing EBSD patterns collected on surfaces perpendicular and parallel to the extrusion direction (Fig. 4a and b, respectively). Our first investigation on a surface perpendicular to the extrusion direction showed all the crystallographic orientations. This suggests that the extrusion direction is characterized by the absence of crystallographic texture (Fig. 4a). However, at the grain scale, it was noted that the crystallographic orientations were not randomly distributed. Indeed, the surface appeared as a mosaic of grain packets, with each packet representing an area up to 100 μm² and having nearly the same orientation. On a plane parallel to the extrusion direction, the inverse pole figure map (Fig. 4b) revealed a microstructure comprising textured bands. One band contained grains of various orientations but mainly oriented ⟨1 1 1⟩ parallel to the extrusion direction, while the other band contained grains possessing only the ⟨0 0 1⟩ axis parallel to the extrusion direction. Moreover, the