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Compression with oscillatory torsion applied after solution treatment and aging treatment of CuCr0.6 alloy for grain refinement: Microstructure, mechanical and electrical properties

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ABSTRACT

Microstructure, mechanical properties and electrical conductivity of the CuCr0.6 alloy processed by compression with oscillatory torsion (COT) at room temperature were investigated. The COT processing was applied for the samples processed with the solution treatment followed by quenching into iced water at 1000 °C for 3 h and for the samples processed using the solution treatment followed by aging treatment at 500 °C for 2 h. Application of the solution and aging processes prior to the COT deformation results in the partial dissolution of Cr precipitates into the Cu matrix and precipitation of the coherent second phase precipitates, respectively. COT processing with different values of the total effective strain (ε_{ft}) of 10, 20, 40 was introduced to the material. It was found that the presence of the second phase precipitates has a significant effect on the formation of the ultrafine grain (UFG) structure during the COT deformation. After the COT deformation with maximal effective strain value of $\varepsilon_{ft} = 40$ of the samples processed by aging, the obtained grain size was about 300 nm and the high angle boundary fraction of about 30%. Application of the COT deformation at the effective strain value of $\varepsilon_{ft} = 40$ for the samples after solid-solution treatment leads to the formation of a UFG microstructure with the average grain size of about 450 nm and the high angle boundary fraction of 13%. Formation of the more refined UFG structure and the presence the dispersed chromium precipitates in the samples after aging contributes to the enhanced ultimate tensile strength (UTS) of 521 MPa, with the electrical conductivity of 85% IACS, which are much higher than the corresponding values of solid-solution-treated samples prior to COT of 353 MPa and 40% IACS.

1. Introduction

It is well-known that metal-forming processes assisted by cyclic loading [1–3] show key advantages with respect to monotonic processes. Many investigations have shown that an application of cyclic torsion enables a reduction of major forces in rolling, drawing or compression [4,5]. This indicates that the reduction of the forming energy is the main beneficial effect of these processes [6,7]. The magnitude of the axial force reduction is especially strongly related to the amplitude and frequency of the torsion cycle [8–11]. Nevertheless, to date, the influence of the frequency and torsion cycles in technological processes has not been effectively determined.

Compression with oscillatory torsion (COT) is a laboratory-scale deformation method with a cyclic loading scheme that was first proposed in Ref. [12]. The subsequent development of this method was focused mainly on the improvement of the technological aspects such as the choice of anvil shape and the geometry or dimensions of the samples. It was found that the creation of the appropriate contact conditions between the deformed material and the tool through the selection of the geometry of the tool or the shape of the handled sample was essential for obtaining effective and controlled changes of the torsion angle.

The introduction of the torsion process into the sample that is simultaneously compressed subjects the sample to a combined scheme of deformation and the presence of the additional deformation in this method allows the realization of large deformations. Therefore, the COT method has been applied to obtain ultrafine-grained materials. The deformation effect is controlled by the variation of the parameters such as the torsion angle, true reduction, compression rate, and torsion frequency [13–15].

The advantage of this method is that the forming procedures are not more complex and furthermore, the deformation process is not time-consuming. Additionally, this method does not require forming facilities with a large load capacity and expensive dies. Previously

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performed investigations have clearly shown that the introduction of a torsion process during compression gives rise to the reduction of the compression force in all phases of the process [15]. Therefore, the use of a combined deformation scheme reduces the deformation work, reducing the energy consumption during the process and decreasing tool wear.

The simultaneous application of two deformation schemes is extremely interesting from the point of view of microstructure changes and hence the mechanical properties. Previous studies have shown that the deformation by torsion is an effective approach for obtaining high plasticity [2,16,17], and the microstructure consists predominantly of subgrains with small dislocation density inside the grains [17,18]. Meanwhile, the compression process is effective for obtaining high mechanical properties, with microstructure composed of elongated/lamellar grains with a high dislocation density. In the context of ultrafine grained materials (UFG) obtained by severe plastic deformation (SPD), the combination of these features is extremely necessary because ultrafine-grained materials are expected to exhibit ultrahigh strength and plasticity [16,17].

Previous studies on the application of COT deformation for grain refinement have been performed for Cu [13] and Al [15] as the most well-studied materials in the SPD deformation. Different deformation parameters of the COT process were adopted to study their effects on the microstructure refinement and mechanical properties of these metals [13,14]. Based on the performed investigations, it was established that very large strains are required to achieve the grain refinement by this method [13,18,19].

Deformation COT has not been yet applied to other alloys which are interesting due to their wide range of applications. For example, no research has been performed on the changes in the microstructure and properties of the Cu-Cr precipitation hardening alloys. Cu-Cr alloys are attractive for various electrical applications because of their enhanced strength and good electrical conductivity [20,21] and can be applied in electrodes for welding and contact wires for railways. The Cu-Cr alloys with higher Cr content show relatively higher thermal stability, which is important for their use as the electrode material, as mentioned above [22,23]. However, Cr exhibits limited solubility in the Cu matrix. The Cr content for the maximum equilibrium solubility is not more than 1% mass [22]. Of course, increased solid solubility allows extensive precipitation and strengthening after aging.

Traditionally, mechanical properties of the Cu-Cr alloys have been improved by work hardening using processes such as cold rolling [24], or thermomechanical processes [23,24]. These alloys can exhibit a higher strengthening after the application of the SPD processes than after the conventional deformation processes. Quite often, the effects of the SPD on the mechanical and electrical properties of the Cu-Cr alloys are discussed for not heat-treatable state or for the solid-solution state. For example, the effect of the equal channel angular pressing (ECAP) route A on the enhancement of the properties of the Cu-0.5Cr alloy in the solid-solution conditions has been discussed in detail in [23] and the significance of the number of ECAP processing passes for improved mechanical properties has been demonstrated, with the ultimate tensile strength (UTS) and electrical conductivity of 484 MPa and 35% international annealed copper standard (IACS), respectively, obtained for the sample processed with $\varepsilon = 6.4$. In the Cu-0.36Cr alloy in solid-solution conditions after ECAP passes with $\varepsilon = 16$, the yield stress (YS) was 410 MPa and the grain size was 0.41 µm [25]. For the Cu-0.5Cr-0.1Ag alloy in the above described initial conditions prior to the deformation, the results for the mechanical properties after the HPT processing with 10 revolutions at 6 GPa were as follows: UTS of 840 MPa and elongation to fracture of 10%. The initial grains were refined to 200 nm [26,27]. The described results obtained by SPD processing [28] show an enhancement in the mechanical properties but no increase in the electrical conductivity.

Obtained dispersed precipitates after quenching and aging also plays an important role in the hardening of the Cu-Cr alloys [29]. It is evident that the increased strength obtained by the SPD deformation should be mainly attributed to the grain refinement strengthening (i.e. the formation of fine and ultrafine grains) and second phase strengthening. It should be expected that the grain refinement in these alloys will lead to improved tensile strength and will also avoid a decrease of electrical conductivity. The good electrical conductivity of Cu-Cr alloys after aging is due to the low solubility of chromium in copper.

To date, the effect of solid solution and precipitation hardening on the microstructure refinement has not been explored in the Cu-Cr alloys. Only few studies have been devoted to the microstructure and mechanical properties of the Cu alloys fabricated by the well-known SPD techniques with the annealing process following the deformation [28–31]. Moreover, the method of the analysis of the grain boundary angles used for the investigation of the evolution of the microstructure at different degrees of deformation has been used in only a few systematic studies based on the ECAP [28] and high pressure torsion (HPT) [29,31] techniques.

As a cyclic deformation method, COT is likely to be of interest as an SPD technique applied in the grain refinement of the Cu-Cr alloys because COT has already been proved to produce pure metals with ultrafine grained structure, as mentioned above. The grain refinement in the Cu-Cr alloy in the processes occurring during cyclic loading, especially for the COT method, remains unknown. Additionally, the effects of second precipitates in the COT deformation on the microstructure, mechanical and electrical properties of these alloys have not been elucidated. Therefore, in the present work we report the results of our experimental studies performed on the CuCr0.6 alloy produced by the COT method with and without the aging treatment.

2. Experimental procedure

Precipitation-hardened copper alloy with the addition of 0.6% wt. Cr (C18200) was used in this work. The alloy was prepared by melting and alloying in the open-air induction furnace, followed by casting into a mold with the diameter of 50 mm. The ingots were hot-rolled into rods with the diameter of 10 mm. The following heat treatment processes were applied to the samples in order to vary the initial structure prior to the COT deformation:

(1) Solution treatment at 1000 °C for 3 h followed by quenching into iced water, with low dislocation density. Only large precipitates were observed after the solution treatment.
(2) Solution and aging treatment at 500 °C for 2 h. In this case, the microstructure consisted of coherent second precipitates.

The detailed characterization of the structural aspects of the samples after the heat treatment is presented elsewhere [32,33]. The initial microstructure consists mainly of equiaxed grains with the average grain size of 72 µm. After the heat treatment, the samples were deformed by the COT method at room temperature. The total effective strain (ε_{ft}) obtained by the change in the deformation parameters in these experiments was 10, 20, and 40 and the procedure for the ε_{ft} calculation is presented in [13]. The COT deformation parameters were intentionally selected on the basis of previous studies [14] and were as follows: torsion angle $\alpha = 6°$, true reduction $\Delta h = 7$ mm, and compression rate $v = 0.04$ mm/s. Three different values of the torsion frequency f of 0.4, 0.8, and 1.6 Hz were used. A schematic illustration of the COT process and the sample geometry are presented in Fig. 1a-c.

Similar to the other well-known SPD techniques, the COT method is characterized by the heterogeneity of the deformation. The heterogeneity of the plastic deformation gives rise to a considerable variation of the mechanical properties and influences the refined structure. Due to the effect of the torsional moment, the most intense deformations in the COT processing is found in the vicinity of the lateral surfaces of the material. Therefore, mechanical measurements and structural investigations were performed in spheres located at the distance of about