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Effects of specimen and grain sizes on compression strength of annealed wrought copper alloy at room temperature

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ABSTRACT

Variations in compression yield strength of annealed wrought CuAl7 copper alloy with specimen diameter (t) in 1–10 mm range and grain size (D) in 24–172 μm range were investigated. Both grain size effect and feature size effect could be observed. The compression yield strength increased with a reduction in grain size or specimen diameter, and varied with the t/D ratio in no particular manner. However, when t was held constant, the compression yield strength increased as the ratio increased. When D was held constant, the strength decreased as the ratio increased. The Hall–Petch relationship between the compression yield strength and the grain size was found to depend on the specimen diameter. The effect of feature size was greater than that of grain size. A new model of the relationship between the compression yield strength and the grain size, specimen diameter, and size factor has been built. The predicted results of the model agreed well with the experimental results. The fit of the model was better than that of a model based on the relationship between the compression yield strength and the grain size and specimen diameter only.

1. Introduction

The explosion of micro scale product development in the electronics, communications, and healthcare markets has the potential to significantly improve quality of life. Microforming is well suited to manufacturing very small metallic parts, and especially mass production. Materials used in microforming technologies can be split into two categories: (1) bulk metallic glasses, such as Zr62Cu17Ni13Al8 [1], Zr65Cu17.5Ni10Al7.5 [2], $Zr_{65}Ni_{35}$ [3], and LaAlNi [4]; and (2) commercial alloys, such as CuZn15 alloy [5], CuNi18Zn20 alloy [6], Zn–22Al zinc alloy [7], 2024 aluminum alloy [8], duralumin [9], pure magnesium [10], AZ31 magnesium alloy [11], AZ31B magnesium alloy [12], pure copper [13], and 316L austenitic stainless steel [14]. For example, using a micro-compressive forming preform, Nguyen et al. examined the micro-forming characteristics of Zr62Cu17Ni13Al8 bulk metallic glass under the effects of various processing parameters in a supercooled liquid region [1]. Wang et al. prepared the Zr65Cu17.5Ni10Al7.5 amorphous micro-gears by hot embossing process [2]. Shan et al. introduced novel hybrid processes combining isothermal enclosed forging process with two kinds of piercing methods to manufacture a 2024 aluminum alloy micro-double gear [8].

Bulk metallic glasses demonstrate unique properties such as large elastic limit and high strength. These properties make them attractive for micro parts productions. However, the high-purity (99.99 wt.%) raw materials and special processing methods (large cooling rates) necessary to prepare bulk metallic glasses increase cost and slow production. In addition, most commercial alloys in use possess low absolute strength. Today's equipment needs to handle increased loads. Thus, there is an urgent need to develop further microforming technology for fabrication of microparts of high-strength commercial alloys.

Cu–Al wrought copper alloys have seen expanded use manufacturers seeking stronger alloys that have good forming properties and conductivity. Many of these high strength alloys with excellent forming properties permit a fabricator to employ thinner metal without reducing the strength of the fabricated part. CuAl7 alloy is used extensively in high strength fasteners, tube sheets, and other corrosion-resistant vessels.

Strength is a key parameter to be considered when designing a structural component. Micropart design is often based on the mechanical properties of a macroscale specimen because of the difficulty in measuring the tensile or compression strength of metallic parts of small dimensions. However, mechanical properties of a microscale specimen are different from those of

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a macroscale specimen because of size effects [6]. This leads to two questions:

(1) Does the strength of a micropart made of annealed CuAl7 copper alloy satisfy the strength requirements?
(2) If a microforming die is made of conventional micro-forming die material and is designed based on the mechanical properties of a macroscale specimen, does the die have enough strength when used in microforming?

Hence, it is necessary to study the size effects on mechanical properties of the CuAl7 copper alloy.

In addition, in the field of micro-plastic forming, such as micro-forging, micro-extrusion, and other micro-bulk forming technology has become an important branch of forming technology, micro bulk forming through the micro–micro-mold that exactly replicate the mold to the micro-fine features workpiece, belonging to near net shape, and the shape of the micro devices, high strength, good surface quality, dimensional accuracy, process is simple and easy to control, especially for micro parts, micro-volume manufacturing cost of the device. There is mainly compressive stress in micro-bulk-metal forming. Hence, this research was conducted to study the effects of specimen and grain size on compression strength of annealed wrought copper alloy at room temperature.

2. Material and methods

2.1. Material and processing

The material tested was commercial CuAl7 copper alloy, which is an aluminum bronze grade wrought copper alloy. It was composed of 92.65% Copper, 0.35% Tin, and 7.0% Aluminum (weight percentages). To acquire different grain sizes, the ingots underwent annealing treatments under atmosphere condition at varied temperatures and durations. The parameters of the annealing treatments are listed in Table 1.

2.2. Compression test at room temperature

Compression tests were carried out on a computerized SANS-CMT5105 tensile testing machine at an initial strain rate of $2 \times 10^{-4}\,s^{-1}$ at room temperature. Cylindrical specimens were machined for compression testing. To ensure effective lubrication during compression, concentric grooves were etched in the specimen faces. Molybdenum-disulfide–graphite paste was used as a lubricant.

To study the effect of feature size, specimens were machined to dimensions of Ø 11 × 13 mm, Ø 6 × 7 mm, or Ø 2 × 2.2 mm. They were then ground to dimensions of Ø 10 × 12 mm, Ø 5 × 6 mm, or Ø 1 × 1.2 mm with 600 grit SiC paper. The ratio of height to diameter of these specimens was 1.2. Twenty specimens were tested for every dimension.

Yield strength of the alloy was determined by the offset method as described in ASTM: E9-89a. The offset was 0.2%.

2.3. Characterization

The specimens were mounted in epoxy resin, ground with 1000 grit SiC paper and polished with 2.5 μm diamond paste. The specimens were then etched with ferric chloride solution containing 5 g ferric chloride, 10 mL hydrochloric acid, and 100 mL water. Microstructural characterization was carried out by optical microscopy. A linear intercept method was applied to the optical micrographs to measure the grain size. The repeat number of the optical micrographs for every direction was 20.

The phases of the annealed alloy were confirmed by X-ray diffractometry (XRD, Bruker D8 X) using Cu Kα radiation.

Table 1
Grain sizes of and annealing process parameters for the CuAl7 alloy.

Anneal technique	600 °C + 1 h	800 °C + 2 h	950 °C + 1 h	950 °C + 8 h
Grain size, μm	23 ± 4	49 ± 8	105 ± 10	172 ± 18

2.4. Two-dimensional microstructures modeled using the Voronoi algorithm

According to the surface model, the grains located at the free surface are less restricted than the grains inside. This leads to less hardening and lower resistance against deformation of surface grains because dislocations moving through the grains during deformation pile up at grain boundaries but not at the free surface. The strength of a material (σ) is a weighted summation of the strength of the surface grains (σ_O) and that of the inner grains (σ_I) [15]:

$$\sigma = \delta\sigma_I + (1 - \delta)\sigma_O \quad (1)$$

Here δ is size factor (the ratio of the number of surface grains to the total grains), making it an important parameter for analyzing the size effect.

The Voronoi algorithm was used to model microstructures of the alloy to calculate δ. The distribution of grains in a cylindrical specimen can be represented by its distribution on the axial symmetry plane. Thus, two-dimensional microstructures were modeled using the Voronoi algorithm. The flow chart and results are shown in Fig. 1. The source code was built using Matlab. The δ and the grain size d for every grain seed amount were the average for 100 pieces of Voronoi graphs.

3. Results

3.1. Microstructure and phases of annealed CuAl7 copper alloy

Microstructures of the specimens are shown in Fig. 2, and their average grain sizes are listed in Table 1. CuAl7 is a single phase alloy, and there was only a rich Cu phase presents in Fig. 2(a)–(c). It was verified by the XRD results, as shown in Fig. 2(d). The specimens exhibited equiaxed grains. Grain size increased with both annealing temperature and time. When the annealing temperature was 600 °C and annealing time was 1 h, grain size was 23 ± 4 μm. It increased to 172 ± 18 μm after 8 h annealing and reaching an annealing temperature of 950 °C.

3.2. Mechanical properties of annealed CuAl7 alloy

Typical strain–stress curves and mechanical properties of the alloys are shown in Figs. 3 and 4, respectively. The compression yield strengths of the specimens with 10 mm diameters ranged from 111 MPa to 143 MPa. The compression yield strength of an 8% aluminum bronze alloy (extruded and drawn rods, ⩽12.7 mm) is 179 MPa. In theory, the strength of an annealed alloy is lower than that of an extruded or drawn alloy. Hence, the compression yield strengths of the alloy in this study were within the expected range of values.

The compression yield strength of the alloy decreased with the grain size D and specimen diameter t, as shown in Fig. 4. The compression yield strength of the specimens with 5 mm diameters was close to that of the specimens with 10 mm diameters. The strength of the specimens with 1 mm diameters was approximately 2 or 3 times that of the specimens with 5 or 10 mm diameters.