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Short Communication

High-strength copper-based alloy with excellent resistance to hydrogen embrittlement

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ABSTRACT

High-pressure components are generally designed with safety factors based on the tensile strength (TS) of the material; accordingly, materials with higher TS permit designed components with thinner walls, which reduce the weight and cost of the parts. However, many high-strength metals are severely degraded by hydrogen. To this point, efforts to develop a high-strength metal with a TS far beyond 1000 MPa and excellent resistance to hydrogen embrittlement (HE) have failed. This study introduces a high-strength metal with an excellent HE resistance, composed of a precipitation-hardened copper-beryllium alloy with the TS of 1400 MPa. Slow strain rate tensile (SSRT) tests of both smooth and notched specimens were performed in 115-MPa hydrogen gas at room temperature (RT). The alloy had a relative reduction in area RRA ≈ 1 and a relative notch tensile strength RNTS ≈ 1, without degradation in either characteristic.

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Introduction

Components used at high pressures are generally designed with safety factors (SFs) based on the tensile strengths (TSs) of the materials used [1–11]. The SF is defined as the ratio of TS to an allowable design stress; high-pressure components are designed based on either an infinite-life design (design by rules, SF = 3.5–4) [1–4] or a finite-life design (design by analysis, SF = 2.4–3) [5–11]. From the definition of the SF, the allowable design stress of the components is increased by using materials with increased TS. Therefore, materials with higher TS permit the design of components with thinner walls, resulting in lighter weight and lower cost per component, provided that the material cost is the same. Hydrogen often degrades the tensile and fatigue properties of metals, a phenomenon known as hydrogen embrittlement (HE) [12–15]. Many metals with TSs exceeding 1000 MPa are severely degraded by hydrogen [16,17]. In order to authorize various metals for use in high-pressure hydrogen gas, many studies on hydrogen-compatible materials have been reported; high-strength austenitic stainless steels with high HE resistances have been developed [18]. However, the TS of the steels is ~800 MPa [18]; no one has succeeded yet in developing a high-strength, high HE resistance metal with a TS far beyond 1000 MPa (cf. Fig. 4).

According to a database from the National Aeronautics and Space Administration (NASA) [16], metals with both face-centered cubic (FCC) structures and low hydrogen solubilities may have excellent resistances to HE. From preliminary investigations, we chose a precipitation-hardened copper-beryllium alloy as a promising high-strength metal with a high resistance to HE. The material is included in the NASA database; however, the alloy shown in the NASA database is solution-treated, while the alloy in this study has been treated differently.

This study presents the hydrogen-diffusion and slow strain rate tensile (SSRT) properties of the precipitation-hardened copper-beryllium alloy. The hydrogen-diffusion properties were determined using cylindrical specimens charged in high-pressure hydrogen gas at elevated temperatures. The SSRT tests were performed with both smooth and notched specimens in air and in 115-MPa hydrogen gas at room temperature (RT). For comparison, a solution-treated copper-beryllium alloy was also tested. The experimental results demonstrated that the precipitation-hardened copper-beryllium alloy had low hydrogen solubility and experienced no degradation in SSRT-measured mechanical properties, while the TS of the alloy was 1400 MPa.

Experimental procedures

Materials

The material was a copper-beryllium alloy, composed of 1.8410 beryllium, 0.2416 cobalt, 0.0067 nickel, and 0.0361 iron in mass percent, with the balance being copper. The precipitation-hardened alloy, labeled CuBe-HT, was fabricated by the following processes: (1) solution treatment at 1053 K for 2 h, (2) cold-drawing at a draw ratio of 30%, and (3) aging at 588 K for 2 h. For comparison, a solution-treated alloy referred to as CuBe–H was also used in this study. CuBe–H is also subjected to cold-drawing at a draw ratio of 30% after the solution treatment. The Vickers hardness *HV* of the matrix was 406 for CuBe-HT and 242 for CuBe–H, as averaged from measurements at 10 points with a 9.8-N load for 30 s loading time. Both CuBe-HT and CuBe–H, produced on an industrial scale, can be formed into various shapes (bars, wires, and plates).

Measurement of hydrogen-diffusion properties

The hydrogen-diffusion properties of solubility and diffusivity were measured using cylindrical specimens charged in 100-MPa hydrogen gas at temperatures of either 543 K or 573 K for times ranging from 300 to 500 h. The cylindrical specimens were prepared with 8-mm diameters and thicknesses ranging from 1 to 3 mm. After exposure, the hydrogen contents of the specimens were measured under constant or increasing temperature by gas chromatography–mass spectrometry (GC–MS). The hydrogen diffusivity was determined by fitting the solution of a diffusion equation to the experimental hydrogen contents measured at various constant temperatures [19–21].

Hydrogen exposure at elevated temperatures may cause changes in microstructure by additional aging; thus, the hydrogen-diffusion properties were measured only for CuBe–HT. The preliminary investigation revealed that the TS of CuBe–HT after exposure at 543 K for 500 h was 5% lower than that for the CuBe–HT with no exposure; therefore, the hydrogen-diffusion properties of the CuBe–HT reported in this study may be slightly affected by additional aging.

Slow strain rate tensile testing

SSRT tests were performed with smooth and notched specimens in air and in 115-MPa hydrogen gas at RT. The smooth specimens had 4-mm diameters and reduced-section lengths of 30 mm; both CuBe–HT and CuBe–H specimens were prepared. The specimen surfaces were carefully finished based on ASTM G142-98 [22], because the surface roughness is known to substantially affect the SSRT behavior in hydrogen gas. The notched specimens had notch-root diameters of 5.6 mm and outer diameters of 8 mm; only CuBe–HT notched specimens were prepared. A circumferential 60° V-notch with a notch radius of 0.083 mm and a stress concentration factor of 5.8 was introduced to the notched specimen.

SSRT tests of both types of specimens were conducted using a servo-hydraulic testing machine equipped with a high-pressure vessel. The purity of hydrogen gas in the cylinder was 99.999% (5N); the measured oxygen contents were always less than 1.0 vol. ppm. The crosshead speed in the SSRT tests was 0.0015 mm/s for smooth specimens and 0.00002 mm/s for notched specimens, in accordance with ASTM G142-98 [22]. For each test condition, a single test was carried out.

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