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Fatigue strengths of Cu–Be alloy with high tensile strengths

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The fatigue strength of Cu–Be alloy with tensile strength ranging from 500 to 1300 MPa was optimized by different treatments. The experimental results demonstrate that the optimum fatigue strength of the Cu–Be alloy at 10^7 cycles is 323 MPa, which does not correspond to the material state with the highest tensile strength. It is indicated that improving the tensile strength cannot always achieve the optimum fatigue strength. The relations between fatigue strength and other mechanical properties are discussed.

Keywords: Cu–Be alloy; Tensile strength; Fatigue strength; Impact toughness

With the new requirement of society and science, it is an important task for scientists and engineers to develop more high-performance metallic materials. In the past century, many high-strength metallic materials have been fabricated and some of them have been applied successfully. However, it is well known that the toughness and/or plasticity of the materials usually decrease with increasing the strength, which gives rise to a trade-off between the strength and plasticity and/or toughness [1]. Meanwhile, most engineering components and structures often fail under cyclic loading conditions; as a result, fatigue strength should be one of the most important properties and must be taken into account in the design of materials and equipment. Traditionally, the fatigue strength of steels, copper alloys, and titanium alloys can be improved by increasing their ultimate tensile strength (UTS) up to the maximum; the fatigue strength cannot be increased by further increasing the UTS [2,3]. Therefore, this brings up two important questions:

(1) At which strength level do the materials have the best fatigue performance?
(2) How can design materials be optimized to obtain the highest fatigue strength?

Copper and copper alloys have widespread applications as functional and structural materials [4]. In terms of their mechanical properties, the UTS (or hardness) is mainly improved by plastic deformation (PD) [4–6], such as rolling, drawing, forging, etc. In recent years, some researchers have focused on improving the strength of materials by severe plastic deformation (SPD), such as equal channel angular pressing (ECAP) [7,8], dynamic plastic deformation (DPD) [9,10] and high-pressure torsion (HPT) [11,12]. Comparing with the different strengthening effects, the ranges of UTS for pure copper and various copper alloys are shown in Figure 1. Among all the data available, it can be seen that Cu–Be alloys have the widest UTS range up to 1558 MPa [6]. Therefore, the wide UTS range of Cu–Be alloy makes it possible to optimize its fatigue strength by different heat-treatment (HT) conditions. In the current study, Cu–2%Be alloy, the most common heat-treatable copper alloy, was chosen to make it in different strength levels and then to optimize its fatigue strength. Finally, the relations between fatigue strength and other properties of the Cu–Be alloy are discussed.

In this study, hot-forged Cu–2%Be alloy bars were received with dimensions of 20 mm × 45 mm × 450 mm and forging ratio of 3.72. The composition of Cu–Be alloy is 1.93 Be, 0.056 Al, 0.13 Fe, 0.14 Ni and 0.11 Si, all in wt.%. The tensile and fatigue specimens with gauge dimensions of 4 mm × 5 mm × 16 mm and total length of 60 and 70 mm, respectively, were machined using a wire-cutting electric discharge machine along the longitudinal direction of the bar. The Charpy V-notch test specimens with the outline dimensions of 55 mm × 10 mm × 7.5 mm were prepared according to ISO 148: 1983. To obtain different strength levels four heat-treatment procedures: solution-treated at 780 °C for 20 min and quenched in water, as hot-forged at 700–780 °C,

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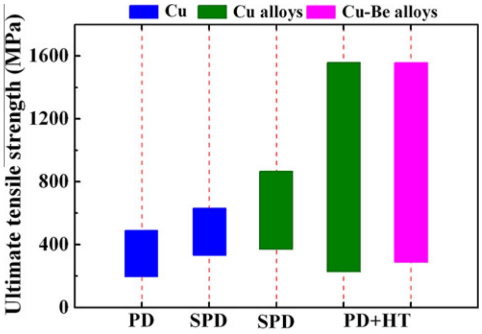

Figure 1. Tensile strength ranges of pure copper and copper alloys strengthened by different methods: pure copper strengthened by PD [4,5], and SPD (ECAP [7], DPD [9], HPT [11,12]); copper alloys strengthened by SPD (ECAP [8], DPD [10]), and PD + heat-treatment (HT) [4,6]; Cu–Be alloys [4,6].

under-aged at 280 °C for 20 min, two-step aged at 220 °C for 90 min and then at 320 °C for 120 min, were employed and the specimens are defined as A, B, C and D, respectively. Then all samples were polished using an emery paper having a mesh of 2000 # in the longitudinal direction. The tensile tests were conducted at a strain rate of $2 \times 10^{-4}\ \mathrm{s}^{-1}$ and cyclic push–pull tests were carried out at a frequency of 40 Hz with the sinusoidal wave shape under applied stress ratio of $R = -1$ up to 10^7 cycles using a servo hydraulic fatigue testing system (Instron 8801). The fatigue strength at 10^7 cycles was determined by the staircase method in which at least six pairs of specimens were tested. The microstructures of the specimens with different strength levels were examined by electron backscattered diffraction (EBSD) with LEO SUPRA35 scanning electron microscope (SEM).

After different heat-treatment procedures the specimens A–D exhibit different microstructures as shown in Figure 2. The longitudinal section of the solution-treated specimen A displays roughly equiaxed grains of supersaturated solid solution of Be in Cu α-phase and non-uniform distribution of β-phase (BeCu2), which formed in the course of taking the specimens from furnace into water. The hot-forged specimen B shows roughly equiaxed fine grains of α-phase and eutectoid phases of $(\alpha + \gamma(\mathrm{BeCu}))$ with chain distribution (see Fig. 2b). The under-aged specimen C demonstrates roughly equiaxed grains of α-phase, a few metastable γ phase and γ phase dispersed, as shown in Figure 2c. For the step-aged specimen D, its microstructure contains roughly equiaxed grains of α-phase, and γ precipitates mostly in the grain boundaries (see Fig. 2d). The average grain sizes of specimens A, B, C and D, measured by intercept method, are about 46 ± 16, 9 ± 6, 47 ± 20 and 46 ± 16 μm, respectively. After repeatedly hot forging, the average grain size of specimen B is much smaller than those of specimens A, C and D. In addition, it can be seen that there are many annealing twins in the grains of the specimens A, C and D, as shown in Figure 2a, c and d.

Figure 3a shows the tensile stress–strain curves of the specimens A–D. It can be seen that the specimens A–D yield at different stresses of 180, 422, 828 and 1135 MPa, respectively. Then all the specimens display different work-hardening ability up to the UTSs of 492, 670, 1047 and 1274 MPa, correspondingly. Figure 2b demonstrates the relationships of yield strength (YS) and UTS versus elongation to failure (EF) or uniform elongation (UE) of the Cu–Be alloy. It is apparent that the elongations of the present Cu–Be alloy show different decreasing trends with increasing strength, which agrees with the inverse relations between tensile strength and elongation to failure of copper and copper alloys [4]. It can be seen from Figure 3c that impact toughness decreases with increasing UTS, which is consistent with the trade-offs between strength and toughness of steels and Al alloys [13].

To obtain the fatigue strengths of the Cu–Be alloy by the staircase method, 20 valid samples were tested for each group in the present experiment. Figure 3d shows the relationship between fatigue strength at 10^7 cycles, the fatigue ratio (the ratio of fatigue strength to UTS) and the UTS for the Cu–Be alloy treated under different conditions. It is found that the fatigue strengths at 10^7 cycles of the specimens A–D are equal to 191, 323, 235 and 185 MPa, respectively. The highest fatigue strength can be as high as 323 MPa, which occurs in the specimen B with the UTS of 670 MPa. With further increasing the UTS, the fatigue strength of the Cu–Be alloy starts to decrease. In this case, the fatigue ratios are equal to 0.39, 0.48, 0.22 and 0.14, respectively, for the specimens A–D, as shown in Figure 3d. The specimen B also has the highest fatigue ratio. From these results above, it can be concluded that both the fatigue strength and fatigue ratio increase simultaneously at low-strength level, then decline with the increase of the UTS at high-strength level. The most important thing is that the specimen D with the highest UTS has the lowest fatigue strength and fatigue ratio, indicating that simply improving the UTS to an extremely high value often leads to the worst fatigue properties of materials, which is consistent with the result that the highest tensile strength can not bring about a higher fatigue strength in the high-strength steels [2,3], and austempered ductile irons [14].

Figure 4 shows that the fatigue strength of pure copper can be improved by PD [4,5], alloying [15,16], and SPD [12,17–19]. The fatigue strength of Cu–Cr alloy [16] can be obviously improved to 170 MPa; especially for Cu–Cr–Zr alloys [20] its fatigue strength can be as high as 285 MPa due to the additional aging after ECAP. However, the fatigue strength of the Cu–2%Be alloy by traditional heat-treatment currently is highest among all the copper alloys, regardless of ultrasonic fatigue (USF, 20 kHz) [21] or pull–push fatigue (PP, current work). At the same time, it is found that the optimum fatigue strength by means of USF is higher than that by PP because of different loading methods and sample sizes [22]. It is implied that traditional heat-treatment technology can more significantly improve fatigue strengths for copper alloy with the precipitation strengthening mechanism.

Since the fatigue strength is one of the significantly important mechanical parameters for engineering materials, it is encouraging for scientists and engineers to find out some relations between fatigue strength and static mechanical properties to summarize some empirical

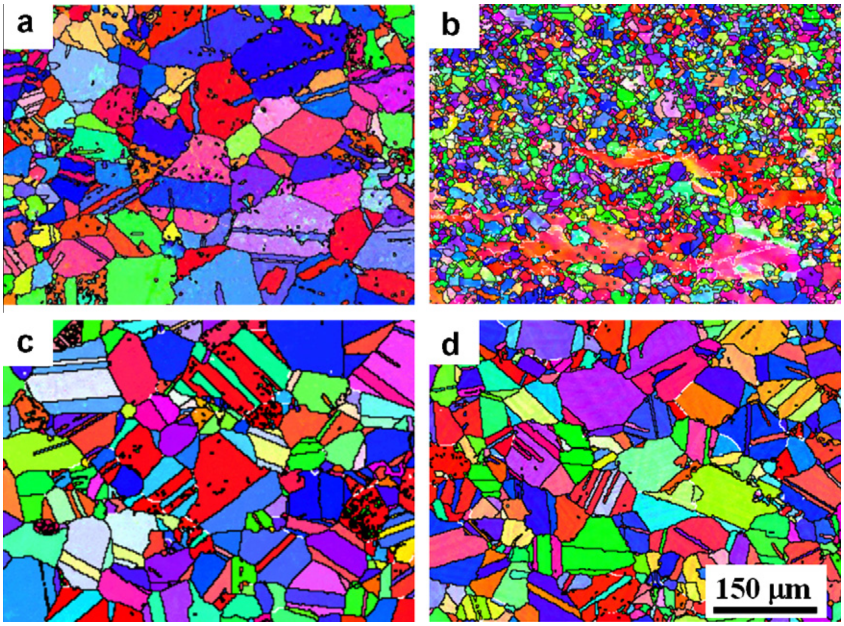

Figure 2. Microstructures of the Cu–Be alloy after different heat-treatment procedures: (a) solution-treated; (b) as hot-forged; (c) under-aged; (d) two-step-aged.

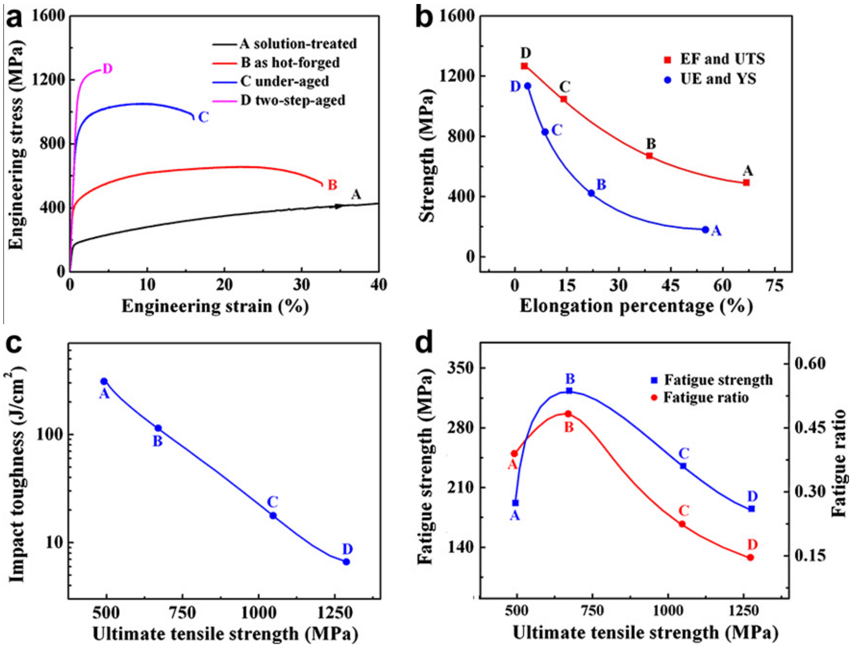

Figure 3. Tensile and fatigue properties of Cu–Be alloy with four different heat-treatment procedures: (a) tensile engineering stress–strain curves; (b) the relation between strength and elongation; (c) the relation between ultimate tensile strength and impact toughness; (d) the relation between ultimate tensile strength, fatigue strength and fatigue ratio.

formulas in Cu alloys, steels, Al, Mg and Ti alloys [1–3]. Normally, there is a linear relationship between the UTS (or hardness) and the fatigue strength; however it is only valid within the low-strength level, beyond which the fatigue strength becomes independent of the tensile strength as widely observed in steel, Al, Ti and Cu alloys [1–3]. For the current Cu–2%Be alloy, it is found that there is also no visible connection between fatigue strength and tensile strength, as shown in Figure 3b and d. In addition, it is considered that the enhancement of toughness to some extent can improve the fatigue properties of materials. However, it is apparent that the fatigue strength of the Cu–Be alloy still shows no direct relation with the impact toughness, as shown in Figure 3c and d. Therefore, this gives rise to an open question: how to predict or optimize the fatigue strength of those high-strength materials by their conventional mechanical properties. This must be significantly important to be investigated, especially for those high-strength materials, such as super-high-strength steels, ultrafine or

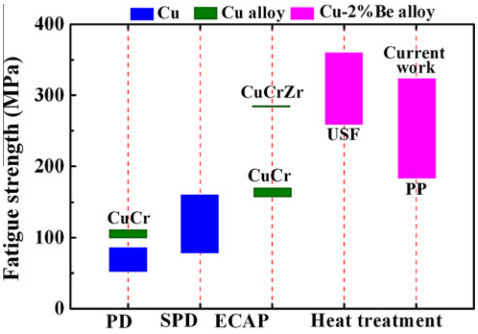

Figure 4. Comparison of fatigue strengths of various pure copper and copper alloys after different strengthening methods, pure copper [4,5] and Cu–Cr alloy [15,16] by PD, pure copper by ECAP [17–19] and HPT [12], Cu–Cr alloys [15] and Cu–Cr–Zr alloy [20] by ECAP, aged Cu–2% Be alloy [21] by ultrasonic fatigue (USF) and PP.

nano-grained materials, bulk metallic glasses, which normally have relatively low fatigue strengths in comparison with their higher tensile strengths [17,23–25].

In summary, the optimum fatigue strength of Cu–2%Be alloy at 10^7 cycles obtained by traditional forging and heat-treatment can be as high as 323 MPa; however, this does not correspond to the material state with the highest tensile strength and the best impact toughness. In comparison with the tensile strength and impact toughness of the Cu–Be alloy, it is found that the optimum fatigue strength can be achieved by optimizing the combination of the two properties. In the design and selection of materials or component parts, it should be noted that the ultra-high tensile strength or impact toughness of materials may not lead to higher fatigue strength.

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