

Mechanical Surface Treatments to Improve Fatigue Performance of cp-Cu

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Abstract

The present study was aimed at evaluating the effect of shot peening and Roller-burnishing on notch sensitivity of SPD-processed cp-Cu. After applying the various mechanical surface treatments the changes in the surface and near-surface layer properties such as roughness, microhardness and residual stress-depth profile were determined. The results shows that RB by providing higher surface strengthening and less surface roughness shows lower notch sensitivity than SP.

Keyword cp-Cu, Roller-burnishing, Shot peening, Fatigue performance

Introduction

Severe plastic bulk deformation of coarse grained materials by method like swaging (SW) is known as grain size refinement of metals like Cu, Al, Mg and their alloys to value of 1 μ m. refining of the grain size results in extreme increases of yield stress, tensile strength and high cycle fatigue strength (HCF) [1]. Mechanical behavior of material processed by SPD depends on their microstructure [2, 3]. As a result of increasing strain, the average dislocation density increases while the individual crystalline size becomes smaller [2, 3, 4]. It is well known that reduction in cross section or notches can markedly reduce the HCF strength of structural compound [5]. From the point of prospective engineering applications it is relevant to have information also on the fatigue notch sensitivity, Because the fatigue performance of notched samples might be very poor even if the fatigue performance of smooth samples is good [6]. The effect of notches on fatigue performance is defined as fatigue notch sensitivity and can be explained as:

$$q = \frac{k_f - 1}{k_t - 1} \quad (1)$$

Where k_f is the fatigue notch factor and k_t , is the theoretical stress concentration factor. k_f is defined as:

$$k_f = \frac{\sigma_{a_{10^7}}^{smooth}}{\sigma_{a_{10^7}}^{notched}} \quad (2)$$

Where $\sigma_{10^7}^{smooth}$, is the fatigue limit of smooth sample and $\sigma_{10^7}^{notch}$, is the fatigue limit of the notched samples. The values of q varies between two limiting cases from $q = 0$, no notch effect to $q = 1$, full theoretical effect. Surface nanocrystallization processes like shot peening, ball-burnishing and laser shock peening (LSP) are often applied to improve high cycle fatigue strength (HCF). Residual stresses, surface roughness and work hardening can be considered as the main surface modifications induced in the surface layers of the materials. Surface hardening and compressive residual stress retard crack nucleation and short crack growth and the increase fatigue life, but the surface roughness can be detrimental to fatigue performance [7, 8]. The present investigation intends to highlight the effect of shot peening and roller burnishing on notch sensitivity of swaged pure copper (99.99%).

Experimental Method

Commercial pure copper (99.99%) rods of 50mm diameter were used as the experimental materials. Bars of the as-received material in 50mm diameters were machined to obtain cylin-

drical samples with 32 mm in diameter for swaging processing. In swaging, the true deformation degree is defined as $\phi = \ln (A_0/A_f)$ with A_0 , starting cross sectional area and A_f final cross sectional area. During swaging at room temperature, the specimen diameters were reduced from 32 to 25, 20, 12 and 7 mm which correspond to true deformation degree of 0.5, 1.0, 2.0 and 3.0, respectively. Microstructure investigations were carried out on an optical microscope (Model: Zeiss Axioskop). Tensile tests were performed using threaded cylindrical specimens on Instron model 5582 universal testing machine using constant crosshead speed 1mm/min, which correspond to a strain rate of $6.67 \times 10^{-4} \text{ s}^{-1}$. HCF tests were conducted by using Mayes-GTG, Rolls Royce rotation-beam fatigue machine ($R = -1$) on hour-glass shaped smooth ($k_t = 1$) and notched ($2.1 \leq K_t \leq 2.8$) specimens. Both specimens' types were electropolished to serve as the reference condition. Shot peening was done using a gravity induced system and spherically condition cut wire (SCCW) having an average shot size of 0.1 mm. The samples were peened in Almen intensities 0.1 and 0.2 mmA. Roller-burnishing (RB) of the notched specimens was conducted using a roller tool with a tip radius of 0.1 mm and a pressure of 1.5 bar. The surface roughness measurement was done using a Perthometer S8P made by the company Perth Mahr. Microhardness-depth profiles and residual stress-depth profiles as determined by the incremental hole drilling method were measured to characterize the process-induced changes in the surface layer properties.

Experimental Results

Fig.1 presents the metallographic pictures comparing as-received (Ar) condition with severe plastic deformation conditions. The microstructure of the initial copper consists of coarse and equiaxed grains and the severe plastic deformation (swaging) to deformation degree of $\phi = 3.0$, results in grain size refinement.

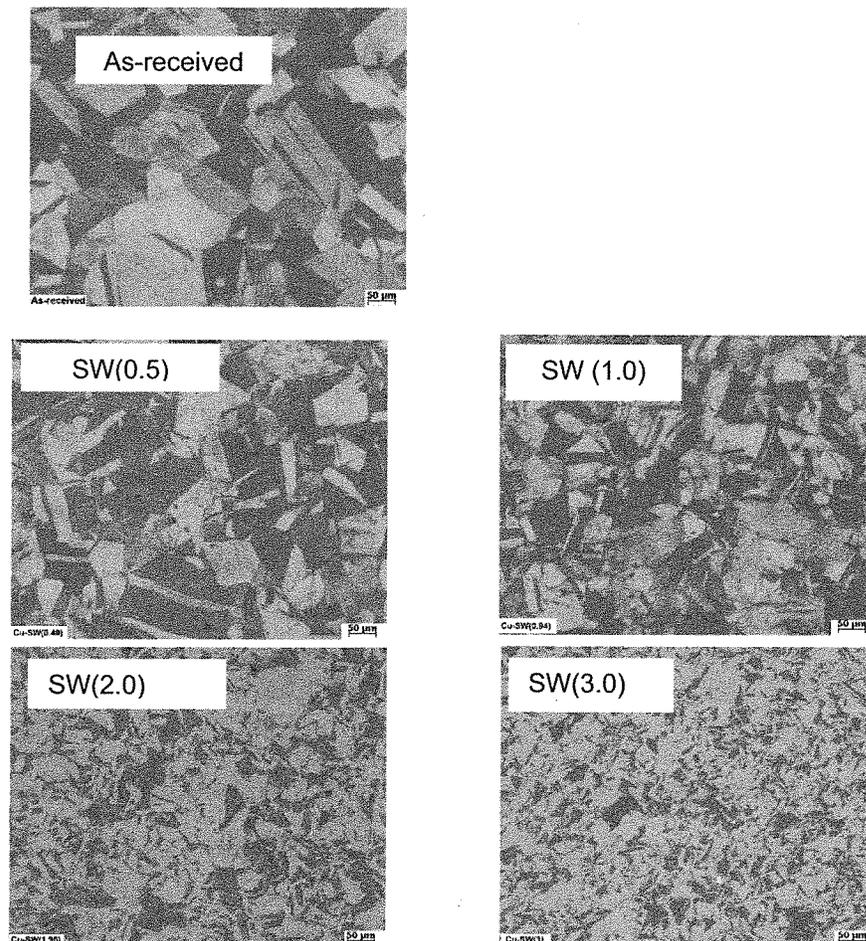


Fig. 1: Optical microstructure after swaging

Tensile properties of the different severe plastic deformations are illustrated in Fig.2.

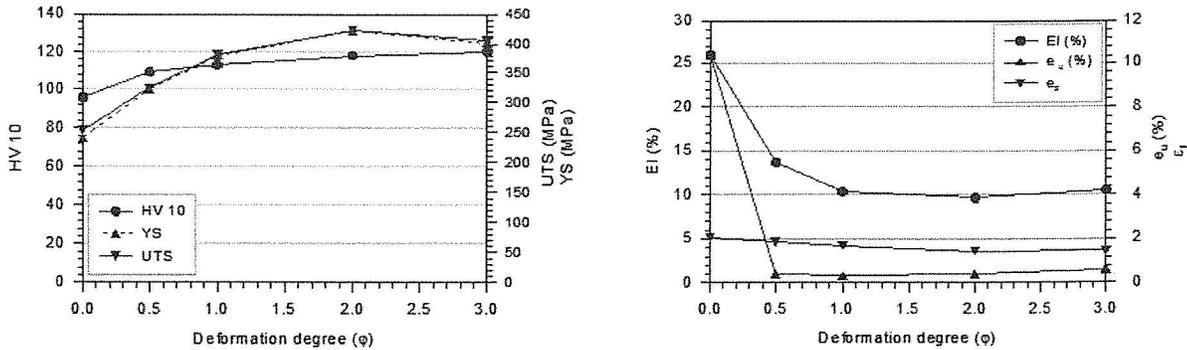


Fig. 2: Tensile test results

The results indicate the strength increases with increasing of strain and saturates in swaging ration of 2.0. In FCC metals processed by severe plastic deformation (SPD), the strength is basically determined by interaction between dislocations [3]. Both tensile elongation (EI (%)) and uniform strain (e_u (%)) decrease with increasing swaging ratio, however the decrease in uniform strain is even more pronounced than the decrease in tensile elongation. This means that the drop in resistance to necking may be the reason for decreasing elongation. It has been reported that the increase of the strength is generally accompanied by a reduction of ductility in SPD-processed metals [2, 4]. The microhardness values versus distance from the surface of specimens are presented in Fig.3. According to this figure, the hardness of 0.2 mmA shot peened specimens is higher than 0.1mmA and hardness decreases with a moderate slope with respect to the surface of two specimens. Therefore, the region where hardness is more than hardness in the depth of specimen could be considered as a region affected by shot peening. As observed in microhardness investigation, the microhardness was increasing proportionally with the almen intensity of shot peening. Because of the amount of cold working and plastic deformation, microhardness was increased [9].

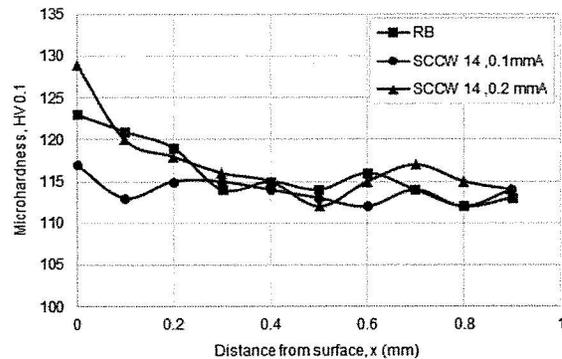


Fig. 3: Micro-hardness depth profiles after SP and RB

As expected, the roughness increases gradually with increasing almen intensity of the shot peening process, table 1.

Table1: Roughness values of cp-Cu after SP and RB

Sample	Rz [μm]
0.1mmA	8.2
0.2mmA	11.9
RB	1.5

The higher almen intensity resulted in more pronounced compressive residual stress, Fig.4, which will increase the fatigue performance [9].

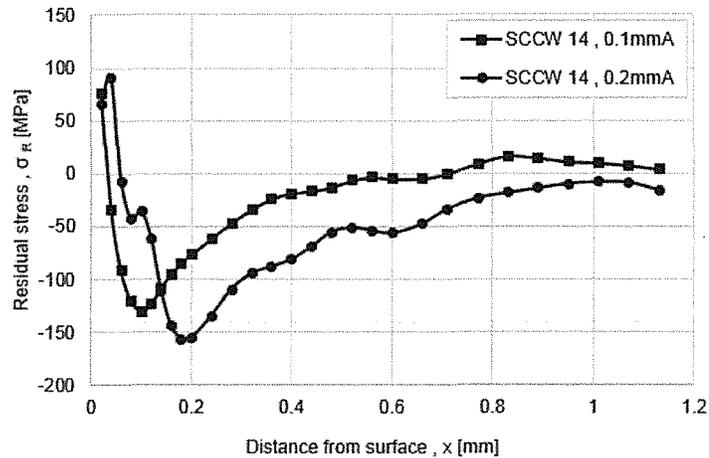


Fig. 4: Residual stress-depth profile after shot peening

In Fig.5, after shot peening the fatigue performance of notched samples was increased clearly in the 0.1mmA almen intensity. For the notched specimens, the maximum stress amplitude at the notch root ($\sigma_a \times k_t$) is also plotted.

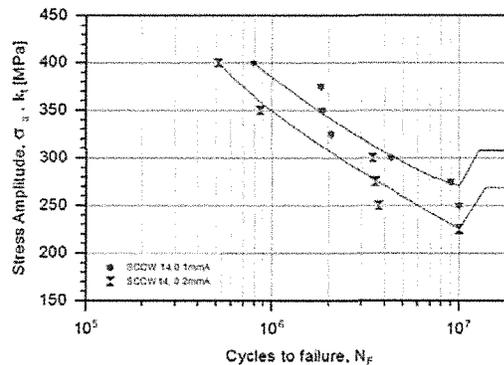


Fig. 5: S-N curves of cp-Cu after shot peening

While shot peening with an almen intensity of 0.2mmA is able to enhance surface strengthening, but because of higher surface roughness condition, the crack nucleation and crack propagation will be easier [9] which results in high notch sensitivity. Therefore, the 0.1 mmA almen intensity shows better fatigue performance than the 0.2 almen intensity. Fig.6 shows S-N behaviors of smooth and notched cp-Cu after swaging under rotation beam loading. Since the variation between fatigue notch factor, k_f , and stress concentration factor, k_t , is dependent on the size of the notch and the strength of the material, so in a material that is very sensitive to notch, k_f is equal to k_t . If the material is very insensitive to notches, k_f will be close to 1. According to data, the results show that fatigue strength of swaged samples in both smooth and notch samples are the same, about 150MPa, and the tensile test results indicate that during severe plastic deformation, work hardening capability decreases. Notch factor, k_t , is 1.9, So notch factor and fatigue notch factor are close to each other, therefore cp-Cu after SPD is almost fully (100%) notch sensitive. In contrary, the fatigue strength of annealed smooth and notched samples, are 75 and 112 MPa, respectively, so $q = 0.25$ and $K_f = 1.2$, therefore after annealing, the tendency to high notch sensitivity decreases.

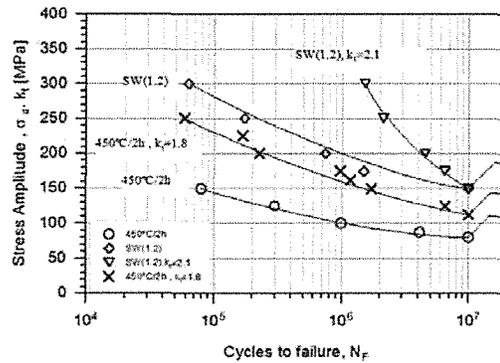


Fig. 6: Effect of SPD on fatigue notch sensitivity

The S-N curves of the swaged samples before and after SP and RB is illustrated in Fig.7. The results show that there is a marked improvement in fatigue life at all tested stress amplitudes. According to table1, and Fig.3, RB provides less roughness, higher hardness as well as work hardening in near-surface layers which led to low notch sensitivity as compared to SP.

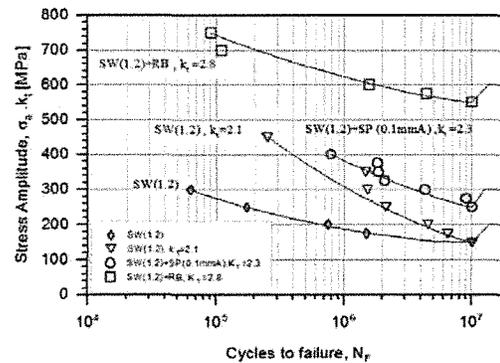


Fig. 7: Effect of SP and RB on notched fatigue performance

Conclusion

In SPD-processed metals, the increase of the strength is generally accompanied by a reduction of ductility [2, 3, 4]. It is generally accepted that high strength materials with low ductility are more notch sensitive than low strength materials with high ductility. Fatigue notch sensitivities can be correlated quite well with the work hardening capabilities (UTS-YS), the higher the work hardening capability, the lower the fatigue notch sensitivity [5]. Mechanical surface treatments such as SP and RB are known to improve fatigue notch sensitivity. This results from near surface high dislocation densities. This increase in dislocation densities led to high resistance to fatigue crack nucleation while the compressive residual stresses were found to stop microcrack growth. Shot peening tends to increase the surface roughness which can be detrimental to fatigue performance. Unlike the effect of surface strength in shot peened samples, roller-burnishing of notched HCF samples with lower surface roughness led to better fatigue performance than SP.

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