Surface Treatments to Improve Fatigue Performance of Age-hardenable CuNi3Si1Mg

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Abstract

In present work, the fatigue performance of CuNi3SiMg alloy has been studied after thermo-mechanical processing and mechanical surface treatment of laser peening (LP) and shot peening (SP). It was observed that fatigue behavior can be improved by a uniform distribution of small-sized precipitates. After LP and SP, the changes in the surface and near-surface layer treated samples could improve fatigue performance by about 70 MPa compared to the electropolished condition.

Keyword CuNi3SiMg alloy, fatigue performance, shot peening, laser peening

Introduction

Pure copper due to high electrical conductivity and reasonable price is the optimum material for conductors, but many wire and cable applications, e.g. connector pins require a strength which exceeds the strength attainable with pure copper [1]. Cu-Ni-Si alloys are precipitation-hardenable copper-base alloys and offer a combination of high strength, good electrical conductivity and stress relaxation resistance [1, 2]. The effect of precipitation hardening on strength and electrical conductivity is dependent on the initial microstructural parameters such as dislocation density, points and grain size [3]. Grain refinement processes after solution annealing, but previous to the age-hardening supports the formation of small-sized and homogeneously distributed precipitates that are effective to enhance the tensile strength and elongation by reducing the inter-precipitate spacing [1,4]. In addition, Surface nanocrystallization processes like shot peening and laser shot 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 of fatigue life, but the surface roughness can be detrimental to fatigue performance [5, 6]. The present investigation was aimed at exploring the best combination of thermomechanical aging and mechanical surface treatment, which may modify suitably the microstructure so as to cause an overall improvement of fatigue performance of CuNi3SiMg alloy.

Experimental Method

The investigated copper alloy is the Corson-type alloy CuNi3Si1Mg which was delivered as rods of 23 mm diameter. The material condition in our present study was extruded, homogenized, and rotary swaged and subsequently precipitation hardened. Typical solution heat treatment (SHT) is 800 °C for 2h .During swaging of solutionized samples at room temperature, the specimens diameter were reduced from 23 to15, 11, 7 and 5 mm which correspond to true deformation degree (φ) of 0.84, 1.5, 2.4 and 3.0. Microstructure investigations were carried out on a light optical microscopy (Model: Zeiss Axioskop). Fatigue studies on samples were made on Mayes-GTG, Rolls Royce rotating-beam fatigue machine (R = -1) at RT (room temperature) and in air as the reference environment. Hour - glass shaped specimens were machined with minimum gauge diameter of 3 mm and 45 mm gauge length. Electropolishing, shot peeing and laser peening as three different surface treatments were carried on the specimen surfaces after machining. Shot peening was done using a gravity induction system and spherically conditioned cut wire (SCCW 14) having an average shot size of 0.36 mm. The surface roughness measurement was done using a Perthometer S8P made by the company Perther Mahr. Laser peening without coating (LPwC) was carried out at Toshiba Corp. in Japan using a compact Q-switched and frequency – doubled Nd:YAG laser with a pulse duration of 8ns and a wavelength of 532nm.

Experimental Results

Fig.1 presents the metallographic pictures comparing as-received (Ar) condition with conditions after different severe plastic deformations. The severe plastic deformation by rotary swaging to deformation degree of $\varphi = 3$, results in grain size refinement. The original samples were extruded at 900 °C, then solution heat treated (SHT) at 800 °C/2h and subsequently water-quenched. The microstructure after this treatment exhibits a recrystallized coarse grain structure with twins within the grains.

Examples of the optical microstructures of CuNi3SiMg, given in figure 2, indicate the effect of severe plastic deformation before age-hardening. Severe plastic deformation results in more grain size refinement. In comparing with SHT+Swaging condition, the optical microstructures reveal no difference after swaging+age-hardening. The microstructure of CuNi3SiMg contains nanoscopically small Ni_2Si embedded in the copper matrix that are not visible in the optical microscope.

Table 1 indicates the mechanical properties of CuNi3SiMg alloy in the initial, solutionized, and after swaging and age-hardening were characterized by tensile tests.

An analysis of the results shows that the swaging process has increased the mechanical strength of the materials. After solution heat treatment the material is very ductile since most precipitates have dissolved. It can be noted that tensile strength and yield stress rapidly increase already at small deformation degree. The maximum value of ultimate tensile strength (UTS) and yield stress were observed for swaging ratio of 2.4 and then they are decreased. Grain refinement obtained after SPD led to the increase of tensile strength. After precipitation hardening, the tensile strength and elongation with smaller grain size were higher than that those with larger grain size. As explained above, the higher tensile strength of CuNi3SiMg with smaller grain size can be explained by higher dislocation density, reducing the inter-precipitate spacing and also smaller precipitates. The enhancement uniform elongation in nanostructures + secondary phase particles (designated as NS+P samples) is due to improvement in the work hardening rate through dislocation accumulation. After tensile testing, a large number of dislocations exist around second-phase particles. These dislocations were likely generated by lattice mismatch at the matrix/particle interface [7].

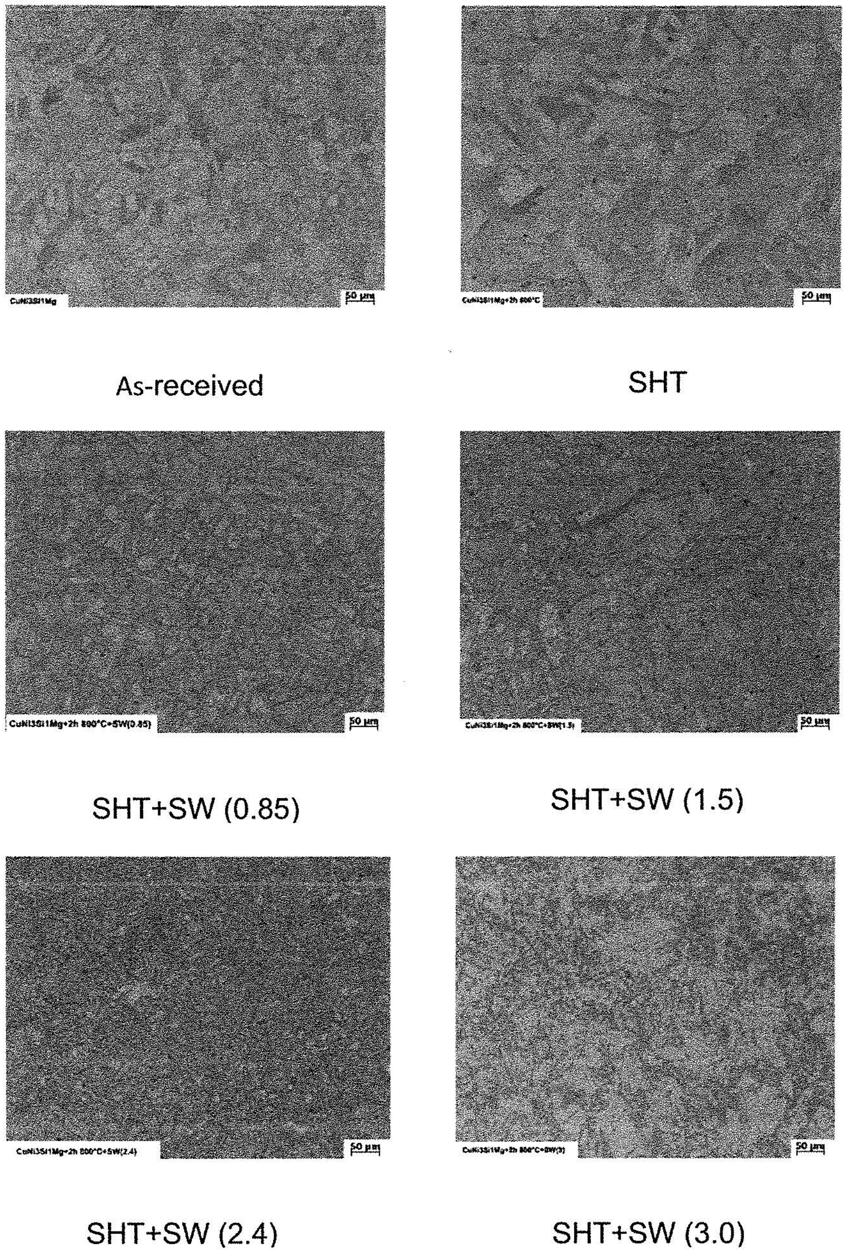

Fig. 1: Optical micrograph of CuNi3SiMg after SHT+ Swaging

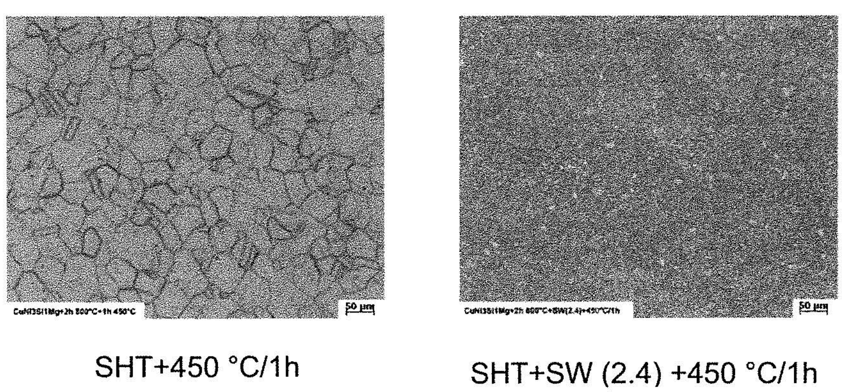

Fig. 2: Effect of SPD on optical micrograph of age-hardened CuNi3SiMg alloy

Table 1: Variation of tensile properties as a function of severe plastic deformation degree and age-hardening

	YS (MPa)	UTS (MPa)	(UTS-YS) (MPa)	e u (%)	El (%)	ε_F
As-received	267	483	216	25	34	1.2
SHT	153	331	178	36	47	1.9
SHT+450 °C/1h	329	548	219	32	40	1.3
SHT+SW(0.85)	506	507	1	0.2	8.2	1.7
SHT+SW(1.5)	514	517	3	0.5	7.6	1.4
SHT+SW(2.4)	587	588	1	0.2	0.5	1.5
SHT+SW(3.0)	555	558	3	0.2	0.6	1.6
SHT+SW(2.4)+450 °C/1h	821	845	24	6.5	11.6	0.5

The effect of cold deformation after solution treatment on fatigue behavior of CuNi3SiMg alloy is illustrated in Fig.3. Before cyclic testing, the samples are electro-polished to obtain a high quality surface. The specimens which received cold work after solution treatment but before aging, having lives at all stress amplitudes superior to those of SHT+ aged and SHT+SW(2.4) conditions. It is seen from the curves that for any value of fatigue life, the corresponding fatigue stress (endurance limit) of the swaged +aged condition is constantly higher than the value obtained on the unworked specimens throughout the range of investigation. The improvement in the fatigue properties associated with the cold work can possibly be related to the finer precipitates, which in the heavily dislocated region will have a lesser tendency to localize the deformation than in the grain-boundary region of the alloy which is not cold-worked [8].

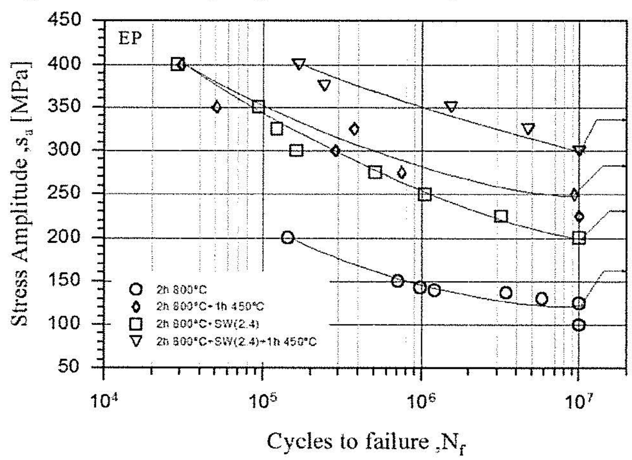

Fig. 3: S-N curves in rotating beam loading (R=-1)

The effect of shot peening using SCCW 14 shot and various Almen intensities on the fatigue life for various conditions is illustrated in Fig. 4. For all conditions, the fatigue life first goes up, reaches a maximum and then drops again. The results indicate the best Almen intensity for conditions SHT+450 °C/1h, and SHT+SW (2.4) +450 °C/1h is 0.2 mmA.

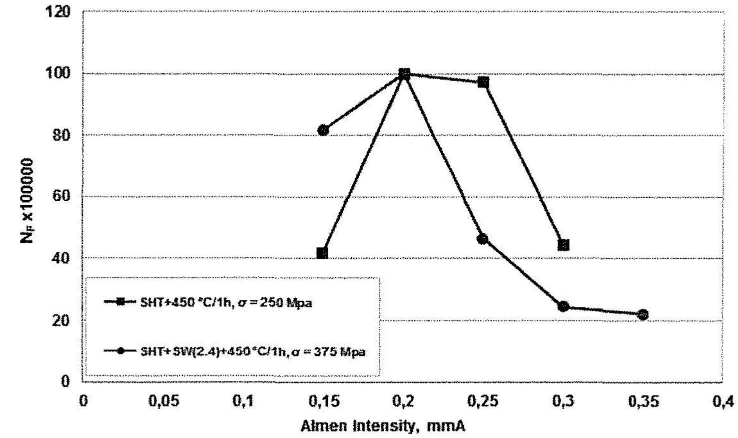

Fig. 4: Fatigue life of CuNi3SiMg alloy after shot peening using various Almen intensity

The change in surface roughness after shot peening (SP) and laser peening (LP) for SHT+SW(7)+450 °C/1h is illustrated in Table 2. Compared to laser peening, the surface roughness is strongly higher after SP. The Vickers hardness (HV 0.1) is shown in Fig. 5. The microhardness values versus distance from the surface of specimen indicates the identical values for both SP and LP on near the surface, but induced cold work, extends deeper into the material after SP.

Table 2: Effect of shot peening and laser peening treatments on surface roughness of SW (2.4) +450 °C/1h

Condition	Roughness, Rz [µm]
EP	0.4
LP	4.6
SP	11.2

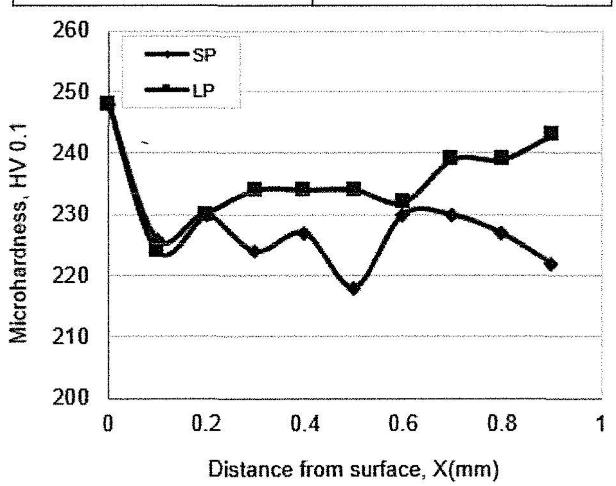

Fig. 5: Microhardness-depth profiles after shot peening and laser peening in SHT+SW (2.4) +450 °C/1h

As illustrated in Fig. 6, the improvement of HCF strength (at 10^7 cycles) was similar between SP and LP. SP and LP increased the HCF strength of SHT+SW(2.4)+450 °C/1h from about 300 MPa (EP) to about 375 MPa (SP and LP). The stress level in SP is slightly higher than LP in higher stress amplitudes. Presumably, residual compressive stress in LP is less stable during loading at higher stress amplitude which may be because of cyclic softening [9].

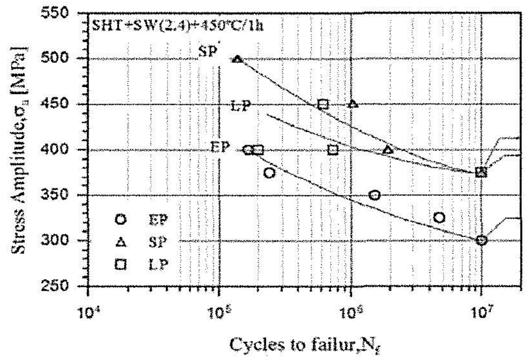

Fig. 6: S-N curves in rotating beam loading after EP, SP and LP

Conclusion

Cyclic plastic deformation of age-hardenable alloys depends on grain size, geometry, size, distribution and coherency of precipitates to the matrix [10]. In CuNi3SiMg alloy, grain refinement process before age-hardening hinders cyclic plastic deformation by increasing of dislocation density and dislocation-precipitates interaction [10]. For the investigated process parameters, HCF strength of shot peened specimens in SHT+SW(2.4)+450 °C/1h in higher stress amplitudes are significantly superior to those of LP possibly because of higher and more stable compressive residual stress than those of LP.

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