Journal of Mechanical Science and Technology 26 (9) (2012) 2711~2717
www.springerlink.com/content/1738-494x
DOI 10.1007/s12206-012-0738-3

Impact of surface hardening treatment generated by shot peening on the fatigue life of brass alloy[†]

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(Manuscript Received March 21, 2011; Revised February 22, 2012; Accepted April 14, 2012)

Abstract

Brass alloy is widely used because of some attractive properties such as high electrical and thermal conductivity. But its fatigue performance after surface treatment is not very well explored in literature. Thus, in the present work, particular emphasis was given to the influence of surface treatment by shot peening on the fatigue life of brass alloy, throughout surface roughness and microstructural evolution. Fatigue tests were performed on unpeened, peened and peened then polished specimens. Various times of surface hardening treatment as 30, 60 and 120 min were considered. Experimental results reveal that the fatigue life of peened brass alloy decrease for all studied hardening treatment conditions. Surface roughness and microstructural properties showed large sensitivity to the shot peening process of brass alloy.

Keywords: Brass alloy; Fatigue life; Mechanical surface treatment; Roughness; Shot peening

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1. Introduction

The majority of mechanical surface treatments enhance mechanical properties; in particular improve fatigue life of metallic materials [1, 2]. Actually, shot peening is the most common surface treatment employed in industry in order to ameliorate the fatigue life of structural metallic materials [3, 4]. The improvement of fatigue strength by shot peening is well studied for conventional materials, including stainless, maraging steels, aluminium, titanium and nickel-based alloys [5-7]. However, only few works investigate the effect of shot peening on the fatigue performance of brass.

Benefits of shot peening are typically attributed to a combination of surface hardening by increased dislocation density, structural modification and introduction of compressive residual stress after a heterogeneous plastic deformation on the surface layer of the peened samples [8-10]. In fact, compressive surface residual stress helps to expand the life of engineering component by retarding fatigue crack initiation and growth [11, 12]. But, at the same time, several studies on residual stress relaxation by cyclic loading have been conducted [13, 14]. It was shown that residual stresses are instable during loading and relax continuously with increasing number of cycles [15, 16]. Stress relaxation is also accentuated with cyclic softening of the investigated materials; especially in the case of low cycle fatigue loading where the percentage of residual stress relaxation can exceed 50% during the few first cycles [17, 18].

In addition to stress relaxation, the beneficial effect of compressive stress may be reduced by the surface damage associated with shot peening of a material [19]. Consequently, fatigue life of structures is known to highly depend on the surface quality, particularly, roughness. Effectively, in many fatigue models, performance was often entirely attributed to the amplitude of surface roughness parameters, in particular the arithmetic average Ra [20-22]. In addition, for a given roughness, residual stress only seems to have a slight influence on the fatigue life and the fatigue behavior is due to a predominant effect of roughness [23]. Furthermore, it has been identified that fatigue cracks generally initiate from free surfaces, especially in short life regime, and then highly depend on the surface topography [24]. Consequently, surface roughness is the main factor affecting fatigue life especially in the case of short life regime [25].

Considering all these studies, it was found that although that fatigue life is heavily influenced by residual stress; both metallurgical conditions of the material (microstructure and microhardness) and the presence of surface irregularities play a key role [26]. The deleterious surface state of shot peened surfaces possibly counterbalances the beneficial influence of residual stress [27]. We conclude that a competition between the detrimental and beneficial effects of shot peening emerges.

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Table 1. Chemical composition of brass (wt. %).

%Cu	%Zn	%Pb	%Sn	%Fe	%Ni	%Li
58.47	38.11	2.79	0.25	0.21	0.11	bal.

Table 2. Mechanical properties of brass by monotonic tensile tests.

Tensile strength	594 MPa
Yield strength obtained employing the 0.2% offset method	450 MPa
Young's modulus	90 GPa
Fracture strain	9.5%

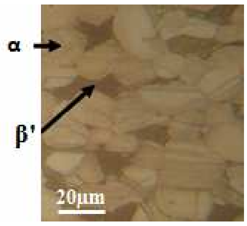

Fig. 1. Microstructure of brass.

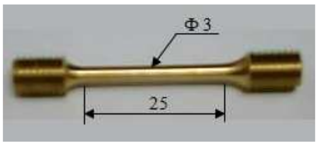

Fig. 2. Specimens geometry.

The main purpose of this research is to investigate the influence of shot peening surface treatment, in particular surface roughness and microstructural evolution, on fatigue life of brass alloy.

2. Experimental details

2.1 Sample preparation

In this study, the tested material is a brass containing an important percentage of lead. The chemical composition of this material is given in Table 1.

The microscopic observation shows a duplex structure with two phases (α + β'). α phase has a face-centered cubic (FCC) structure, while β' phase has a centered cubic (CC) structure (Fig. 1).

For industrial purposes, rounded specimens with a diameter of 3 mm and a gage length of 25 mm were prepared for low cycles fatigue tests and monotonic tensile characterization. An example of such as specimen is represented by Fig. 2.

Monotonic characterization of the brass by tensile test was made at room temperature and a strain rate of 10 mm/min ($\dot{\varepsilon}$ = 6.6 x 10^{-3} s^{-1}). Mechanical properties as measured are given in Table 2.

2.2 Shot peening process

The shot peening process consists in using C45 spherical steel shot with a diameter of 0.5 mm on a rotating barrel at the speed of 300 rpm. Specimen shot peening was applied for 30 min, 60 min and 120 min. Peening procedures were done to full coverage.

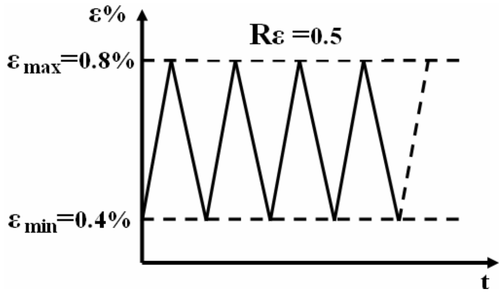

Fig. 3. Illustration of cyclic loading.

2.3 Characterization of shot-peened specimens

Structural changes occurring in the near-surface regions were characterized by micrographic tests using an optical microscope. The observed surfaces were beforehand prepared by mechanical polishing to 1200 grit SiC abrasive paper followed by 3 μm and 1 μm diamonds. The chemical attack used in this study consists of a solution of nitric acid (HNO_3).

For comparison purposes and estimation of the contribution of the surface treatment in terms of mechanical properties, mechanical characterization of the unpeened and peened samples by monotonous tensile tests was carried out. Surface and sub-surface Vickers hardness of specimens were measured using a 402 MVD micro-hardness testing machine. Measurements on the normal section of specimen were realized describing a profile from the surface to the depth.

Roughness measurements were carried out on a TR200 Surface Roughness Tester.

2.4 Fatigue testing procedure

For the majority of applications, the industrial constituents are subjected to structural deformations, particularly in the zones of stress concentration. In this case, it is more suited to consider the fatigue under load subjected to the control of deformation to simulate the real load in the structure and also to correlate better the cyclic mechanical behavior and the microscopic structures [28].

The structural and morphological modifications generated by shot peeing which affect a layer on the near-surface, will induce a cyclic behavior different from the basic material. Low cycle fatigue tests under axial tensile-compression loading conditions are carried out on non-treated samples and 30, 60 and 120 min treated ones. A triangular wave signal was used for total strain control under strain ratio Rε = 0.5; (Rε = $\varepsilon_{min}/\varepsilon_{max}$). A constant strain rate $\dot{\varepsilon}$ = 6.6 x 10^{-3} s^{-1} was considered (Fig. 3).

To confirm results and to have a solid comparison, Wöhler

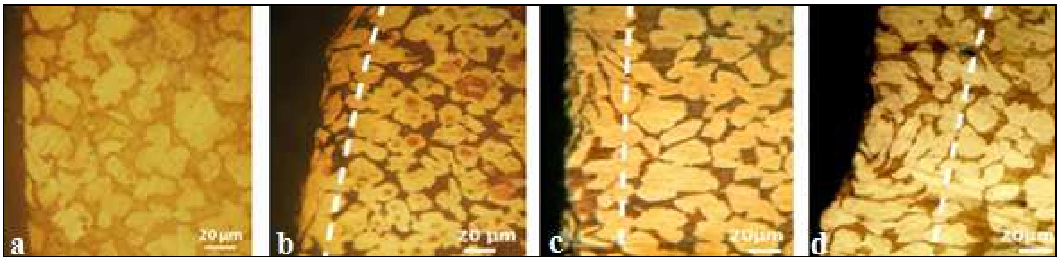

Fig. 4. Microstructural evolution of brass subjected to shot peening during three different periods: (a) reference state: non peened sample; (b) 30 min peened sample; (c) 60 min peened sample; (d) 120 min peened sample.

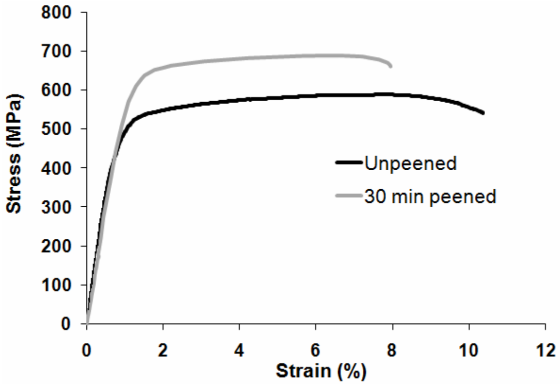

Fig. 5. Monotonic tensile stress-strain curves of unpeened and 30 minute peened materials.

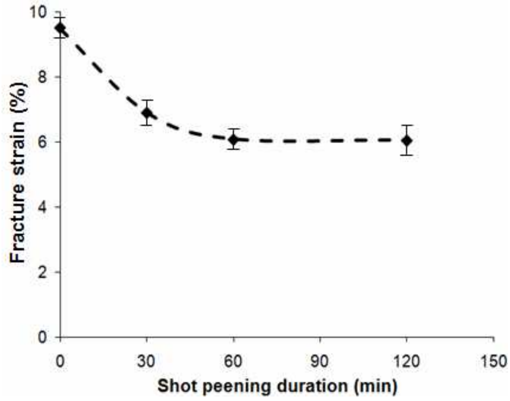

Fig. 6. Fracture strain evolution as a function of the shot peening duration.

curves of unpeened and peened (treated for 30 minutes) materials were constructed by scanning a margin of strain amplitude from 0.2 to 1.4%.

To reveal the contribution of roughness generated by shot peening on the fatigue life of the studied material, a slight polishing of the circumferential surface of specimens was performed in order to decrease roughness without suppression of the near surface layer.

The idea consists in keeping the totality of the modified layer to investigate just the effect of roughness. Fatigue tests with the same parameters indicated previously are applied on 30, 60 and 120 min peened then polished specimens.

3. Results and discussion

3.1 Shot peening evaluation

Shot peening is a mechanical surface treatment which affects the surface of the sample by getting modifications of the microstructure, surface properties and mechanical properties. An evaluation of these modifications is deemed necessary to qualify the contribution of shot peening on fatigue life and analyze experimental results.

3.1.1 Microstructural evolution

Fig. 4 shows micrographic observations revealed by optical microscope after chemical attack on samples subjected to different shot peening periods: 30, 60 and 120 min.

Shot peening generates modifications at a superficial layer which thickness depends on the processing time (zones limited by dashed white lines, as shown in Fig. 4(b)-(d). The thickness of this layer increases with a logarithmic evolution as a function of treatment time from 20 µm for 30 min peened samples to 60 µm for 120 min peened ones. According to the same figure, the change in grain shape is an indication of structural modification due to compressive stress. Grains having a globular shape at the beginning (Fig. 4(a)) become more elongated after shot peening (Fig. 4(b)-(d)) and the peened surface exhibits many created craters indicating the variation of the roughness.

3.1.2 Monotonic characterization

The monotonic characterization of both unpeened and peened materials gives a clear indication on the resulting mechanical properties modifications of the material after shot peening.

According to the tensile stress-strain curves represented by the Fig. 5, the yield strength and the tensile strength of peened material are larger than those of unpeened material. This result indicates the presence of compressive residual stress. The fracture strain (A%) decreases considerably after shot peening from 9.5% for the unpeened alloy to 6.9% for the 30 min peened alloy (Fig. 6). This is probably due to the impact of surface state.

The Young modulus, which is an intrinsic property of the material, remains invariable.

Table 3. Thickness of the affected layer according to shot peening duration.

Shot peening duration (min)	30	60	120
Transformed thickness (µm)	80	120	130

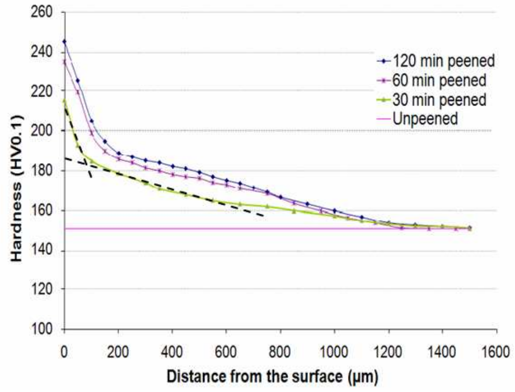

Fig. 7. Micro-hardness evolution as function of distance from surface for different shot peening duration.

3.1.3 Micro-hardness profiles

To determine the thickness of the near-surface affected by shot peening, Vickers micro-hardness measurements from the surface to the depth of specimen were realized.

Results are given in Fig. 7 and the thicknesses of the transformed layer are included in Table 3. The hardness decreases gradually as the position moves away from the surface. We use the intersection of both slopes (dashed black lines) appearing on the profile of micro-hardness to determine the transformed layer thickness.

This superficial layer is very large in comparison to microstructural modification appearing just on a small layer which not exceeds 60 µm for 120 min peened samples. The width of plastic deformation appears less propagated than the work hardening.

3.1.4 Roughness surface characterization

Another particularity of mechanical surface treatments is the generation of a new surface state as it was shown by microstructural observations.

In the case of shot peening, a deterioration of the surface state is frequently observed [29]. In this study, the arithmetical roughness values (Ra) of peened samples show an important variation compared to the roughness of unpeened ones. A large increase is recorded after shot peening. The initial roughness measured on unpeened specimens is 0.8 µm while that measured on peened specimens exceeds 6 µm and depends on the processing time (Fig. 8). The variation of roughness is important. Roughness seems to be an influencing parameter to consider in this study.

3.2 Shot peening effects on cyclic behavior

Superficial mechanical treatment induces plastic deformation on the superficial layers of samples and introduces modifications of stress distribution via generation of residual stress. Furthermore, this type of treatment generates various degrees of roughness. This roughness creates stress concentration zones generating a localized plastic strain area and then, privileged sites of cracks initiation [30].

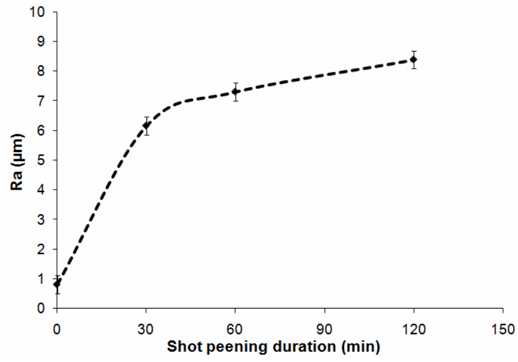

Fig. 8. Roughness variation as function of shot peening duration.

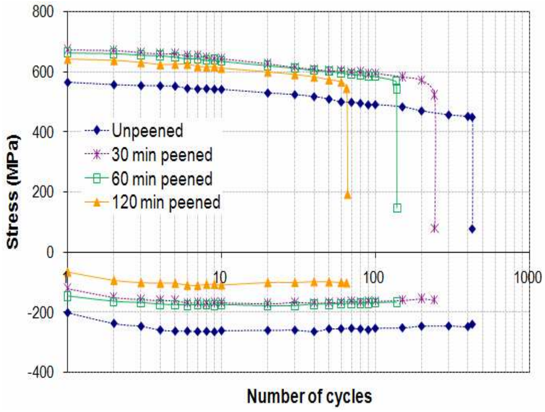

Fig. 9. Maximum and minimum stress values as function of number of cycles of unpeened and peened brass during: (a) 30 min; (b) 60 min; (c) 120 min.

The low cycle fatigue performance before and after shot peening, under tension-compression (axial) loading, is given by Fig. 9. It is noticed that the number of cycle to failure (Nf) decreases after shot peening. The more the treatment duration increases, the more the number of cycles to failure decreases.

A clear difference in number of cycles to failure appears by comparing the unpeened (430 cycles) and 120 min peened alloy (70 cycles). Furthermore, it should be mentioned that peened and unpeened specimens exhibit a pronounced linearly decrease of mean stress with the number of cycle which can be attributed to a cyclic softening phenomena.

To confirm decrease of fatigue life at various strain amplitudes, Wöhler curves of unpeened and 30 min peened material was realized (Fig. 10). Experimental results show that the life curve of unpeened material is situated above that of the shot peened one. This result confirms the previous observations in various loading conditions.

It is known that the fatigue life of a material subjected to

Table 4. Plastic strain amplitudes as a function of the duration of shot peening.

Peening duration (min)	0	30	60	120
$\Delta\varepsilon_p$ (%)	0.603	0.637	0.690	0.709

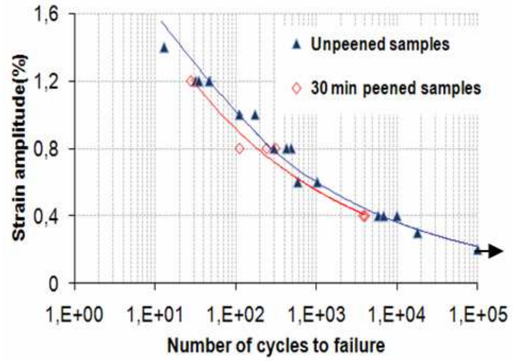

Fig. 10. Low cycle fatigue life curves.

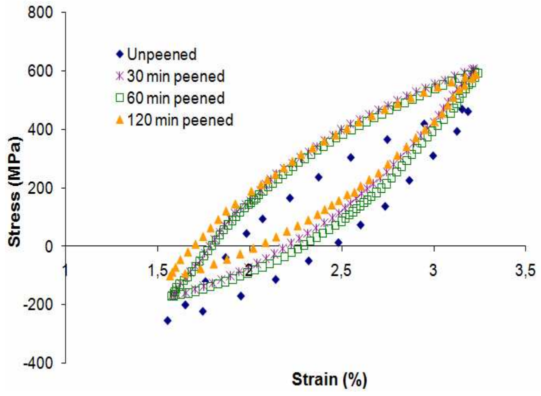

Fig. 11. Hysteresis loops of unpeened brass, 30 min, 60 min and 120 min peened samples.

cyclic loads depends on the amplitude of the generated plastic strain $\Delta\varepsilon_p$. For this reason, hysteresis loops were plotted and the amplitudes of plastic strain were determined at approximately the half-life of each specimen (Fig. 11). Plastic strain amplitudes as measured are given in Table 4. The measures were released with reference to a graphical method [31] based on Eq. (1):

$$\Delta\varepsilon_t/2 = \left(\varepsilon_{\max} - \varepsilon_{\min}\right)/2 = \varepsilon_p + \varepsilon_e \tag{1}$$

where $\Delta\varepsilon_t$ denotes the total strain amplitude, ε_{max} is the maximal strain, ε_{min} is the minimal strain, ε_p is the plastic strain and ε_e is the elastic strain.

Results are presented in Table 4 ($\Delta\varepsilon_p = 2\ \varepsilon_p$).

Firstly, it is noted that a low variation of the plastic strain amplitude accompanies the fatigue life evolution after shot peening of the studied material. Such variation does not justify the important diminution of the fatigue life.

Secondly, this shows that an important relaxation of residual stress happened, in a way that similar amplitudes of plastic strain were measured at the half-life of cycles for all tested specimens. In fact, as mentioned in literature, the compressive residual stress can be beneficial for fatigue life provided that they are stable. The residual stress may get relaxed during loading [32]. The main relaxation of residual stress normally takes place in the first cycle, followed by gradual relaxation during the lifetime [33, 34]. It is associated with dislocation movement and correlated to the plastic strain amplitude and number of cycles [35]. Then the behavior of the brass on fatigue loading which exhibits a cyclic softening justifies its relaxation and the similar measurements of plastic amplitudes of deformation.

These observations have made it possible to consider that other factors can be at the origin of the fatigue life evolution as a function of shot peening duration and will have a serious effect on the fatigue performance of these materials.

For this purpose, by evaluating the modifications brought to peened material, it is noted that an important roughness variation of the tested specimens is registered. For this reason, we study the influence of the surface state of peened specimens on the low cycle fatigue life.

3.3 Surface state contribution

In addition to samples tested before and after shot peening, another series of low cycle fatigue on peened then polished specimens was led to show the influence of roughness on the fatigue performance. The polishing of peened samples was made in such a way as we regenerate the initial surface state of unpeened samples and we keep the near-surface layer intact.

Curves of cyclic softening of unpeened, peened and peened then polished samples are represented below in Figs. 12 and 13. To correlate the axial fatigue behavior to the effect of the surface state, measures of roughness are given in Tables 5 and 6. The same approach is applied to 30 min (Fig. 12 and Table 5) and 120 min peened specimens (Fig. 13 and Table 6).

Experimental results illustrated by Figs. 12 and 13 show that the number of cycles at failure of peened then polished material increases compared to the peened material. In this case, the variation of the number of cycles at failure can be attributed to the roughness of tested specimens.

However, their life is still lower than that of the unpeened one. This is due to polishing which is not made in an equivalent way on the entire tested specimen. There are some persisting craters at the extremity of the gage length which cannot be well polished.

Consequently, for our experimental conditions, the surface state of a brass alloy is an important factor which influences significantly the fatigue life performance of the treated material. We conclude that shot peening, as being a mechanical treatment of surface, does not lead necessarily to the improvement of fatigue life which can result from the introduction of residual stress in compression. Shot peening can introduce privileged sites of cracks initiation due to roughness increase and thus less fatigue resistance especially for material

Table 5. Roughness measures of unpeened brass, 30 min peened samples, 30 min peened then polished samples.

Treatment	Unpeened	30 min peened	30 min peened then polished
Roughness Ra (μm)	0.8	6.1	0.8

Table 6. Roughness measures of unpeened brass, 120 min peened samples, 120 min peened then polished samples.

Treatment	Unpeened	120 min peened	120 min peened then polished
Roughness Ra (μm)	0.8	8.3	0.8

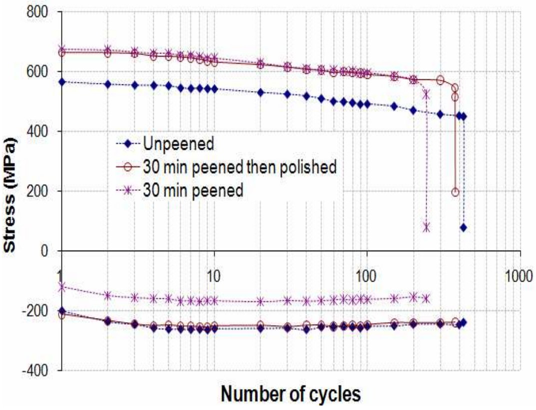

Fig. 12. Maximum and minimum stress values as function of number of cycles of unpeened samples, 30 min peened samples, 30 min peened then polished samples.

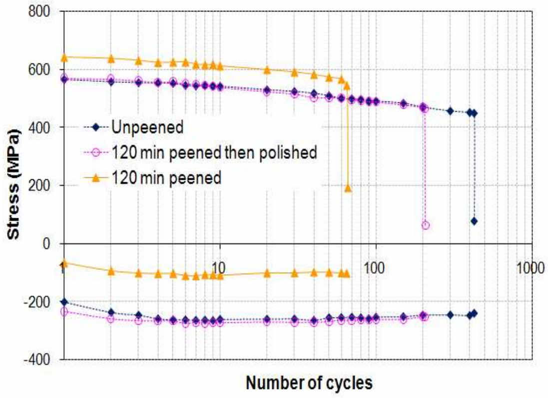

Fig. 13. Maximum and minimum stress values as function of number of cycles of unpeened samples, 120 min peened samples, 120 min peened then polished samples.

presenting a cycling softening during fatigue test.

4. Conclusions

For industrial purpose, an experimental study on the effect of surface hardening treatment generated by shot peening on the low cycle fatigue life of brass alloy was established. Results revealed that the cyclic behavior of peened brass is different compared to unpeened material and that fatigue life corresponding to the number of cycles at failure decrease after shot peening.

A very low variation of the plastic strain amplitude is noted after shot peening. This shows that an important relaxation of residual stress was happened in a way that we get back equivalent plastic amplitudes of deformation after a certain number of cycles. Such variation justifies that compressive residual stress does not contribute intensely on the fatigue life of brass alloy.

In addition, we can conclude that the fatigue life of materials which exhibit cyclic softening after hardening treatment is more affected with:

- The surface state of mechanical structures by means of a significant elevation of the roughness that changes the local stress concentration compared to unpeened surfaces. The larger the surface roughness, the larger the strain concentration and then the lower fatigue life.

- The microstructural state by the compaction of the two phases α and β' in the near-surface layer.

The surface state is then an important factor in fatigue performance of the material especially for those presenting a cycling softening during fatigue test.

Acknowledgement

The authors gratefully acknowledge SOPAL company (Tunisia) for their continuous help and specimens preparation. Special thanks to its manager for his valuable support.

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