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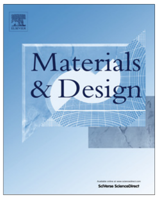

Effect of severe shot peening on ultra-high-cycle fatigue of a low-alloy steel

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ABSTRACT

It is well known that shot peening is able to increase the fatigue strength and endurance of metal parts, especially with a steep stress gradient due to a notch. This positive effect is mainly put into relation with the ability of this treatment to induce a compressive residual stress state in the surface layer of material and to cause surface work hardening. Recently the application of severe shot peening (shot peening performed with severe treatment parameters) showed the ability to obtain more a remarkable improvement of the high cycle fatigue strength of steels. In this paper severe shot peening is applied to the steel 50CrMo4 and its effect in the ultra-high cycle fatigue regime is investigated. Roughness, microhardness, X-ray diffraction residual stress analysis and crystallite size measurement as well as scanning electron microscopy (SEM) observations were used for characterizing the severely deformed layer. Tension–compression high frequency fatigue tests were carried out to evaluate the effect of the applied treatment on fatigue life in the ultra-high cycle region. Fracture surface analysis by using SEM was performed with aim to investigate the mechanism of fatigue crack initiation and propagation. Results show an unexpected significant fatigue strength increase in the ultra-high cycle region after SSP surface treatment and are discussed in the light of the residual stress profile and crystallite size.

1. Introduction

Present development of new industrial machines requiring higher efficiency and cost savings must provide possibility of higher loading, higher operation speeds and high reliability together with reduced requirements for maintenance. For example, components of high speed train Shinkanzen in 10 years of operation have to withstand approximately $N = 10^9$ cycles and failure of a main component can have fatal consequences [1]. These facts increased requirements for fatigue life testing in so called ultra-high cycle region and to assess if the fatigue strength of a material could be really considered constant for more than 10 million cycles, conventional number of cycles used to determine the so called fatigue limit. Anyway, after the first tests performed by exceeding this endurance, it was obvious that fatigue failures can happen even for applied stress amplitudes lower than the fatigue limit, for a number of cycles much more than 10^7 and that the damage and failure process could be different form the usual ones.

However, to set a fatigue test program aimed at investigating the ultra-high cycle region requires the development of new testing devices to strongly increase the loading frequency. A symposium on this special topic was held in Paris in June 1998 where data obtained by high speed testing machines were presented by Stanzl-Tschegg [2] and Bathias [3] using ultrasonic fatigue testing machines capable of a frequency of 20 kHz, by Ritchie et al. [4] using a 1 kHz closed loop servo-hydraulic testing machine and by Davidson [4] using a 1.5 kHz magneto-strictive loading machine [1]. From that time many solutions were proposed but still the most commonly used machines for this kind of tests are based on concept of Manson from 1950 and uses frequencies close to 20 kHz. They represent a good balance between the strain rate, the determination of number of cycles to rupture and the duration of the fatigue test ($N = 10^{10}$ cycles are achieved in about 6 days). Other devices able to get higher loading frequencies are rarely used because they cause extremely high deformation rates and, since the test lasts for only few minutes, a remarkable error in the cycle counting is expected [5].

But the investigation of a material in the ultra high-cycle fatigue regime also raises other questions about the successful application of the methods commonly used to improve the fatigue behavior of metal alloys and structural/machine parts. In particular, it is well known that mechanical treatments can be successfully used to increase the fatigue limit, especially in the case of notched parts, but just a few investigations explore their application in the ultra high cycle fatigue.

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Among these latter treatments, shot peening can be considered the most widely used, due to its flexibility, its relative low cost and due to the fact of reducing the environmental impact with respect of other treatments used with the same aim.

The positive effect of shot peening on the fatigue properties is generally related to its ability to introduce a compressive residual stress state in the surface layer of material and to the surface work hardening caused by the not uniform plastic deformation caused by the multiple impacts of the shot flow [6–10]. Many experimental evidences show that shot peening is more effective with steep gradient of the applied stress, while the effect is less evident when applied to smooth specimens subjected to axial fatigue, due to the fact that in this case the beneficial effect of the treatment on the surface can only shift the crack initiation point in the inner material (generally in correspondence of an internal material defect), without a relevant increment of the applied stress.

Recently, the possibility to use shot peening as a severe plastic deformation process was also investigated. Usual air blast devices with unusual severe process parameters (higher Almen intensity and coverage), characterized by high kinetic energy proved the ability to accumulate a great amount of plastic deformation causing grain refinement up to nanometer scale [11–16].

This treatment, called severe shot peening (SSP), resulted in improved properties of the treated layer of material: deeper residual stresses and surface work hardened layer, increased surface hardness. Some data [11] show also that SSP should be able also to increase the corrosion resistance, while it is known that conventional shot peening could decrease the corrosion properties [17]. Undesired side effect of SSP is an increment of the surface roughness.

However just a few data exists about the effect of SSP on steel fatigue behavior [11,12] and, even if they show a general positive effect of SSP on the fatigue strength (especially for notched specimens), it is true that the data are referred to just to few steel grades that do not allow to generalize the expected increment of the fatigue strength. Besides, the number of cycles chosen to define the run-out condition cannot guarantee that the improved behavior is maintained for more than 10 million cycles.

In this study steel 50CrMo4 used in automotive industry for car wheel hubs has been investigated. This component is cyclically loaded and subjected to fatigue; after years of operation may accumulate quite a number of fatigue cycles, greatly exceeding 10 million cycles, usually considered for conventional fatigue limit evaluation. Anyway, there are practically no available data about fatigue behavior in the ultra-high cycle region of this material.

Axial fatigue tests aimed at investigating the ultra-high cycle fatigue behavior were executed. Two series of smooth specimens were considered: mechanically polished and severely shot peened, being the aim to investigate the ability of this treatment to increase the fatigue strength of the material for very long expected endurance and to compare it with the non-treated state.

Roughness, microhardness, X-ray diffraction residual stress analysis and crystallite size measurement as well as scanning electron microscopy (SEM) observations were used for characterizing the severely deformed layer. Tension–compression high frequency fatigue tests were carried out to evaluate the effect of the applied treatment on fatigue life in the ultra-high cycle region. Fracture surface analysis was performed with aim to investigate the mechanism of fatigue crack initiation and propagation by using SEM. Results show an unexpected significant fatigue strength increase in the ultra-high cycle region after SSP surface treatment and are discussed in the light of compression residual stress profile and crystallite size.

2. Material characterization

Quenched and tempered steel 50CrMo4 was considered in this study. The nominal chemical composition is shown in Table 1. Test specimens were machined from a die forged car wheel hub. The die forging was done in temperature range 850–1050 °C. After forging, the flange was quenched from austenitization temperature of 860 °C (holding time 1 h) to mineral oil. Right after quenching, the steel was tempered on temperature 600 °C for 1 h and then it was left to cool on calm air. The heat treatment resulted in mechanical properties shown in Table 2.

Due the big diameter of the forged piece (∅75.5) the critical cooling rate for quenching could not be obtained in the whole diameter of the piece and the microstructure was changing from the surface towards to the core. Specimens were machined in position according to Fig. 1a so the axis of the specimen was distant 12 mm from the surface. This avoided the influence of decarburization and the gauge length of specimen represented the same microstructure as would be present in the surface layers of machined wheel hub.

To obtain the microstructure of the material in the gauge length of the specimen where fatigue damage occurs, a longitudinal cut of a specimen with initiated crack was done; the result is shown in Fig. 2. The microstructure consists of sorbite, bainite and imperfectly transformed ferrite and pearlite.

2.1. Surface characterization

Machined specimens were divided into two groups, each with 11 PCS. The first group was grinded and polished with diamond metallography emulsion (this group is marked as NP – not peened). The second group was treated by severe shot peening with S170 medium (steel shots, ∅ = 425 μm), Almen intensity 15.6 A and coverage 1000% (this group is marked as SSP – severely shot peened). Two rods were machined for residual stress measurement (Fig. 1b) and treated as mentioned above (one NP and one SSP). Areas subjected to surface treatment for all specimens are marked A in Fig. 1b and c.

In Fig. 3 the surface layer of NP and SSP specimen is shown. The surface layer of NP specimen (Fig. 3a) after mechanical polishing has no deformed surface layer and high quality surface with low roughness. On the contrary, the surface layer of SSP specimen (Fig. 3b) has a deep strongly deformed surface layer and also increase of surface roughness is obvious.

Due the character of quenched and tempered microstructure it is not appropriate to consider a grain size value which is mainly referred to optical microscopy analysis. In terms of X-ray diffraction the analysis is referred to crystallite size which is the size of coherently diffracting domains of crystals and grains may contain several of these domains. After plastic deformation of a single crystal several sub-crystals will be created and these can be considered as the crystallites. For more information about crystallite size measurement by XRD diffraction, the reader can refer to [18,19]. According to XRD measurement (X'Pert PRO diffractometer, Co radiation, diffraction angles from 45° to 130° (2θ), parallel plate collimator, crystallite size evaluated with TOPAS software according to all four diffraction lines {110, 200, 211, 220}), the crystallite size on the surface decreased from average value of 74 ± 3 nm for the NP specimen to 38 ± 4 nm for the SSP specimen. This layer with different appearance in secondary electron SEM analysis corresponds to so called "nano grained" or "ultra-fine grained" surface layer of material (Fig. 4). Plastic deformation was so intensive that part of the surface layer peeled off (Fig. 5) and also caused a remarkable increase of surface roughness compared to the NP specimens, as shown in Table 3.

2.2. Hardness measurement

Presence of compressive residual stress and surface hardened layer can be indirectly evaluated by microhardness measurement,