Engineering Fracture Mechanics 81 (2012) 56–68

Contents lists available at ScienceDirect

Engineering Fracture Mechanics

journal homepage: www.elsevier.com/locate/engfracmech

Fatigue behavior of a low-alloy steel with nanostructured surface obtained by severe shot peening

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ARTICLE INFO

Keywords:
Severe shot peening (SSP)
Fatigue strength
Nanograins
X-ray diffraction
Roughness

ABSTRACT

Severe shot peening aimed to generate a nanograined layer over specimens' surface has been applied by means of standard air blast equipment but using peening parameters essentially different from typical ones. Different experimental processes including microscopy observation, microhardness, roughness and X-ray diffraction measurements have been performed to characterize the treated surface of specimens. The results confirm the generation of a nanocrystallized surface layer. Rotating bending fatigue tests are then performed on smooth specimens to evaluate the effect of the nanocrystallized layer on fatigue strength. The results indicate improvement of fatigue life notwithstanding the specimen's very high surface roughness: a refinement of the treatment parameters aimed at reducing the roughness is proposed.

1. Introduction

Mechanical failures are mostly sensitive to the structure and properties of the surface material and in most cases originate from the exterior layers of the work piece. Therefore it is considerably effective to enhance material properties on component's surface.

Among the treatments used to improve surface behavior, the ones that allow generating a nanocrystal layer by severe plastic deformation are receiving increased attention in the recent years. A variety of severe plastic deformation processes have been proposed to produce surface nanocrystallization. Among these latter, alternative methods of shot peening have been applied due to relative simplicity and applicability for different classes of materials. Shot peening is a popular mechanical surface treatment generally aimed at generating compressive residual stresses close to the surface and at work hardening the surface layer. These effects are very useful to totally prevent or greatly delay the part failure [1–3] under fatigue, fretting and stress corrosion cracking load conditions.

Recently researches have successfully revealed that particular shot peening processes which are different from conventional air blast shot peening, not only for the needed technological facilities but also for the mechanics of the treatment, have been applied to achieve ultrafine grained materials on the surface of treated parts [4]. However, these processes are not so popular from an applicative point of view, since they require dedicated facilities and do not allow adequate production rates. On the other hand, it could be convenient to adapt conventional shot peening to obtain ultrafine or nanocrystallized (NC) surfaces, since its flexibility makes it possible to be used for components of almost any shape and dimension of interest.

It is well known that fatigue properties of materials are highly sensitive to their grain size. A small grain size can enhance the fatigue crack initiation threshold and coarse grains may deflect the propagation paths of fatigue cracks by grain boundaries, thus introducing crack closure and decreasing the rate of crack growth [5]. Since most fatigue cracks initiate from the

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0013-7944/$ - see front matter
doi:10.1016/j.engfracmech.2011.06.011

Nomenclature

lr	roughness sampling length (mm)
ln	roughness evaluation length (mm)
Ra	arithmetic mean deviation of the assessed profile (μm)
Rq	root mean square deviation of the assessed profile (μm)
Rz	maximum height of profile (μm)
Rt	total height of profile (μm)

Abbreviations

NC	nanocrystallized
SNH	surface nanocrystallization and hardening
SMAT	surface mechanical attrition treatment
NP	not peened
SSP	severe shot peen
CSP	conventional shot peen
RSSP	repeened severe shot peen
SEM	scanning electron microscopy
TEM	transmission electron microscopy
XRD	X-Ray diffraction
SAD	Selected area diffraction

surface and propagate to the interior, a component with a NC surface layer and coarse grained interior is expected to have improved fatigue properties because both fatigue crack initiation and propagation are inhibited by fine grains near the surface and coarse grains in the interior, respectively. Under high cycle fatigue conditions, the crack initiation process dominates a vast majority of the fatigue life time. Even under low cycle fatigue conditions, without pre-existing defects, the crack initiation phase is a necessary precursor to fatigue failure. An important key to enhanced fatigue performance in NC metals lies in the potential for these materials to suppress the crack initiation process [6].

Especially in case of surface nanocrystallization shot peening based processes, the induced residual compressive stresses can also effectively delay the propagation of fatigue cracks. In fact the presence of induced compressive residual stresses at the surface, surface microstructures including stable NC grains, high dislocation densities, martensite and second phases [7–9] that can play an important role in improving fatigue strength, make the interpretation of improved fatigue properties more difficult [6].

Few studies have been performed on fatigue behavior of surface nanocrystallized material. Tension-tension fatigue tests ($R = 0.1$) on commercially pure titanium, surface nanocrystallized by sandblasting carried out at room temperature [10] showed an improvement of 11% with respect to surface coarse grained material.

Roland et al. [11] performed tension-compression fatigue tests ($R = -1$) with a frequency of 10 Hz on 316 stainless steel after surface mechanical attrition treatment (SMAT). The fatigue limit was improved by 21% for the obtained surface nanocrystallized material treated with 3 mm diameter shots. In the case where 2 mm diameter shots were used to perform the SMAT, the benefit to the fatigue strength was rather low (almost 16%) for the higher stress amplitudes, that is the higher part of *S–N* curve. By combining the SMAT treatment with a post annealing treatment, the fatigue strength was improved by approximately 5–6% compared with only surface nanocrystallized state [11].

Li et al. [12] also performed pulsating fatigue tests ($R = 0$) on SMAT treated stainless steel plates. The results indicated that the SMAT process improved the fatigue strength by as much as 13% for surface nanocrystallized stainless steel 400.

Nickel based C-2000 super alloy specimens treated with surface nanocrystallization and hardening (SNH) process for 30 min, were subjected to the four point bend fatigue test ($R = 0.1$) and exhibited a 50% fatigue resistance enhancement compared to the not peened (NP) specimens. Increasing the treatment time resulted in considerable decrease in fatigue strength. It is mentioned that for the SNH treated samples, a large amount of surface contaminations and damages were introduced during the process. These flaws were potential stress concentration sites during the fatigue test [13–16].

In another study medium carbon steel plates with two different hardness values were subjected to severe surface deformation induced by shot peening to obtain surface nanocrystallized material. The fatigue limit investigated by four point bend tests showed for harder material an improvement of 8% with respect to NP specimens. On the other hand for the material with lower hardness, the fatigue strength of shot peened and NP specimens was almost the same due to the large surface roughness. It is mentioned that the surface roughness acted as a defect under fatigue loading [17].

A feature of the available data which bears discussion is the fact that the experiments have been performed on a wide variety of materials surface nanocrystallized through various processes, using different test set ups, specimen geometries, stress ratios and consequently resulting in disparate and essentially incomparable results. This highlights an important challenge in assessing the mechanical behavior of surface nanocrystallized metals; as also indicated by Padilla and Boyce [6], variations in microstructure and test method can have significant effects on the final results.