Fatigue analysis of shot peened smooth and notched steel specimens

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Abstract

Shot peening effects are mainly related to its ability to induce compressive residual stresses and work-harden the surface layer of material. It is well-recognized that the extent of these latter effects is essentially correlated to the process parameters, however an approach able to suggest the optimal choice of the peening parameters with respect of the treated material, component geometry and its in-service conditions is still lacking. In particular, this is true for not surface hardened materials. In this paper smooth and notched specimens of a low-alloy quenched and tempered steel are shot peened by different combination of peening parameters, to assess the influence of the process parameters on the fatigue strength. The results are elaborated by defining an approach able to estimate the fatigue limit with respect of the specimen geometry and the way the treatment is performed.

Keywords: Fatigue, shot peening, residual stresses, 40NiCrMo7 steel.

Introduction

Shot peening (SP) is a popular mechanical surface treatment generally applied to improve fatigue behaviour of metallic components. It is aimed to create compressive residual stresses on the surface and also to work-harden the near surface layer of material. These effects are very useful in order to totally prevent or greatly delay the failure of the part [1, 2]. The most challenging aspect of shot peening is to relate its main parameters consisting of shot size, shot speed and treatment time to the induced residual stresses and other beneficial effects of the process.

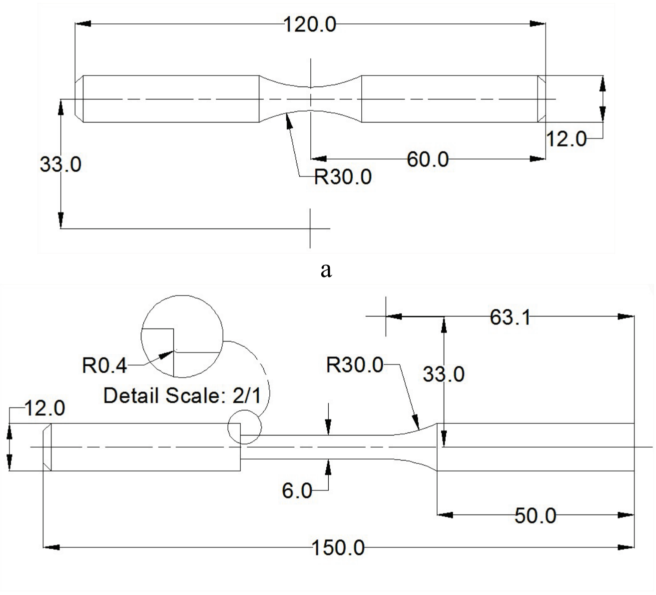
In this paper low alloy smooth and notched steel specimens are considered to investigate the effect of different shot peening treatments on fatigue strength. The applied peening parameters vary from light conventional parameters to higher Almen intensities. The induced residual stresses have been characterized by X-Ray diffraction (XRD) measurements. A set of fatigue tests are carried out to assess the improvement of specimens' fatigue strength obtained via shot peening. In the final part of the paper the results are critically discussed.

Material and Experimental procedure

Different series of smooth and notched specimens of low alloy steel 40NiCrMo7 (according to the Italian nomenclature) are subjected to different approaches of air blast shot peening using unlike parameters presented in Table 1. Each series consists of 15 specimens. Specimen geometries are also shown in Fig. 1. The stress concentration factor of the notch (K_t=2) is common in many machine elements such as crankshafts or threaded components. To study the state of residual stresses, XRD analysis of surface layer in the as-treated specimens was performed using an AST X-Stress 3000 X-ray diffractometer (radiation Cr Kα, irradiated area 1mm^2, sin^{2}ψ method, diffraction angles (2θ) scanned between -45 and 45). Measurements have been carried out in depth step by step removing a very thin layer of material using an electro-polishing device in order to obtain the in-depth trend of residual stresses. Roughness measurements have also been performed on treated surfaces. Room temperature rotating bending fatigue tests are performed on the specimens to investigate the effect of the applied processes on their fatigue strength.

Table 1. Aspects of the performed shot peening treatments

Shot type and diameter (mm)	Almen Intensity (0.001 inch)	Coverage%
CE70 (ceramic, ϕ=0.1)	10N	100
S110 (steel, ϕ=0.3)	6A	100
S170 (steel, ϕ=0.43)	12A	100



a

b

Figure 1. Treated specimen’s geometry a. smooth specimen b. notched specimen

Experimental Results

Residual stress profile. XRD measurement results presented in Fig. 2, demonstrate high surface tensile stresses due to machining and preparation process and trivial values of compressive residual stresses for not peened (NP) specimens, as expected. In case of shot peened series, the residual stress profiles imply that increasing kinetic energy of the process that is increasing the applied Almen intensity leads to increase the on-surface and maximum values of residual stresses.

Estimation of work-hardened layer thickness. Another parameter measured by XRD shown in Fig. 3 represents the full width of the diffraction peak at half of the maximum intensity (FWHM). FWHM is assumed as an index of hardening of the material. As it is observed in Fig. 3 the on-surface amount of FWHM is growing with increasing kinetic energy of the peening process. It is to be noted that the thickness of the work-hardened layer can be estimated as the thickness of the layer which shows considerably increased FWHM values in comparison with the core material. As the results demonstrate this thickness is slightly increasing by enhancing the Almen intensity of the process.

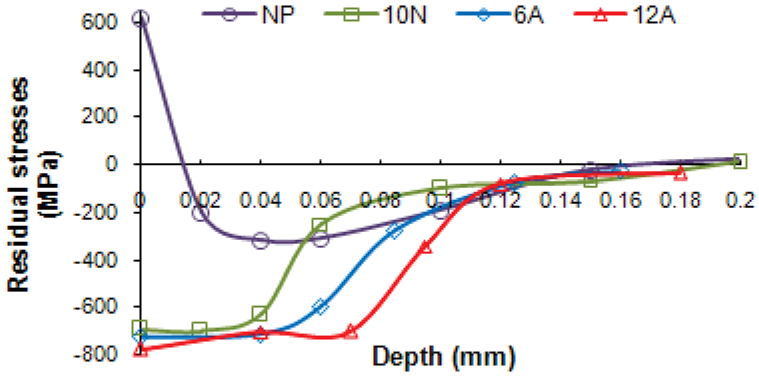


Figure 2. Distribution of residual stresses obtained by XRD for different shot peened series

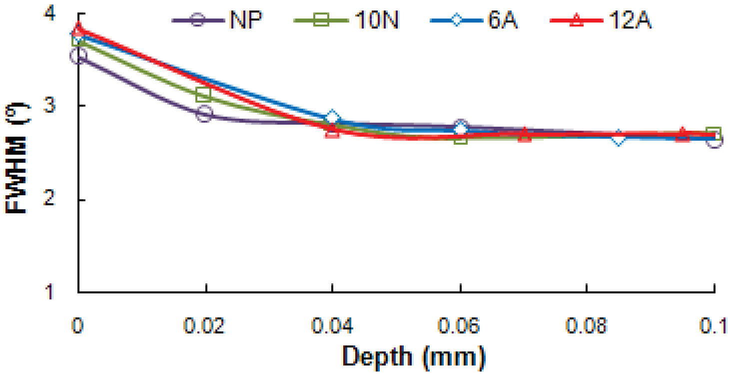


Figure 3. FWHM profile obtained by XRD for different shot peened series

Fatigue tests. Rotating bending fatigue tests (stress ratio R=-1) have been carried out at room temperature on the as received NP, and differently shot peened notched and smooth specimens. Fatigue limit has been calculated via the Stair-case method [3] for all series. The specimens were considered run-out after passing 5.000.000 cycles. The obtained fatigue limits for the tested series are presented in Table 2.

The considerable difference between the fatigue limit of notched and smooth series, can be attributed the in-depth distribution of both residual stresses and applied load stresses. In fact notched components take more benefit from shot peening due to presence of high stress gradient [4]. In notched specimens, the high strain gradient just under the notch, results in considerable decrease in stress level while the crack is still very small, thus decreasing crack growth rate [4, 5].

The Eichlseder model [6, 7] which describes the effect of stress gradient on fatigue limit has been adopted on the results. This model proposes interpolation of fatigue limit in bending (σ_{bf}) and in uniform stress loading conditions (σ_{tf}) on un-notched specimens (with diameter b) made of the same material, to describe the local fatigue limit of components with arbitrary stress gradients. Eichlseder characterizes the relationship between fatigue limit and relative stress gradient as a function of the relative stress gradient (RSG) (Eq. (1)), described in Eq.2 (for stress ratio R = -1).

$$\chi' = \left(\frac{1}{\sigma_{max}}\right)\left(\frac{d\sigma}{dx}\right) \tag{1}$$

$$\boldsymbol{\sigma_f = \sigma_{tf}[1 + (\frac{\sigma_{bf}}{\sigma_{tf}} - 1)(\frac{\chi'}{(2/b)})^{K_D}]} \tag{2}$$

in which the exponent K_D describes how σ_f behaves between σ_{tf} and σ_{bf} and is characteristic of material type.

Table 2. Fatigue limits of tested series

	Fatigue limit (MPa)			
	NP	10N	6A	12A
Smooth series	597	707	676	710
Notched series	393	440	492	518

Olmi et al. [8] have implemented the Eichlseder approach on shot peened notched specimens considering the effective distribution of stresses at notch root as a sum of the stress due to the external load and the residual stresses due to shot peening; then adjusting the obtained fatigue limit, considering the actual mean stress of the cycle and consequently the modified R, by constructing the Haigh diagram (Goodman linear model) [8].

This approach was applied to the fatigue limit of the notched series presented in Table 2 with some supplementary considerations. Initially a static finite element simulation has been performed on the notched specimens to obtain the distribution of the applied stresses; the results have been superimposed on residual stresses obtained from XRD measurements to get the effective stress distribution and consequently the stress gradient at notch root for each series.

Eichlseder approach is not originally developed for shot peened specimens, thus it does not take account of surface roughness which is a well-recognized side effect of shot peening that normally leads to fatigue strength reduction. Table 3 represents the common surface roughness parameters [9] measured on the four studied series. Since relatively high surface roughness values have been observed on all shot peened series, a roughness factor has been introduced in to the calculations based on the diagrams made by Buch [10].

Table 3. Surface roughness of shot peened series

Series	R_a (μm)	R_q (μm)	R_z (μm)	R_t (μm)
NP	1.37	1.64	5.84	6.21
10N	1.49	1.88	8.50	9.80
6A	1.73	2.11	9.28	12.36
12A	2.35	2.85	12.07	14.32

Other complementary issues that have been considered in analytical estimation of the local fatigue life are the stress relaxation and effect of surface work hardening in terms of FWHM. XRD stress measurements have been performed on shot peened specimen after cyclic loading. The results as presented in Fig. 4 imply that in case of 10N series, the near surface residual stresses are significantly decreased up to almost half the original value; while in case of 6A and 12A series a minor stress relaxation is observed. Experiments show that this stress relaxation occurs after very few numbers of loading cycles [11], accordingly the new distribution of residual stresses has been considered for the fatigue life estimation. In case of FWHM, the ratio of FWHM (after fatigue loading) to that of NP series has been implemented in the estimation. The final results are compared with the experimental local fatigue limits in Table 4. As it can be noted, the difference between the experimental fatigue limits and the analytical estimation is within an acceptable range (0-8%) taking into account that the roughness factors taken from Buch's diagrams [10] are not specifically precise since they do not consider the real surface texture of the peened specimen.

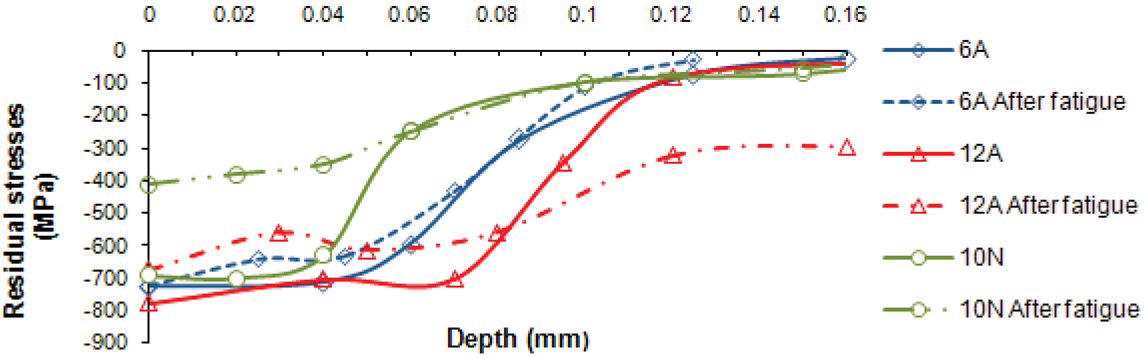


Figure 4. Residual stress after cyclic loading

Table 4. Comparison of local fatigue limit: relative stress gradient (RSG) method vs. Experiment

	Local Fatigue limit (MPa)		
	10N	6A	12A
Experimental	880	984	1036
RSG	878	1032	954

Conclusions

Fatigue tests have been performed on smooth and notched specimens made of a common low-alloy steel. The results allowed estimating different effects of treatment parameters on smooth and notched specimens, underlining the importance of surface roughness on the expected fatigue strength. In particular, the lightest considered treatment, notwithstanding the significant residual stress relaxation, proved to be effective as the strongest one, at least for the smooth specimens. In the notched series the strong stress gradient make shot peening more effective. On the basis of the experimental results a predictive approach able to consider the applied and residual stresses and their gradient, surface roughness, work-hardening and the residual stress relaxation was developed. The results are in good agreement with the experimental ones.

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