Analysis of vibratory finishing effect on the fatigue behavior of shot peened notched 40NiCrMo7 steel notched specimens

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Abstract
In this paper the influence of surface roughness on fatigue behavior of notched specimens has been studied. Series of notched specimens of 40NiCrMo7 quenched and tempered steel, shot peened with different parameters followed by a vibratory finishing process, were subjected to room temperature rotating bending fatigue tests in order to study the influence of roughness on fatigue behavior. The effect of all treatments were characterized by means of roughness measurements, X-ray diffraction measurements and scanning electron microscopy (SEM) analysis. The results show that vibratory finishing affects the surface condition of shot peened specimens in two ways: decreasing surface roughness and removing a very thin layer of material with compressive residual stresses. This effects influence fatigue behavior, and confirm that high surface roughness does not necessarily lead to reduced fatigue strength.

Keywords: shot peening, vibratory finishing, fatigue, roughness.

Introduction
Shot peening (SP) is well known to be one of the most efficient treatments to improve fatigue behavior of metals and metal alloys. This treatment is a cold working process where metal parts are blasted by a flux of small spherical elements called shot, usually up to the point where the surface is fully covered by the impacts (98-100% coverage). The main effects produced in the material are the creation of a compressive residual stress field and a work hardening in the surface layer of the material. A side effect is the modification of the surface roughness [1]. These effects are responsible for the improvement of the fatigue behaviour of treated components [2-4].
Although the global effect of SP is beneficial from the point of view of fatigue behaviour, not all the single effects are positive for fatigue strength. While residual stresses and work hardening inhibit or retard crack initiation and possible growth, the altered surface topography and the possible defects introduced in the surface by the impacts tend to facilitate crack initiation [5, 6]. In order to reduce surface defects and to decrease surface roughness with the aim to decrease negative effects, different techniques have been studied. Vielma et al. [5] showed in their study that post-peening treatments as mechanical grinding, electro-polishing and lower intensity SP (re-peening), improve fatigue behavior after a high Almen intensity SP of a quenched and tempered structural steel. This latter treatment, in fact, induces a deep compressive residual stress field and a notable hardness increase on the surface layer but can also cause surface damage, reducing the beneficial effect of residual stresses and work hardening on fatigue behavior.
In this paper the effect of the surface super-finishing obtained by vibratory treatment on the fatigue strength of a low alloy steel shot peened with different parameters is investigated. This paper is the second part of previous study dealing with smooth specimens on notched samples [7].
Series of 15 notched specimens were shot peened using different combinations of process parameters. After SP treatments, some series were submitted to a vibratory finishing (VF) post-process with the aim to evaluate the effect of roughness on the fatigue limit. The effect of all treatments was characterized by means of roughness, X-ray diffraction measurements and SEM analysis. Rotating bending fatigue tests were carried out to assess the influence on fatigue behaviour. In the final part of the paper the results are critically discussed.

Methodology

Five series of notched specimens of quenched and tempered 40NiCrMo7 steel, with chemical composition shown in Table 1, were fatigue tested to investigate the effect of the SP and post-peening surface finishing on their fatigue behavior. Four of these series were submitted to shot peening treatments, two of them using low Almen intensity (10N; series SP10N) and other two under high Almen intensity (12A; series SP12A). SP parameters are described in Table 2. After shot peening treatments two series (one treated with 10N and other with 12A) were submitted to VF, with the aim to reduce the surface roughness induced by the SP treatments. VF is a versatile process that is used in many industries globally for brightening, deburring, fine finishing, cleaning, burnishing, descaling of components, reducing surface roughness, and stress relieving among others [8]. During this process, workpieces are submerged in conjunction with media and compound in a VF machine. Media are the main element responsible for imparting the necessary surface finish to the components and compound are the water-based lubricants and coolants in the process. The machine vibrates causing the contents to move in a circular motion and the media to grind against the part to get the desired finishing [9]. In the final step, the compound is rinsed from the machine with a neutral soap. At the end of the process, specimens' surface is completely rubbed off getting a very smooth surface. The surface finishing depends on the duration of this treatment, which in this work is about 60h. The detailed parameters used for the VF process are retained confidential.

Table 1. Nominal chemical composition of quenched and tempered 40NiCrMo7 steel [%]

C	Si	Mn	S	P	Ni	Cr	Mo	Cu
0.389	0.29	0.68	<0.003	<0.009	1.81	0.84	0.23	0.09

Table 2. Shot peening parameters

Shot type and diameter (mm)	Almen Intensity (0.0001 inch)	Surface Coverage%
CE70 (ceramic, φ=0.1)	10N	100
S170 (steel, φ=0.43)	12A	100

Rotating bending fatigue test (stress ratio R=-1) have been carried out a room temperature at a nominal frequency of 20 Hz on the NP (not peened), SP10N (shot peened with Almen intensity of 10N), SP10N+VF (shot peened with Almen intensity of 10N followed by VF), SP12A (shot peened with Almen intensity of 12A) and AP12A+VF (shot peened with Almen intensity of 12A followed by VF) series. Specimens' geometry, chosen according to ISO 1143, is shown in Fig.1. The theoretical stress concentration factor K_t=2.

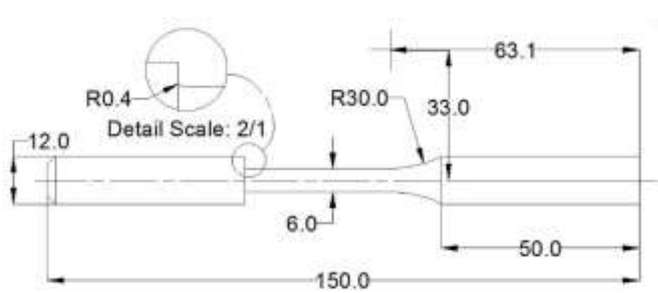

Figure 1. Geometry of notched specimens (K_t=2)

Roughness measurements have been performed on the surface of treated and untreated specimens by means of a roughness tester according to EN ISO 4287 standard. Three measurements were performed on each specimen.
The state of residual stresses of treated specimens were also studied by means of XRD technique. Measurements were performed using an AST X-Stress 3000 X-ray diffractometer (radiation Cr Kα, irradiated area $1mm^2$, $\sin^2\psi$ 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. The results of the XRD measurements were corrected using the method described by Moore and Evans [10] in order to account for the removed material.
At the same time, the full width of the diffraction peak at half of the maximum intensity (FWHM) was measured by XRD. FWHM parameter is assumed as an index of hardening of the material [11].
Surface and fracture surface were also analysed by means of SEM observations.

Results and analysis

Roughness analysis

The average of the main roughness parameters measured on all specimens are presented in Table 3. The results indicate a clear decrease in surface roughness after finishing process. The average thickness of removed material for each series after the same finishing treatment duration is measured to be 0.03 mm and 0.01 mm respectively for 10N and 12A series.

Table 3. Surface roughness parameters of SP and SP+VF specimens

Treatment	l_n[mm]	l_r [mm]	R_a [μm]	R_z [μm]	R_t [μm]
NP	4.0	0.80	1.37	5.84	6.21
10N	4.0	0.80	1.49	8.50	9.80
10N+VF	4.0	0.80	0.22	2.00	2.96
12A	4.0	0.80	2.35	12.07	14.32
12A+VF	4.0	0.80	1.26	7.26	9.93

XRD measurements

Residual stresses

Residual stresses profiles of specimens submitted to SP treatment using 10N and 12A of Almen intensity are presented in Fig. 2. Both treatments introduced compressive residual stresses field.
It should be noted that the 12A treatment led to deeper residual stresses while surface and maximum compressive residual stresses were of comparable magnitude.

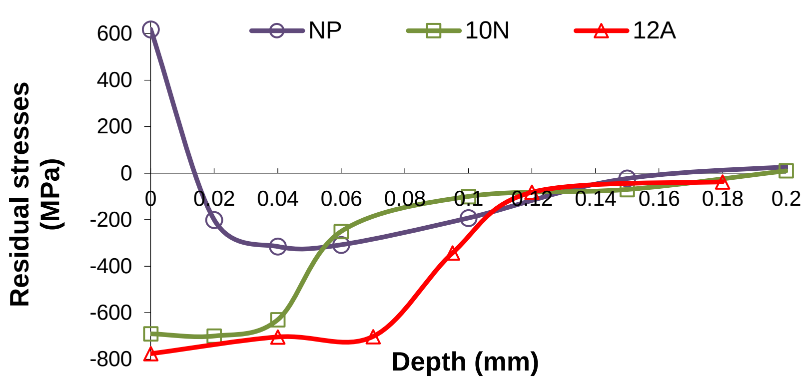

Figure 2. Residual stresses profiles of treated specimens

XRD measurements are not conducted on specimens after VF. However, in the literature the VF process is reported to have no measurable effect on residual stresses trend; it shifts the original distribution of residual stresses in the sample, simply taking out the stresses in the removed surface layer [12].

FWHM
As it is observed in Fig. 3, the on-surface amount of FWHM increases with peening process kinetic energy. The thickness of the work-hardened layer can be estimated as the thickness of the layer that 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.

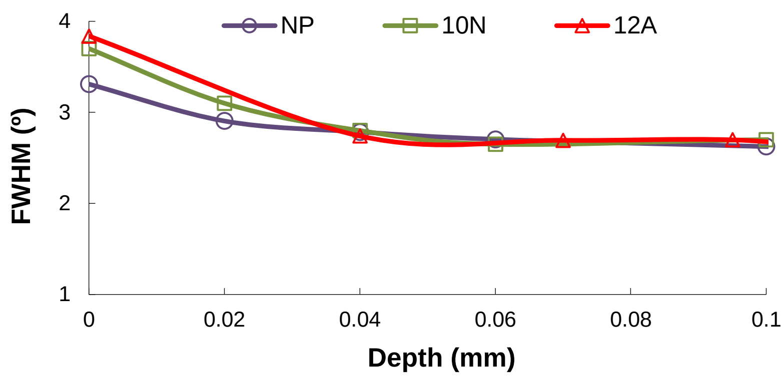

Figure 4. FWHM profile of treated specimens

Fatigue strength
Staircase procedure was employed to calculate the fatigue strength of all series (15 specimens each) corresponding to 5 million cycles using the data obtained from the rotating bending tests. Results are presented in Table 4. The data was analyzed according to ASTM standard E739-91 [8].

Table 4. Fatigue limit of tested series

Treatment	NP	SP10N	SP10N+VF	SP12A	SP12A+VF
Fatigue Limit (MPa)	393	440	458	518	487
Shot peening effect (%)		12	17	31.8	24
Shot peening +Vibratory finishing effect (%)			+4		-6

Table 4 suggests that all the applied peening treatments have been effective in increasing the fatigue limit of the base material (12% of improvement for 10N series, 17% for 10N+VF, 31.8% for 12A, and 24% for 12A+VF series). This improvement depends on the kinetic energy of the applied surface treatment, directly related with Almen intensity, and especially on the surface characteristics of the treated specimens. In spite of the fact that surface roughness is well-known to have detrimental effects on fatigue strength [5, 6], the 12A series, which has the highest surface

roughness, result in the highest fatigue limit, due to the deeper residual stress field and of thicker work-hardened surface layer.
After VF treatment, this series exhibit a slight decrease in fatigue limit (6%), even though it presents lower roughness value and maintains the same surface hardened layer with residual stresses field [8]. In the case of SP10N+VF series, with lower values of roughness parameters compared to SP10N, fatigue limit experiences a slight improvement. A more detailed analysis of the results suggests that even if the surface roughness R_a is strongly reduced by VF, R_t, the roughness factor that mainly affects the fatigue strength, does not considerably vary; thus it introduces a sort of a micro-notch effect that in the case of the SP12A+VF is even more pronounced, when compared to the SP12A series. This can be explained bearing in mind that the superposition of multiple notches can reduce the overall notch effect of the single notch, even if further investigations are on course for a deeper and quantitative understanding of this effect. We postulate that effect of residual stress relaxation can be neglected, as previous studies have indicated that VF commonly causes shifting in the distribution of residual stresses rather than stress relaxation [12].

Conclusions

The influence of vibratory finishing treatment after shot peening on the fatigue behaviour of 40NiCrMo7 quenched and tempered steel was studied, with the aim to analyze roughness effect. Rotating bending test were carried out in notched specimens.
The results revealed that the series with the highest intensity had the best fatigue strength and was able to strongly alleviate the notch effect. At the same time the results of the vibratory finishing samples show that the roughness is not a key factor for both the considered shot peening treatments: while for the 10N series there is a small improvement of the fatigue strength (5%) after surface finishing, in the 12A specimens the fatigue strength is slightly reduced (-6%). This can be explained by the limited ability of surface finishing to reduce the R_t roughness parameter; thus leaving severe local micro-notches that affect the fatigue strength even more than in the case of the shot peened surface. Accordingly, it is concluded that the stress flow in the 12A specimen is smoother than in the case of the same series of specimens after finishing process, due to the presence of local surface defects able to intensify the stress concentration.

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