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Fatigue properties of nanocrystallized surfaces obtained by high energy shot peening

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Abstract

An unconventional method of shot peening aimed to generation of a nanograined layer over the surface of specimens has been applied by means of the standard air blast equipment but using peening parameters essentially different from typical ones. Surface nanocrystallization is verified and affirmed through different experimental procedures. Rotating bending fatigue tests are performed to evaluate the effect of this high energy shot peening and the nanocrystallized layer on fatigue life. First series results are available and the other tests are still in progress.

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1. Introduction

Majority of failures in engineering materials such as fatigue fracture, fretting fatigue, wear and corrosion, are very sensitive to the structure and properties of the material surface, and in most cases failures originate from the exterior layers of the work piece. Therefore it would be considerably effective to apply an approach to enhance the material properties on the surface of the part.

It is well known that a small grain size can effectively enhance the fatigue-crack-initiation threshold. On the contrary, coarse grains may deflect the propagation paths of fatigue cracks by grain boundaries, thus introducing crack closure and decreasing the rate of crack growth. Since most fatigue cracks initiate from the surface and propagate to the interior, a component with a nanostructured surface layer and coarse-grained interior is expected to have highly 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. If nanocristalization is obtained by using a severe plastic deformation process, the introduced residual compressive stresses during the can also effectively contribute to stop or retard the initiation and propagation of fatigue cracks [1].

Meanwhile a variety of processes have been proposed to produce nanocrystal surfaces among which alternative methods of shot peening (SP) has received considerable attention due to their relative simplicity and applicability for different classes of materials. Shot peening is a popular mechanical surface treatment generally aimed at creation of compressive residual stresses close to the surface and work hardening of the same layer of material. These effects

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are very useful to totally prevent or greatly delay the failure of the part [2-4]. Recently researches have successfully shown that particular SP processes which are different from conventional method, that is air blast shot peening (ABSP), not only in the needed technological facilities but also for the mechanics of the treatment, have been aimed at achieving ultrafine grained materials on the surface of treated parts [5]. However, these processes are not so popular form an applicative point of view, since they require dedicated facilities. On the other hand it would be convenient to adapt conventional shot peening to obtain ultrafine or nanostructured surface, since its flexibility makes it possible to use it for components of almost any shape and because of the fact that it can be performed on commercial scale with a high productivity. Anyway, a relation between the process, its parameters and also the mechanical properties of the NC layers obtained by shot peening is to be established.

The present study focuses on the application of conventional shot peening to obtain surface nanocrystallized materials. The SP method developed in this study uses a combination of severe peening parameters to multiply the kinetic energy of the conventional SP. The fatigue characteristics of the treated surfaces using different combinations of peening parameters are experimentally tested and compared.

2. Experimental procedure

Steel (39NiCrMo3, according to the Italian nomenclature) specimens with the chemical composition shown in Table 1 are subjected to different approaches of ABSP using unlike parameters. Table 2 also represents particular combinations of SP parameters. It shall be noted that cast steel shots have been used in all performed peening procedures.

Table 1. Chemical composition of steel specimens in mass density

C (wt%)	Si(wt%) max	Mn (wt %)	P wt(wt%) max	S (wt%) max	Cr (wt%)	Mo (wt%)	Ni (wt%)
0.35-0.43	0.40	0.5-0.8	0.025	.035	0.60-1.00	0.15-0.25	0.70-1.00
±0.02	±0.03	±0.04	+0.005	±0.005	±0.05	±0.03	±0.05

Table 2. Aspects of the three SP processes

Type of treatment	Shot diameter (mm)	Air speed (m/s)	Almen Intensity (0.0001 inch)	Treatment time (s)
Not peened (NP)	-	-	-	-
Typical shot peening (TSP)	0.42	30-40	10A	10-20
Severe shot peening (SSP)	0.6	90	7C	450

X-ray diffraction (XRD) analysis of surface layer in the as-treated samples have been performed using an AST X-Stress 3000 X-ray diffractometer (radiation Cr Kα, irradiated area 1 mm^2, sin2ψ method, diffraction angles (2θ) scanned between -45° and 45°). To obtain the sub-surface trend of residual stresses, measurements have been carried out in depth step by step removing a very thin layer of material using an electro-polishing device.

Microstructure observations are carried out through scanning electron microscopy (SEM). Specimens for SEM observations have been etched by 2% Nital. Surface roughness measurements have also been performed on all sets of specimens.

Rotating bending fatigue tests are performed to investigate the fatigue strength of the specimens. The tests have been performed at room temperature.

3. Results and discussion

3.1. Surface roughness

Increase in roughness is well-recognized as a side effect of SP process. In the case of specimens treated with severe parameters the obtained surface was considerably rougher than that of the specimens treated with typical parameters. Fig. 1 shows the surface roughness of the as-received specimens: NP, typical SP and SSP. As shown in Fig. 2 through these processes, arithmetic-mean value of roughness (R_a) is increased from 0.57 µm for NP specimen to 3.53 µm for TSP specimen and to 8.58 µm for SSP specimen.

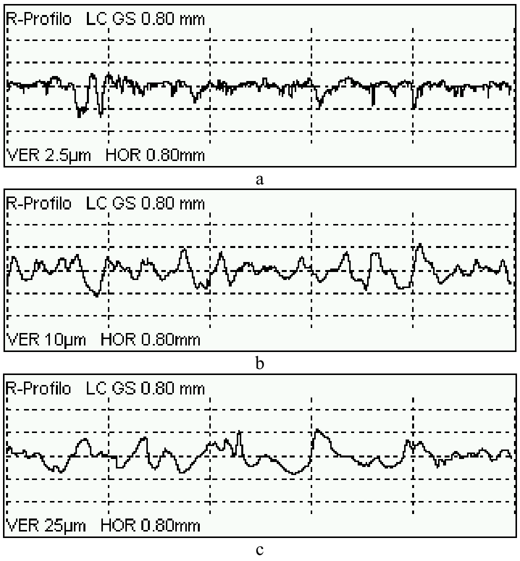


Fig. 1. Surface roughness profile of peened specimens (a) NP; (b) TSP; (c) SSP

The high values of roughness obtained in case of SSP specimens are consistent with the SEM observations which detected several defects on the surface of the treated specimen, as shown in Fig. 2.

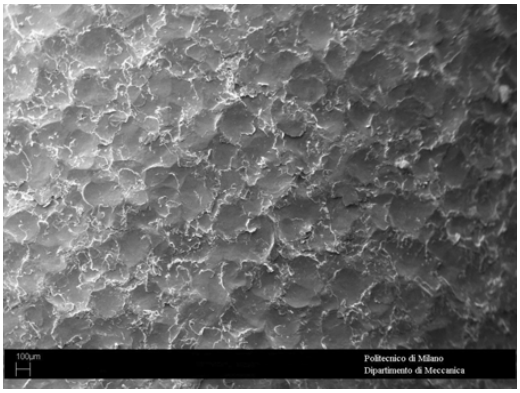


Fig. 2. SEM micrograph showing the surface morphology of the SSP specimen.

3.2. XRD measurements

Distribution of macroscopic residual stresses on the plane parallel to the impacted surface determined by XRD is shown for three specimens in Fig. 3.

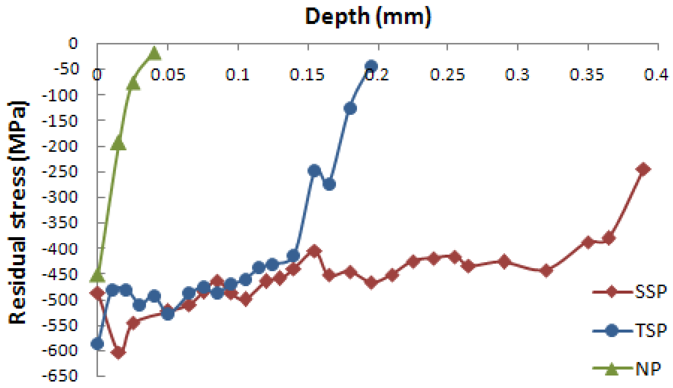


Fig. 3. Residual in-plane stress profile of treated specimens as a function of position measured from the impacted surface

As shown in Fig. 3, the obtained maximum stress values in cases of specimen SSP and TSP are quite similar while the depth of the layer with significant compressive residual stresses in SSP specimen (~360 µm) is more than two times thicker than that of TSP (~140 µm) and the difference is still more evident with regards to NP specimen where the introduced residual stresses are confined to a very shallow surface layer within ~40 µm. The considerable depth of the layer containing compressive residual stresses in SSP specimen is a consequence of the great extent of plastic deformations induced by the high kinetic energy of the process.

Another parameter measured by X-ray diffraction is FWHM that is the width of the diffraction peak at half the maximum diffraction. FWHM, shown in Fig. 4, is a factor related to the surface state of the material and characterizes grain size and internal strain of the crystals. It is also measured as an index of hardening of material.

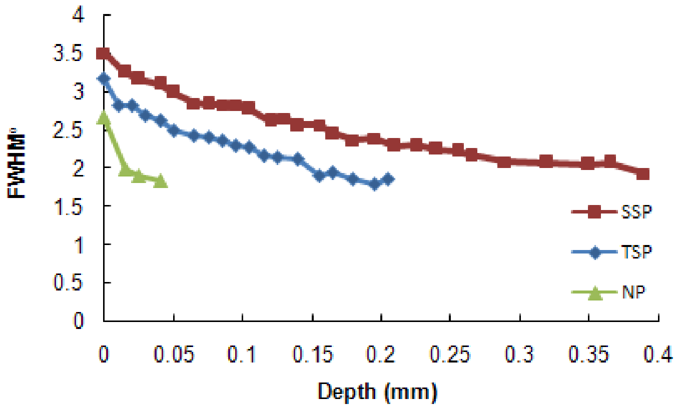


Fig. 4. FWHM profile of treated specimens as a function of position measured from the impacted surface

As shown in Fig. 4 for all specimens the maximum FWHM is observed on the surface of the specimen, declining down to the depth. In case of NP specimen, due to the performed machining in specimen preparation stage, the surface layer turns out to be hardened to some extents but just few micrometers under the surface, this effect vanishes totally. While in cases of SSP and TSP specimens, this hardened layers seem to be more persistent and extent to higher depths. The FWHM declines gradually up to a particular depth where it becomes almost constant. As it is observed again the depth which represents increases values of FWHM is thicker in case of SSP specimen in comparison with TSP specimen.

The remarkable increment in FWHM for SSP specimen with respect to TSP and also NP, as well as stresses, can be attributed to the grain refinement, micro-strain development and micro distortions of the crystalline lattice due to high kinetic energy multiple impacts.

3.3. Microstructure

As illustrated in Fig. 5, from the overall view of the cross sections in SEM observations, a distinct dense region separated with sharp boundaries from the underlying layer is easily recognized on the top surface. This uniform contrast layer near the surface which extends up to almost 10 µm in depth, as stated by Saitoh et al. [6] is considered to be the fine grained layer which changed the color after etching. It is reported that the repeatedly folding of the deformed regions leads to the formation of such fine grained regions so-called white etching layers at the surface of the specimens.

Beneath this region, the severely deformed work hardening area can be seen, while these two regions are separated by sharp boundaries. The microstructure difference between the near surface layers and the core material can be clearly observed in Fig. 5. Repeated shot peening with high energy creates dislocations which may be annihilated or recombined (rearranged) to form small angle grain boundaries separating individual grains, as proposed by Fecht in analyzing the grain refinement of metals during ball milling [7].

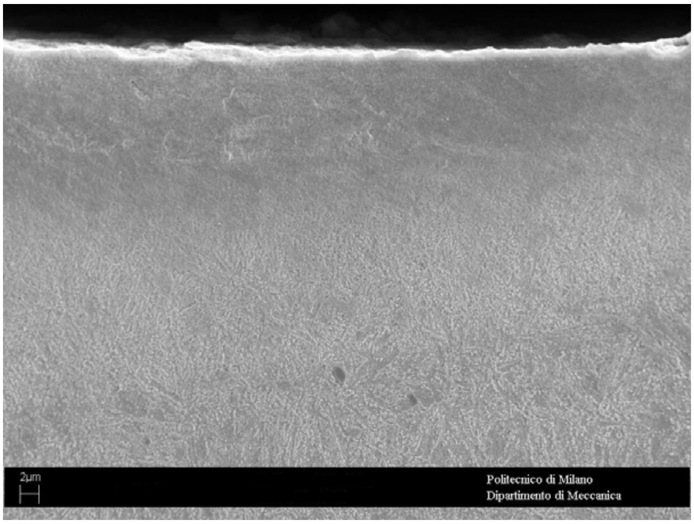


Fig. 5. Cross-sectional SEM observation of the SSP specimen.

3.1. Fatigue strength

Rotating bending fatigue tests have been conducted on the as received (NP), and a set of SSP specimens. To prevent the experiments from being prolonged and time consuming, the fatigue tests were continued up to N=3E+10 cycles. Tests for TSP specimens are still in progress and yet not all the tests are concluded. However the S-N diagram obtained from the performed tests is presented in Fig. 6.

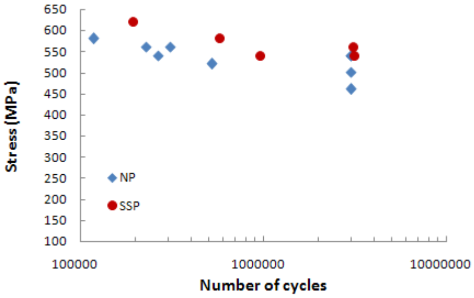


Fig. 6. Fatigue behavior of the samples.

In case of SSP specimens the formation of a fine grained layer with considerable compressive residual stresses in the surface of specimen is expected to considerably improve fatigue performance, but the rough surface created by SSP method has to great extents masked the beneficial effect of a surface microstructure. Notwithstanding the unfavorable effects of the high roughness, the SSP treatment has proved to be able to obtain fatigue strength a little bit larger than NP specimens, as can be observed in Fig. 6.

Indeed, roughness generally induces stress concentration at specific points, thus facilitating crack initiation under fatigue conditions [8-11]. A method should be applied in order to decrease the surface roughness and avoid its undesirable effects on fatigue strength. Different alternatives have been tried in this study; one of which has been to perform the surface mechanical treatments in regimes, which would provide the lowest surface roughness characteristics.

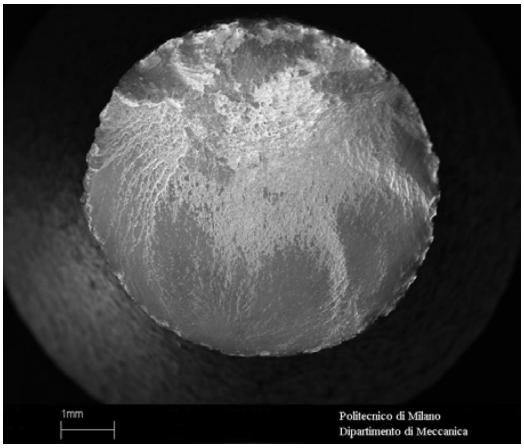
SP in general can produce the lowest surface roughness only after relatively prolonged treatment times. Dai et al. put forward a general trend for roughness evolution as a function of processing time stating that during the SP process roughness increases initially since the indents created by impacting shots are separated, afterward as the entire surface is covered by indentations and some regions have been impacted several times, roughness decreases, and finally as the processing time rises, the roughness stabilizes at a constant value due to the fact that the rate of generating peaks and valleys is in dynamic equilibrium with the rate of reducing the height of peaks [12]. Based on this theory some SSP specimens were treated doubling the peening time (900s) with the aim to reach the steady state stage in roughness evolution. However, roughness measurements performed on specimens treated with prolonged process time, didn’t indicate of considerable change in comparison with SSP specimens treated for 450s. It is concluded that treatment time shall be again increased to reach the decreasing and then steady state stage of roughness; however longer treatment time leads to higher costs.

Other tested methods to reduce the high surface roughness values have been to apply different approaches for removing a thin layer of the surface material. The applied techniques have been grinding via sandpaper and electro polishing by acid. Applying the two mentioned methods, a layer of almost 50 µm was removed from the surfaces. In fact both methods remove the entire nanocrystallized layer on the surface since the thickness of this layer, measured to be in the order of 10 microns, is out of the convenient range for both the applied methods. Anyway although, the nanolayer is removed but still the thick layer work hardened characterized by high compressive residual stresses contributes to fatigue strength improvement, as it can be observed for the few SSP specimens tested and represented in Table.3.

Table 3. Results obtained from fatigue test of SSP specimens after surface material removing.

Material removing method	Stress (MPa)	Number of cycles
Sandpaper	560	3000000
Sandpaper	580	3000000
Sandpaper	600	3000000
Sandpaper	620	622000
Sandpaper	620	160000
Electro polishing	600	152000

Based on the results, it seems that grinding by sandpaper is more effective than electro polishing. This can be attributed to the rougher surface of electro polished SSP specimen in comparison with grinded ones. SEM observation of the fracture surface of a SSP specimen is shown in Fig.7. As it is observed different defects on the surface has contributed to the final fracture.



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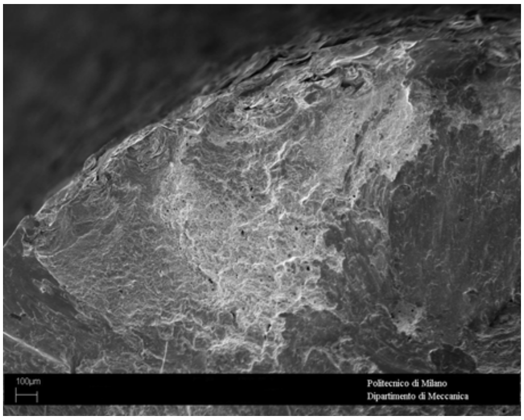

b

Fig. 7. SEM micrographs showing the fatigue fracture surface of a grinded SSP specimen (a) overall view of the fracture surface; (b) close view of the defects

4. Conclusions

39NiCrMo3 steel specimens have been treated by different methods of ABSP in order to obtain nanocrystallized layer of material on specimens' surface. Properties of treated specimens have been investigated through roughness measurements, XRD measurements, SEM observations and rotating bending fatigue tests. The following conclusions can be drawn:

- Roughness values have been considerably increased by increasing the kinetic energy of the process. This issue has negative effects on fatigue performance of the specimens.
- The severe peening process has lead to a significant increase the depth affected by residual stresses.
- Results indicate that a fine grained layer has been created on the surface of the specimens. The change of FWHM seems to follow the structure gradient from fine grained surface layer to coarse-grained bulk material.
- In spite of the high surface roughness values of SSP specimens, they show improved fatigue strength.
- Different techniques including increasing treatment time, surface grinding via sandpaper and electro polishing has been tried in order to decrease the surface roughness and consequently amplify the desired effects of SSP process on fatigue strength. Among the mentioned methods, grinding by sandpaper seems more efficient, although it leads in cutting off the nanocrystallized layer.

These experimental results indicate that the applied SP process is a promising method for producing advanced materials for strength-intensive service applications, taking into account that a proper technique should be worked out to decrease the unfavorable effects of the roughness induced by the impact of high kinetic energy shots. The data collected till now are not sufficient to express a definitive judgment of the treatment; however tests are still on course and will permit to assess the beneficial effect of high energy shot peening.

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