Effect of severe shot peening on microstructure and fatigue strength of cast iron

S. Bagherifard [a,*], I. Fernandez-Pariente [b], R. Ghelichi [a], M. Guagliano [a,*]

[a] Politecnico di Milano, Department of Mechanical Engineering, Via La Masa1, 20156 Milan, Italy
[b] University of Oviedo, Department of Materials and Metallurgy Engineering, Campus de Viesques, 33203 Gijón, Spain

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1. Introduction

In view of the fact that in most cases mechanical failures originate from the exterior layers of the components, it is considerably effective to apply approaches and treatments able to improve mechanical properties on component's surface. Surface nanocrystallization produced by severe plastic deformation (SPD) processes is receiving increased attention in the recent years. Among all the proposed SPD techniques, alternative methods of shot peening (SP) seem to be very promising due to their relative simplicity and wide applicability to different classes of materials and metal parts. SP is a mechanical surface treatment generally aimed at generating compressive residual stresses close to the surface and at work hardening almost the same layer of material. The effects induced by impact based processes are very useful to totally prevent or greatly delay the part failure [1–4] under fatigue, fretting and stress corrosion cracking load conditions. Recent studies have demonstrated that particular SP processes, here called as severe shot peening (SSP), which use more intense parameters compared to conventional air blast shot peening can be used for achieving ultrafine or nanograined materials on the surface of treated parts [5].

These methods are expected to result in fatigue strength enhancement since fatigue properties of materials are known to be highly sensitive to 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 [6]. A recent study performed on effects of surface grain size and the grain size gradient induced by surface nanocrystallization methods on the fatigue damage of metallic materials, revealed that short crack growth rate diminishes with the decrease of the surface grain size and grain size gradient along depth. The growth rate in the grain is proportional to the grain size, so the smaller grain brings longer fatigue life, since surface nanocrystallization induces more obstacles (grain boundaries, sub-boundaries, etc.), which produce, more hinders during the short crack propagation [7]. In case of surface nanocrystallization through SSP, the high compressive residual stresses and work hardening effect induced are expected to take part in additional fatigue life enhancement.

There is few published literature on fatigue behaviour of surface nanocrystallized material obtained through SPD processes. Tension-tension fatigue tests ($R = 0.1$) on commercially pure titanium, surface nanocrystallized by sandblasting carried out at room temperature [8] showed an improvement of 11% with respect to surface coarse grained material. Roland et al. [9] performed tension-compression fatigue tests ($R = -1$) on 316 stainless steel after surface mechanical attrition treatment (SMAT). The fatigue limit improvement was reported to vary from (21–16%) based on the treatment parameters. By combining the SMAT treatment with a post annealing treatment, the fatigue strength was improved by approximately 5–6% compared to just surface nanocrystallized

* Corresponding authors. Tel.: +39 0223998667; fax: +39 0223998202.
E-mail addresses: sara.bagherifard@polimi.it (S. Bagherifard), inesfp@uniovi.es (I. Fernandez-Pariente), ramin.ghelichi@polimi.it (R. Ghelichi), mario.guagliano@polimi.it (M. Guagliano).

state [9]. Li et al. [10] 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 were subjected to 4-point bend fatigue test ($R = 0.1$) and exhibited a 50% fatigue resistance enhancement compared to the not peened specimens. Increasing the treatment time resulted in considerable decrease in fatigue strength. It was mentioned that for the SNH treated samples, a large amount of surface contaminations and damages were introduced during the process [11–13]. In another study surface nanocrystallized medium carbon steel treated by SP was investigated by 4-point bend tests. The fatigue improvement depending on the material hardness varied from 8% to 0% with respect to as received specimens. It was shown that the surface roughness acted as a defect under fatigue loading [14].

Bagherifard et al. applied SSP to low alloy steel UNI EN 10083 smooth and notched specimens and studied its effects on mechanical properties of the treated materials and their fatigue strength. The experimental and numerical results indicated of obtaining surface nanocrystallization and fatigue strength improvement with respect to conventionally treated specimens despite the considerably high surface roughness [15–18].

Wu et al. [19] studied the effect of ultrasonic nanocrystal surface modification on the fatigue behaviour of plasma-nitrided S45C steel. Depending on the treatment parameters, the studied series showed different fatigue strength alterations. In some cases the sub-surface cracks were almost restrained from propagation due to the effects of the applied treatment [19].

The cited experiments have been performed on a wide variety of materials surface nanocrystallized through various processes, using different test conditions including geometries, materials and set ups; the results indicate that variations in microstructure and test method can have significant effects on the final results.

In this paper, fatigue strength of a surface nanocrystallized nodular cast iron obtained by application of SSP process performed by a conventional air blast SP device has been studied. The applied SSP treatment uses a combination of severe peening parameters to increase the kinetic energy of the conventional SP and the total exposure time. Treated specimens' surfaces have been characterized using roughness, microhardness, X-ray diffraction (XRD) measurements and microscopy observations; eventually rotating bending fatigue tests have been performed on the specimens. The results are critically discussed.

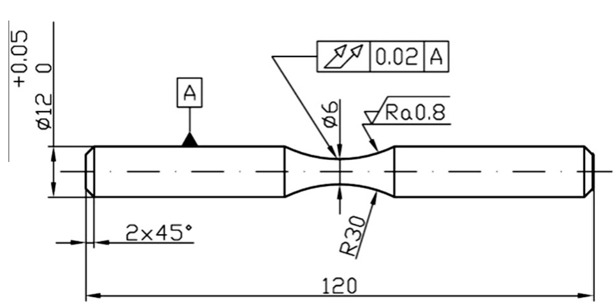

Fig. 1. Geometry of the specimens; all dimensions are in mm.

2. Material, experimental procedures and results

2.1. Specimens preparation

Nodular cast iron smooth specimens with ferrite–pearlite matrix were cut and machined with the geometry shown in Fig. 1. The nominal chemical composition of the nodular cast iron is presented in Table 1.

2.2. Shot peening treatment

The specimens were subjected to different SP treatments using air blast SP equipment. Table 2 shows the applied SP parameters on different series of specimens. CSP treatment is applied with the conventional parameters used in the industry for this class of materials, SSP is applied increasing the kinetic energy of the peening process by higher Almen intensity and surface coverage and eventually re-peened severe shot peening (RSSP) is carried out adding a second peening step to the SSP treatment in order to improve the surface state of the SSP specimens. Repeening with light parameters has been found to be effective in improving surface roughness of SP specimens in previous works [17]. Almen Intensity [1] and surface coverage [20], presented in Table 2, are the important measuring parameters of SP that indicate the total kinetic energy of the process and are related to the total accumulated plastic strain. Cast steel shots have been used in all performed peening procedures. Chemical compositions of peening media are presented in Table 3.

2.3. Microscopy observations

Microstructure observations are performed by optical microscopy and transmission electron microscopy (TEM). Specimens

Table 2
Shot peening parameters.

Treatment	Shot diameter (mm)	Almen intensity (0.0001 in.)	Surface coverage(%)
Conventional shot peening (CSP)	0.70	21 A	100
Severe shot peening (SSP)	0.70	28 A	1500
Re-peened severe shot peening(RSSP)	0.28	15 N	100

Table 3
Chemical composition of shots (wt.%).

Treatment	Shot's chemical composition
CSP/SSP	0.85–1C; 0.6–1.2 Mn; Si 0.4 min; S 0.050 max; P 0.050 max
RSSP	68 ZrO_2; 32 SiO_2

Table 1
Nominal chemical composition of nodular cast iron (wt.%).

C	Si	Mn	P	S	Cr	Mo	Ni	Mg
3.00–3.50	2.10–2.15	0.45–0.50	0.040–0.045	0.005–0.007	0.25–0.30	0.017–0.023	0.08–0.12	0.055–0.060

for optical observations have been first wet ground with 1200, 2500 grit SiC papers and polycrystalline diamond water base suspension with average scratch size of 1 µm, subsequently etched by 2% Nital.

TEM observations have been carried out using a Philips CM12 microscope operating at 120 kV. To perform TEM observations very thin pieces of specimens were first cut by electrical discharge machine, then were mechanically polished from the untreated side and finally the last step of thinning was performed by means of ion milling with proper incident angles.

Cross section optical microscopy observations of not peened (NP), CSP and SSP specimens are shown in Fig. 2.

Fig. 3 shows TEM bright field image and the corresponding selected area diffraction (SAD) pattern obtained at impacted surface of SSP specimen. The bright field image represents irregularly shaped crystals in nano range (30–100 nm) with no crystal size sharp distribution.

2.4. Hardness measurement

Microhardness measurements are performed on the cut section of the specimens using a diamond Vickers indenter, applying a maximum force of 200 gf (1.96 N). The load was applied gradually at a constant rate of 0.1 N/s with a dwell time of 15 s. Three measurements were performed at each depth and the average value is reported to account for material's heterogeneity and measurement errors. Variations of the microhardness from the shot peened surface to the bulk material are presented in Fig. 4.

2.5. Analysis of the residual stress profile

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 CrKα, circular irradiated area of 1 mm diameter, $\sin^2\psi$ method and diffraction angles

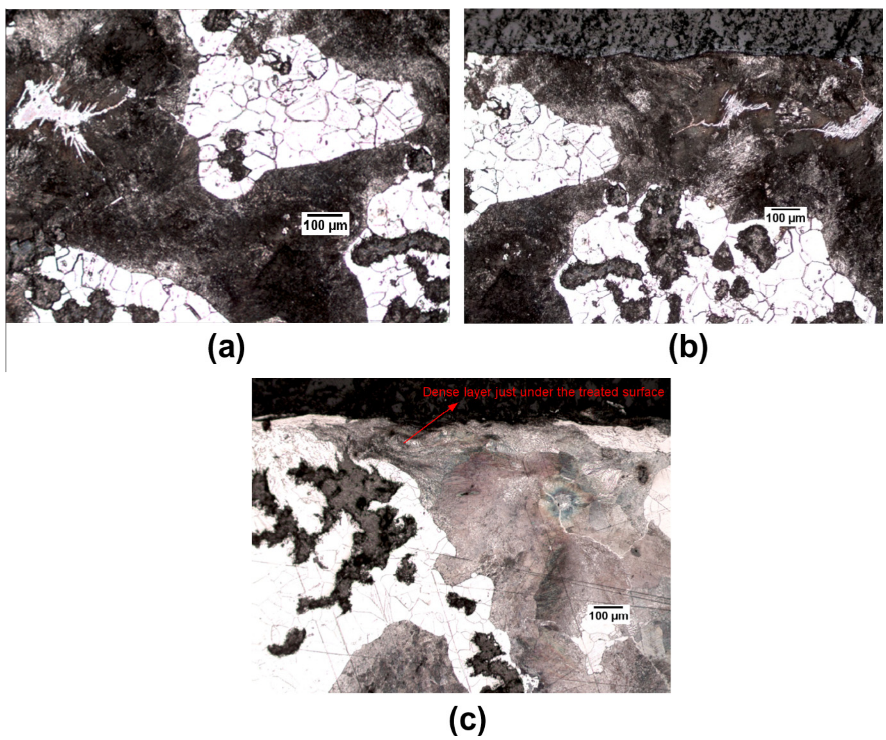

Fig. 2. Cross section optical microscopy observation of specimens: (a) NP, (b) CSP and (c) SSP.

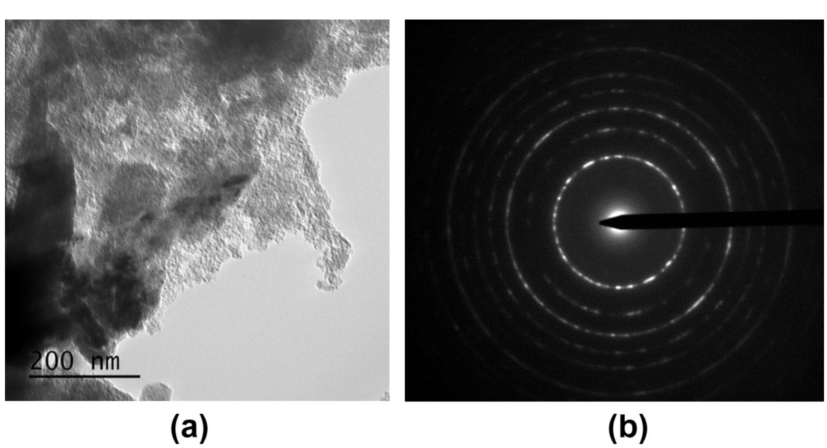

Fig. 3. Impacted surface TEM image of the SSP specimen: (a) bright field image and (b) correspondent SAD pattern.

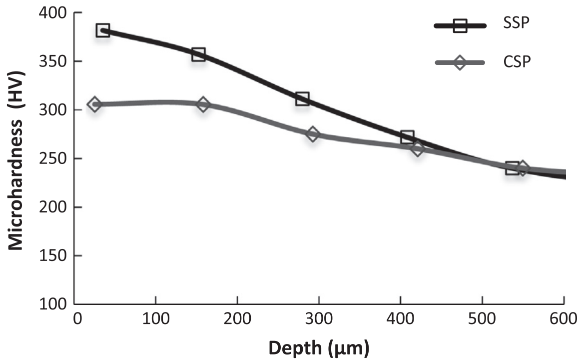

Fig. 4. Microhardness profiles for the shot peened specimens.

ψscanned between 45 and −45). Measurements have been carried out in depth step by step removing a very thin layer of material using a solution of 60% Nital in order to obtain the in-depth profile of residual stresses. The average of the in plane (longitudinal, tangential and 45°) distributions of the residual stresses in-depth are shown in Fig. 5.

The X-ray diffraction measurements allow obtaining additional important information about the surface state of material in terms of the width of the diffraction peak at half the maximum intensity (FWHM). This quantity is assumed as an index of hardening of the material. Fig. 6 represents the average distribution of FWHM parameter for CSP and SSP specimen.

2.6. Roughness measurements

Increasing roughness is a side effect of SP process. Surface state of treated specimens has been characterized in terms of surface roughness. Mahr profilometer PGK, an electronic contact instrument,

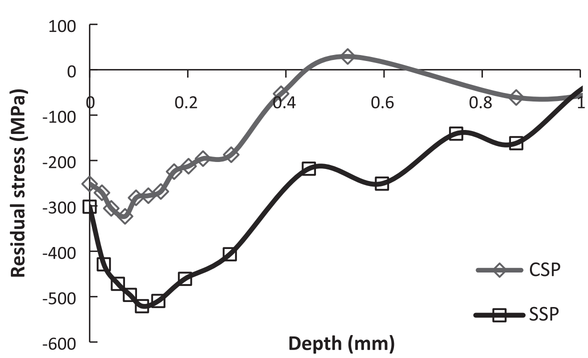

Fig. 5. In-depth distribution of residual stresses.

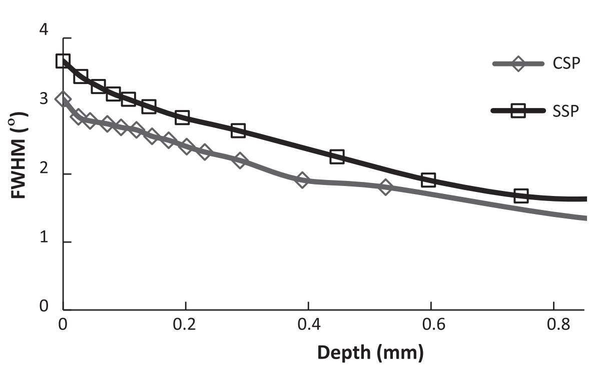

Fig. 6. In-depth distribution of FWHM.

equipped with MFW-250 mechanical probe and a stylus with tip radius of 2 µm was used to trace the surface profiles with a speed of 0.5 mm/s. The acquired signal was then elaborated by Mahr Perthometer Concept 5 software to obtain the standard roughness parameters. The measurements have been performed on three different locations of each specimen's surface and the average values are reported in Table 4 for CSP, SSP and RSSP series. Surface roughness parameters R_a, R_t and R_q are correspondingly representing arithmatic mean, maximum height of the profile and root mean square based on the definitions of ISO 4287 [21].

Scanning electron microscopy (SEM) observations of specimens' surface treated by different peening parameters, are also presented in Fig. 7 to give a better illustration of different surface states.

2.7. Fatigue tests results

Rotating bending fatigue tests (stress ratio $R = -1$) have been carried out at room temperature at a nominal frequency of 20 Hz on as-received NP, CSP, SSP and RSSP specimens using an Italsigma test machine. Each series included 15 specimens. The run out limit for the fatigue test was considered 3 million cycles. The staircase method presented by Dixon and Massey [22] was used for performing the tests with a stress step of 20 MPa. Hodge–Rosenblatt [23] method was also used to calculate the fatigue strength corresponding to a fatigue life of 3 million cycles without appreciable difference with respect of the Dixon-Massey method; the results are presented in Table 5. Results of fatigue tests stress amplitude vs. number of cycles to failure (or run-out) curve) are presented in Fig. 8.

SSP specimens did not show any improvement in terms of fatigue limit and indeed the specimens failed with a considerable scatter, thus the fatigue tests were paused after few specimens failed at low stresses and the definite fatigue limit is not reported.

Fig. 9 shows the SEM fractography images of SSP and RSSP specimens. Fracture surfaces represent combined ductile and brittle fracture marks. In both cases the presence of multiple crack initiation points are observed as it is typical of notched components' fracture. This is due to the presence of numerous indentations and dimples induced by high energy impacts acting as surface defects.

3. Discussion

Surface nanocrystallization by increasing the kinetic energy of the impacts during SSP process, is expected to intensify the favourable effects of SP on fatigue strength. This study has been performed to characterize the effects of SSP process on mechanical behaviour of nodular cast iron, particularly on its effects on fatigue behaviour.

Cross sections of differently treated specimens were observed with optical microscope. Overall view of the optical microscopy cross sectional observation of SSP treated specimen shows a distinct region (marked in Fig. 2 (c) separated from the underlying layer on the top surface. This dense layer which is not observed on the surface of the NP and CSP specimens, as stated by Saitoh et al. [24] is considered to be the fine grained material that is generated due to the severe plastic deformation.

Mechanism of grain refinement induced by severe plastic deformation is investigated in numerous materials [25–27]. Generally

Table 4
Surface roughness parameters of shot peened specimens.

Treatment	R_a (µm)	R_t (µm)	R_q (µm)
CSP	6.60	46.40	8.36
SSP	14.89	137.96	19.98
RSSP	12.68	93.83	15.90

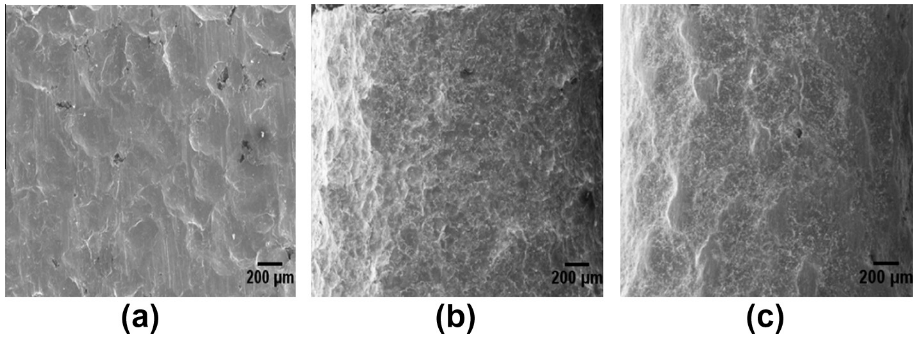

Fig. 7. Surface morphology SEM observation of the shot peened specimens: (a) CSP, (b) SSP and (c) RSSP.

Table 5
Obtained fatigue limits.

Treatment	Fatigue limit (MPa)	Improvement(%)
NP	145	–
CSP	211	31
SSP	<145	0
RSSP	242	67

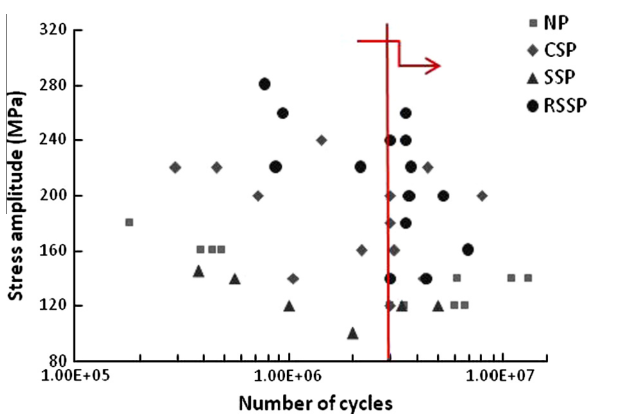

Fig. 8. Rotating bending fatigue results of shot peened specimens (the vertical line and arrow represent the run out tests).

speaking, grains are refined through the formation and rearrangement of defects (dislocations or twins) dividing the original coarse grains into ultrafine/nanocrystals. The SSP process provides repeated high energy impacts at high rates onto the specimen surface. These impacts will generate dislocations and highly deform the surface layer of the material. Repeated impacts increase the number of dislocations that will be annihilated or recombined (rearranged) to form small angle grain boundaries separating individual crystals, as proposed by Fecht [28] in analysing the grain refinement under SPD.

TEM observation in Fig. 3, performed on the near surface deformed layer of SSP specimen showed the presence of nanosize grains. The microstructure is composed of fine grains with the size of 50–80 nm and the grain boundaries are not well defined. The corresponding selected SAD pattern, shown in Fig. 3b, is composed of partially continuous diffraction rings which confirm that the as-received large crystalline grains have been broken down at this region. These nanosize crystals possess random crystallographic orientations, as indicated in the SAD patterns. Accordingly the microscopical observations confirm the grain refinement up to nano scale on the surface layer of cast iron samples subjected to SSP treatment.

Microhardness measurements (Fig. 4) show the highest microhardness in both cases is observed at topmost surfaces; these values decrease going towards the core material. In both cases, the thickness of layer with increased surface microhardness compared to the core material is approximately 500–550 µm; going further in depth the microhadness values stabilize around 250 HV. A considerable increase of almost 26% in on-surface microhadness is observed for SSP specimens with respect to CSP series.

XRD measurements results show that a considerable depth of material is characterized with high compressive residual stresses. This is verified by comparison of in-depth residual stress profile for CSP and SSP specimens shown in Fig. 5; a notable increase is observed for SSP specimen also in terms of FWHM, indicating also the increased depth of work-hardened layer. Indeed the results

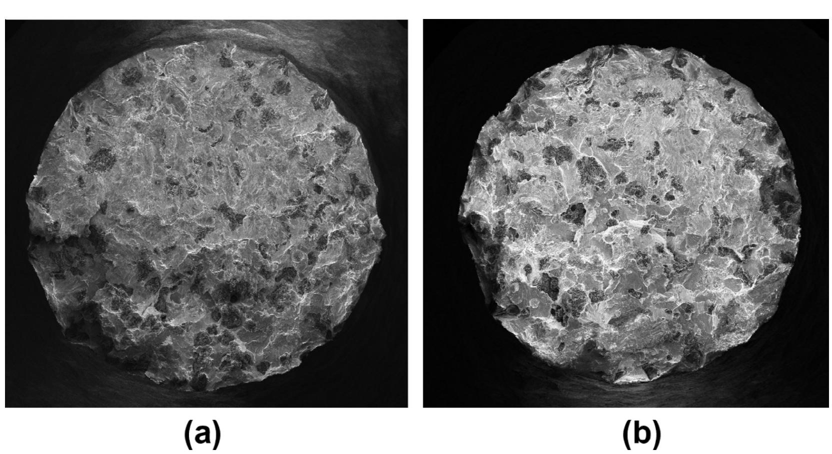

Fig. 9. Fracture surface SEM observation of: (a) SSP and (b) RSSP specimens.

indicate that the SSP treatment has been more effective in work-hardening with respect to CSP specimen; the effect of this treatment can be observed upto the depth of 1 mm, as shown in Fig. 6.

Surface roughness measurement results indicate that SSP specimens have a considerably rougher surface compared to the specimens treated with CSP parameters. Indeed previous studies have reported that roughness increases with increasing shot diameter and/or shot velocity; it rises also with increasing surface coverage, though in the latter case, roughness tends to reach a stable state, as the process time goes on [29]. The fact that surface roughness increase by increasing impact energy is verified by comparing the scanning electron microscopy (SEM) observations of the surface of the specimens treated by different peening parameters, as presented in Fig. 7. As can be observed in Fig. 7b and c, repeening treatment causes a more regular surface state. This issue has been verified also in previous studies [17].

In terms of fatigue data, the RSSP series of specimens, despite the very high surface roughness, showed a considerable improvement of almost 67% with respect to the NP series, doubling the improvement generated by CSP treatment. The presence of the nanocrystallized structure, thick layer of material with high compressive residual stresses and a remarkable surface work hardening effect of the SSP treatment have contributed to the fatigue strength improvement. In case of SSP series, the high surface roughness has a deteriorating effect, masking the beneficial influence of all the aforementioned parameters. Hence, it can be concluded that the repeening process is essential to uncover the effect of SSP on fatigue strength of the studied material. The fatigue life enhancement of RSSP series with respect to SSP specimens is attributed to the surface modifications applied by repeening process, although RSSP series still show very high values in terms of surface roughness parameters.

Optical observations have been performed on cross sections of some SSP and RSSP specimens after fatigue tests. The observations, as shown in Fig. 10, indicate the presence of several micro-cracks on the surface of SSP specimen that are due to the very high kinetic energy of the SSP treatment. Even if the repeening process was not able to strongly reduce the surface roughness to values comparable with the one of CSP, it seems that it was able to change the surface state, smoothing sharp corners and somehow closing the microcracks generated on the surface during SSP process. That is to say that conventional roughness parameters are not able to justify the fatigue results and that should not be used for fatigue behaviour assessment of SSP and RSSP specimens.

4. Conclusions

Various shot peening treatments including conventional shot peening, severe shot peening and a soft repeening after severe shot peening have been applied to nodular cast iron specimens. The specimens were analysed based on the microscopy observations, microhardness and surface roughness measurements, distribution of residual stresses and fatigue strength tests. In view of the obtained results the following conclusions can be drawn:

- Microscopy observations indicate a highly deformed near surface layer for specimens treated by severe shot peening and the presence of a surface nanocrystallized layer.
- The surface and near surface hardness values of the shot peened specimens increases with increasing the treatment impact energy.
- X-ray diffraction results show that severe shot peening process causes notable increment in the depth affected by high residual stresses and surface work hardening compared to conventionally shot peened series.
- Surface roughness increases with increasing the impact energy of shot peening process. Several defects and microcracks were observed on the surface of the severe shot peened specimens, generated by the high kinetic impacts during the process. This detrimental effect is attenuated by soft repeening.

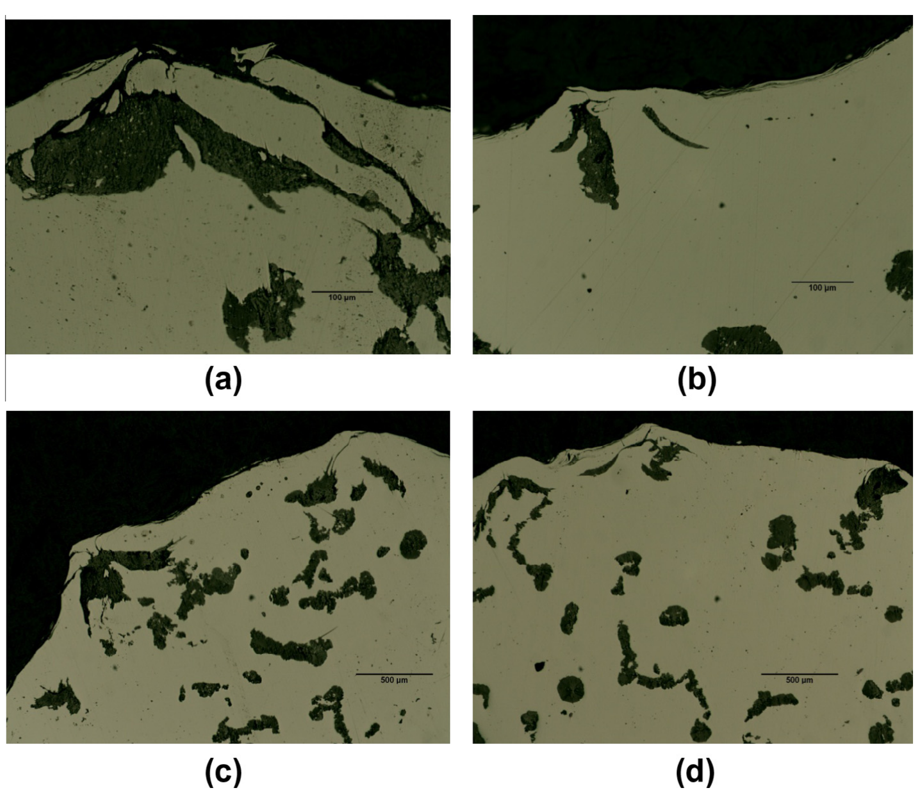

Fig. 10. Cross section SEM observation of the specimens: (a) SSP (200×), (b) RSSP (200×), (c) SSP (50×) and (d) RSSP (50×).

– Fatigue tests results indicate noteworthy fatigue strength improvement for RSSP series, notwithstanding its considerable surface roughness, while SSP series shows no notable effect. This was interpreted in the light of the different surface morphologies.
– The results show the inability of conventional roughness parameters to describe the effect of surface finishing on the fatigue behaviour of the severely shot peened specimens.

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