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

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ABSTRACT

Effect of nanocrystalline surface obtained by severe plastic deformation on fatigue strength of nodular cast iron has been studied in the paper. Surface nanocrystallization has been applied by means of standard air blast shot peening equipment with particularly severe parameters compared to the usual ones used for similar classes of material. Microscopy observation, microhardness, surface roughness and X-ray diffraction measurements were carried out to characterize the treated surface of differently shot peened specimens. Rotating bending fatigue tests were performed to investigate the effects of process parameters on fatigue behaviour. The results indicate a sensible fatigue strength improvement obtained through application of severe shot peening with respect to conventional shot peening, notwithstanding the specimen's very high surface roughness due to high energy impacts. The obtained results are critically discussed.

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

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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.

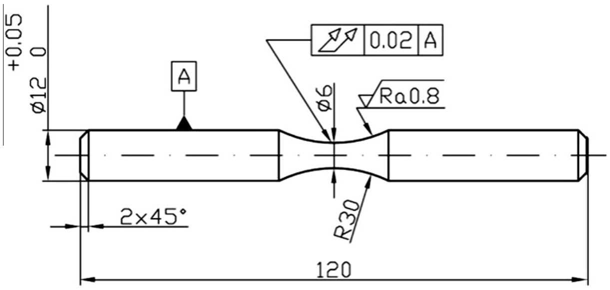

Fig. 1. Geometry of the specimens; all dimensions are in mm.

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