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Evaluation of the residual stresses induced by shot peening on some sintered steels

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Abstract

The effect of shot peening treatment on sintered steels plates were analyzed in terms of micro-structural and mechanical properties and residual stress profiles. Two high performances powder metallurgy steels were considered: the former was obtained starting from diffusion bonded powders, whereas the latter starting from pre-alloyed powders. Two different nominal densities were considered, 6.9g/cm^3 and 7.1g/cm^3. After a preliminary optimization, two shoot peening cycles were selected and carried out on the investigated materials. Residual stresses after the treatment were measured by means of the hole drilling technique and related to the mechanical properties and the surface densification of both steels, varying the nominal density.

Keywords: Powder Metallurgy; Shot Peening; Residual stresses; Hole Drilling

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1. Introduction

Powder Metallurgy (PM) is a technology able to produce net-shaped parts with both good geometrical precision and mechanical properties. In the conventional process, the mechanical parts produced by PM are characterized by some residual porosity after sintering, which is known to affect the final mechanical properties. Fatigue resistance is significantly reduced by residual porosity, because fatigue cracks are favoured to nucleate in correspondence of clusters of pores and tend to propagate along the pores network [1, 2]. Nevertheless, in the applications PM parts are often submitted to fatigue loadings. A potentiality for enhancing fatigue strength is to increase the density of the part, so having only a few percent of residual porosity. But this cannot be achieved by the conventional processes, especially if the part has a

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complex geometrical shape and large sections. A good alternative is to increase the density limited to the surface of the part by specific densification techniques, such as rolling [3] or shot peening. Shot peening is a cost effective technique traditionally used for improving fatigue resistance in wrought steels due to compression residual stresses and strain hardening. Applied to some PM steels, it was demonstrated to produce also a surface densification, so giving rise to an important improvement of the high cycle fatigue resistance [3] and the knowledge of the effective stress distribution in the near-surface region of a component is fundamental for the correct estimation of the service life. Among the different methods developed, X-ray diffraction method (XRD) and blind hole drilling (BHD) are widely employed for wrought steels. XRD is based on the measurement of the lattice deformations of crystalline materials and it is demonstrated able to provide very accurate results, even if they require expensive equipment and a long procedure for the residual stress depth profiling [4]. The BHD method is relatively simple and cheaper and can be easily applied to many *in-situ* measurements. The technique is semidestructive as it is based on the measurements, obtained by strain gauges, of the surface strain relaxed during the incremental drilling of a small hole in the sample surface. In the technical literature some papers can be found comparing the hole-drilling and XRD methods for measuring the residual stresses in shot-peened wrought metallic materials, while few information is available about the application of the hole-drill method on sintered steels. In this paper the BHD method is applied for measuring the stresses profiles on different sintered steels submitted to different shot peening cycles. The obtained results were discussed and related with the results obtained from the metallographic analysis and hardness measurements. The data were completed with Scanning Electron Microscope (SEM) analysis of the surface. Finally, the BHD results were compared with the data obtained from XRD.

Nomenclature

E	Elastic modulus
σ_y	Yield strength
HV	Vickers Hardness
ρ	Relative density

2. Experimental procedure

Two high performance PM steels from diffusion bonded and pre-alloyed powders were considered. The nominal chemical composition of the powders are reported in Table 1.

Table 1: Nominal chemical composition of the powders

Powder Code	Ni %wt	Mo %wt	Cu %wt	Mn %wt	C§ %wt
1	4.00*	1.41	2.00*	-	0.60
2	0.90	0.90	2.00*	0.20	0.60

* added by diffusion bonding § added by graphite

Plates with square cross section (65 x 65 mm^2) and 10 mm height were compacted at 6.9 g/cm^3 and 7.1 g/cm^3 nominal density and sintered, under N_2/H_2 atmosphere, at 1150°C, for 25 minutes in belt-type industrial equipment at Stame, srl, Arosio, Italy. After sintering, the plates were fast cooled in the same furnace by sintering gas (sinterhardening). Finally, the samples were submitted to a stress relieving at 200°C. Table 2 summarizes the codes of the investigated materials. The plates were submitted to two different shot-peening cycles, according to the parameters reported in Table 3. Steel shots (1% C and 0.8% Mn) hardened to 60–62 HRC were used. The microstructure of the as-sintered materials was analyzed at the light optical microscope (LOM). The steels from 1 powder showed a mixture of bainite and martensite, with predominance of martensite. Some areas of perlite and upper bainite can be detected. Presence of residual austenite and transforming austenite can be found around the pores (Figure 1). The steel from powder 2 showed mainly a martensitic microstructure with some areas of bainite. Poor presence of residual austenite was detected. (Figure 2). Hardness and tensile properties of the as-sintered steels are reported in Table 4. After shot peening, the microstructure of the specimens was analyzed at the light optical microscope (LOM), for investigating the surface densification. The thickness of the densified layers was measured by an image analysis software and the HV0.1 microhardness profiles were investigated for detecting strain-hardening. At the Scanning Electron Microscope (SEM) the surface morphology was investigated.

Table 2. Codes of the investigated materials.

Material Code	Powder	Density [g/cm^3]	Sintering Temperature [°C]
1LL	1	6.9 (L)	1150 (L)
1HL	1	7.1 (H)	1150 (L)
2LL	2	6.9 (L)	1150 (L)
2HL	2	7.1 (H)	1150 (L)

Table 4: Hardness and tensile properties of the investigated PM steels.

Material Code	HV30	UTS [MPa]	σ_y [MPa]
1LL	302±17	950	600
1HL	350±31	1075	690
2LL	314±18	1000	700
2HL	340±13	1185	830

Table 3: Parameters characterizing the shot peening cycles.

Shot peening Code	Shot type	Shot diameter	Coverage	Almen A [mm]
E	ASH 330	0.8 mm	500%	0.5-0.6
G*	ASH330 + ASH 70	0.8 mm + 0.2 mm	100% + 500%	0.2-0.3 + 0.2-0.3

* The G cycle was composed by two single shot-peening cycles

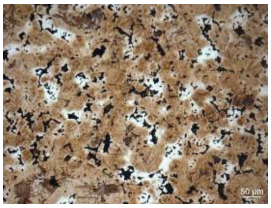


Figure 1: 1LL steel microstructure.

Figure 2: 2LL steel microstructure

Residual stress measurements were carried out by means of the “Hole drilling” incremental method, following the ASTM E837-08 Standard [5]. The high speed air turbine drilling system constructed by SINT Technology, automatically and electronically controlled, was used for this aim. An accurate alignment of hole and gauge centre is guaranteed by a microscope positioned along the drilling axis, which also permits a precise determination of post-drilling residual eccentricity, thus allowing the introduction of the correspondent correction in the measurements elaboration. Three grids HBM 1-RY61-1.5/120S rosettes were employed for this research. Small depth increments were used near the surface, namely of 5 µm, in order to keep the expected high stress gradient. Strain gauges readings were automatically performed at each increment by means of a HBM Spider8 instrumentation. The measurements were elaborated using the integral Schajer’s method [6-7], particularly suitable for non-uniform residual stresses determination.

3. Results and discussions

3.1 Surface densification

Examples of the surface of the 1LL samples after sintering and shot peening are shown in Figure 3. The figures clearly show the presence of a densified surface layer after shot peening, where porosity was almost completely eliminated. The thickness of this layer was measured by image analysis of ten LOM micrographs. The obtained results, expressed as average values, are reported in Table 5, where fully densified thickness stands for a thickness with porosity lower than 1%, while transition thickness stands for the thickness where porosity is between zero and the porosity of the bulk.

Figure 3: Aspect of the surface in the as-sintered 1LL specimen (a), in 1LLE specimen (b), in 1LLG specimen (c)

Table 5: Data on the densified thickness of the porous steels.

Material Code	1LLE	1LLG	1HLE	1HLG	2LLE	2LLG	2HLE	2HLG
Fully densified thickness [mm]	0.169	0.074	0.103	0.082	0.032	0.019	0.145	0.080
Transition thickness [mm]	0.019	0.008	0.081	0.009	0.107	0.065	0.016	0.009

3.2 Microhardness measurements

The microhardness profiles show a negligible strain hardening which is confirmed for all the tested conditions.

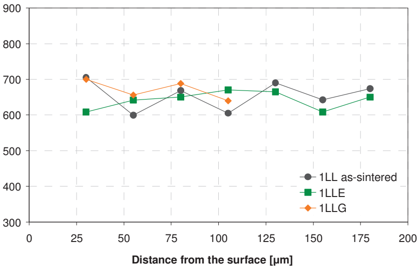


Figure 4: HV0.05 profiles for 1LL samples

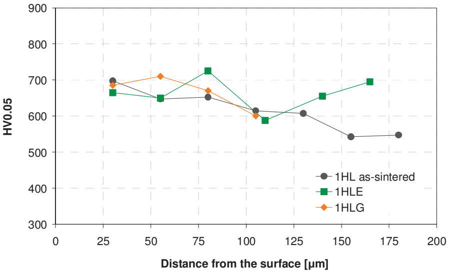
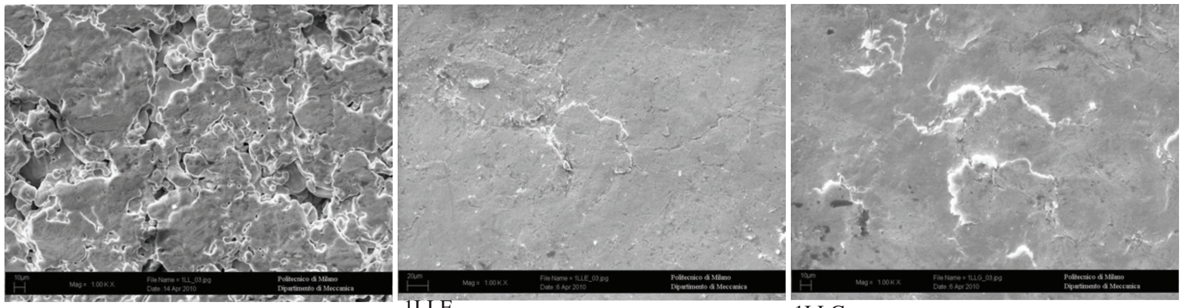


Figure 5: HV0.05 profiles for 1HL samples

3.3 SEM analysis

Figures 6 shows examples of the surface morphology of the samples after sintering and after shot-peening.



1LL as sintered

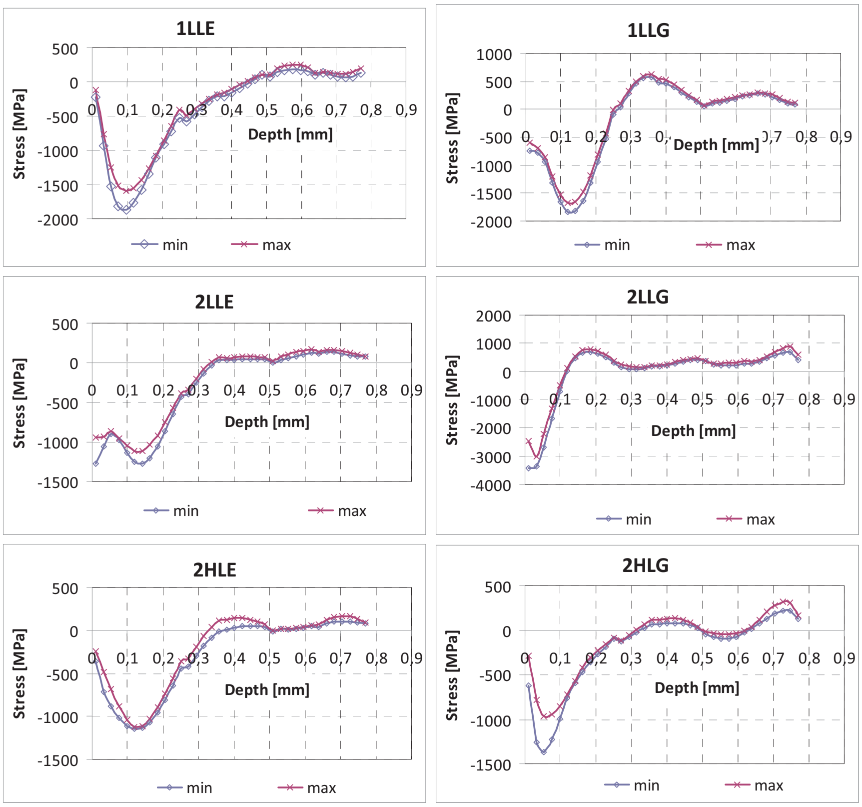
1LLE

1LLG

Figure 6: SEM image of the samples surface after sintering and after shot-peening.

3.4 Residual stresses measurements

Examples of the obtained results are reported in Figure 7.


1LLE

1LLG

2LLE

2LLG

2HLE

2HLG

Figure 7: BHD results for the experimented materials.

4. Discussion

The two principal residual stresses resulted quite similar for each specimen, thus highlighting the presence of a prevailing equi-biaxial stress state, as expected in shot peened components. Some limitations in the BHD measurements have to be highlighted, due to the following approximations:

1. all the measurements were carried out considering the elastic modulus equal to the value of the fully dense steel. Actually, the local mechanical properties of the material change by varying the porosity as a consequence of the shot peening. For each material, in the fully densified thickness: $E = E_{fd}$,$\sigma_y = \sigma_{y\ sp}$; in the bulk material: $E = E_{bulk}$; $\sigma_y = \sigma_{y\ bulk,}$, where E_{fd} = 210000 MPa , $E_{bulk} = E_{fd}\ \rho^{3.4}$ and ρ is the relative density. $\sigma_{y\ bulk}$ is given by the data on the as-sintered material reported in Table 4, while, as suggested in [8], the local yield strength $\sigma_{y\ sp}$ in the near-surface region can be estimated from the microhardness data. The obtained data are summarized in Table 6.

   In the materials, like 2LLE and 2LLG, where limited values of the densified thickness were found, an overestimation of the peak stresses is justified and high values of the surface stresses can be explained if considering the influence of the subsurface porosity on the surface measurements.

Table 6: Estimated yield strengths of the densified thickness

Material Code	1LLE	1LLG	1HLE	1HLG	2LLE	2LLG	2HLE	2HLG
$\sigma_{y\,sp}$ [MPa]	1308	1456	1309	1297	1512	1568	1345	1440

2. residual stresses elaboration was carried out under linear elastic hypothesis; however, the high values so obtained show that this hypothesis is not fulfilled for most specimens, i.e. some plasticization occurs near the hole border [9]. Due to the above approximations, the BHM results reported in fig. 7 have to be considered as overestimated and therefore qualitative at this stage, in particular for specimens 1LLE, 1LLG and 2LLG.

Nevertheless, they give useful indications when examined from a comparative point of view:

- as a general trend, it can be observed that the residual stresses profiles show a typical subsurface peak and the depth of the peak seems not to be affected by the experimented parameters of the shot peening for 1LL materials, while for both the 2 materials the E treatment tends to increase the depth of the peak, as theoretically expected
- for each material, the surface stress is higher for the G treatment if compared with the E treatment. This is in accordance with the correspondent parameters of the shot-peening treatments.

5. Concluding remarks

Residual stresses were measured by means of the hole drilling technique on PM steels after shot peening, carried out with different processing parameters. The obtained results show the presence of two principal residual stresses quite similar for each specimen, as expected in shot-peened components. Some limitations were observed and can be explained if considering the influence of the local porosity on the value of the elastic moduli and if considering the linear elastic hypothesis assumed in the data elaboration. If the profiles are considered from a comparative point of view, they can give useful information which are in accordance with the parameters of the shot peening treatments and with the data obtained from the metallurgical analysis. For comparison, XRD measurements will be carried out on the same samples.

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