Fatigue Strength of a Low-Alloy Steel Shot Peened with Ultra Fine Hard Steel Media

S. Bagherifard[1], M. Bandini[2], M. Guagliano[1], C. Morel[3], J. Samuel[3]

1 Politecnico di Milano, Dipartimento di Meccanica (Italy)
2 Peenservice srl, Bologna (Italy)
3 WINOA Group (France)

Abstract
In this paper, a low alloy steel widely used in mechanical constructions has been considered and investigated. Rotating bending fatigue tests were executed both on smooth and notched samples, not peened and shot peened; different peening media and parameters were considered. In particular, new ultra fine and hard steel media were used to assess the fatigue strength increment obtained by using this media and to compare it with the fatigue strength of samples peened with conventional media.
Roughness, hardness and residual stress measurements were executed to completely characterize the treated surface and to relate the surface state to the fatigue behavior.
The test results show a marked positive action of the new media, enabling to obtain a strong increment of the fatigue strength even with low peening intensities.

Keywords fatigue, shot peening media, residual stresses

Introduction
Shot peening is a well-known mechanical surface treatment generally used to improve fatigue behavior of metal parts. Final aim of the process is to induce compressive residual stresses close to the surface and to work-harden the same layer of material. These effects are very useful in order to totally prevent or greatly delay the failure of the part [1-2]. On the other hand, increasing the roughness is well-recognized as a side effect of shot peening. Since fatigue cracks initiate predominantly at the free surface of a part and are greatly influenced by surface finishing, the increased roughness could lower the benefit that can be got by applying shot peening. In other words, the final effect of shot peening is associated to the choice of the process parameters, like Almen Intensity, coverage, shot dimension and material and to their combined effect in the peened part. In fact, combination of these parameters will cause the generation of compressive residual stresses in the surface layer of material, the hardening of the surface and the modification of the surface roughness. In particular, while residual stresses and surface work hardening give a positive contribution to enhance the fatigue behavior, roughness can be seen as an undesired effect, since an increment of the roughness causes the decrease of the fatigue strength. Bearing in mind these last sentences, it can be concluded that the choice of the treatment parameters and media are able to maximize the difference between the positive effect of residual stresses and surface hardening and the negative effect of roughness. If the attention is drawn to shot peening media, recent researches have focused on the so called "fine particles", characterized by their small dimension (20-200 µm) and high hardness (750-1000 HV). In [3] the application of a modified pneumatic shot peening system for fine particle bombarding is described: in that process metallic or non-metallic fine particles with the aid of an air nozzle jet system are bombarded on a material surface to improve the functionality of the collided surface. This treatment has proved to be effective in improving the behavior of mechanical parts [i.e.: 4, 5], especially as regards fatigue (the best investigated property) with better results compared to those from conventional media and standard shot peening. Besides the better mechanical performances that fine particles bombarding is able to achieve, the fine shots can also be used for components with geometrical details that would not be possible to treat by using conventional media. It is interesting to note that while the papers published up to now show the comparison of fatigue tests carried out on different fine particles treated specimens and parts, to the best of our knowledge there is no systematic study regarding the comparison of the fatigue results for fine bombarding with different set up

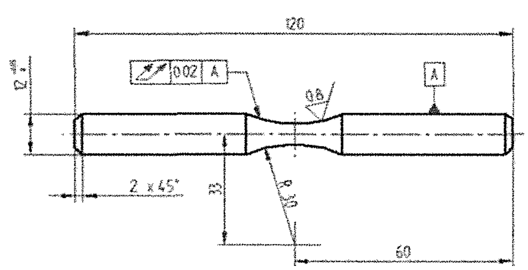
of conventional shot peening; being the aim to have a more comprehensive understanding of the real advantages of fine particle bombarding with respect of the conventional shot peening by considering its possible variables and treatment parameters. Such an approach can help assessing the role of the different shot peening parameters in the quantitative values of the main shot peening effects (residual stresses, surface work hardening and roughness).
In this paper a new ultra fine steel shot (UFS) is considered and fatigue tests are performed both on smooth and notched specimens made of a low alloy steel. The result are then compared with the ones of different shot peening treatments performed considering Almen intensities ranging from 10N to 12A obtained by considering both ceramic and steel shots. A fine characterization of the surface properties of the treated samples allowed clarifying the main effects of the treatments while the critical analysis of the fatigue test results allowed to have a wide view of the possible practical applications of UFS.

Material and experiments

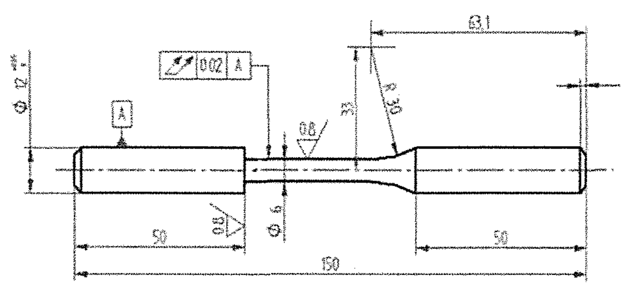
Quenched and tempered steel 40NiCrMo7 (SAE4340) with the chemical composition presented in Table 1 was considered and subjected to rotating bending fatigue tests.

Table 1. Nominal chemical composition of steel 40NiCrMo7 (wt%)

C	Si	Mn	S	P	Ni	Cr	Mo	Cu
0.39	0.29	0.68	<0.003	<0.009	1.81	0.84	0.23	0.09



(a)



(b)

Figure 1 – Geometry of the specimens used for the fatigue tests: (a) smooth specimens, (b) notched specimens ($k_t = 2$).

In Figure 1 the geometry of the smooth and notched specimens is shown; The theoretical stress concentration factor of the notched specimen is equal to 2.
Five different series of specimens were considered; the first includes the as-received not peened specimens (NP series), the second series shot peened with an Almen intensity of 10N (10N series), the third group shot peened with an intensity of 6A, the fourth group considers the intensity of 12A (series 12A) while the fifth one considers 10N as Almen intensity but was obtained with the new ultra fine steel shots (UFS) (UFS series). This new shot peening media, UFS, existing under different sizes ranging from 50 to 150 μm, is characterized by a high hardness (770-900 Hv) compared to typical steel shots available on the market, and a highly spherical shape (thanks to an exclusive production process developed by Winoa Group). In the present study, UFS with a diameter of 40-70 μm were used. The shot peening machine used is a standard air compressed wth direct pressure unit.
Coverage is set equal to 100% for all series. In Table 2 the summary of the shot peening parameters corresponding to each treatment is shown.
By looking at the data shown in Table 2, it is clear that the most directly comparable data are the ones of series 10N and UFS, both as regards the dimension of the shots and also as concern the possible practical application of these media for the treatment of complex and small geometrical details.
Before the fatigue experiments were performed, the state of the surface was characterized with roughness and X-ray measurements.

Table 2. Summary of the treatment parameters of the series of specimens considered.

Series	Shot type and diameter (mm)	Coverage (%)
10N	CE 70 (ceramic, 0.1 mm)	100
6A	S110 (steel, 0.3 mm)	100
12A	S170 (steel, 0.43 mm)	100
UFS (10N)	Ultra fine shots (steel, 0.040-0.070 mm)	100

Roughness measurements

Roughness measurements were performed on three specimens of each series using a Mahr PGK, MFW-250 device. The measurements were performed according the standard UNI EN ISO 4288:2000. The results in terms of average values presented in Table 3, are the mean value of three measurements performed on each series. As expected by intensifying the Almen intensity of the process that is its kinetic energy, the surface roughness increases, but the maximum value of the roughness parameters are achieved with the UFS series, due to the greater values of the hardness of these media.

Table 3. Results of the roughness measurements (l_r = 0.8mm, l_n = 4.0mm)

Series	R_a (μm)	R_z (μm)	R_t (μm)
NP	0.22	2.00	2.96
10N	1.49	8.50	9.80
6A	1.73	9.28	12.36
12A	2.35	12.07	14.32
UFS	2.75	15.95	18.29

X-ray diffraction (XRD) measurements

To study the state of residual stresses, XRD analysis was performed on all series of specimens using an AST X-Stress 3000 Xray diffractometer (radiation Cr Kα, circular irradiated area with a diameter of 1 mm^2, $\sin^2\theta$ method, diffraction angles (2θ) scanned between -45° and +45°). Measurements were 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. A solution of acetic acid (94%) and perchloric acid (6%) was used for electro-polishing. The results of the measurements are shown in Figure 2.

The graphs reported Figure 2 show that UFS is able to induce a residual stress profile with approximately the same maximum compressive value obtained through using the conventional shots, showing a trend that is comparable with that of 10N series. However, the depth of the compressive residual stress field is less pronounced compared to the one of the samples peened with higher Almen intensities using conventional shots. Another parameter measured by XRD is FWHM. This parameter, the distribution of which is shown in Fig. 3, represents the full width of the diffraction peak at half of the maximum intensity. It can be assumed as an index of hardening of the material [6]. As it is observed in Fig. 3 the on-surface value of FWHM is growing with increasing the Almen intensity of the peening process i.e. increasing the kinetic energy of the impacts. This issue has been validated also numerically in authors' previous study [7]. It is to be noted that the thickness of the work-hardened layer can be estimated as the thickness of the layer, which 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 of the process and is significantly increased for UFS specimens compared to all other series. It can be clearly noted that while the depth affected by surface work hardening induced by shot peening is almost the same, the UFS media are able to cause a more pronounced surface hardening than the one caused by 12A shot peening.

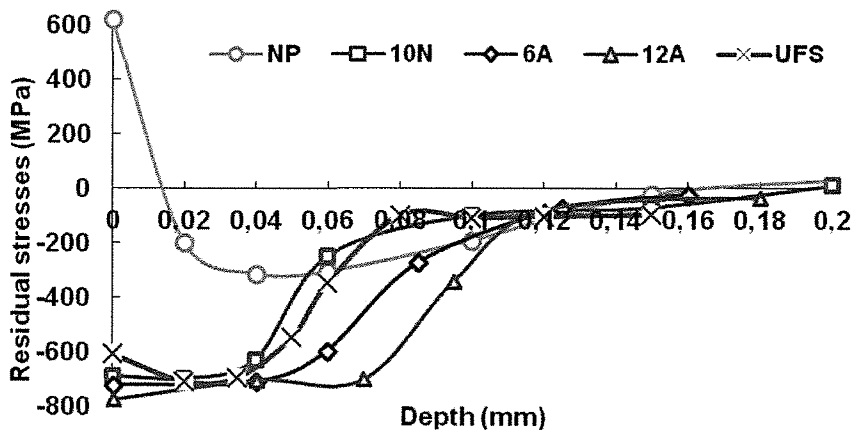


Figure 2 – In-depth residual stress trend in all series

Fatigue tests and results

Rotating bending fatigue tests (stress ratio R=-1) [8] have been carried out at room temperature at a nominal frequency of 20 Hz on the NP and shot peened smooth and notched specimens shown in Figure 2. Fatigue strength corresponding to a fatigue life of 5 million cycles has been obtained by a staircase procedure, planned by employing 15 specimens. The data are elaborated according to ASTM standard E739-91 [9]. The results of the reverse bending fatigue tests in terms of fatigue strength at N=5E06 cycles are compared in Table 4 (smooth specimens) and Table 5 (notched specimens) for the different treated series of specimens. The presented fatigue endurance corresponds to $5x10^6$ cycles.

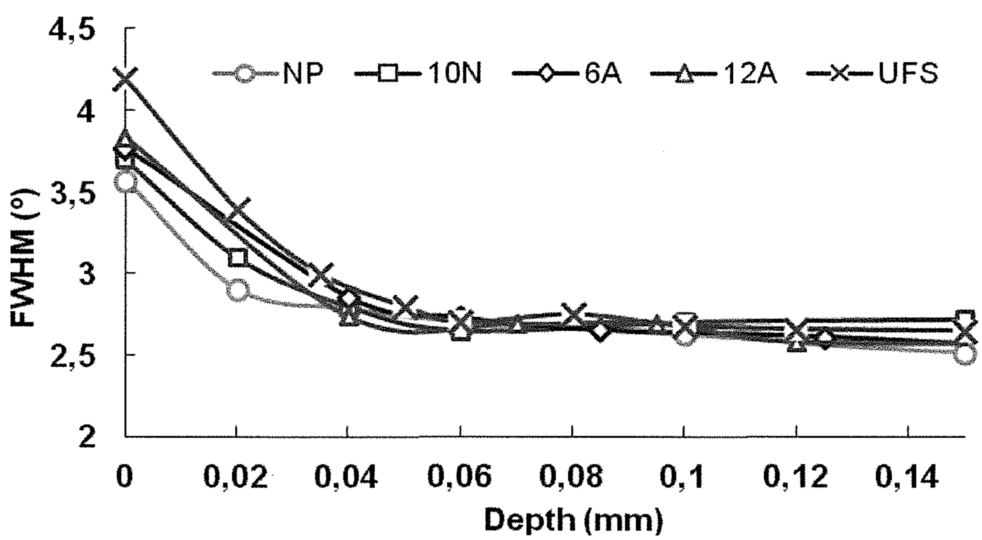


Figure 3 – In-depth FWHM trend of all series

As indicated in Table 4 and 5 all the applied peening treatments have been effective in improving the fatigue strength. In Figure 4 the complete S-N curves of the notched specimens are also shown: in the finite life region of the curve, the effect of shot peening remains evident even if it is less important when the stress range increases.

This improvement depends on the applied Almen intensity and specially the surface characteristics of the treated specimens. Notwithstanding the fact that surface roughness is well-known to have detrimental effects on fatigue strength, the UFS, series which have the highest

surface roughness, results, as regards the smooth specimens, in the highest fatigue limit, due to the more effective residual stress field and of the induced surface work-hardening.
As regards the notched specimens, the geometry and the related steep stress gradient makes more important the in-depth stress trend, which, if deeper, remain more stable under the fatigue loading and more suitable to stop possible microcracks starting form the notch root. In this case, the 12A series, which present the most effective residual stress trend, is the most effective treatment but UFS results in a remarkable improvement of the fatigue limit, aligned with the one obtained with 6A aeries and much more than the fatigue limit of the 10N series: this can be mainly attributed to the stronger surface work hardening caused by UFS treatment.

Table 4 – Fatigue strength at 5 million cycles, smooth specimens

Series	Fatigue strength (MPa)
NP	602
10N	705
6A	676
12A	710
UFS	733

Table 5 – Fatigue strength at 5 million cycles, notched specimens

Series	Fatigue strength (MPa)
NP	390
10N	433
6A	492
12A	518
UFS	495

Discussion and Conclusions

The results of the fatigue tests show that all treatments are effective in improving the fatigue strength of both the smooth and the notched specimens. If attention is drawn to UFS and on its comparison with the 10N series, that consider the most similar treatment to UFS in terms of media size, intensity used and possible applications, it is clear that UFS is able to induce a more pronounced improvement of the fatigue life and strength.

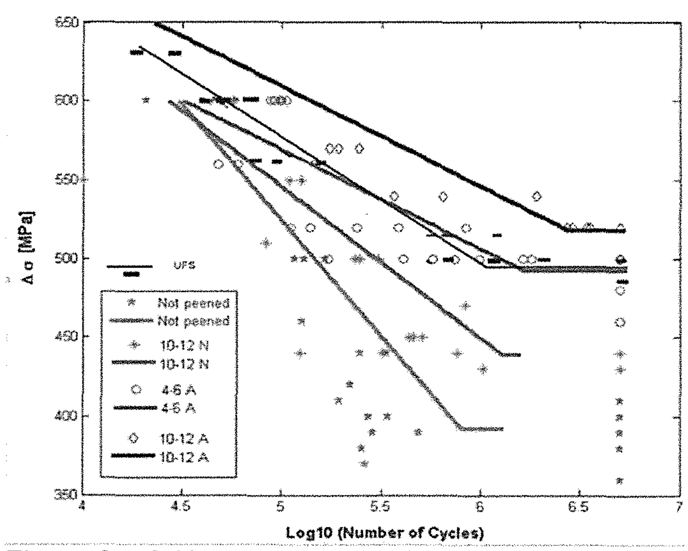


Figure 6 – S-N curves of the different series of notched specimens.

Since the induced residual stresses do not appear more effective than the ones of the other series and roughness is even higher, this can be explained especially by considering the more pronounced surface work hardening induced by UFS, able to compensate the negative effect associated with the increased roughness. The notable work had=rdening can be directly associated with the increased hardness of these media. The effect of UFS is more evident if the notched specimens compared to the smooth ones, even if in this case its beneficial effect is comparable with that of the 6A series and less than that of the 12A series.

References

[1] K.J. Marsh, Shot Peening: Techniques and Applications. (London: EMAS; 1993).
[2] V. Schulze, Modern Mechanical Surface Treatment, states, stability, effects. (WILEY-VCH; 2006).
[3] K. Mase. Y. Miyasaka: Method of Surface thermo-mechanical treatment for metal-product, Japan Patent, No.1594395 (1990).
[4] C. Kagaya, Y. Yamada: Fine Particle Bombarding Technology and Functional Development of Metal Surface. Proceedings of the 10th International Conference on Shot Peening (ICSP 10, Tokio, 2008).
[5] M. Yoshizaki: improvement in tooth surface strength of carburized transmission gears by fine particle bombarding process. Proceedings of the 10th International Conference on Shot Peening (ICSP 10, Tokio, 2008).
[6] S. Bagherifard, M. Guagliano: Fatigue behaviour of a low-alloy steel with a nanostructured surface obtained by severe shot peening. Eng Fract Mech 2012; 81:56–68.
[7] S. Bagherifard, I. Fernandez-Pariente, R. Ghelichi, M. Guagliano: Fatigue behavior of notched steel specimens with nanocrystallized surface obtained by severe shot peening. Materials and Design 2013; 45: 497-503.
[8] ISO 1143: 1975. Metals- Rotating bar bending fatigue testing.
[9] ASTM standard E739-91: Standard Practice for Statistical Analysis of Linear or Linearized Stress-Life and Strain-Life Fatigue Data, 2004.