Influence of severe shot peening on high and ultra-high cycle fatigue life of 50CrMo4 steel

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Abstract
In this study the effect of severe shot peening to improve fatigue properties of quenched and tempered 50CrMo4 steel, used for manufacturing of car wheel hubs is described. Two sets of specimens were machined and one set was mechanically polished and the second one was severely shot peened with use of S170 peening medium (steel shots, ø = 425 μm), Almen intensity 15.6A and coverage of 1000 % (marked SSP). Results of crystallite size analysis show a decrease of the crystallite size on the surface from average value of 74 ± 3 nm for the NP specimen to 38 ± 4 nm for the SSP specimen. Fatigue tests show a significant increase of the steel's fatigue strength mainly in the ultra-high cycle region.

Key words: high and ultra-high cycle fatigue, severe shot peening, nanostructured surface layer, 50CrMo4 steel, high frequency fatigue testing

Introduction
Severe shot peening uses general air blast devices with unusual severe process parameters (higher Almen intensity and coverage), characterized by high kinetic energy. It has been proved that it is able to accumulate a great amount of plastic deformation causing grain refinement up to nanometer scale and enhance the fatigue resistance of various metals [1-6]. It is well known that many properties of a solid part strongly depend on the surface state: corrosion, fretting, fatigue, wear and so on. These are strictly related to the surface and less to the bulk material. This means that severe shot peening treatment is possible to provide the advantages of superior mechanical properties of nano-crystalline materials with possible application on large structural components with difficult shapes, what is not possible with techniques for bulk nanocrystallization. Present development of new industrial machines requiring higher efficiency and cost savings must provide possibility of higher loading, higher operation speeds, higher durations and high reliability with low requirements for maintenance. For example, components of high speed train Shinkanzen in 10 years of operation have to withstand approximately 10^9 cycles and failure of a main component can have fatal consequences [7]. These facts increased requirements for fatigue life testing in the so called ultra-high cycle region and to ensure if the fatigue strength of a material could be really considered constant for more than 10 million cycles, that is the usual number of cycles used to determine the so called fatigue limit (mainly steels). After the first tests performed by exceeding this endurance it was obvious, that fatigue failures can happen even for applied stress amplitudes lower than the fatigue limit, after a number of cycles much more than 10^7 and that the damage and failure mechanism could be different form the usual ones [8]. This is the reason why it is necessary to set up a fatigue testing program aimed at investigating the ultra-high cycle region, so it is possible to ensure the value of fatigue strength beyond the conventional fatigue limit.

Material and experimental tests
In this study quenched and tempered low-alloy steel 50CrMo4 was considered. This steel is used for high loaded structural components which are often subjected to cyclic loading, as in car wheel hubs (part of a car which holds the wheel disc). The nominal chemical composition according to DIN EN 10083-3 standard is shown in Table 1. Test specimens were machined from a car wheel hub manufactured by die forging which was carried out within temperatures ranging from 850 °C up to 1050 °C. After forging the flange was quenched from austenitization

temperature of 860 °C (holding time 1 hour) to mineral oil. After quenching, the steel was tempered on temperature of 600 °C for 1 hour and then it was cooled in calm air. The heat treatment resulted in mechanical properties shown in Table 2.

Table 1. Chemical composition of steel 50CrMo4 according to DIN EN 10083-3 (wt. %).

C	Mn	Si (max.)	P (max.)	S (max.)	Cr	Mo	Fe
0.46 ÷ 0.54	0.50 ÷ 0.80	0.40	0.025	0.035	0.90 ÷ 1.2	0.15 ÷ 0.30	rest

Table 2. Mechanical properties of steel 50CrMo4 after quenching and tempering.

UTS (MPa)	Proof stress (MPa)	Elongation (%)	Reduction of area (%)
929	702	15.0	54.7

Fatigue test specimens (Figure 1) were machined in position in which the gage diameter represents the surface layer of machined and finished wheel hub. To obtain the microstructure of the material in the gauge length of the specimen where fatigue damage occurs, a longitudinal cut of a specimen with initiated fatigue crack was done; the result is shown in Figure 2. The microstructure consists of sorbite, bainite, imperfectly transformed ferrite and pearlite and residual austenite.

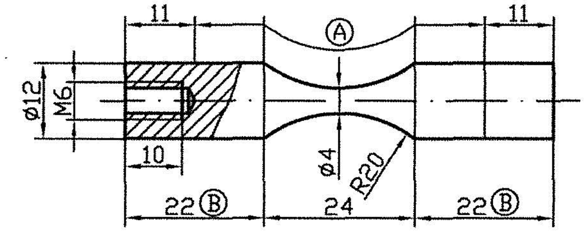
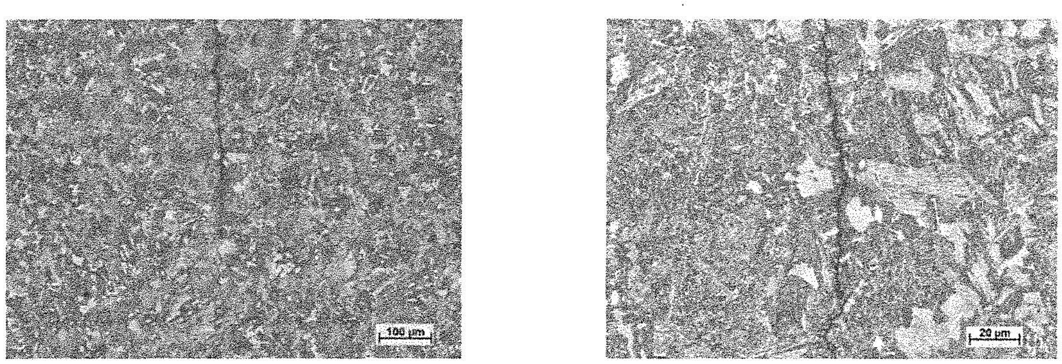


Figure 1. Geometry of specimens used for high frequency fatigue tests. Dimensions are given in mm.



(a) *(b)*

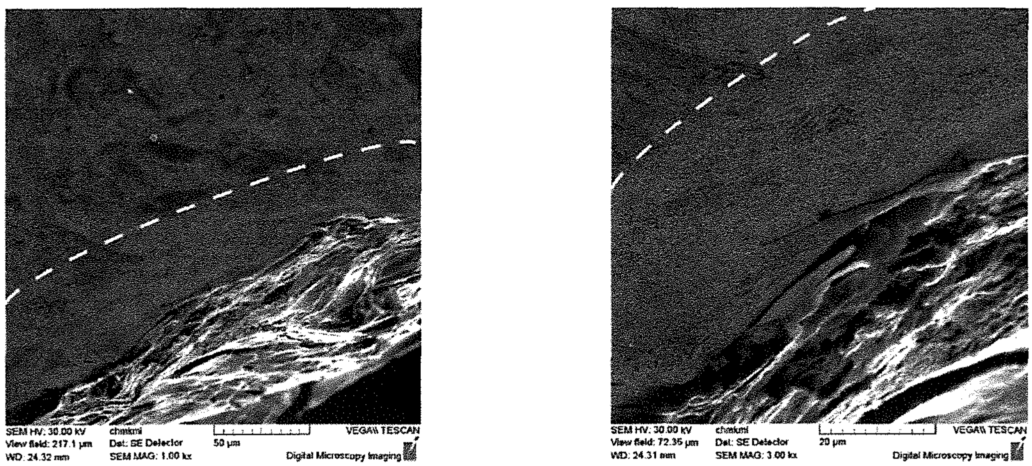
Figure 2. Microstructure of 50CrMo4 steel in the gage length of the specimen: microstructure character (a) and in detail (b); longitudinal cut, etch. Nital.

Surface characterization

Machined specimens were divided into two groups, each with 11 PCS. The first group was grinded and polished with diamond metallography emulsion (this group is marked as NP – Not Peened). The second group was treated by severe shot peening with the S170 medium (steel shots, ø = 425 µm), Almen intensity 15.6 A and coverage of 1000 % (this group is marked as SSP – Severely Shot Peened). Area subjected to surface treatment is marked with A in Figure 1. In Figure 3 the in-depth character of the severely shot peened surface layer by means of scanning electron microscopy is shown. It can be seen that the treated surface layer has a slightly different appearance than the core of the material (the approximate boundary is marked by white dashed line). According to X-ray diffraction (XRD) measurement (X'Pert PRO diffractometer, Co radiation, diffraction angles from 45° to 130° (2θ), paralel plate collimator, crystallite size evaluated with TOPAS software according to all four diffraction lines {110, 200, 211, 220}), the crystallite size on the surface decreased from average value of 74 ± 3 nm for the NP specimen to 38 ± 4 nm for the SSP specimen. According to these results the layer with different appearance in secondary electron SEM analysis corresponds to so-called "nano- grained" or "ultra-fine grained" surface layer of material (Figure 3). Plastic deformation was so intensive that it damaged the surface integrity and the surface layers started to peeled off (Figure 4). The severe shot peening also caused a remarkable increase of surface roughness when compared to the NP specimens, as shown in Table 3.

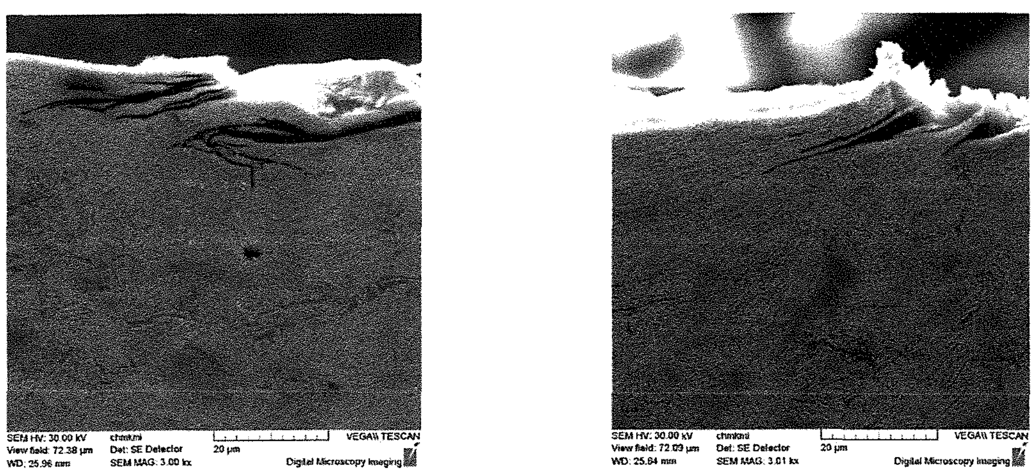
Table 3. Roughness parameters of used specimens.

	Ra (μm)	**Rz (μm)**
Not peened	0.4	2.6
Severe shot peened	5.4	27.9



(a) (b)

Figure 3. Surface of a SSP specimen with nano (ultrafine) grain character (a) and in detail (b), white dashed line marks the approximate boundary between the nano-grained surface layer and the base material; longitudinal cut, etch. Nital.

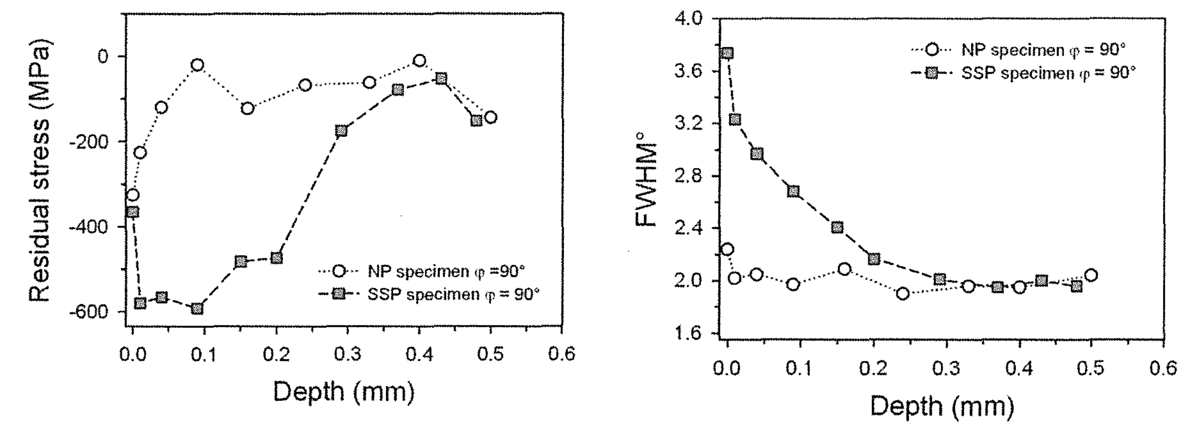


(a) (b)

Figure 4. Damage of the surface layers – material peeling off from the surface (a), sharp notch under the peeling off material layer (b); longitudinal cut, etch. Nital.

Besides the effect of grain refinement, severe shot peening treatment induces compressive residual stresses in the sub-surface layers of material. To obtain quantitative values of the residual stresses in the material X-ray diffraction measurements were carried out by means of X-Stress 3000 StressTech device (Cr radiation Kα, irradiated area of 1 mm^2, $\sin^2\psi$ method, diffraction angles (2θ) scanned at 11 different ψ angles ranging from -45° and 45°). Due the curvature of the fatigue specimen the measurements were executed in the φ = 90° direction (circumferential residual stresses) while it was not possible to measure other stress components to determine the complete stress tensor and the principal stresses.

According to the residual stress profile (Figure 5a), after machining a polishing (NP) the strengthened layer of material is very thin and the compressive residual stress disappears in 0.1 mm distance from the original surface. On the contrary, the compressive residual stress after SSP application has maximum in depth of 0.04 mm and then slightly decreases until depth of 0.2 mm. In higher depths the residual stress starts to rapidly decrease and meets the value of NP material in the approximate depth of 0.4 mm. During the residual stress measurement the FWHM parameter (Full With at Half Maximum) was also obtained, which is defined as the width of the diffraction peak in half of its height and it is related to the instrument used and both to residual micro-strain in the material and to the grain size [9]. By summarizing it can be considered as a comparative index of the surface work hardening. According to FWHM profile (Figure 5b) it can be noted the strong surface hardening after SSP and that the SSP trend meets the FWHM profile of NP specimen in depth of 0.4 mm, what in good correlation with the residual stress profile.



(a) *(b)*

Figure 5. Residual stress (a) and FWHM (b) profiles of NP and SSP specimens.

Fatigue tests

High frequency tension – compression fatigue tests (stress ratio R = -1, frequency f ≈ 20 kHz, temperature T = 20 ± 5 °C) in high and ultra-high cycle region were carried out on high frequency experimental test device KAUP (complex acoustic fatigue toughness) of the Department of Materials Engineering, University of Žilina, Slovakia. During the test, the specimen is cooled in water with anticorrosive inhibitor which use is based on work [10] to provide full short-time passivation of the steels' surface. Results were approximated by the Basquin function with use of least square method [11].

According to the fatigue test results and regression curves (Figure 6) it can be seen, that fatigue strength of experimental material after SSP (15.6A/1000 %) significantly increases in the ultra-high cycle region (after $N = 10^7$ cycles) and the fatigue strength increase gets higher with increasing number of cycles (Table 4). The lowest tested stress amplitude applied on a NP specimen was $\sigma_a = 309$ MPa and the specimen withstood $N = 7.28 \times 10^8$ cycles before fracture. After SSP application, run-out at $N = 1.55 \times 10^9$ cycles was achieved at stress amplitude $\sigma_a = 365$ MPa. On the contrary, in the region under $N = 10^7$ cycles, the regression curves are getting closer and in the region near $N = 4 \times 10^6$ cycles the curves tend to converge. From this point, it is possible to predict that the fatigue strength at lower number of cycles will be lower for SSP specimens than for NP specimens [12].

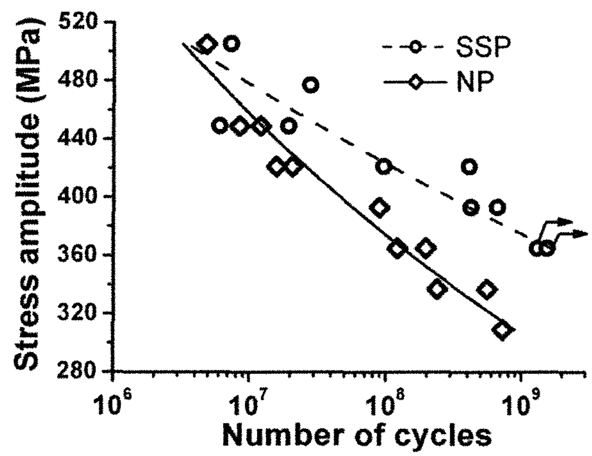


Figure 6. S - N curves of NP and SSP specimens (R = -1, f ≈ 20 kHz, T = 20 ± 5 °C).

Table 4. Fatigue strength for N = 10^7, N = 10^8, N = 10^9 cycles according to regression curves.

Surface treatment	Fatigue strength for N = 10^7 (MPa)	Fatigue strength for N = 10^8 (MPa)	Fatigue strength for N = 10^9 (MPa)
Not Peened	458	374	306
Severely Shot Peened	478	423	375
Increase $\Delta\sigma_a$	20 (4 %)	49 (13 %)	69 (23 %)

Discussion

Experimental evidence shows that severe shot peening can improve the fatigue strength of 50CrMo4 steel and that the improvement increases with the number of cycles of interest. Indeed the improvement of the fatigue strength is as usual (about 5 %) if N=10^7 is considered for run-out specimens and the effect tend to decrease by decreasing the number of cycles. But if longer durations are considered the effect induced by severe shot peening becomes more and more marked and the increase is about 23 % if N = 10^9 is considered. These results can be interpreted by considering all modifications induced by severe shot peening in the surface layer of material [8,12].

If the experimental XRD measurements and the SEM observations are considered, it is clear that severe shot peening induces strong changes of the material structure by refining the crystallite size up to less than 100 nanometers. The experiments show also that the thickness of the material layer affected by SSP is about 0.03 mm in terms of grain refinement to the nanoscale and about 0.4 mm in terms of work-hardened layer. This means that the layer of material where fatigue damage mainly takes place is modified by SSP. This is supposed to be the main factor for the improved fatigue behaviour of the SSP specimens in the ultra-high cycle fatigue regime [1-4,8].

Conclusions

Fatigue tests of 50CrMo4 low-alloy steel in the high and ultra-high cycle regime were performed. One set of test specimens was severely shot peened and the results were compared to a set of not peened specimens (mechanically grinded and polished). In the light of the results the following conclusions can be drawn:

- Severe shot peening is able to induce grain refinements up to less than 100 nm, thus producing a nanostructured surface layer of material.
- The visible depth of grain refined surface layer is approximately 0.03 mm.
- Severe plastic deformation of the surface by severe shot peening treatment can cause damage of the surface integrity when layers of material start to peel-off, creating small sharp notches on the surface.
- The severe shot peening treatment created compressive residual stress field in the subsurface layers of material with approximate depth of 0.4 mm.

- The results of the fatigue tests show an appreciable positive effect of SSP, especially in the ultra-high cycle fatigue regime (up to $N = 10^9$ cycles): in this case the improvement due to SSP is about 23 % while in the high cycle fatigue regime ($N = 10^7$) the improvement is less evident.

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References

[1] S. Bagheri, M. Guagliano, *Review of shot peening processes to obtain nanocrystalline surfaces in metal alloys*, Surface Engineering, Vol. 25 (2009), pp 3-14.
[2] S. Bagheri, M. Guagliano, *Fatigue behavior of a low alloy steel with nanostructured surface obtained by severe shot peening*, Engineering Fracture Mechanics, Vol. 81 (2012), pp 56-68.
[3] A.L. Wen, R.M. Ren, S. Wang, J. Y. Yang, *Effect of surface nanocrystallization method on fatigue strength of TA2*, Materials Science Forum, Vol. 620-622 (2009), pp 545-549.
[4] T. Roland, D. Retraint, K. Lu, J. Lu, *Fatigue life improvement through surface nanostructuring of stainless steel by means of surface mechanical attrition treatment,* Scripta Materialia, Vol. 54 (2006), pp 1949-1954.
[5] D. Li, H.N. Chen, H. Xu, *The effect of nanostructured surface layer on the fatigue behaviors of a carbon steel*, Applied Surface Science. Vol. 255 (2009), pp 3811–3816.
[6] L.L. Shaw, J.W. Tian, A.L. Ortiz, K. Dai, J.C. Villegas, P.K. Liaw, R. Ren, D.L. Klarstrom, *A direct comparison in the fatigue resistance enhanced by surface severe plastic deformation and shot peening in a C-2000 superalloy*, Materials Science and Engineering, Vol. 527 (2010), pp 986–994.
[7] Y. Murakami, *Metal Fatigue: Effects of Small Defects and Nonmetallic Inclusions*. Oxford: Elsevier, 2002. 369 p.
[8] L. Trško, O. Bokůvka, F. Nový, M. Guagliano, *Effect of severe shot peening on ultra-high-cycle fatigue of a low-alloy steel,* Materials & Design. Vol. 57 (2014), pp 103-113.
[9] G.H. Farrahi, J.L. Lebrun, *Surface hardness measurement and microstructural characterization of steel by X-ray diffraction profile analysis*, International Journal of Engineering, Vol. 8 (1995), pp 159-168.
[10] B. Hadzima, P. Suchý, *Short-time pasiivation of WNr. 1.7139 steel surface*, Materials engineering - Materiálové inžinierstvo, Vol. 14 (2007), pp 31-34.
[11] J. Kohout, S. Věchet, *Regrese experimentálních závislostí v materiálovém inženýrství (Regression of experimental dependences in materials engineering)*. Letná škola únavy materiálov '2010 (conference proceedings). Žilina: EDIS, 2010. pp 122-131 (in Czech).
[12] L. Trško, O. Bokůvka, M. Guagliano, F. Nový, M. Hazlinger, *Ultra long fatigue life of 50CrMo4 steel with strengthened surface by high energy shot peening*. 30th Danubia – Adria Symposium on Advances in Experimental Mechanics (conference proceedings). Zagreb: Croatian Society of Mechanics, 2013. pp 131-132.