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VERY HIGH CYCLE FATIGUE PROPERTIES OF FERRITIC-PEARLITIC STEEL AFTER MICRO-SHOT PEENING

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An alloyed ferritic-pearlitic steel is studied after micro-shot peening with balls from a high-speed steel. The morphology and the roughness of the surface of the specimens are determined. Specimens with smooth and notched surfaces are subjected to multi-cycle fatigue tests. The fatigue resistance of the specimens with a smooth surface and with a notched surface increases by 22 and 27%, respectively, after the shot-peening. Observation of crack growth in specimens with small holes shows that micro-shot peening hinders crack propagation.

Key words: micro-shot peening, multicycle fatigue, fatigue limit, residual compressive stresses.

Shot peening is a traditional method for raising the fatigue resistance of materials due to formation of a surface hardened layer and creation of residual compressive stresses on this surface [1 – 4]. However, the balls used in traditional shot peening have a diameter exceeding 0.6 mm, which elevates the roughness of the surface and hence lowers the fatigue strength of the materials [5, 6]. The microdamage caused by shot peening (surface dents and cracks) becomes a place of initiation of fracture during cyclic loading [7, 8]. In addition, if the radius of the root of the notch of the specimen is less than the shot diameter, it is impossible to raise the fatigue resistance of the metal by shot peening. The recently developed method of micro-shot peening, where the ball diameter is less than 0.2 mm, can create high residual compressive stresses in the surface layer, which are more steady than in the conventional shot peening, and this increases substantially the fatigue resistance of the material [10, 12, 13]. It is assumed that micro-shot peening raises the fatigue resistance of structures, but its effect on the fatigue properties of alloy steels has not been studied well enough. Application of the method is restricted, because its effect on the appearance of fatigue cracks and on the fatigue behavior remains unclear.

The aim of the present work was to study the fatigue resistance and crack growth in specimens of an alloy ferritic-pearlitic steel after micro-shot peening with fine steel balls.

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METHODS OF STUDY

We studied specimens of an alloy ferritic-pearlitic steel with composition (in wt.%) 0.17 C, 0.015 S, 0.016 P, 1.7 Cr, 1.6 Ni, 0.55 Mn, 0.27 Si, 0.08 Cu, 0.026 Mo. The steel had the following mechanical properties: $E = 212$ GPa, $\sigma_{0.2} =$ 636 MPa, $\sigma_r = 945$ MPa, $\delta = 24\%$. The specimens for the fatigue tests were cut from a bar with diameter 100 mm. The sizes of the specimens are presented in Fig. 1. The minimum

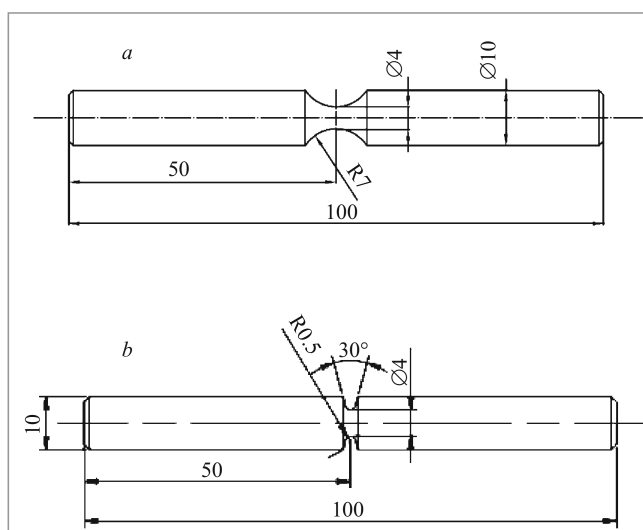

Fig. 1. Drawings of specimens for fatigue tests (mm): *a*) smooth specimen; *b*) notched specimen.

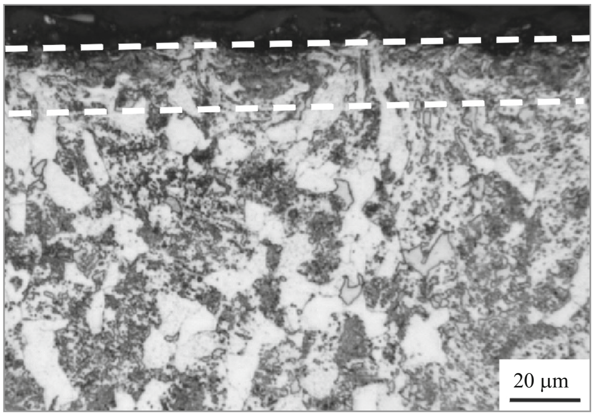

Fig. 2. Microstructure of the surface of a specimen subjected to micro-shot peening.

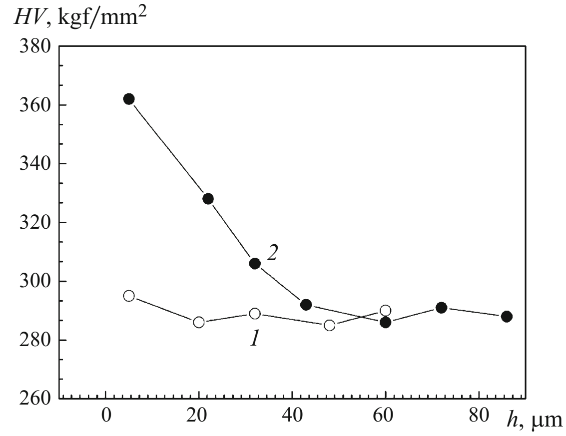

Fig. 3. Distribution of the hardness of specimens in the surface layer (h is the distance from the surface): *1*) smooth specimen; *2*) notched specimen.

diameter of the specimens (at the place of the notch) was 4 mm. The coefficient of elastic stress concentration of a smooth specimen was 1.04 (Fig. 1*a*); that of a notched specimen was 1.8 (Fig. 1*b*).

Specimens of the two types were subjected to a high-speed micro-shot peening with balls from a tool steel with a mean diameter of 50 μm. The hardening was applied to the middle part of the specimens. The treatment conditions were as follows: air pressure 0.4 MPa, length of the bending arc 0.12 mm (for the notched specimens); coverage of the surface > 200%. The bending arc determined the treatment intensity and was measured using the Almen test. The standard for the Almen test was a plate 76.2 × 19.05 × 0.79 mm in size (3 × 0.75 × 0.031 inch). The thickness of 0.79 mm corresponded to a notched specimen. The measuring Almen plate was placed into the grips of a special device and subjected to shot peening. After the peening, the plate was withdrawn to measure the bending arc.

A cross section of the hardened specimen was placed into the holder, covered with a plastic, polished, and etched with a 4% solution of nital. The structure was observed under an optical microscope. The Vickers microhardness was measured suing an HVS-1000Z device at a load of 0.25 N with a hold for 15 sec.

The surface morphology and the average roughness of the treated and untreated specimens were studied simultaneously with the help of confocal laser scanning microscopy using an OLS4100 device. The compressive surface stresses were measured using a Rigaku PSPC-RSF/KM x-ray diffractometer. The radial distribution of the stresses was studied after removing the surface layer by electrolytic polishing.

The bending fatigue tests with rotation were conducted in air at room temperature with the help of a special RB4-3150-V1 facility with cycle asymmetry factor –1 at a frequency of 52.2 Hz. The tests were performed for up to 10^9 cycles and then stopped. The surface of the untreated specimens was polished with an emery paper with grain size 2000 to remove the 30-μm-thick external layer. The crack growth was determined on specimens with specially drilled holes with diameter 100 μm. The sizes of the cracks were measured by the replica method.

After the fatigue tests, we measured the residual compressive stresses on the surface of the specimens. The fractures were observed under a JSM-6610 scanning electron microscope to study the behaviors of the cracks.

RESULTS AND DISCUSSION

Figure 2 presents the microstructure of a specimen after micro-shot peening. The dashed lines mark the layer of plastic deformation, which has a fine microstructure. The distribution of microhardness over the thickness of the hardened layer is presented in Fig. 3. It should be noted that the distribution of the microhardness is similar for the smooth-surface specimens and for the notched specimens. After the shot peening, the hardness increases, the thickness of the hardened layer is about 40 μm; the maximum hardness is 362 *HV.*

The morphology of the surfaces of specimens determined with the help of confocal laser scanning microscopy is presented in Fig. 4. The surface of the unpeened specimen has a profile represented by parallel grooves, while the surface of the micro-shot-peened specimen bears a great number of dimples; the roughness R_a of the surfaces is 0.08 and 0.92 μm, respectively. Thus, the surface roughness after the micro-shot peening is higher than that of the unpeened specimens but lower than that of the specimens subjected to traditional shot-peening [7, 8]. The method is beneficial when the article requiring surface hardening by shot peening should simultaneously possess a high surface quality, because the low surface roughness permits elimination of the operation of final polishing.

Figure 5 presents the distribution of residual stresses on the surface of specimens. The unpeened specimens have a low residual compressive stress, i.e., about –55 MPa. After

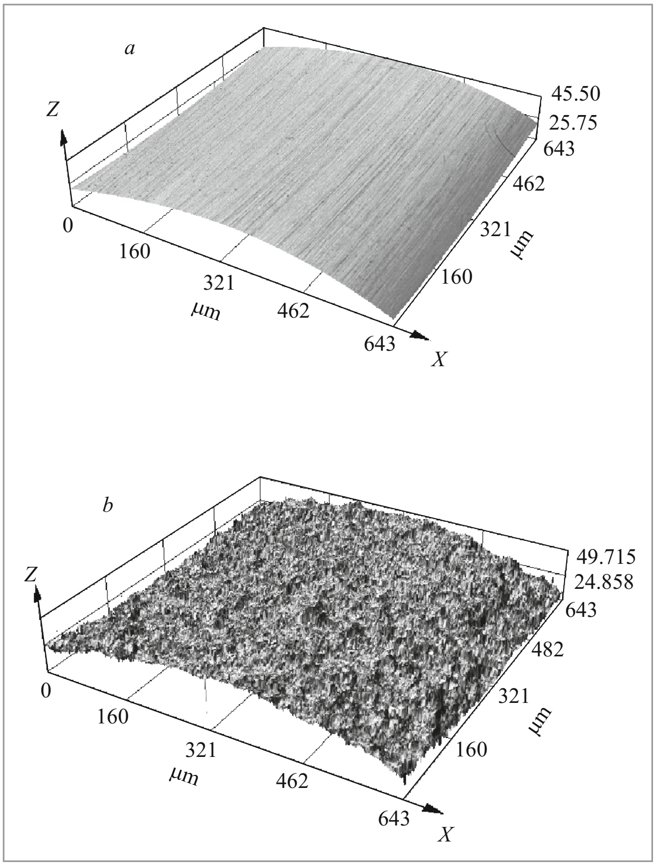

Fig. 4. Morphology of the surface layer of untreated (*a*) and treated (*b*) specimens.

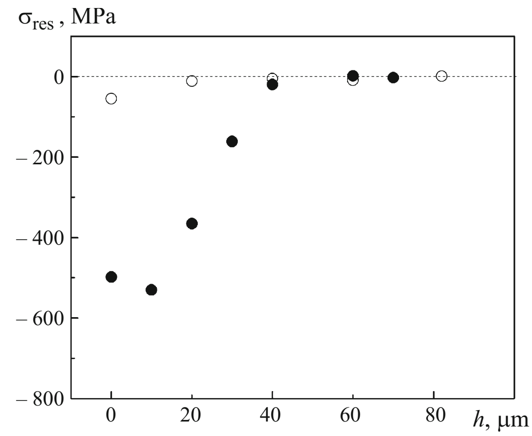

Fig. 5. Distribution of residual stresses in the surface layer of specimens (*h* is the distance from the surface): ○) smooth specimen; ●) notched specimen.

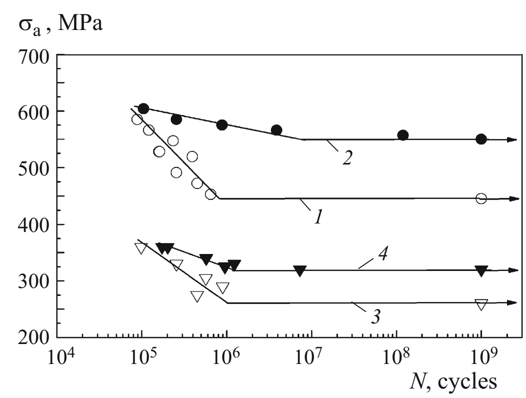

Fig. 6. Fatigue curves: *1*) untreated smooth specimen; *2*) treated smooth specimen; *3*) untreated notched specimen; *4*) treated notched specimen; →) not fractured specimens.

the micro-shot peening, we observe a surface layer with a thickness of about 40 μm where the residual compressive stresses have a maximum value of –530 MPa.

The fatigue curves obtained after the tests are presented in Fig. 6. They have an inclined part and a horizontal part for specimens of the types. If the specimen does not fail in 10^9 cycles at a low stress amplitude, it is assumed that it has a conventional yield strength in the mode of low-cycle fatigue. The fatigue limit in the unpeened specimens with a smooth surface amounts to 450 MPa; in the notched specimens it is 260 MPa. After the micro-shot peening the values are increased to 550 and 330 MPa, respectively. Thus, the residual stresses increase by 22% in the specimens with smooth surface and by 27% in the notched specimens.

By the data on the fatigue limit, the fatigue strength reduction factor K_f amounts to 1.73 and 1.67 for the unnotched and notched specimens, respectively. The value of this factor approaches the elastic stress concentration factor (1.8), which may be associated with the relatively large notch radius [14]. Thus, the shape of the notch determines the fatigue resistance, and the factor K_f approaches K_t with growth of the diameter of the notch [15].

Fracture surfaces of the specimens are presented in Fig. 7.

The fracture surfaces of the notched specimens bear more places of crack nucleation than those of the smooth specimens. All the specimens have failed before 10^7 cycles except for a single peened specimen that has failed after 1.2×10^8 cycles. The microstructure of the fracture surface of this specimen is presented in Fig. 8. We may state that the specimen has fractured from the surface. Such crack behavior has also been observed in other alloy steels, and it us assumed that it is caused by crack propagation at a very low speed [16 – 18].

It can be inferred from the fatigue curves (Fig. 6) that the growth of the fatigue resistance in the low-cycle range is lower than in the high-cycle range. In our opinion, this is a result of different degrees of relaxation of residual compressive stresses. We also measured the residual stresses on the surfaces of the treated specimens that have not failed after the low-cycle fatigue test (10^9 cycles). The mean value of the residual stresses was –241 MPa. It can be assumed that the

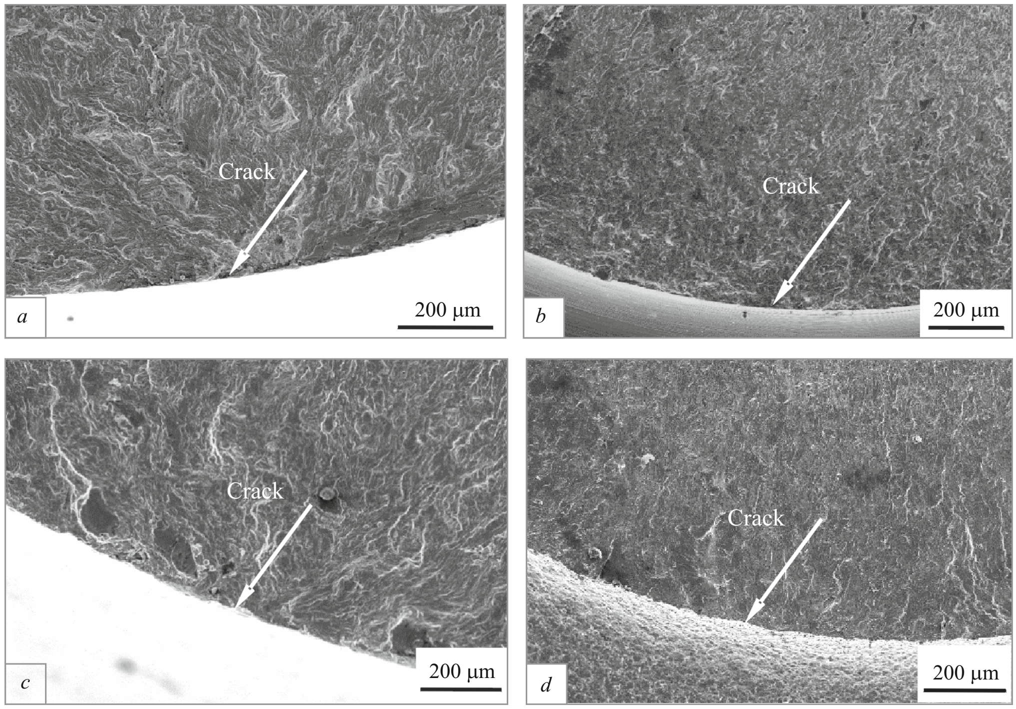

Fig. 7. Microstructure (SEM) of untreated (*a*, *b*) and treated (*c*, *d*) specimens: *a*, *c*) smooth specimens; *b*, *d*) notched specimens.

growth of the fatigue limit of the treated specimens depends in the first turn on the hardening induced by the residual compressive stresses due to micro-shot peening.

The growth dynamics of the fatigue crack in unnotched untreated specimens and in the specimens with a drilled hole from the same series is presented in Fig. 9. In the range of short cracks, the rate of their growth on the hardened specimen is noticeably lower than on the untreated specimen. For example, the micro-shot peening affects positively the lowering of the crack growth rate in the early stages of crack propagation. In this stage the residual compressive stress on the surface and the fine microstructure of the surface can decelerate the growth of the crack.

Thus, micro-shot peening can improve the fatigue resistance of both smooth and notched specimens. The roughness of the surface in this case is comparatively low. Therefore, we may state that micro-shot peening can be used for treating parts of structures without subsequent polishing. For further elevation of fatigue resistance, we should study the fatigue properties of specimens treated by a combination of conventional shot peening and micro-shot peening.

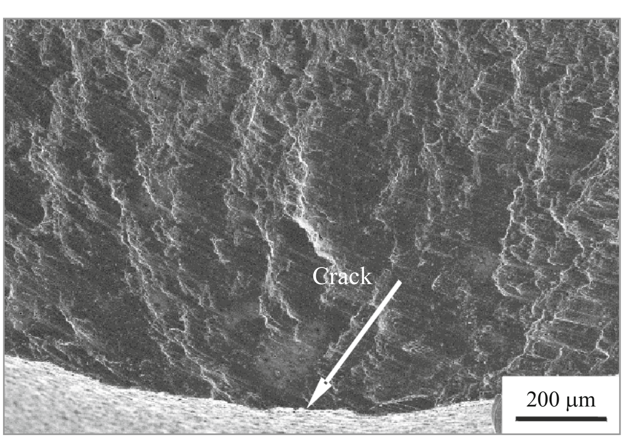

Fig. 8. Microstructure of hardened specimen fractured in the mode of very high cycle fatigue.

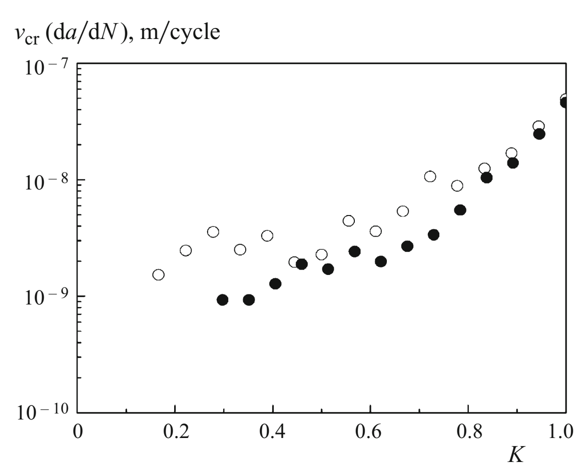

Fig. 9. Rate of crack growth (v_{cr}) in specimens with drilled holes: ○) untreated specimen; ●) treated specimen; K is the fatigue life ratio.

CONCLUSIONS

1. Micro-shot peening can improve the surface hardness of a steel without considerable worsening of the roughness.

2. Both groups of hardened and not hardened specimens (with and without a notch) have a specific fatigue limit in the VHCF regime, and all of them fracture from the surface.

3. Under micro-shot peening, the fatigue limit of smooth specimens increases by 22% and that of notched specimens increases by 27%, which is explainable by growth of the residual compressive stresses.

4. In the range of short lengths of fatigue cracks, the rate of their propagation in the specimens hardened by micro-shot peening is considerably lower than in the untreated specimens.

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REFERENCES

1. P. Fu, C. Jiang, Z. Zhang, and V. Ji, "Residual stress and microstructure of GCr15 steel after multistep shot peening," *Surf. Eng.*, **30**, 847 – 851 (2014).
2. M. A. S. Torres, D. T. Harada, C. A. Reis Pereira Baptista, and M. P. Cindra Fonseca, "Effect of shot peening on fatigue behavior of AISI 4340 in different loading conditions," *Key Eng. Mater.*, **713**, 30 – 33 (2016).
3. O. Kwang Keun, K. Yeon Wook, and K. Jae Hoon, "High cycle fatigue characteristics of aluminum alloy by shot peening," *Adv. Mater. Res.*, **1110**, 142 – 147 (2015).
4. A. Ghasemi, S. M. Hassani-Gangaraj, A. H. Mahmoudi, et al., "Shot peening coverage effect on residual stress profile by FE random impact analysis," *Surf. Eng.*, **32**, 862 – 870 (2016).
5. K. Dai, J. Villegas, Z. Stone, and L. Shaw, "Finite element modeling of the surface roughness of 5052 Al alloy subjected to a surface severe plastic deformation process," *Acta Mater.*, **52**, 5771 – 5782 (2004).
6. H. Y. Miao, D. Demers, S. Larose et al, "Experimental study of shot peening and stress peen forming," *J. Mater. Proc. Technol.*, **210**, 2089 – 2102 (2010).
7. J. Sakamoto, Y. S. Lee, and S. K. Cheong, "Effect of surface flaw on fatigue strength of shot-peened medium-carbon steel," *Eng. Fract. Mech.*, **133**, 99 – 111 (2015).
8. J. C. Kim, S. K. Cheong, and H. Noguchi, "Evolution of residual stress redistribution associated with localized surface microcracking in hot-peened medium-carbon steel during fatigue test," *Int. J. Fatigue*, **55**, 147 – 157 (2013).
9. S. Kikuchi, Y. Nakamura, K. Nambu, and M. Ando, "Effect of shot peening using ultra-fine particles on fatigue properties of 5056 aluminum alloy under rotating bending," *Mater. Sci. Eng.*, **652**, 279 – 286 (2016).
10. Y. Harada, K. Fukaura, and S. Haga, "Influence of microshot peening on surface layer characteristics of structural steel," *J. Mater. Proc. Technol.*, **191**, 297 – 301 (2007).
11. K. I. Sugimoto, Y. Mizuno, and T. Hojo, "Effects of fine particle peening on fatigue strength of transformation-induced plasticity (TRIP)-aided martensitic steel," *Key. Eng. Mater.*, **665**, 85 – 88 (2016).
12. D. Yonekura, J. Noda, J. Komotori, et al., "The fatigue properties of ferrite-pearlite steel modified by WPC process," *Trans. Japan Soc. Mechan. Eng., Part A*, **67**, 69 – 74 (2001).
13. J. W. Zhang, L. T. Lu, K. Shiozawa, et al., "Analysis of fatigue property of microshot peened railway axle steel," *Mater. Sci. Eng.*, **528**, 1615 – 1622 (2011).
14. N. Dowling, *Mechanical Behavior of Materials: Engineering Methods for Deformation. Fracture and Fatigue*, Pearson Education, New Jersey (2012).
15. Y. Akiniwa, N. Miyamoto, H. Tsuru, and K. Tanaka, "Notch effect on fatigue strength reduction of bearing steel in the very high cyclic regime," *Int. J. Fatigue*, **28**, 1555 – 1565 (2006).
16. T. Iwaya, M. Takeuchi, N. Tanaka, et al., "Statistical fatigue properties of tempered SCM435 steel in long life region in rotating bending," in: *Proc. 3rd Int. Conf. on Very High Cycle Fatigue, Kusatsu, Japan* (2004), pp. 657 – 664.
17. S. E. Stanzl-Tchegg, "Fracture mechanisms and fracture mechanics at ultrasonic frequencies," *Fatigue Fract. Eng. Mater. Struct.*, **22**, 567 – 579 (1999).
18. J. W. Zhang, L. T. Lu, K. Shiozawa, et al., "Effect of nitrocarburizing and post-oxidation on fatigue behavior of 35CrMo alloy steel in very high cycle fatigue regime," *Int. J. Fatigue*, **33**, 880 – 886 (2011).