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Carburization induced extra-long rolling contact fatigue life of high carbon bearing steel

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Abstract: For the first time, vacuum carburization surface treatment was applied to high carbon bearing steel 100Cr6. The rolling contact fatigue (RCF) life and the wear behavior of 100Cr6 with and without carburization were compared and the microstructure was characterized. The carburization results in 30 vol.% cementite and ~ 20 vol.% retained austenite in the surface layer, significantly higher than those processed by the conventional heat treatment. RCF life (L10) is significantly enhanced by more than 10 times from 1×10^7 cycles to $\geq 1 \times 10^8$ cycles by carburization. This enhancement is attributed to plate/rod cementite and retained austenite.

Key words: Vacuum carburization; High carbon bearing steel; Rolling contact fatigue; Coefficient of friction; Gradient distribution of carbides

1. Introduction

Bearing is one of the components widely used in our daily lives and industry, such as the airplane, the ship, the automobile and the machining tools with a high turning

speed and high accuracy [1-3]. The bearing steel can be divided into two distinct categories[4-5]. One is the surface hardened (CH) bearing steel with carbon content about 0.10 - 0.20%, such as the 20CrNi2Mo (AISI4320) steel, which needs to be carburized to increase the surface hardness up to no less than 58 HRC with carbon content increasing up to 0.65-1.1% in the carburized surface layer [4,6]. The other is the through hardening (TH) bearing steel with carbon content around 0.9 - 1.1%, such as the 100Cr6 (AISI52100) steel, which is normally heat treated by quenching and tempering to get a bulk hardness of no less than 58 HRC. Previous investigations have shown that the life factor (LF) of the surface hardened bearing steel is significantly higher than that of the through hardening bearing steel due to the higher compressive residual stress in the surface layer. The high surface residual compressive stress and the higher surface hardness result in a higher RCF life [6,7]. Recently, much effort have been put on the TH bearing steel to increase the RCF by heat treatment [8-10]. It was reported by the SKF company that for the TH bearing steel increasing the surface hardness with about 1-2 HRC could increase the RCF life up to 2 times, indicating an important role of surface hardness to increase the RCF life of the TH bearing steel [6]. It was also demonstrated that the RCF life (L_{10}) could be significantly increased by 5 folds by the refinement of both prior austenite grain size and the carbide size [8,11]. In addition, As the introduction of the retained austenite in the surface layer is beneficial to the rolling contact fatigue life, the maximum enhancement of the rolling contact fatigue life could be realized when increasing austenite volume fraction from 7 vol.% to 50 vol.%, resulting in 10 times' enhancement of rolling contact fatigue life

[12]. Although it has been proved by many researchers that the carburization is effective to increase the surface residual compressive stress, the surface hardness and the residue austenite volume fraction [13-15], this type of surface treatment technology has never been applied in the TH bearing steel and no microstructure evolution has been reported in literature [16].

In light of the higher RCF life of the CH bearing steel, the carburization of the TH bearing steel of 100Cr6 was carried out in this study. The comparison of the RCF life of 100Cr6 with and without carburization was performed. The microstructure and the surface hardness after carburization process were examined and analyzed. The formation mechanism of the surface carbides and the enhancement of the RCF life were discussed. Our aim is to reveal the possibility to increase the RCF life of the TH bearing steel by carburization.

2. Material and methods

The high carbon bearing steel of 100Cr6 with nominal chemical composition of 1.05 wt.% C and 1.42 wt.% Cr was fabricated by the second refining, continuous casting(CC) and hot rolling, and finally rods with a diameter of 60 mm were cut out from the plate in the steel plants. The chemical composition was examined by a chemical elements spectral analyzer and is listed in Table 1. It can be seen that the total oxygen content is only about 4 ppm and the nitrogen content only about 19 ppm, indicating a very high metallurgical quality.

Table 1 Composition of 100Cr6 steel (wt.%)

C	Si	Mn	P	S	Cr	Ti	N	O
1.05	0.29	0.31	0.014	0.014	1.42	0.009	19 ppm	4 ppm

The rods with a diameter of 60 mm were treated by a spheroidizing annealing by first heating up to 820 °C and kept for 4 hours, then cooling to 720 °C and kept for 4 hours, and finally cooled down to room temperature. In order to reveal the effect of carburization on the RCF life, two different heat treatments were carried out on two groups of specimens, as shown in Fig. 1. 20 pieces of specimens were austenized at 840 °C for half an hour and tempered at 170 °C for 3 hours after oil quenching, and these specimens are called conventionally heat-treated specimens (hereafter called CH bearing steel). The other 20 specimens were carburized at 950 °C for about 6 hours in the vacuum carburizing furnace, stabilized at 840 °C for half hour, and then quenched into oil and finally tempered at 170 °C for 3 hours, and these specimens are called surface-hardening-treated specimens (hereafter called SH bearing steel). The surface of all the specimens were ground and polished with sand abrasive papers with a grit of 1000 to unify the surface conditions by the same procedure and to reduce the surface roughness.

Figure 1. Sketch shows the conventional heat treatment and the surface hardening heat treatment of the high carbon bearing steel where AT represents austenite treatment, OQ oil quenching, TM tempering, CH carburization heat treatment and HD holding time for carbon diffusion.

The RCF tests were carried out in a thrust rolling machine of TRF-1000/5-H with six balls rolled on the disc specimen along the load axis (see Fig. 2 for more details), and the tests were interrupted at 1×10^8 cycles. The RCF-life (number of cycles to failure) was recorded at room temperature with a maximum Hertzian stress of 4.5 GPa, a rotating speed of 1500 rpm and well-controlled lubricating conditions. The RCF life of L_{10} is calculated at the failure probability of 10% according to the Weibull distribution between the failure probability of $P(i)$ and the cycles to failure ($N(i)$), where the failure probability $P(i)=i/(k+1)$ was calculated based on the rank number of i in the ascending sequence of the cycles of the RCF and the total number of the samples test (k) [17]. Similarly, in order to explore the effect of carburization on the wear behaviors, specimens with and without carburization were examined by an OAT-U-HT2 (TKS company, Japan) wear machine to measure the frictional coefficient under a constant contact stress between the bulk specimens and the circular wear part.

Figure 2. Sketch and picture show the set-up and the machine for the rolling contact

fatigue.

The sample microstructure was characterized by optical microscopy and scanning electron microscopy (SEM), electron backscatter diffraction (EBSD) and X-ray diffraction (XRD). The details for sample preparation can be found elsewhere [18-22]. The Vickers microhardness, HV0.2, was measured using a Struers Durascan microindenter with a load of 200 g.

3. Results

3.1 Microstructure

The microstructure of the CH bearing steel samples and the inner matrix microstructure of carburized SH bearing steel specimens are tempered martensite and retained austenite with submicron/micron-sized cementite particles, which can be found elsewhere [23]. So, the focus of microstructural characterization in the present study is the subsurface gradient structure of the SH carburized specimens. Fig. 3 shows the subsurface gradient microstructure and the hardness profile in the carburized SH specimen. The hardness profile shows the increase from around 680 HV0.2 in the matrix to 755 HV0.2 at the surface with the gradient thickness around 700 μm in the carburized specimen. The plate/rod carbides (width: 1 ~ 20 μm ; length: 15 ~ 65 μm) can be easily observed in the surface layer with a thickness around 500 μm . The amount of these carbides decreases with the distance from the surface, in accordance with the microhardness profile. No plate/rod carbides can be found away from the surface region of the carburized specimens as shown in Fig. 3.

Figure 3. Micrographs and microhardness profile of the subsurface gradient structure of SH 100Cr6 bearing steel.

To identify these plate/rod carbides and the phases, XRD and EBSD have been used and the results are shown in Fig. 4. The volume fraction of retained austenite was identified by XRD as around 18 % in the carburized surface layer and as about 20 % in the matrix. The crystal structure of plate/rod carbides is characterized as Fe_3C with orthorhombic structure by the HKL software with the NSD database (Fig. 4c and 4d). These carbides occupy around 30% of the area in the carburized surface with a thickness around 200 μm . It should be noted that the retained austenite is difficult to characterize by EBSD due to the fineness of the structure, so the combination of XRD and EBSD reveals the microstructure quite well. By comparing the XRD result on the content of retained austenite (18 vol.%) with that in the EBSD map (Fig. 4d), it shows that most of the zero solution area is occupied by retained austenite. It should be noted that not only the high volume fraction of both retained austenite and carbide but the large micro-sized cementite characterizes the SH bearing steel specimens, which is

significantly different from that of the specimens processed by conventional heat treatment (CH bearing steel) [11].

Figure 4. Microstructure and phase identification in the matrix and carburized surface layer by XRD (a and b) and EBSD (c and d). (c) and (d) show the same area in the carburized surface layer. The band contrast coloring for carbides is shown in (c). The phase coloring is applied in (d), where red represents Fe_3C carbides, blue represents martensite and yellow represents austenite. The dark grey represents zero solution in (c) and (d).

3.2 Wear and rolling contact fatigue properties

Before testing the RCF properties, these two groups of specimens with conventional heat treatments (CH) and with surface hardening treatments (SH) were tested for wear properties with the focus on the starting process of the wear and the coefficient of friction (Fig. 5a). Although the stabilization process shows the similar characteristic after 10 seconds, differences can also be observed for these two types of specimens: the CH bearing steel has the average coefficient of friction around 0.50 with the fluctuation around 0.05 while the SH steel has the coefficient of friction around 0.48

with the fluctuation around 0.01. The smaller coefficient of friction and fluctuation may imply a smoother topography, which is consistent with the hardness, as reported elsewhere [24-27].

The rolling contact fatigue behaviors of the CH and SH bearing steel are shown in Fig. 5b with the failure probability versus the cycle life. As it was shown in Fig. 5b, the rolling contact fatigue life, L_{10} , of CH steel is about 1.0×10^7 cycles and only 4 out of 20 specimens did not fail after 10^8 cycles. However, no failure of all the 20 specimens was observed in the SH steel processed by surface carburization. This means that for the SH bearing steel, the rolling contact fatigue life, L_{10} , is at least 1×10^8 cycles, which is about 10 times higher than that of the CH bearing steel.

Figure 5. Coefficient of friction for wear testing and failure probability versus cycle life of rolling contact fatigue of the high carbon bearing steel processed by conventional (CH) heat treatments and surface hardening (SH) heat treatments.

4. Discussions

4.1 Hardness increase by carburization

The carburization of SH bearing steel has introduced a large volume of cementite in the surface layer. The hardness of this surface layer can be estimated by using the law of mixtures as following:

$$HV = HV_{\text{cementite}} \cdot V_{\text{cementite}} + HV_{\text{matrix}} \cdot (1 - V_{\text{cementite}}) \quad (1)$$

where $HV_{\text{cementite}}$ and HV_{matrix} are the hardness of cementite (1040 HV [27]) and matrix (680 HV as measured in this study as shown in Fig.2) respectively, and $V_{\text{cementite}}$ is the volume fraction of cementite, measured as 30%. This estimation gives the hardness around 788 HV, which is in good agreement with the measurement as shown in Fig. 3.

4.2 Formation of large volume of carbides and retained austenite during carburization

Compared with the conventional heat treatment, the carburization process during the surface hardening (SH) heat treatments of the high carbon bearing steel introduces the interesting gradient microstructure with high content plate/rod of Fe_3C carbides in the surface layer. The gradient microstructure consists of three areas: (i) Area A: the top surface area with a thickness of 200 μm with a volume fraction of plate/rod Fe_3C carbides around 30 %, (ii) Area B: the gradient area with a thickness around 500 μm with decreasing volume fraction of plate/rod Fe_3C carbides with the distance from the surface and (iii) Area C: the inner matrix without plate/rod Fe_3C carbides. It is quite interesting that the carbide shape, amount and distribution are completely different from the reported results of the carburized low carbon bearing steel [23]. Based on the observation that the volume fraction of plate/rod Fe_3C carbides decreases with the distance from surface and diminishes in the center region, it should be related to the carbon content in the austenite at the carburizing temperature of 950°C. A simple calculation based on the Fe-C phase diagram in the thermal-calc software gives that the equilibrium carbon content in the austenite at 950°C is about 1.15 wt.% and that

the total carbon content in Area A is around 2.78 wt.% taking into account ~ 30 vol.% cementite. Thus the carburization and the excessive carbon content are the main reason for the formation of large volume plate/rod Fe₃C carbides, which is supported by the fact that no such kind of Fe₃C carbides form in the carburized layer of the low carbon bearing steel because the carbon content in the carburized layer of the low carbon bearing steel is usually less than 1.0 wt.% [28].

Not only the morphology but also the orientation of these plate/rod Fe₃C carbides are quite different from the carbide network in the austenite grain boundary, which is usually found in the high carbon bearing steel. The orientation of the plate/rod cementite is usually parallel to each other, indicating a possible crystallographic growth characteristic. However, the detailed characterization and analysis of 3D morphology and the crystallographic orientation relationship of these cementite with austenite is for future investigation, with the focus on the forming mechanisms compared with Widmanstätten cementite in high carbon steels [29-33]

Apart from the large volume fraction of cementite, the retained austenite with a volume fraction around 20 % is also found in both the carburized layer and the inner region, which is significantly higher than that of about 5% in the high carbon bearing steel processed by conventional heat treatment. This higher retained austenite could be interpreted by the high austenization temperature because the austenization temperature for the carburized 100Cr6 is the carburization temperature of 950°C, which is significantly higher than that of 840°C used in the conventional heat treatment (see Fig. 1).

4.3 Mechanism of enhanced rolling contact fatigue life of 100Cr6 bearing steel by carburization

As shown in Fig. 5b, the rolling contact fatigue life (L_{10}) of the high carbon SH bearing steel is no less than 1×10^8 cycles, which is about 10 times higher than $\sim 1 \times 10^7$ cycles of the high carbon CH bearing steel. This large difference of the RCF life is inevitably related to the different surface hardness and the different microstructure resulted from the different heat treatments as the other conditions are the same. As it is observed from the microhardness measurements, the surface hardness of the SH bearing steel is about 755Hv ($\sim 62.5\text{HRC}$), which is about 11% higher than that of the CH bearing steel, 680Hv ($\sim 59.2\text{HRC}$). According to the contribution of increasing surface hardness to the RCF life, 31% increase of L_{10} RCF life can be obtained through Eq. (1) [6], which is significantly smaller than 10 times enhancement of L_{10} as revealed in Fig. 4b. Thus only a minor role of the increased surface hardness on the enhanced fatigue life could be expected.

$$\frac{L_{10}^{HRC2}}{L_{10}^{HRC1}} = \exp(0.1(HRC2 - HRC1)) \quad (2)$$

where L_{10}^{HRC1} and L_{10}^{HRC2} is the RCF of L_{10} at surface hardness of $HRC1$ and $HRC2$, respectively.

Then the major reason for the improvement of the RCF life lies in the microstructure of the SH bearing steel. As it is shown in Fig. 2 and 3, the carbide volume fraction in the carburized surface layer is about 30% and the retained austenite volume fraction is about 20% as well, both of which are significantly higher than those in surface layer of the high carbon bearing steel processed by conventional heat treatment (less than

10 vol.% carbides and less 5 vol.% retained austenite). Due to the brittle nature, the large volume fraction of the carbides in the carburized layer could be detrimental to the RCF life because the carbides could act as the origin of the crack [34]. However, this drawback can be overcome by the size, distribution and morphology and its combination with other microstructure as in the present surface. The plate/rod shaped cementite distributed in a separate way and did not form a network, at the same time they are coupled by the large volume fraction of retained austenite (~ 20 vol. %) and martensite. As demonstrated in literature, the introduction of the retained austenite is beneficial to the rolling contact fatigue life because it may suppress the propagation of the crack during rolling contact fatigue test, and the maximum enhancement of the rolling contact fatigue life could be realized when the austenite volume fraction reaches 20-30%, which could result in several times enhancement of rolling contact fatigue life [12, 35].

Apart from the contribution of the enhanced RCF life from the carbide and retained austenite developed by the carburization, the residue stress in the carburized surface could also be another reason to increase the RCF life. However, the nearly same austenite content both in the carburized layer and the inner part of the SH specimen imply that limited residual stress retained in the surface layer because of the similar phase transformation throughout the SH specimen. Thus it is believed that the enhancement of the rolling contact fatigue life is a combined contribution from both the large volume retained austenite and the large volume and distribution of micron-sized plate/rod cementite in the carburized high carbon bearing steel.

5. Conclusions

In this study, the rolling contact fatigue life and the microstructure of the high carbon bearing steel of 100Cr6 are examined and compared after conventional heat treatment and carburization processing, separately. The main conclusions could be made as follows.

1. The rolling contact fatigue life is significantly enhanced from 1×10^7 cycles of 100Cr6 processed by the conventional heat treatment to at least 1×10^8 cycles treated by carburization, which provides a promising way to enhance the rolling contact fatigue life of the high carbon bearing steel.

2. Carburization of 100Cr6 introduces a gradient structure consisting of three areas: (i) Area A: the top surface area with a thickness of 200 μm with a volume fraction of plate/rod Fe_3C carbides around 30 %, (ii) Area B: the gradient area with a thickness around 500 μm with decreasing volume fraction of plate/rod Fe_3C carbides with the distance from the surface and (iii) Area C: the inner matrix without plate/rod Fe_3C carbides.

3. The volume fraction of carbides (about 30 vol.% in the surface) and retained austenite (~ 20 vol.%), is significantly higher in the carburized steel than that processed by conventional heat treatment (less than 10 vol.% carbides and less 5 vol.% retained austenite).

4. The enhancement of the rolling contact fatigue life in the carburized high carbon bearing steel is ascribed to a combined effect of both the large volume retained austenite and the large volume and distribution of plate/rod cementite.

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References

- [1] M. Nagao, K. Hiraoka, Y. Unigame, Influence of nonmetallic inclusion size on rolling contact fatigue life in bearing steel. Sanyo Tech. Rep. 12 (2005) 38-45.
- [2] T. Seki Evaluation of nonmetallic inclusions size by statistics of extreme value and prediction of fatigue life in bearing steels. Aichi Tech. Rep. 15 (1995) 24-29.
- [3] Y. Chi, Z. Deng, M. Zhu, Effect of ladle usage on cleanliness of bearing steel. Metall. Mater. Trans. B 49 (2018) 440-450.
- [4] M. Gafitanu, D. Nastase, S. Cretu et. al., Rolling bearings: design and technology, Volume 1, Technical Publishing House, Romania, 1985.
- [5] C. Radu, It's All About the Steel: the Importance of bearing steel cleanliness for long-life applications. RKB Technical Review, March 2011.
- [6] E.V. Zaretsky, Rolling bearing steels: a technical and historical perspective. Materials Science and Technology 28 (2011) 58-69.
- [7] T.V. Philip, New bearing steel beats speed and heat, Power Transmission Des. 28 (1986) 43-46.
- [8] K.O. Lee, S.K. Hong, Y.K. Kang, H.J. Yoon, S.S. Kang, Grain refinement in bearing steels using a double-quenching heat-treatment process. Int. J. Automotive Technol. 10 (2009) 697-702.
- [9] E.C. Santos, K. Kida, T. Honda, H. Koike, J. Rozwadowska Fatigue strength improvement of AISI52100 bearing steel by induction heating and repeated quenching. Mater. Sci. 47 (2012) 67-82.
- [10] R. Padmanabhan, W.E. Wood, Microstructural analysis of a multistage heat-treated ultrahigh strength low alloy steel. Mater. Sci. Eng. 66 (1984) 125-143.
- [11] Z. Cao, Z. Shi, F. Yu, K. Sugimoto, W. Cao, Y. Weng, Effects of double quenching on fatigue properties of high carbon bearing steel with extra-high purity. International Journal of Fatigue, 128 (2019) 105176.
- [12] D. Zhu, F.-X. Wang, Q.-G. Cai, M.-X. Zheng, Y.-Q. Cheng, Effect of retained austenite on rolling element fatigue and its mechanisms. Wear, 105 (1985) 223-234.
- [13] Z.N. Yang, Y.L. Ji, F.C. Zhang, M. Zhang, B. Nawaz, C.L. Zheng, Microstructural evolution and performance change of a carburized nanostructured bainitic bearing steel during rolling contact fatigue process. Mater. Sci. Eng. A, 725 (2018) 98-107.
- [14] Z. Chen, T. Zhou, R. Zhao, H. Zhang, S. Lu, W. Yang, H. Zhou, Improved fatigue wear resistance of gray cast iron by localized laser carburizing. Mater. Sci. Eng. A, 644 (2015) 1-9.
- [15] T. Noda, M. Okabe, S. Isobe, Hard surfacing of TiAl intermetallic compound by plasma carburization. Mater. Sci. Eng. A, 213 (2015) 157-161.

- [16] R.C. Dommarco, K.J. Kozaczek, P.C. Bastias, G.T. Hahn, C.A. Rubind, Residual stresses and retained austenite evolution in SAE 52100 steel under non-ideal rolling contact loading. *Wear* 257 (2004) 1081-1088.
- [17] Z. Cao, Z. Shi, F. Yu, G. Wu, W. Cao, Y. Weng, A new proposed Weibull distribution of inclusion size and its correlation with rolling contact fatigue life of an extra clean bearing steel. *International Journal of Fatigue* 126 (2019) 1-5.
- [18] G.H. Fan, Q.W. Wang, Y. Du, L. Geng, W. Hu, X. Zhang, Y.D. Huang, Producing laminated NiAl with bimodal distribution of grain size by solid-liquid reaction treatment. *Mater. Sci. Eng. A* 590 (2014) 318-322.
- [19] S. Chen, J. Hu, X. Zhang, H. Dong, W. Cao, High Ductility and Toughness of a Micro-duplex Medium-Mn Steel in a Large Temperature Range from -196°C to 200°C . *Journal of Iron and Steel Research International* 22 (2015) 1126-1130.
- [20] X. Zhang, A. Godfrey, G. Winther, N. Hansen, X. Huang, Plastic deformation of submicron-sized crystals studied by in-situ Kikuchi diffraction and dislocation imaging. *Mater. Charac.* 70 (2012) 21-27.
- [21] X.D. Zhang, W. Liu, A. Godfrey, Q. Liu, The effect of long-time austenization on the wear resistance and thermal fatigue properties of a high-speed steel roll. *Metall. Mater. Trans. A* 40 (2009) 2171-2177.
- [22] X. Zhang, C.V. Nielsen, N. Hansen, C.M.A. Silva, P.A.F. Martins, Local stress and strain in heterogeneously deformed aluminum: a comparison analysis by microhardness, electron microscopy and finite element modelling. *Int. J. Plast.* 115 (2019) 93-110.
- [23] H.K.D.H. Bhadeshia, Steels for bearings. *Prog. Mater. Sci.* 57 (2012) 268-435.
- [24] K. Monma, R. Maruta, T. Yamamoto, Y. Wakikado, Effect of particle sizes of carbides and amounts of undissolved carbide on the fatigue life of bearing steel. *Journal of the Japan Institute of Metals* 32 (1968) 1198-1204.
- [25] C.A. Stickels, Rolling contact fatigue tests of 52100 bearing steel using a modified NASA ball test rig. *Wear* 98 (1984) 199-210.
- [26] S. Das Bakshi, P.H. Shipway, H.K.D.H. Bhadeshia, Three-body abrasive wear of fine pearlite, nanostructured bainite and martensite. *Wear* 308 (2013) 46-53.
- [27] X. Zhang, W. Liu, D. Sun, Y. Li, The transformation of carbides during austenization and its effect on the wear resistance of high speed steel rolls. *Metall. Mater. Trans. A* 38 (2007) 499-505.
- [28] G. Krauss, *Steels: Processing, Structure, and Performance*. ASM International, 2005
- [29] M.X. Zhang, P.M. Kelly, Crystallography and morphology of Widmanstätten cementite in austenite. *Acta Mater.* 46 (1998) 4617-4628.
- [30] W. Pistch, *Acta metall.* 10 (1962) 897.
- [31] R.W. Heckel, J.H. Smith, H.W. Paxton, *Trans. metall. Soc. A.I.M.E.* 218 (1960) 566.
- [32] D.S. Zhou, G.J. Shiflet, A new orientation relationship between austenite and cementite in an Fe-C-Mn steel. *Scripta Metall. Mater.* 27 (1992) 1215-1218.
- [33] S.W. Thompson, P.R. Howell, The orientation relationship between intragranularly nucleated widmanstätten cementite and austenite in a commercial

hypereutectoid steel. *Scripta Metall.* 21 (1987) 1353-1357.

[34] E.V. Zaretsky, Rolling bearing and gear materials, in 'Tribology for aerospace applications', (ed. E.V. Zaretsky), STLE SP-37, 325–451; 1997, Society of Tribologists and Lubrication Engineers, Park Ridge, IL

[35] G.T.C. Ooi, S. Roy, S. Sundararajan, Investigating the effect of retained austenite and residual stress on rolling contact fatigue of carburized steel with XFEM and experimental approaches. *Mater. Sci. Eng. A* 732 (2018) 311-319