Fatigue life of carburized steel specimens under push-pull loading

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Abstract— Various articles dedicated to effect of surface layer on fatigue life have been published in recent years. However, most of these articles are dedicated to the steels with nitride layer and only limited number of papers is dedicated to the carburizing. Results of extended experimental investigation of fatigue resistance of gas and low pressure carburized specimens made of the low-alloy high-strength steel are presented. The specimens were subjected to push-pull loading of different *R*-ratios. The application of plasma carburizing can lead to about 25% increase in the fatigue resistance in the high cycle region (over 10^5 cycles). On the contrary, in the case of low cycle fatigue often has a negative effect on the service life.

Keywords— Carburizing, fatigue life, sub-surface crack, high-strength steel, push-pull loading.

I. Introduction

METAL fatigue is a significant problem because it can occur due to repeated loads below the static yield strength. This can result in an unexpected and catastrophic failure [1-7]. Therefore, influence of various types of surface treatment on the fatigue life. Curently, gas and liquid carburizing, low pressure carburizing, pack carburizing and nitrocarburizing are widely used surface treatments. These techniques in applications where mechanical properties, such as wear and fatigue resistance, are in major koncern [7-17]. Their comparatively low cost in combination with their wide applicability of steel grades explains the success of these techniques. Several investigations have been carried out to determine the influence of nitriding treatments on mechanical properties and fatigue life but, the influence of carburization was much less studied. Therefore, the estimation of fatigue life of a component under multiaxial loading is fundamental to correct desing and operational life of mechanical assemblies.

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A. Role of Hard Surface Layer

In the case of high-cycle fatigue or ultra-long fatigue resp. gigacycle fatigue, the fatigue crack in smooth specimen initiates from the inclusion formed during cyclic loading and became a source of local stress concentration [7,10-12]. Therefore, by increasing surface hardness, the initiation of a fatigue crack can be retarded by restraining the dislocation movement on the surface [7,10]. Highly durable coating prevents slip deformation on the specimen surface due to the relatively less applied stress, the fatigue crack should be made at other position. Therefore, it is possible that a fatigue crack may occur due to stress concentration at a void or an inclusion that exists at a position close to the specimen surface but not hardened [7,10,12].

B. Role of Inclusions in Fatigue Fracture Process

High-cycle fatigue cracks or ultra-long fatigue cracks are characterized two remarkable features: a) crack nucleation on the nonmetallic or mixed inclusion, b) propagation of a crack inside the specimen. The subsurface crack usually occurs on the inclusion located at the interface of cemented layers and core of material. In the case of nitridation or in the case of ultralong life ($N_f > 10^7$) this subsurface crack have typical form, known as "fish-eye crack". This type of subsurface cracks has been extensively studied on samples with nitrided layer [7,10,12]. The creation of subsurface cracks on inclusion can be explained as the result of the presence of residual stress in the surface layer. Residual stress prevents cracks on the surface of the sample. The value $K_{I,max}$ of the stress intensity factor on the surface of an ellipsoidal inclusion can be expressed as:

$$K_{I,\max} \approx \frac{13}{20}\sigma\sqrt{\pi\sqrt{S_{incl,ef}}} \approx \sqrt{\pi d_{incl,ef}} \qquad (1)$$

where S_{incl} is the area of a cross-section of the inclusion and $d_{incl,ef}$ is the effective diameter of nonmetallic inclusion [3]:

$$S_{incl} = \frac{1}{4}\pi d_{incl}^2 \qquad (2)$$

The fatigue limit σ_C can then be assessed as follows:

$$\sigma_C = \frac{20 K_{critical}}{13\sqrt{\pi \cdot d_{incl,ef}}} \qquad (3)$$

where $K_{critical}$ is the critical threshold value of stress intensity factor. The residual compressive stresses in the carbon rich surface layer change the loading asymmetry [7,12]. Thus the critical threshold value varies depending on the depth from specimens surface. The relationship between critical threshold value of stress intensity factor and the loading asymmetry can be described as:

$$K_{critical(R)} = \frac{1.8K_{critical(R'=0)}}{\left\{\frac{1+R}{1-R} + \left[\left(\frac{1+R}{1-R}\right)^2 + 4\right]^{1/2}\right\}^{a/2}} \quad (4)$$

.

where $K_{critical(R=0)}$ = 2.58 MPa.m$^{1/2}$ is the critical threshold value for $R = 0$, position $R = 0$ in the surface layer corresponds to the tempered steel in the core of specimen. Calculated relation between critical threshold value $K_{critical}$ and the depth inside the carburized surface (calculation is made from the surface up to the tempered core) is plotted in Fig. 1(a).

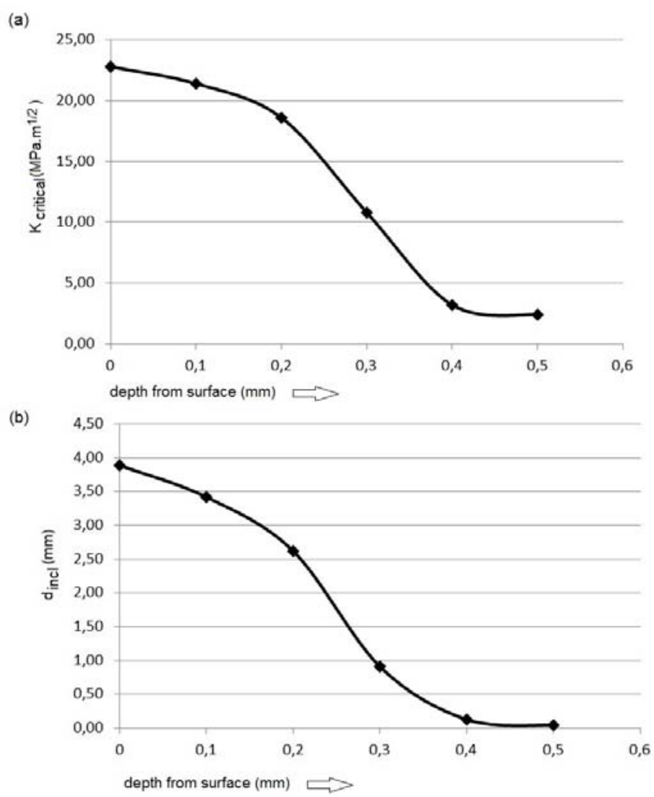

Fig. 1 (a) Distribution $K_{critical}$ in surface layer, (b) Critical dimension of inclusion.

Based on this knowledge, a critical inclusion dimension, $d_{incl,ef} = d_{critical}$, necessary for the crack initiation, can be assessed by using (3). The result is presented in Fig. 1(b). The critical dimension inside the carburized layer exceeds hundredfold the inclusion size of tens of microns as commonly found in commercial steels. This is also the reason why the crack initiates on inclusions inside the tempered core of specimen and cracking is not observed on inclusions in carbon-rich layers (in the case of high-cycle fatigue). On the other hand, the diameter $d_{incl,ef}$ of an sulfide inclusion in the core (in the distance of about 0.5 mm from the surface) fully corresponds to a real dimension of inclusions.

In the center of the "fish-eye" crack, an inclusion is found and in the case sufficiently long fatigue process (over 5.10^5 cycles in the case of surface-refined material and in the case of specimen without coating/surface layer over 10^7 cycles, thus in the case of ultralong fatigue) there is the optically different region in vicinity of initiation inclusion [10,17].

II. Experimental Material and Specimens

A. Material Composition

The cylindrical specimens were made of the steel DIN 17210 (equivalent to 20NiCrMo2-2 EN 10084-94). The chemical composition of the materials is (weight %): C 0.015, Si 0.43, 0.04 P, 0.035 S, 0.65 Cr, 0.28 Mo, 0.48 Ni, 0.013 Al. The basic mechanical properties of the material are minimal yield strength $\sigma_{y,min}$= 930 MPa and ultimate strength S_u= 1170 MPa. One of the surface treatment methods improving the some materials properties is carburizing. Carburizing is a heat treatment process in which steel is heated in the presence of another material (in the range of 880 to 980 °C) which liberates carbon as it decomposes. Depending on the amount of time and temperature, the affected area can vary in carbon content. Longer carburizing times and higher temperatures lead to greater carbon diffusion into the part as well as increased depth of carbon diffusion. When the iron or steel is cooled rapidly by quenching, the higher carbon content on the outer surface becomes hard via the transformation from austenite to martensite, while the core remains soft and tough as a ferrite or pearlite microstructure.

Nowadays, several different methods of carburizing are known. Gas carburizing is used for parts that are large and liquid carburizing is used for small and medium parts and pack carburizing can be used for large parts and individual processing of small parts in bulk. Low Pressure Carburizing (Vacuum carburizing) can be applied across a large spectrum of parts. The samples used in this work were refined by the gas carburizing and by low-pressure carburizing.

B. Details of Gas Carburizing Process

In gas carburizing, commercially the most important variant of carburizing, the source of carbon is a carbon-rich furnace atmosphere produced either from gaseous hydrocarbons, for example, methane (CH_4), propane (C_3H_3), and butane (C_4H_{10}), or from vaporized hydrocarbon liquids. Parameters of gas-carburizing process are: carburizing temperature T_C = 880 °C, time of carburizing t_{TC} = 4 hours for first group of samples, for second group is T_C = 920 °C and time t_{TC} = 2.2 hours and the third group is T_C = 920 °C and time t_{TC} = 2.2 hours, time of cooling t_{cool} = 2.5 hours for all type of specimen. In this case the application of the atmosphere composed of 23% CO, 36% H_2, 40% N_2, 2% CH_4 and 2% (CO_2 + H_2O). In the role of carburizing agents are in this case CO and CH_4. The obtained depth of hardened layer was h_{CS} = 0.25mm, h_{CS} = 0.55mm and h_{CS} = 0.9mm. After carburizing the samples were twice hardened, first at 900°C and again at 780°C. In all cases were endurance time at hardening temperature t_H = 35 min and time of cooling t_{cool} = 30 min. As a cooling medium was used water solution with 10% NaOH. The specimens were tempered at 180°C (2 hours).

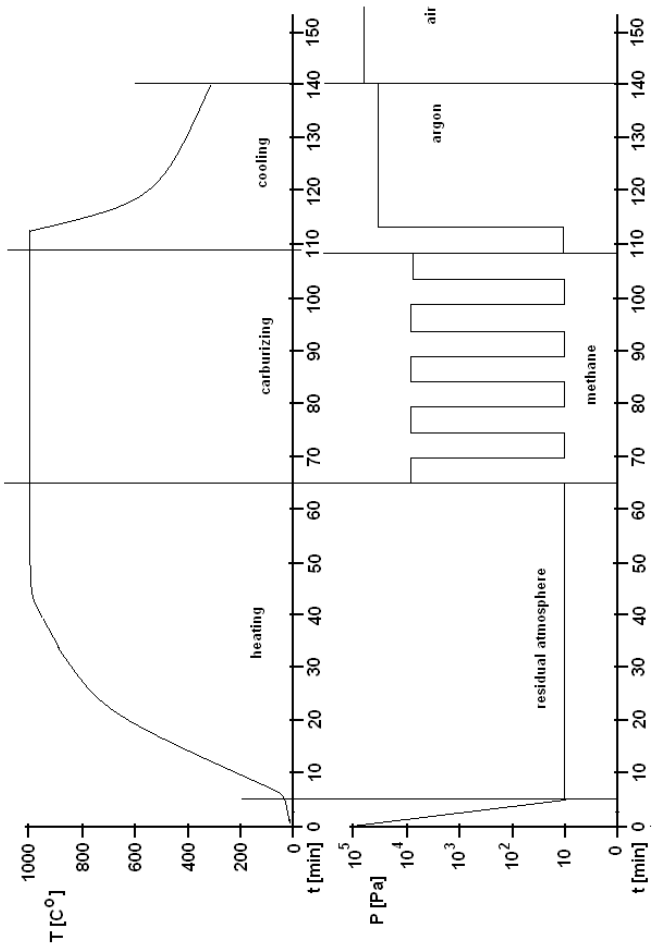

Fig. 2 Diagram of Low pressure carburizing with plasma assistance for surface depth h_{CS} = 0.9mm. Carburizing temperature T_C = 970 °C. Six pulses were used in the proces, see. pulse in the graph. Cooling medium was argon.

C. *Details of Low Pressure Process*

Low Pressure Carburizing is an example of case hardening process carried out in a vacuum furnace using hydrocarbon gases (methane CH_4, propane C_3H_3, ethylene C_2H_4 or acetylene C_2H_2) at very low pressure and elevated temperatures to obtain a hardened surface layer of tempered martensite and a tough core. The treatment is used to increase the wear resistance and fatigue life of components. Important benefit Low Pressure Carburizing (called LPC) is elimination of inter-granular oxidation in surface layer. Elimination of inter-granular oxidation causes improvements of fatigue resistence. It is known, that the methane molecule does not dissociate under low-pressure conditions. Therefore, it is necessary to use plasma assisted process. The glow discharge breaking then the molecule at the immediate vicinity of the surface, becose methan can be considered as inert gas. Dissociation of hydrocarbon molecules in the plasma assisted process can be expressed as $CH_4 \Rightarrow C + 2H_2$. In this case the process is called Low Pressure Carburizing with Plasma Assistance (LPC-PA).

When propane, acetylene or ethylene is used, gas moleculs dissociates without plasma assistance. Nowadays applications using either propane or acetylene represent something like 95% of the cycles run worldwide. Specimens used in this analysis were carburized by methan and acetylene dissociation ($C_2H_2 \Rightarrow 2C + 2H_2$). The obtained depth of hardened layer were h_{CS}= 0.25mm, h_{CS} = 0.55mm and h_{CS} = 0.9mm. Parameters of low pressure carburizing with plasma assistance can be read from Fig. 2. In the Fig. 2 the horizontal axis shows time t [min] and on vertical axis is temperature T [°C] and pressure P [Pa] in furnace. By carburizing temperature T_C = 970 °C for was obtained surface depth h_{CS} = 0.9mm. Cooling was carried out in argon atmosphere.

III. Fatigue Experiments

Fatigue tests of steel 20NiCrMo2-2 EN 10084-94 in tempered and carburized states were performed by means of the resonance testing machine Rumul – Mikrotron 20 kN using cylindrical specimens with diameter 6 mm. Two stress ratios were used: R_{SrA} = 0.1 for tension – tension loading and R_{SrA} = –0.053. The latter asymmetry was set up with respect to the total load capacity of the testing machine. Frequency of loading was 80 Hz. These experiments fall in high-cycle region.

The low-cycle experiments were performed only for stress ratio R_{SrA} = 0.1. The fatigue experiments were made at the room temperature. The specimens were loaded to final rapture.

IV. Experimental Results And Discussion

A. *Push-Pull Loading and Effect of Stress Asymmetry*

The effect of carburizing technology on the sensitivity to the loading asymmetry is expressed by means of the Smiths diagram constructed for both tempered and carburized specimens (Fig. 3) by using fatigue limits presented in Table 1.The fatigue life of specimens with surface layers h_{CS}= 0.55mm and h_{CS}= 0.25mm is independent on carburizing method. On th contrary in the case of carburized surface depth h_{CS}= 0.9mm, LPC-PA method gives better results, see. Fig. 4. This result is caused by elimination of inter-granular oxidation in surface layer.

From the diagram, the fatigue limit for R_{SrA} = -1 can be deduced. Presented values indicate a sensitivity of the carburized steel to the loading asymmetry. The application of carburizing increases the fatigue limit in case of R_{SrA} = .1 (σ_m = 0). When pull loading prevails (R_{SrA} = 0.053), the increase in the fatigue limit amplitude is only moderate and, for the fully pull loading (R_{SrA} = 0.1), the contribution of carburizing to fatigue resistance becomes negligible. In the case of low-cycle fatigue, the fatigue resistance decreases with the thickness of the carbon-rich layer. Carbide particles in the surface layer are cracking under cyclic loading and become the point of crack initiation, and the effect of carburizing on the fatigue resistance become negative.

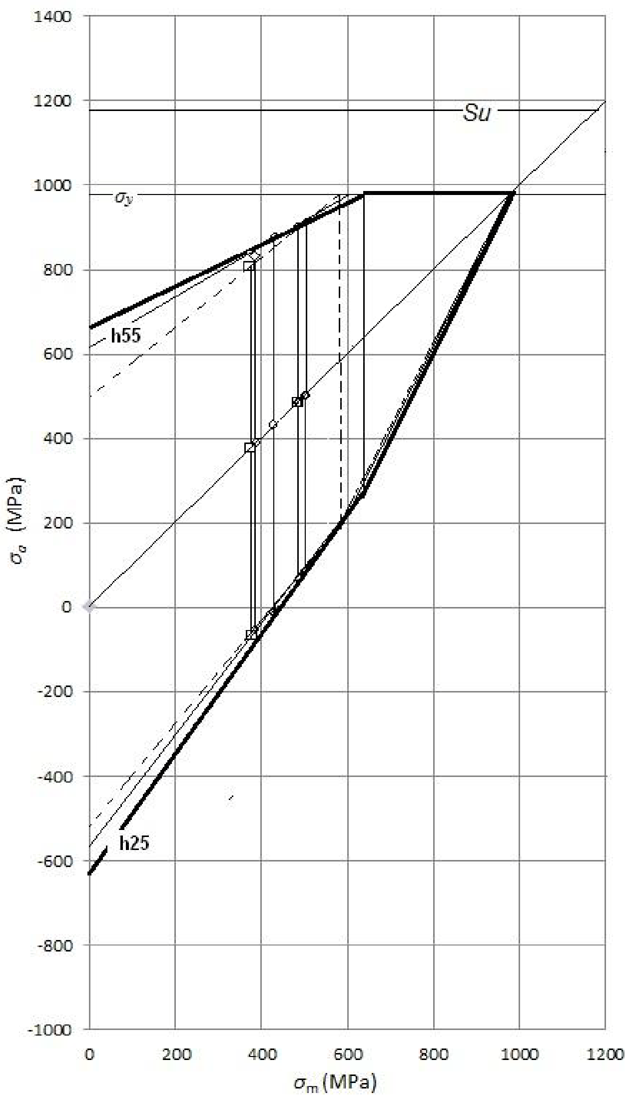

Fig. 3 Smiths diagram designed for the tempered state (dash line) of steel and the carburized state: h_{CS} = 0.55mm (thick line) and h_{CS}= 0.25 mm (thin line). The difference between the fatigue life of samples (with same depth of surface layer) carburized by gas-carburizing and LPC method is negligible.

Table 1. Comparison of fatigue limits for different stress asymmetry ratios R_{SrA}.. h is depth of surface layer, t_{CT} time of carburizing

R_{SrA}		-0.053		0.1		-1
Stress [MPa]		σ_m	σ_a	σ_m	σ_a	σ_m
Treatment/ t_{CT} [hours]	h [mm]					
tempering	0	370	±440	500	±400	±500
t_{CT} 2.5	0.25	440	±440	520	±400	±680
t_{CT} 4	0.55	390	±430	540	±420	±600

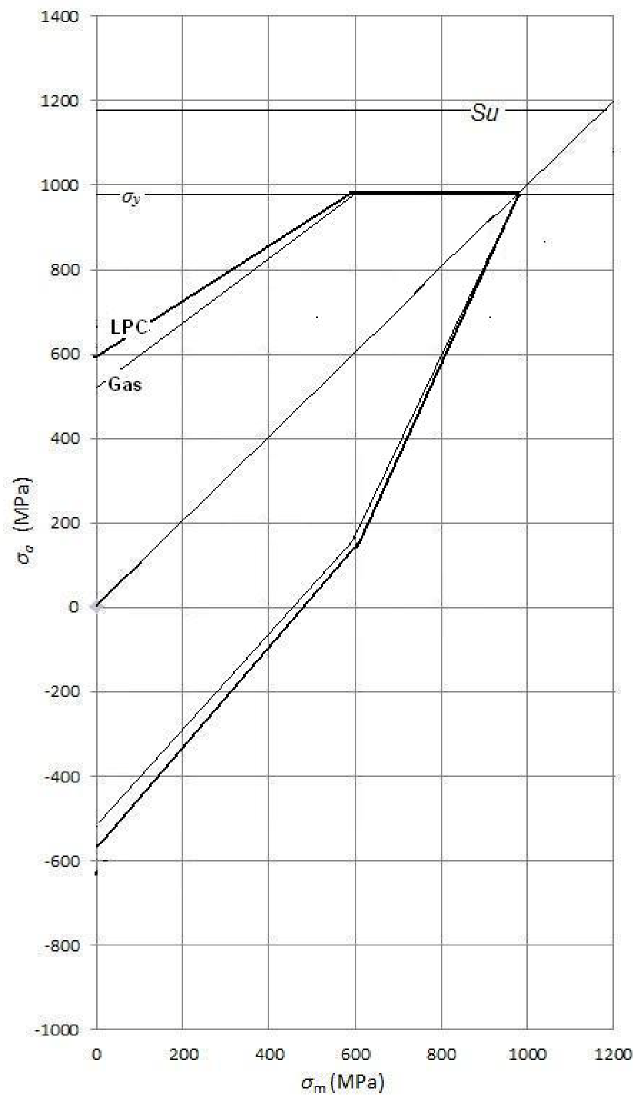

Fig. 4 Smiths diagram designed for the carburized steel with surface laye h_{CS}= 0.9mm obtained by different methods> Gas carburizing (thin line) and LPC method (thick line).

B. Effect of carburized layer depth

The effect of layer depth on the fatigue life was measured for the asymmetry R_{SrA} = -0.053, and the results are shown in Fig. 5. It seems that the optimal layer depth ranges from 0.2 to 0.4 mm. The optimum depth of about 0.35 mm corresponds to the carburizing time of 2.5 hours. For the case of R_{SrA} = 0.1, the fatigue life even decreases with increasing depth of the carburized layer. It means that thicker carburized layer needs not always lead to a longer fatigue life; there is an optimal layer depth for each type of steel and loading.

C. Effect of annealing of surface layer

A very important factor, influencing the fatigue resistance of specimen, is the depth of surface film of carbides (compound layer) deposited onto the carburized layer. A heterogeneous compound layer is often a site of an early fracture initiation. This fact has been confirmed, as well as was in experiments, where the compound layer was mechanically removed by fine grinding [7]. This type of sample modification completely changed the type of fracture initiation particularly at high levels of loadings. Before this operation, fracture started from the specimen surface inside the compound layer. After the process of grinding, the epicenter of fracture transferred out of the diffusion layer into the specimen core. This alteration in fracture mode was accompanied by a significant increase in the fatigue life.

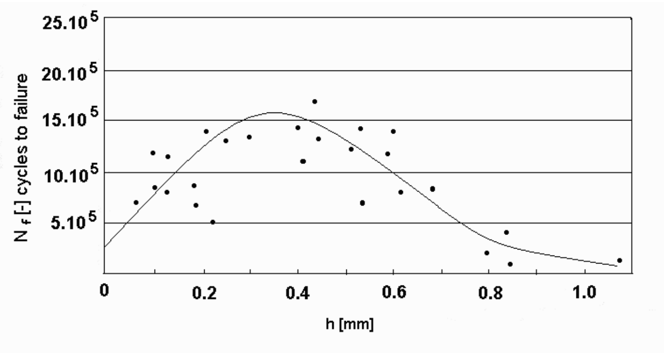

Fig. 5 Dependence of the fatigue life on the layer depth for the asymmetry R_{SrA} = –0,053

A reduction of the compound layer depth can also be achieved by the annealing treatment after carburizing. It removes the carbide film, increases the depth of diffusion layer and reduces the gradient of carbon concentration throughout the layer. On the other hand, the annealing treatment decreases the level of residual stresses in the diffusion layer. To evaluate the efficiency of such treatment, three sets of specimens were prepared:

1) depth of carburized layer 0.25 mm, compound layer of about 0.002 mm.
2) depth of carburized layer 0.25 mm, compound layer of about 0.004 mm.
3) Annealing 565°C, without compound layer, carburized layer of about 0.6 mm.

Experimental results are shown in Fig. 6 in the form of Wöhler curves, plotted for the maximum stress in the loading cycle. The lines marked with the symbol (a) show levels of fatigue limit and endurance in the tempered state. Lines marked by symbols (b), (c) and (d) correspond to the above mentioned carburizing treatment. Also, levels of the yield stress, σ_y, are marked out in this diagram. It is clear from the graph, that the fatigue limits of carburized specimens (b) and (c) are higher than the fatigue limit of only tempered specimens. A reduced thickness of the compound layer increased the fatigue limit (of nearly 5 %). Moreover, the annealing strongly reduces both the fatigue limit and the fatigue endurance despite of an increased depth of the diffusion layer. The reason lies, most probably, in the release of compressive residual stresses since prevailing tension internal stresses were found on the surface of annealed specimens.

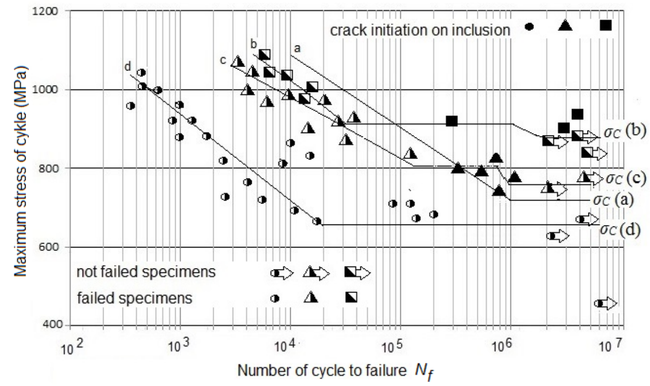

Fig.6 Wöhler curves of the steel 20NiCrMo2-2 (a) quenched and tempered, (b) carburized, depth of the compound layer of 0.002 mm, (c) carburized, depth of the compound layer of 0.004 mm, (d) carburized and annealed at 565°C.

V. Conclusion

The main results of investigations can be summarized into the following points:

1) The application of plasma carburizing can lead to about 25% increase in the fatigue resistance in both the low- and the high cycle region. It holds for a wide range of loading types as symmetrical push-pull loading, However, the fatigue strength dramatically drops when the peak stress in the cycle reaches the strength of the carburized compound layer. This is typical for highly asymmetric push-pull loadings
2) The elimination of the compound carbide film by annealing after carburizing led to a significant reduction of fatigue limit even in comparison to only tempered (virgin) specimens. The reason lies in inducing tensile residual stresses on the surface.
3) In case of sufficiently homogeneous carburized layers, the crack initiation in the high cycle region starts near the inclusions outside the layer, close to the layer-core interface. It leads to the fish-eye fracture morphology. This phenomenon can be explained by the concept of the threshold stress intensity factor with respect to the existence of residual stresses in the carburized layer.

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References

[1] Š. Major, Š. Hubálovský, 2013, International Journal of Mechanics, Issue 2, Volume 7, 65-72.
[2] I. Salam, M. Abid, M.A. Malik, 2007, International Journal of Systems applications, Engineering & Development, Volume 3, Issue 1, 51-55.
[3] W. Krason, J. Malachowski, 2008, International Journal of Mechanics,Issue 1, Volume 2, 16-23.
[4] K. Salmalian, M. Soleimani, S. Rouhi, 2012, nternational Journal of Mathematical Models and Methods in Applied Sciencies, Issue 1, Volume 6, 1-10.

[5] M.X. Calbureanu, R. Malciu, D. Tutunea, A. Ionescu and M. Lungu, 2013, International Journal of Mechanics, Issue 4, Volume 7, 467-473
[6] A. Lakshminarayana, R. Vijaya Kumar, G. Krishna Mohana Rao, 2012, International Journal of Mechanics, Issue 1, Volume 6, 1-8.
[7] Š. Major, J. Papuga, J. Horníková, J. Pokluda, Comparison of Fatigue Criteria for Combined Bending- torsion Loading of Nitrided and Virgin Specimens, 2008, Strenght of Materials, Vol. 40, No. 1,64-66.
[8] J. Bernal,A. Medina, L. Béjar, S. Rangel, A. Juanico, 2011, International Journal of Mathematical Models and Methods in Applied Sciencies, Issue 2, Volume 5, 395-403
[9] D. Manas, M. Ovsik, M. Manas, M. Stanek, P. Kratky, A. Mizera and M. Bednarik, 2013, International Journal of Mechanics,Issue 4, Volume 7, 526-533.
[10] Y.Murakami: Metal Fatigue: Effects of Small Defects and Nonmetallic Inclusions, Elsevier, 2002.
[11] K.Slámečka; J.Pokluda; M.Kianicová, Š.Major, I.Dvořák, International Journal of fatigue, 2010, vol. 32, No. 6, s. 921-928.
[12] J. Pokluda, I. Dvořák, Š. Major, H. Horáková: Influence of Plasma-Nitriding surface layer on fatigue life of steel specimens under push-pull and bending-torsion . Fatigue Congress 2006, Atlanta, USA
[13] Shao Mei Zheng et al., 2011, Advanced Materials Research, 214, 564-568
[14] Li Na Guo, Jin Chen, Jun De Pan, 2012, Applied Mechanics and Materials, 217-219, 1257-1260
[15] Gao Hui Zhang, Ping Ze Zhang, Ming Zhou Yu, Zhong Xu, 2008, Advanced Materials Research, 47-50, 1197-1200
[16] Hassan A. Wahab, M.Y. Noordin, S. Izman, Z. Kamdi, Denni Kurniawan 2013, Advanced Materials Research, 845, 378-381
[17] K.Shiozova, L. Lu, S. Ishihara, Fatigue Fract. Eng. Mater. Struct. 24, 2001, pp. 781-790.