

Effect of carburizing on fatigue life of high-strength steel specimen under push-pull loading

Štěpán Major, Vladimír Jakl and Štěpán Hubálovský

Abstract— Many articles are dedicated to effect of surface layer on fatigue life. However, most of these articles are dedicated to the steels with nitride layer and only small number of papers is dedicated to the carburizing. Results of extended experimental investigation of fatigue resistance of plasma-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, bending-torsion..

I. INTRODUCTION

NOWADAYS, gas and plasma nitriding, carburizing and nitrocarburizing are widely used surface treatments in applications where mechanical properties, such as wear and fatigue resistance, are in major concern [1-8]. 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 but, the influence of carburization is much less studied.

A. Role of Surface Layer

Under the high-cycle fatigue loadings, the fatigue crack of a smooth metal specimen initiates from the inclusion formed during cyclic loading and became a source of local stress concentration [3,4]. Therefore, by improving surface hardness, the initiation of a fatigue crack can be retarded by restraining the dislocation movement on the surface [3,4]. If it is hard enough to prevent 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

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or an inclusion that exists at a position close to the specimen surface but not hardened [2,3].

B. Role of Inclusions in Fracture Process

Long life fractures usually reveal 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 nitrated layer [6-8]. 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:

$$K_{I,max} \approx 0.65\sigma\sqrt{\pi\sqrt{S_{incl,ef}}} \approx \sqrt{\pi d_{incl,ef}} \quad (1)$$

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]:

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

The fatigue limit σ_C can then be assessed as follows:

$$\sigma_C = \frac{K_{critical}}{0.65\sqrt{\pi \cdot d_{incl,ef}}} \quad (3)$$

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 [3]. 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 $K_{critical(R=0)} = 2.58 \text{ MPa}\cdot\text{m}^{1/2}$ 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). 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.

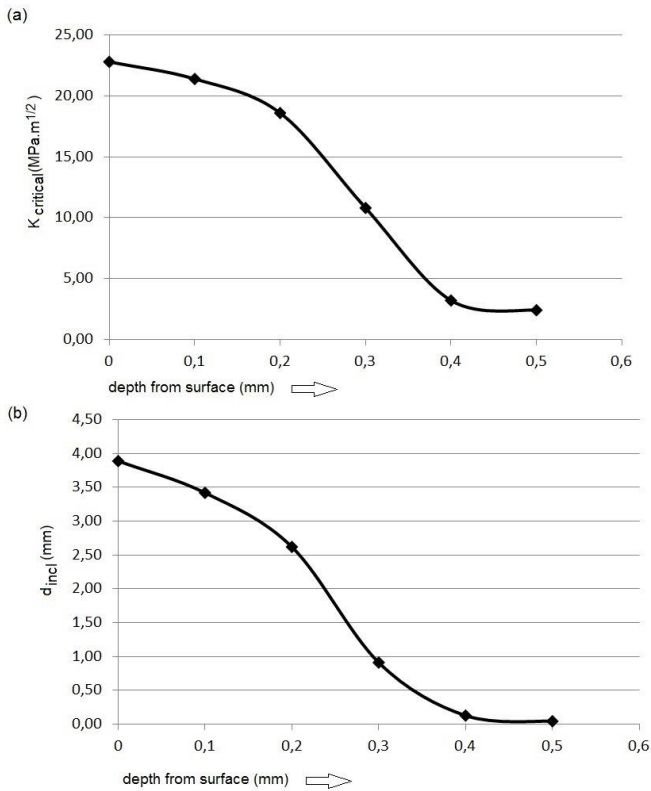


Fig. 1 (a) Distribution $K_{critical}$ in surface layer, (b) Critical dimension of inclusion.

In the center of the “fish-eye” crack, an inclusion is found and in the case sufficiently long fatigue process (over $5 \cdot 10^5$ 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 [2,9].

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 $\sigma_{y,min} = 930 \text{ MPa}$ and ultimate strength $S_u = 1170 \text{ MPa}$. 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 ferritic or pearlite microstructure.

B. Details of 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_8), and butane (C_4H_{10}), or from vaporized hydrocarbon liquids. Parameters of gas-carburizing process are: carburizing temperature $T_C = 880 \text{ °C}$, time of carburizing $t_{TC} = 4$ hours for first group of samples and for second group is $T_C = 920 \text{ °C}$ and time $t_{TC} = 2.2$ hours, time of cooling $t_{cool} = 2.5$ hours for both 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% ($\text{CO}_2 + \text{H}_2\text{O}$). In the role of carburizing agents are in this case CO and CH_4 . The obtained depth of hardened layer was $h_{CS} = 0.65 \text{ mm}$. After carburizing the samples were twice hardened, first at 900 °C and again at 780 °C . In both cases were endurance time at hardening temperature $t_H = 35 \text{ min}$ and time of cooling $t_{cool} = 30 \text{ min}$. As a cooling medium was used water solution with 10% NaOH . The specimens were tempered at 180 °C (2 hours).

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. 2) by using fatigue limits presented in Table 1.

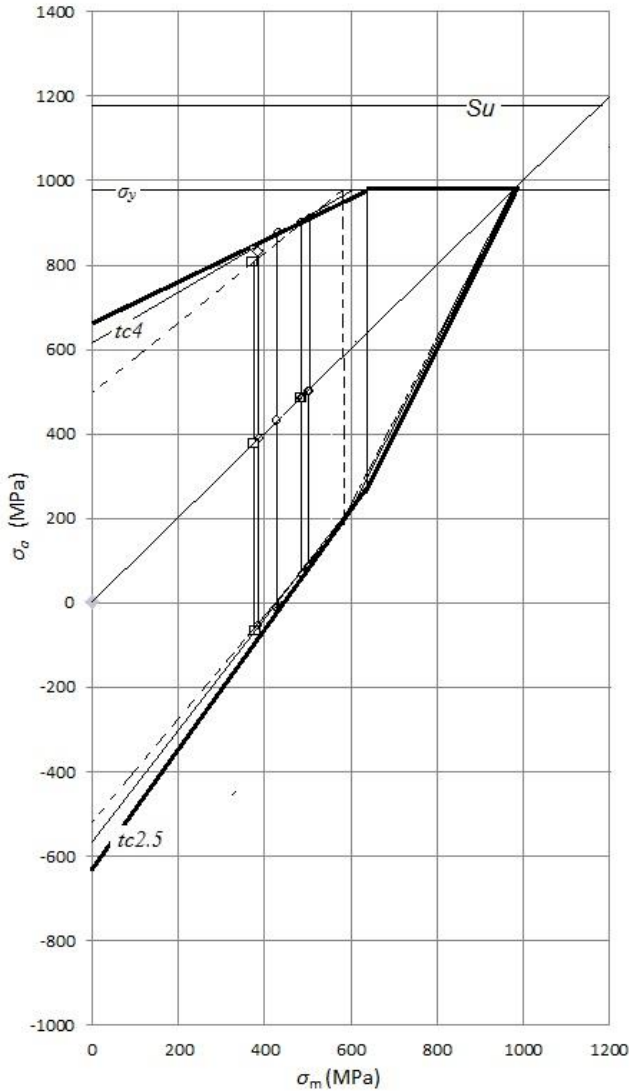


Fig. 2 Smiths diagram designed for the tempered state (dash line) of steel and the carburized state: time of carburizing $t_{CT} = 4$ hours (thick line) and $t_{CT} = 2.5$ hours (thin line).

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 $R_{SrA} = .1$ ($\sigma_m = 0$). 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.

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

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. 3. 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.

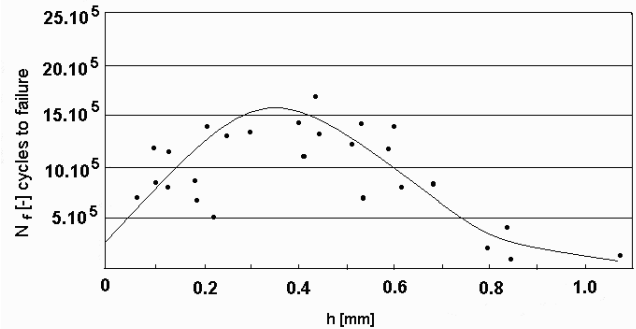


Fig. 3 Dependence of the fatigue life on the layer depth for the asymmetry $R_{SrA} = -0,053$

C. Effect of annealing of surface layer

A very important factor, influencing the fatigue resistance of specimen, is the depth of surface film of carbids (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 [1]. 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 epicentre 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.

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. 4 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.

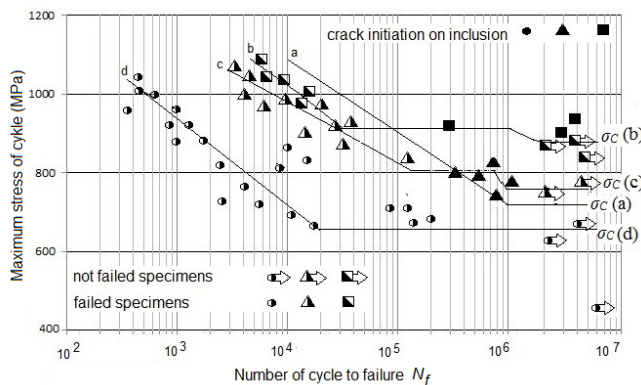


Fig.4 Wöhler curves of the steel 20NiCrMo2-2 (a) quenched and tempered, (b) carburized, depth of the compound layer of 0.002 mm, (c) carburized, depth of the compound layer of 0.004 mm, (d) carburized and annealed at 565 C.

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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