World Academy of Science, Engineering and Technology
International Journal of Mechanical and Mechatronics Engineering
Vol:5, No:4, 2011

The Effect of Ion Nitriding and Carbonitriding on Fretting Fatigue of Steels

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***Abstract*—**The paper deals with the effect of ion nitriding and carbonitriding on fatigue strength of steel parts under the fretting conditions. Instrumented fatigue tests were carried out on surface treated flat bars from EA1N and EA4T steels with different strength. The chosen surfacing decrease importantly an unfavorable fretting effect. Nitridation suppressed the unfavorable effect of fretting almost entirely, while the influence of carbonitridation was less striking. The results were compared with those ones obtained on bars without surfacing. The causes of favorable influence of surfacing are discussed.

***Keywords*—**Carbonitriding, fatigue, fretting, nitriding, steel.

I. Introduction

Fretting effect decreases usually significantly fatigue strength of machinery steel parts. It occurs e.g. in fatigue loaded shafts with pressed gear wheel hubs, in railway vehicles axles with pressed traversing wheels and traction gears, in the dovetail roots of blades of steam turbine and turbo compressor rotors and in riveted joints of aircraft coverings subjected to alternating stress as well.

Our recent works carried out on fatigue loaded parts of EA1T and EA4T axle steels with pressed hubs [1], [2] showed that the increase of strength of the base material did not lead usually to the successful solution of the problem. Fatigue strength of parts with pressing having the strength of the base material from 590 to 1040 MPa did not differ markedly. This conclusion confirmed the results of further works carried out under the simplified model conditions on flat bars of the same steels with the fretting effect [3]. On the other hand, Tanaka et al. [4] found on two spring steels with markedly different strength (713 and 1677 MPa) that fatigue limit values under the fretting conditions were higher in the steel with higher strength. Husheng et al. [5] have drawn the attention to the influence of slip amplitude; the differences of fatigue fretting limits are lower at higher slip amplitude.

Our work aims at the increasing of fatigue strength of parts subjected to fretting in another way – by the surfacing owing to ion nitriding and carbonitriding.

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II. Specimens, Experimental Methods, Materials, Heat Treatment

A. Specimens

Experimental works were performed on flat test bars of 23x5 mm cross-section in the central part (Fig. 1). Fatigue testing took place on the resonance fatigue machine PHT Schenck with range up to 200 kN.

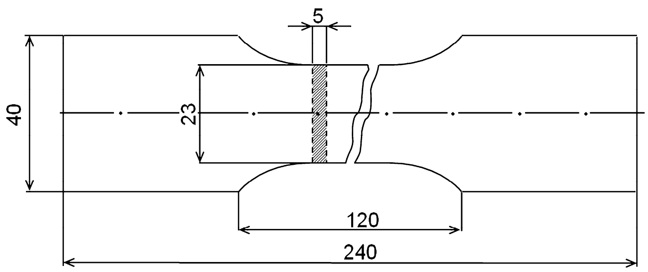

Fig. 1 Test specimen

B. Test Methods

To reach the contact friction effect on test bars, special jig developed for this purpose was used (Fig. 2). Two pairs of opposite bridges with pads made of EA4T steel, the hardness of which was 225 HV 30, were pressed to the bar. The width of contact pads was 3 mm and their pitch 25 mm. The adherence pressure was made by a screw over the spherical contact area. The force effect was evaluated by means of strain gauge measurements carried out after the calibration of loading system by tensile-strength testing machine. Possible deviations of the adherence force were compensated according to the indications of strain gauge apparatus.

The adherence force value 3 kN corresponding to the specific pressure 21.7 MPa was used in all tests performed.

During the test, temperature was measured by thermocouple fastened to the test bar and recorded by line recorder. Fatigue tests under the fretting conditions were carried out without lubrication.

C. Slip Parameters

Slip amplitude is predominantly given by the cyclic deformation level of tested bar between the bearing surfaces of the pads. Loading at the fatigue limit corresponds to slip amplitude 13 – 17 μm (low level of slip).

The fatigue tests were performed at repeated tensile stress, with low value of lower cycle stress (σ_{min} = 13 MPa). The frequency of fatigue fretting tests was 32 – 33.5 Hz. The tests were performed up to 10^7 cycles or to fracture.

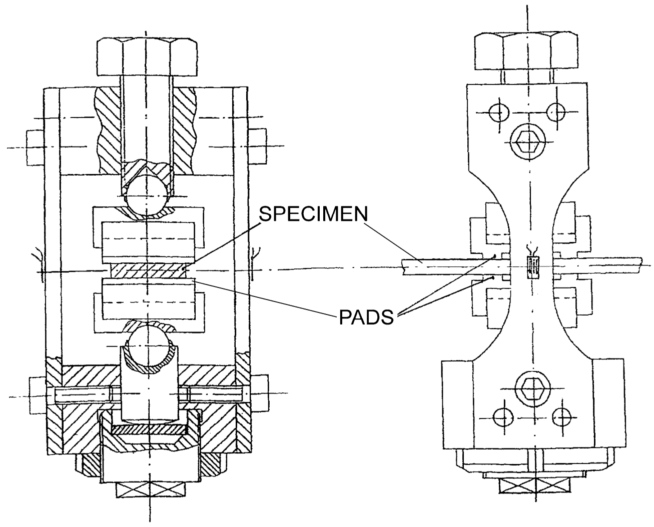

Fig. 2 Jig for testing with fretting

D. Material and Heat Treatment of Specimens

Test bars were made of EA1N and EA4T steel used for axles. The carbon steel EA1N (0.39 % C; 0.34 % Si; 0.77 % Mn) has lower strength and yield point values (R_m = 578.3 MPa, R_{eH} = 379.3 MPa). The low-alloy EA4T (0.287 % C; 0.27 % Si; 0.75 % Mn, 1.14 % Cr; 0.2 % Mo) is heat treated (R_m = 736.4 MPa, $R_{p0.2}$ = 572.5 MPa).

After the production of test bars, the chemical heat treatment, carried out in the Technical University in Brno, followed. Some of them were ion nitrided, the others were ion carbonitrided.

E. Ion Nitriding

After the 45 minutes cleaning cycle in the $H_2 + N_2$ mixture atmosphere at 800 V and 500 °C, the nitriding at 500 °C for 8 h in the mixture atmosphere H_2 (30 dm^3/h) + N_2 (8 dm^3/h) under the pressure 2.5 mbar and voltage 520 V was carried out. It followed diffusion annealing at 480 °C for 2 h in H_2 atmosphere (20 dm^3/h) under the pressure 1.5 mbar.

F. Ion Carbonitriding

Cleaning cycle was the same as mentioned above. The following carbonitriding was performed in the mixture atmosphere H_2 (10 dm^3/h) + N_2 (30 dm^3/h) + NH_4 (2.4 dm^3/h) at 550 °C, 2.8 mbar and 510 V for 12 h.

G. Hardness and Microstructure of Ion Nitrided and Carbonitrided Layers

Typical values of hardness in surface layers of EA4T steel are shown in Fig. 3, those ones of EA1N steel are shown in Fig. 4.

It follows from Fig. 3 that the hardness values at the surface are 750 – 850 HV 0.04, in the base material 250 – 290 HV 0.04. Layer thickness is approximately 0.45 – 0.5 mm, including the transition to the base material.

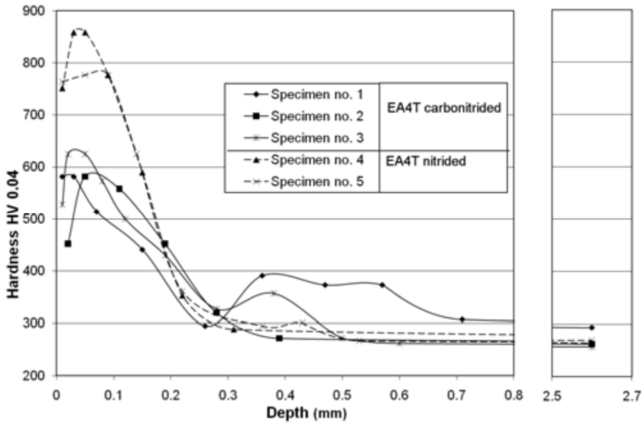

Fig. 3 Hardness variation in nitrided and carbonitrided surface layer of EA4T steel

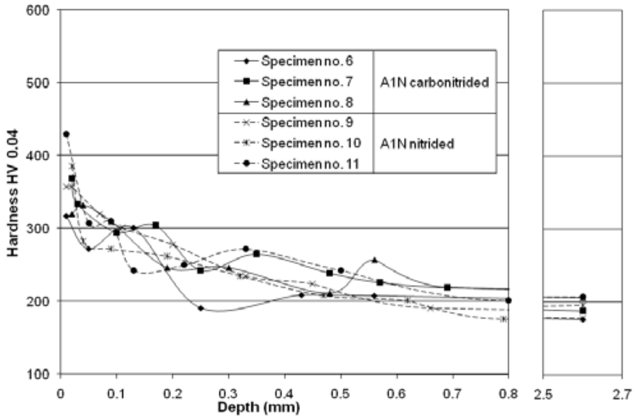

Fig. 4 Hardness variation in nitrided and carbonitrided surface layer of EA1N steel

The microstructure of nitrided layer consists of thin surface compact layer (cca 2.5 μm) of nidrides and carbonitrides (ε+γ') and a more fine structure inside the nitrogen diffusion zone (Fig. 5).

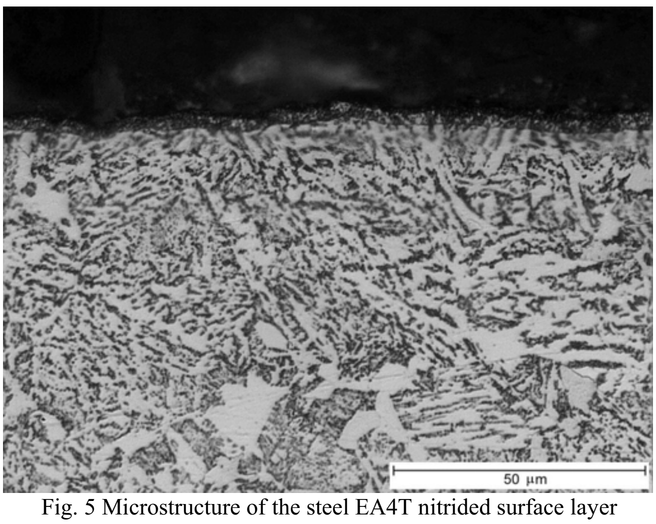

Fig. 5 Microstructure of the steel EA4T nitrided surface layer

Carbonitrided specimens of EA4T steel have lower surface hardness (max. 580 – 630 HV 0.04). Layer thickness – including the transition zone – is 0.5 – 0.6 mm (Fig. 3).

The microstructure is formed by thin white layer, probably of carbonitride ε, the thickness of which is 3.6 – 4 μm and by finer structure in the diffusion affected zone (Fig. 6).

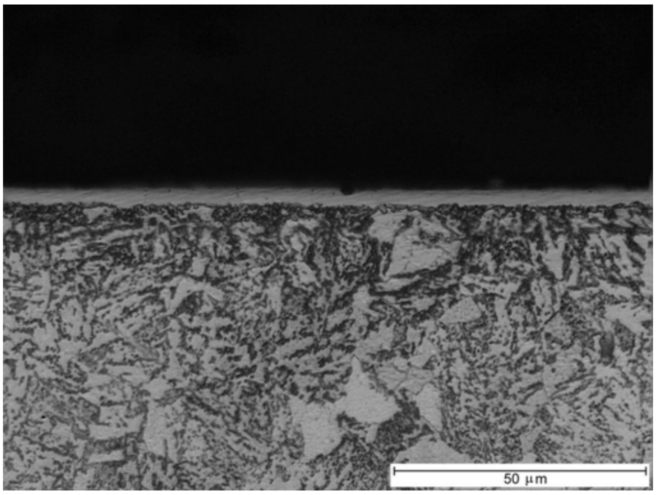

Fig. 6 Microstructure of the steel EA4T carbonitrided surface layer

In the case of EA1N steel, the surface hardness of ion nitrided layer is substantially lower (Fig. 4). It is caused by the absence of the main nitride forming elements (Cr, Al) that form very hard nitrides. The hardness reaches only 320 – 420 HV 0.04 at the surface and 170 – 210 HV 0.04 in the base material. Total thickness of the nitriding layer is 0.5 – 0.6 mm.

The microstructure contains a thin compact surface layer of complex nitrides and carbonitrides, the thickness of which is 2.6 – 5.26 μm (Fig. 7). Under this layer, only very small isolated nitride particles occur in the ferritic grains.

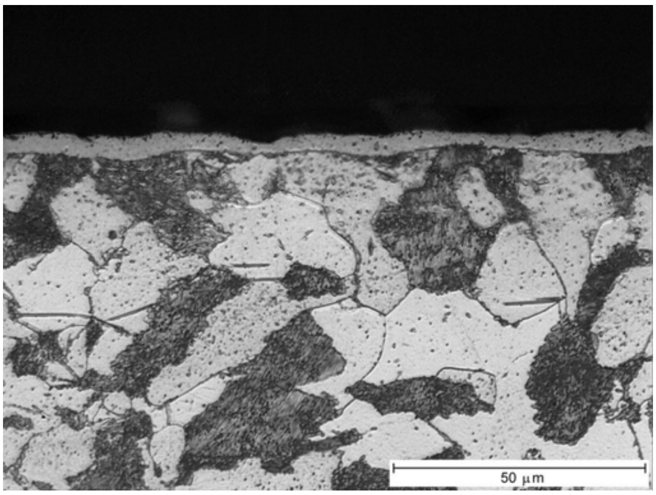

Fig. 7 Microstructure of the steel EA1N nitrided surface layer

Carbonitrided layers of EA1N steel specimens have approximately the same surface hardness as the nitrided ones (320 – 370 HV 0.04); these values are only somewhat higher than those measured in the base material. Layer thickness is 0.45 – 0.6 mm.

In the microstructure, a compact surface layer of carbonitrides, thick 4-6 μm, occurs. The structure of diffusion zone under the surface layer does not differ from the structure of the base material (Fig. 8).

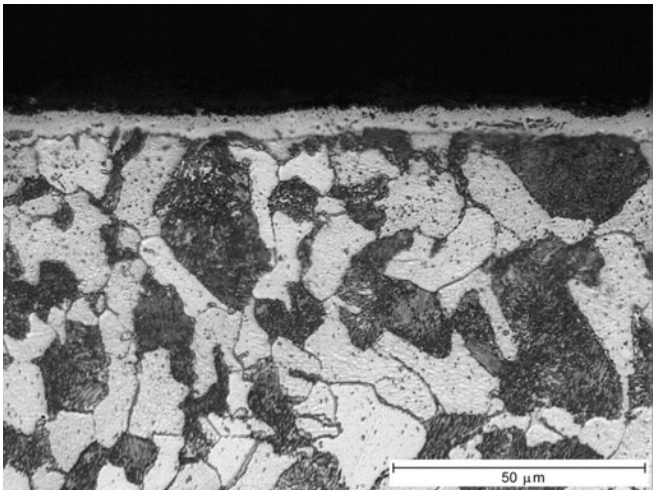

Fig. 8 Microstructure of the steel EA1N carbonitrided surface layer

III. Results

The results of fatigue tests are summarized in Fig. 9, 10. Fig. 11 shows the comparison of the fatigue limits of bars of both steels with various treatments.

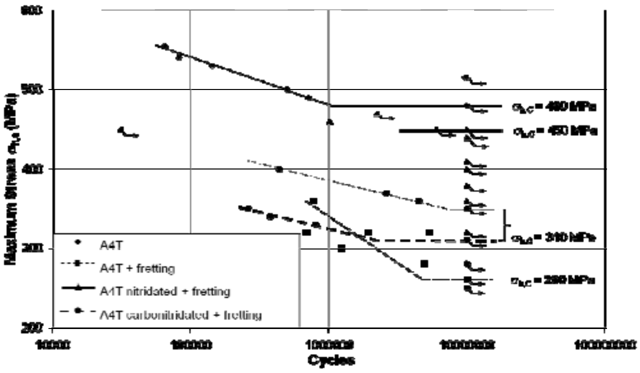

Fig. 9 Results of the fatigue fretting tests on EA4T specimens

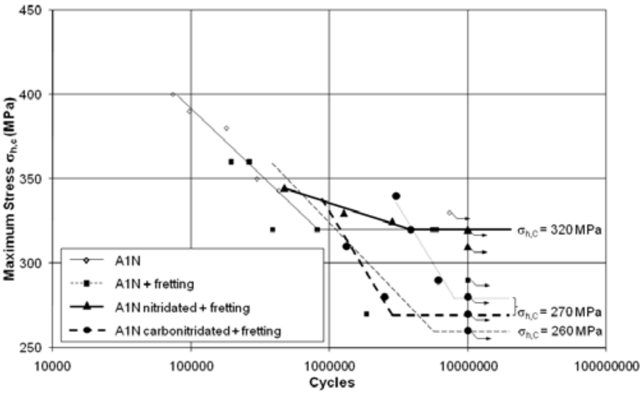

Fig. 10 Results of the fatigue fretting tests on EA1N specimens

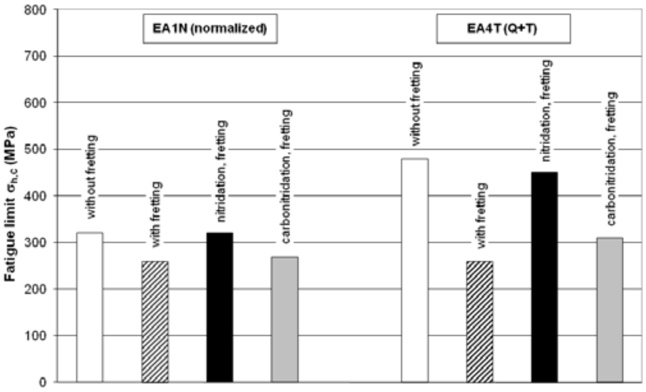

Fig. 11 Comparison of fretting fatigue limits the EA4T and EA1N specimens

In addition to the results obtained on the nitrided and carbonitrided specimens, some results of work [3] are also given. There are the results of fatigue tests carried out on EA1N and EA4T steels with the base heat treatment, without surfacing, with and without fretting. The fatigue limit values are characterized by upper stress of cyclic loading σ_{hC}.Fatigue limits σ_{hC} values of heat treated EA4T steel are the following (Fig. 11):
480 MPa - heat treated bars, fatigue tests without fretting,
260 MPa - heat treated bars, fatigue tests with fretting,
450 MPa - ion nitrided bars, fatigue tests with fretting,
310 MPa (up to 350 MPa) – ion carbonitrided bars, fatigue tests with fretting.

Fatigue limits σ_{hC} values of carbon EA1N steel are the following:
320 MPa - normalized bars, fatigue tests without fretting,
260 MPa - normalized bars, fatigue tests with fretting,
320 MPa - ion nitrided bars, fatigue tests with fretting,
270 - 280 MPa) - ion carbonitrided bars, fatigue tests with fretting.

Favorable effect of surfacing practically entirely eliminated the unfavorable fretting effect. Especially in the case of EA4T nitrided bars, and also in some EA1N nitrided steel specimens, fatigue fracture originated outside the contact area (Fig. 12). In these cases, it was sometimes difficult to determine the whole S-N curve, thus, only the fatigue limit was obtained (Fig. 9).

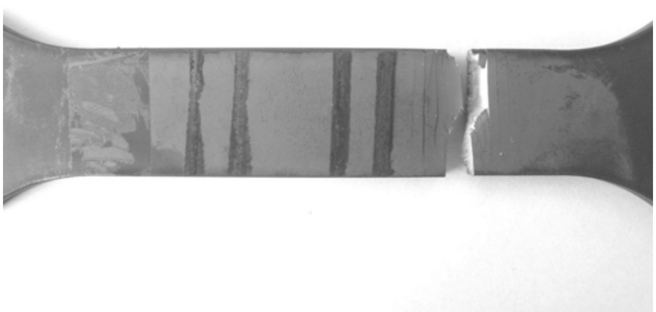

Fig. 12 Fatigue fracture developed out of the fretting zone. Nitrided EA4T specimen

Fretting effect on the fatigue strength can be also described with the help of strength reduction factor β_{KaC} obtained from the loading amplitude at the fatigue limit, σ_{aC}. The values of these parameters are summarized in Table I.

TABLE I
FATIGUE STRENGTH REDUCTION FACTOR β_{KaC}

Steel	Chemical – heat treatment	Fatigue testing	Fatigue limit - maximum stress σ_{hC} (MPa)	Fatigue limit – amplitude σ_{aC} (MPa)	Fatigue strength reduction factor β_{KaC}
EA4T (Q+T)	-	without F	480	233.5	-
	-	with F	260	123.5	1.90
	nitriding	with F	450	218.5	1.07
	carbo-nitriding	with F	310	148.5	1.57
EA1N (N)	-	without F	320	153. 5	-
	-	with F	260	123.5	1.24
	nitriding	with F	320	153.5	1.00
	carbo-nitriding	with F	270	128.5	1.19

$\beta_{KaC} = \sigma_{aC}$ without fretting / σ_{aC} with fretting
Q+T quenching and tempering
N normalizing
F fretting

IV. Discussion of Results And Fretting Damage

It follows from the results of fatigue tests that the effect of surfacing (ion nitriding and ion carbonitriding) in specimens fatigue loaded with fretting was favorable. In the case of nitrided specimens, the unfavorable effect of fretting was entirely suppressed. Fatigue limit of nitrided EA1N steel bars with fretting is the same as this one of the base material, σ_{hC} = 320 MPa. In the case of nitrided EA4T steel bars with fretting, the fatigue limit σ_{hC} = 450 MPa is only somewhat lower than that of the heat treated bars σ_{hC} = 480 MPa.Nitrided and carbonitrided layers have in both steels higher hardness, as compared with the base material. The best situation is in the nitrided EA4T steel bars (Fig. 3). Hardness in the surface layer reaches 750 – 850 HV 0.04. In the cabonitrided EA4T bars is the hardness of surface layer 580 – 630 HV 0.04, which is lower than in the case of nitrided bars, but substantially higher than in the base material (250 – 290 HV 0.04).Fretting damage process is, in the stage of growth of the first cracks, affected by high compression residual stresses in the surface layer which can reach, according to our recent measurements carried out on nitrided specimens, up to 1000 MPa [5]. Particularly, they can intensively retard the growth of these cracks.Carbon EA1N steel that does not contain important nitride forming elements has the surface hardness 320 – 420 HV 0.04 in the case of nitridation and 320 – 370 HV 0.04 in the case of carbonitridation. These values are substantially lower than those ones of EA4T steel, but considerably higher than in the base material, 170 – 210 HV 0.04.

During the first stages of the test, cyclic friction causes the roughness and wear of the surface (Fig.13). Rough surface and the presence of released oxide particles lead to the changes of friction coefficient. However, the measurements of temperature on the bar surface near the contact areas did not show a marked increase of the specimen temperature. In contradistinction to unnitrided specimens, in which the friction forces cause the cyclic plastic deformation in the thin surface layer, this possibility is considerably restricted in the hard nitrided layers.

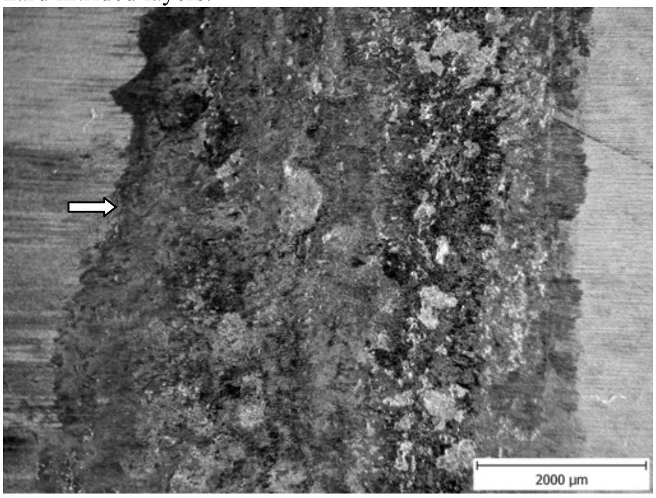

Fig. 13 Development of coarsening and first seizing in contact area. Nitrided EA4T specimen

In some places of the pressed zone, seizing occurs (Fig. 14) and local fine welds are observed. The increase of the size of wear products in these areas leads to the increase of nonuniformity of the specific pressure, and, consequently to higher values of friction coefficient as well as to the deterioration of the friction conditions. Finally, small cracks with different orientation caused by fretting are formed. These small fretting cracks act as the initiation places of fatigue crack, which is oriented approximately perpendicularly to the cyclic force direction (Fig. 15).

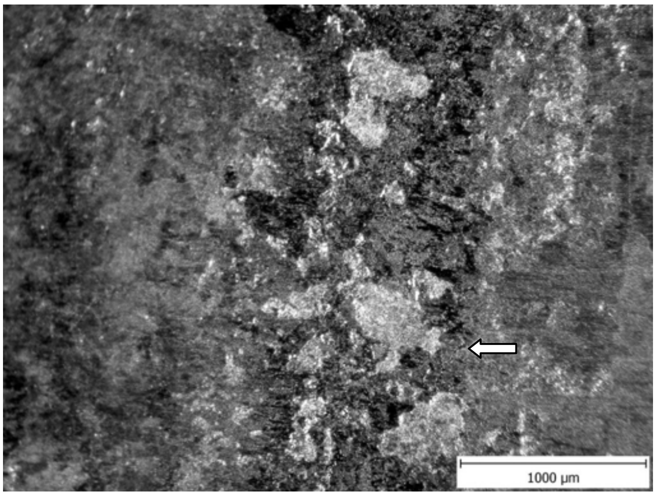

Fig. 14 Areas with seizing. Nitrided EA4T specimen

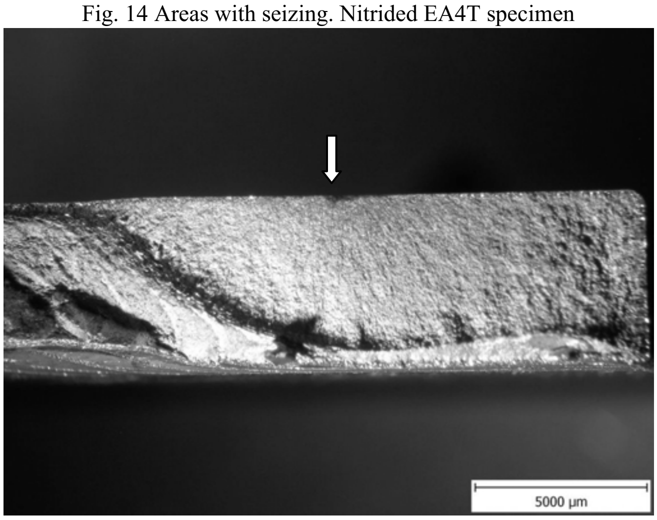

Fig. 15 Example of a fatigue crack development from fretting areas. Nitrided EA4T specimen

The favorable effect of the applied surfacing under the fretting conditions is probably connected above all with the increased hardness in the surface layer. Compression residual stresses are especially effective during the cracks development caused by fretting; in the course of whole fatigue life they seem to be less important.

V. CONCLUSIONS

The data on fatigue strength under the fretting conditions on nitrided and carbonitrided flat bars of carbon EA1N steel (strength 578.3 MPa) and low-alloy CrMo EA4T steel (strength 736.4 MPa) were obtained. The tests were performed at repeated tensile stress on the resonance fatigue testing machine with the use of special jig for fretting. Specific contact pressure was 21.7 MPa, slip amplitude 13 – 17 µm. The results were compared with the results of fatigue tests with and without fretting obtained on bars of the same steels without surfacing.

- Fatigue strength of nitrided and carbonitrided bars of investigated steels under the fretting conditions is in all cases higher than that of bars without surfacing.

- In the case of *nitrided* bars, the fatigue limit of both steels is the almost same as in the case of bars without surfacing and without fretting. Fretting fatigue limit of nitrided low-alloy EA4T steel bars is σ_{hC} = 450 MPa, which is only slightly lower than this one (σ_{hC} = 480 MPa) of bars without surfacing and without fretting. Carbon EA1N steel bars show the value of fatigue limit σ_{hC} = 320 MPa which is the same as in the bars without surfacing and without fretting. The unfavorable effect of fretting was completely suppressed in this case.
- In the case of *carbonitrided* bars, the favorable effect of surfacing under fretting conditions is lower in both steels. EA4T steel carbonitrided bars have fatigue limit under the fretting conditions σ_{hC} = 310 MPa, which is higher than the value obtained on the bars without surfacing and with fretting (σ_{hC} = 260 MPa); on the other hand, the unfavorable effect of fretting was not entirely suppressed in this case. Fatigue limit of bars without surfacing and without fretting is (as mentioned above) considerably higher, σ_{hC} = 480 MPa. Fatigue limit of EA1N steel bars under the fretting conditions and with surfacing is σ_{hC} = 270 MPa, which is only slightly higher value as in the case of bars with fretting and without surfacing, σ_{hC} = 260 MPa.
- According to the hardness measurements, the favorable effect of surfacing, especially of nitriding, seems to be caused by an increased hardness in the surface layer as compared with the base material. This is the most striking in the nitrided EA4T low-alloy steel bars with high hardness values in the layer. High compression residual stress in the surface layers have a retardation effect during the development of cracks resulting from fretting and their influence on the fatigue strength of bars is less important.

ACKNOWLEDGMENT

This work was carried out within project supported by Ministry of Education, Youth and Sport of Czech Republic, grant MSM 2579700001

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