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Fatigue failure of micro-alloyed 23MnB4 steel

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Properties

ABSTRACT

Purpose: In the following paper there have been the structure and fatigue properties of micro-alloyed 23MnB4 steel in initial state and after heat treatment evaluated.
Design/methodology/approach: Fatigue test of micro-alloyed 23MnB4 steel was completed by metallographic and fracture analyses. For scope the methods of the light microscopy and SEM were used.
Findings: Microstructure of examined alloy in initial state was characterized mostly by fine ferrite with pearlitic net and in state after heat treatment was formed by martensite or partly by bainite and after tempering was formed by tempered martensite. Objective of this work consisted in determination of fatigue characteristics of micro-alloyed 23MnB4 steel, including fracture analyze. Results of fatigue testing at various stress levels for the samples in initial state and after the heat treatment have confirmed that obtained values of cycles to rupture were at least 585 000 cycles. Change of fatigue properties in dependence on heat treatment of the used steel.
Research limitations/implications: For define fracture area a samples must be provide with notch. The experiment was limited by occurrence a void in cast alloys.
Practical implications: The results may be utilized for application of the investigated material in process of manufacturing.
Originality/value: These results contribute to explanation of fracture mechanism of micro-alloyed 23MnB4 steel.
Keywords: Mechanical properties, Micro-alloyed 23MnB4 steel, Fatigue test, Fracture characteristics

1. Introduction

Progress in development of new structural steels present micro-alloy steels. Micro-alloying is used in steels in the range from very low carbon contents up to eutectoid composition. Most important micro-alloying elements are V,Ti, Nb and lately also B Micro-alloying enables obtaining of the required plastic properties in materials with simultaneous preservation of strength properties. Suitable required material properties are achieved in low-carbon steels containing 0.2-0.3% C and in alloyed steels with 1-1.5% Mn (see Table 1), which contributes also to grain refinement and decrease of transformation temperature, which has positive influence on solubility of micro-alloying elements. Addition of Niob increases resistance against grain coursing to temperature 1300°C and minimalizes arising of bainite. Most affectivity of Nb is in the case of fine disperse carbonitride Nb(C,N) The required properties are obtained by appropriate combination of all these elements together with suitable selection of technological parameters.

Influence of refinement of ferritic grain down from 10 to 5 μm in current micro-alloyed steels is manifested by increased yield strength by 70 MPa and by decrease of transition temperature by 40 °C [12, 15].

2. Used experimental methodology and material

For experiment commercial made steel was use in form of wire. Wire from steel 23MnB4, which belongs to low-carbon steels, is determined for pressing and stamping. Steel wire is suitable for fastening purposes (bolts, nuts, rivets). Surface quality of wire is highly non-uniform. Wires determined for cold drawing are rolled from crude (non-cleaned) bars. That's why quality of wire surface is the critical parameter of these grades [10, 11]. Surface defects are admissible max. into depth of 0.25 mm.

Table 1.
Chemical composition of 23MnB4 steel

Contents of elements	C	S	P	B	Ti	Al	V
Mass [%]	0.24	0.01	0.01	0.003	0.02	0.03	0.003

Mo	N	Mn	Si	Cu	Ni	Cr
0.009	0.008	0.87	0.06	0.04	0.03	0.3

2.1. Heat treatment

Due to possible use of material in condition after heat treatment, part of samples was subjected to heat treatment. Selected types of heat treatment corresponded to normally used types for these steel grades [13, 14]. Part of samples was studied in state after quenching and the other part in state after quenching and tempering. Reheating of samples for quenching and tempering was done in electric laboratory furnace LH09/13 MT600 with automatic temperature regulation under protective argon.

1) Quenching parameters: reheating to temperature of 910°C, dwell 35 min followed by cooling in oil heated to temperature of 80°C.
2) Tempering parameters: reheating to temperature of 425°C and 480°C, dwell 50 min followed by cooling on air.

2.2. Execution of tests

Evaluation of fatigue properties of investigated micro-alloyed steels was made with use of samples in initial state and after selected heat treatment [8].

Fatigue tests were realised by available method of fatigue testing at rotation on quadruple fatigue testing machine UBM 4.

Fatigue tests were made in conformity with requirements of the relevant standards related to fatigue. Initial material for evaluation of fatigue properties of investigated micro-alloyed steels was supplied in the form of formed bars with diameter of 11.8 mm. The samples 220 mm long needed for fatigue testing at rotation on quadruple fatigue testing machine UBM 4 were cut from these bars.

Due to the used testing machine, expected use of investigated steel, dimensions of test bars and possibilities at their modification for fixation (diameter of final semi-product was by 0.2 mm smaller than required diameter – i.e. 12 mm – for fixation into sample holder in the fatigue testing machine UBN 4; when a foil was used as a kind of insert, at the point of fixation in the holder there occurred preferential rupture, which influenced results of testing and moreover damaged the holder), that's why there was use a bar with a notch – peripheral groove. Notch radius was 1mm. This modification has eliminated the drawbacks mentioned above.

3. Results of testing

3.1. Metallographic evaluation of structure

Selected samples from bars in initial state and after the above mentioned heat treatment were subjected to metallographic evaluation of structure in cross-section. The samples were after usual metallographic preparation if surface etched in nital and structure was evaluated with use of the microscope Neophot 2.

Structure was in initial state formed mostly by fine ferrite with pearlitic net [1, 7, 9] structure of samples after quenching is formed by martensite, or partly by bainite, and samples after tempering are formed by tempered martensite.

Samples after heat treatment showed mild decarburisation right next to the surface of samples.

3.2. Determination of basic mechanical properties

Basic mechanical properties if used steel in initial state and after the heat treatment mentioned above were determined by tensile test on bars with smooth head in accordance with the standard EN. The samples were subjected also to hardness tests according to Vickers HV30 with use of hardness tester HPO 250. The resulting value was determined from 10 values (see Table 2).

Table 2.
Results of mechanical properties, hardness tests and fatigue tests

Material	Mechanical properties					
	R_m [MPa]	$R_{p\,0,2}$ [MPa]	A_{30} [%]	Z [%]	HV30	σ_{0C} [MPa]
V- initial state	460	432,0	30,7	74,3	145	160
K-quenched state	1100	1051	13,3	55,6	406	115
P-tempered state	980	924,0	13,3	66,4	307	105

The initial state structure, after quenching and tempering are visible in Figs. 1-4.

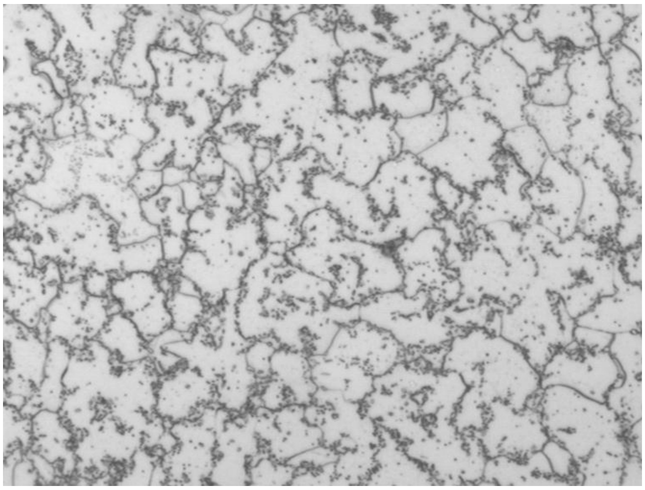

Fig. 1. Structure in initial state (Mag 500×)

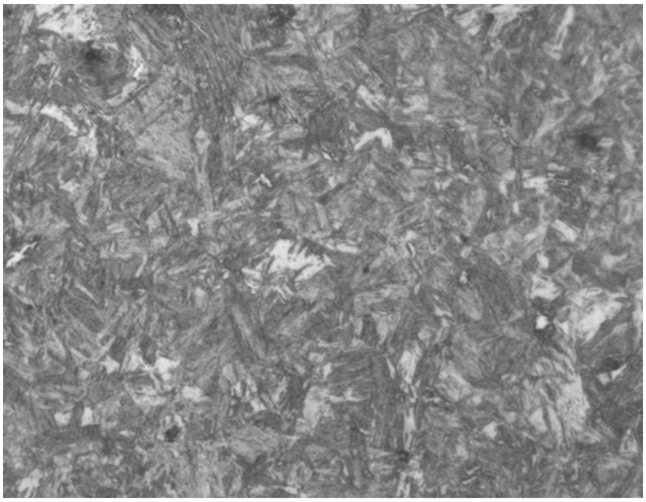

Fig. 2. Structure after quenching (Mag 500×)

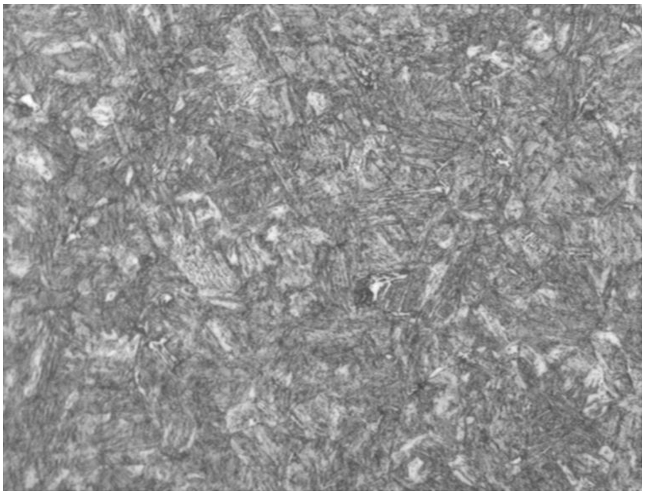

Fig. 3. Structure after tempering 425°C (Mag 500×)

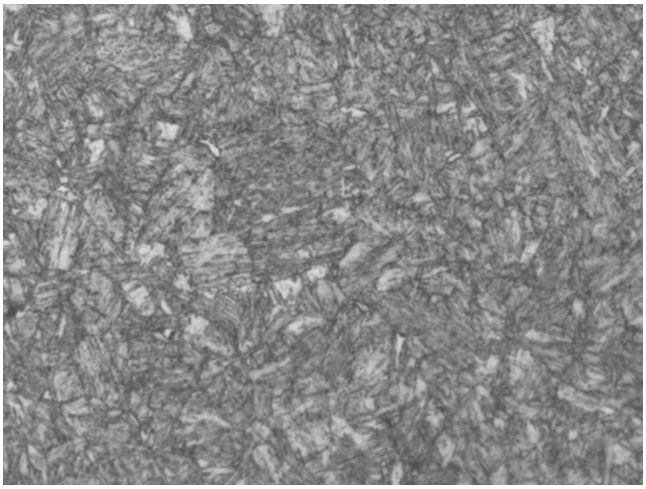

Fig. 4. Structure after tempering 480°C (Mag 500×)

3.3. Evaluation of fatigue tests

Results of fatigue tests at various levels of stress for the samples in initial state and after heat treatment described above are shown in the diagram in Fig. 5. Fatigue properties after annealing were investigated on bars, which were tempered after quenching to the temperature of 480°C. This diagram shows noticeable change of fatigue properties in dependence on heat treatment of the used steel [2-6].

Fatigue properties after quenching and tempering were lower than in initial state. After tempering fatigue properties improvement in comparison with as quenched state, although fatigue limit was increased only slightly. Values of fatigue limit σ_{0C} are also given in the Table 2. Results of fatigue tests had a considerable scatter, particularly in samples in initial state. Afterwards fracture surfaces were investigated on all bars of the used steel. The paper presents some selected examples.

3.4. Evaluation of fracture surfaces

Manifestations of fatigue damage were investigated on fracture surfaces of the above mentioned specimens. The specimens were marked according to the applied heat treatment by numeric symbol (specification of load in kp according to the scale on the fatigue machine). On all the fracture surfaces there was found presence of radial surface cracks, very fine in case of low stress, medium and very thick in case of stress nearing the fatigue limit. The largest range was in specimens K. Macroscopic photos of fracture surfaces (Macro FS) of selected specimens and details of fracture surface obtained by SEM on the microscope Jeol 50A are shown in Figures 6-22.

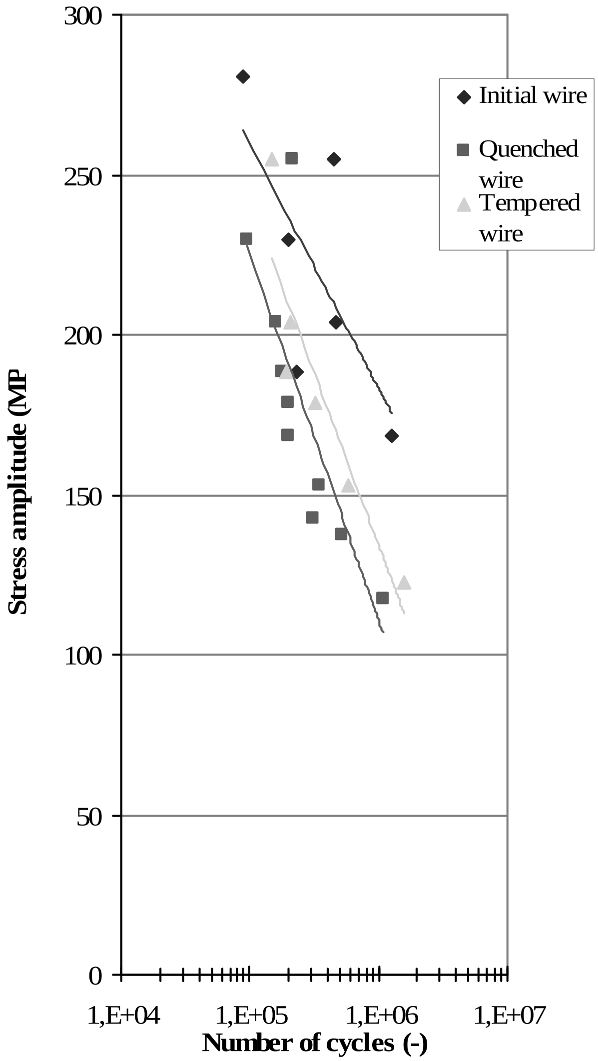

Fig. 5. Results of fatigue tests

Specimens V – initial state

In sub-surface areas of fracture there appeared in the specimens V indications of grooving near present radial cracks. Size of cracks increased from fine cracks in specimens. V 32 (see Figs. 6 and 7), V 35, V 40 up to very thick cracks in the specimen V 50 (see Fig. 8). This zone was mostly followed by the zone of striate, manifested distinctively e.g. in places V 40 D and V 50 D (see Fig. 9). In the next zone of fatigue crack propagation there were present in large quantities short cracks, often inter-connected, e.g. in places V 32 C, or V 50 D and V 50 E. In vicinity of cracks on the fracture surface grooving was also present. This zone was directly followed by the zone of static final rupture of tested sample, where the fracture surface was created by mechanism of trans-crystalline permanent damage (TPD), or trans-crystalline splitting (TS). In the samples V 32 and V 50 there occurred final rupture by mechanism TPD (see Fig. 10), in the specimen V 40 there was present also large zone of TS (see Fig. 11).

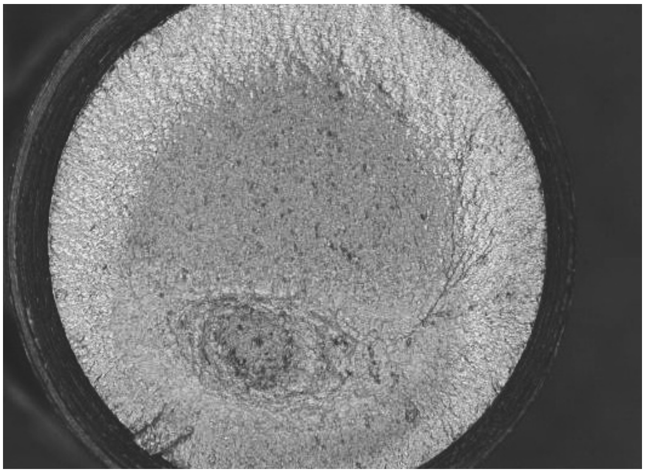

Fig. 6. Macro FS, spec. V32

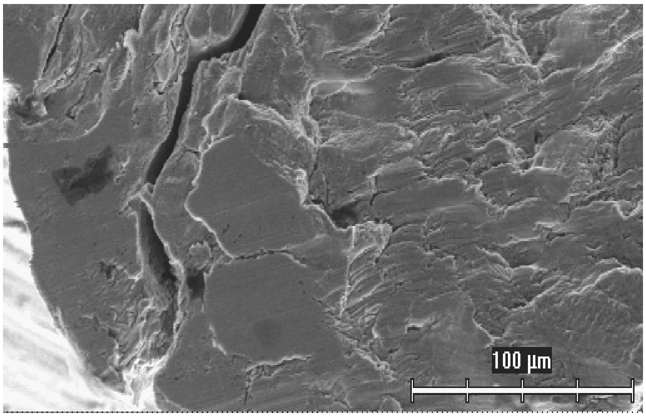

Fig. 7. Detail of fracture surface, spec. V32

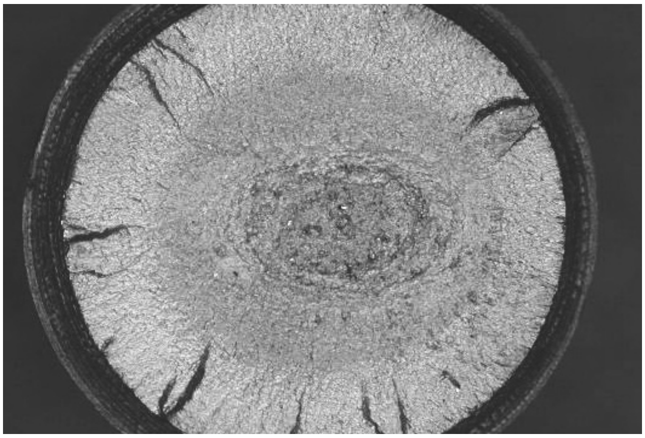

Fig. 8. Macro FS, spec. V50

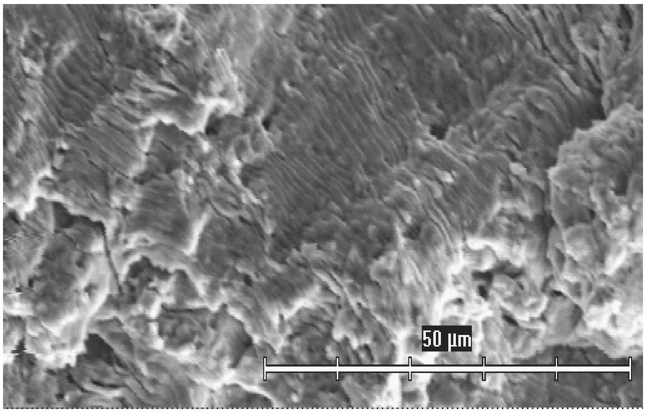

Fig. 9. Detail of fracture surface, spec. V50

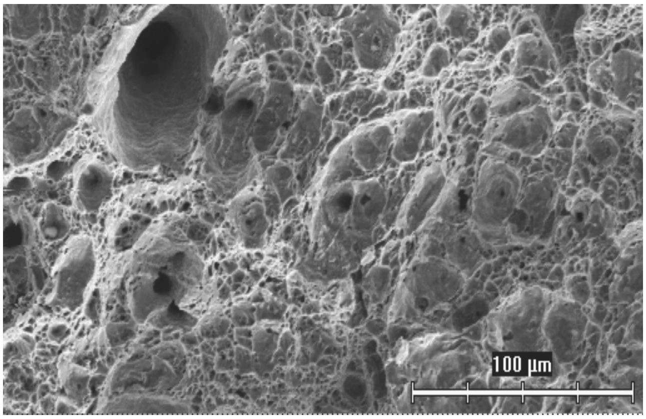

Fig. 10. Detail of finish fracture, spec. V32-TTP

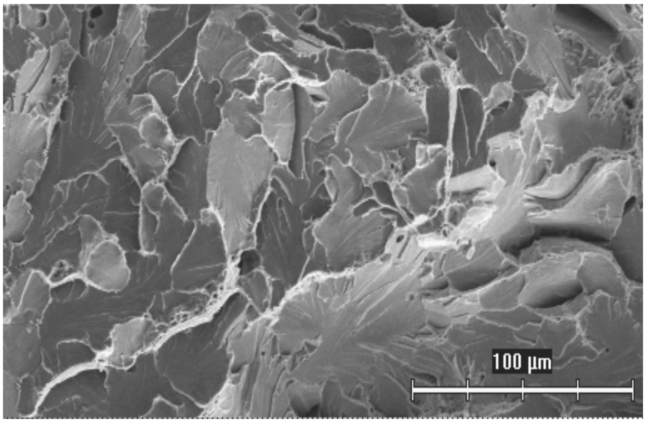

Fig. 11. Detail of finish fracture, spec. V40-TS

Specimens K – state as quenched

In quenched samples the range of occurrence of radial surface cracks was the greatest. Zones of grooving were more distinct – K 30, K 37 (see Figs. 12, 13) and they occurred at lower stress than in the spec. V. The related following zone of occurrence of short cracks – e.g. K 30, K 37 (see Fig. 14a, b) was directly related with the zone of final rupture, which was created mostly by the mechanism TPD – K 23 (see Fig. 15). In the spec. K 30 C and K 37 C – there was influence not only of mechanism TPD, but partly also mechanism TS – K 30 C, K 37 (see Fig. 16).

Specimens – P – state as quenched and tempered

Range of occurrence of radial cracks was lower than in the previous case (see Fig. 17), with the exception of the spec. P 24 and P 40 (see Fig. 18). Mechanism of propagation of fatigue crack was similar as in case of quenched specimens. In majority of specimens it was possible to observe a distinct zone of grooving - P 22, P 37, P 40 (see Figs. 19, 20) and zone of occurrence of short cracks – P 22 (see Fig. 21) P 37, P 40, linked to the zone of static final rupture – P 22, P 37. Final rupture occurred mostly by mechanism of trans-crystalline plastic deformation with cavity morphology (see Fig. 22).

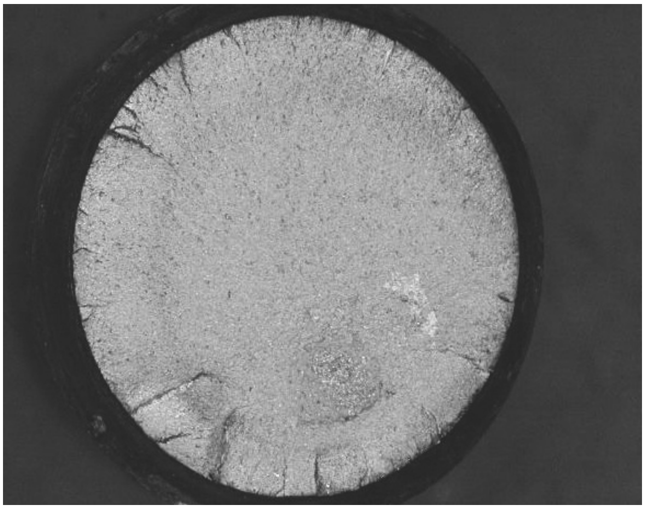

Fig. 12. Macro FS,,spec. K30

Fig.13. Macro FS,,spec. K37

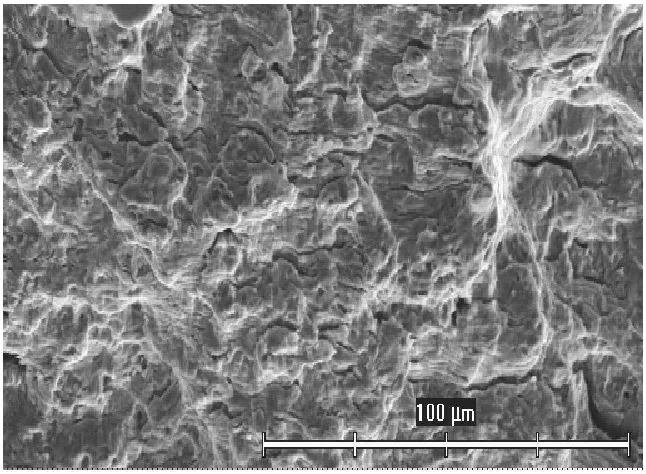

Fig. 14a. Detail of fracture surface, spec. K30

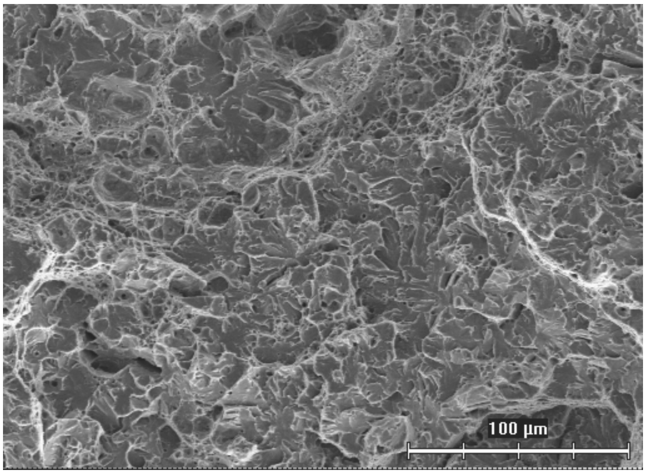

Fig. 16. Detail of finish fracture, spec. K30

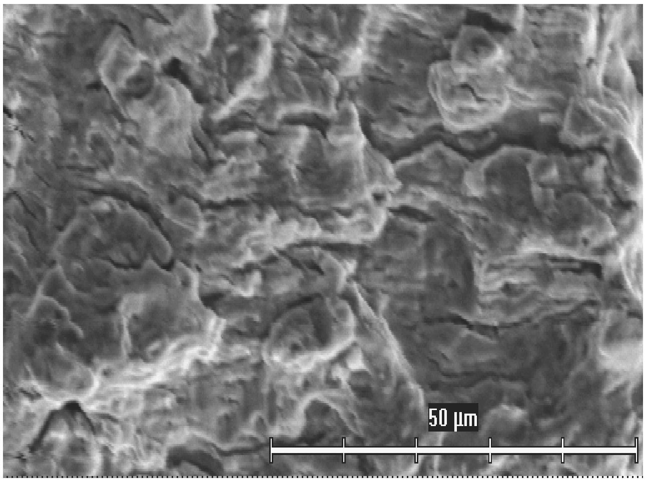

Fig. 14b. Detail of fracture surface, spec. K30-zoom

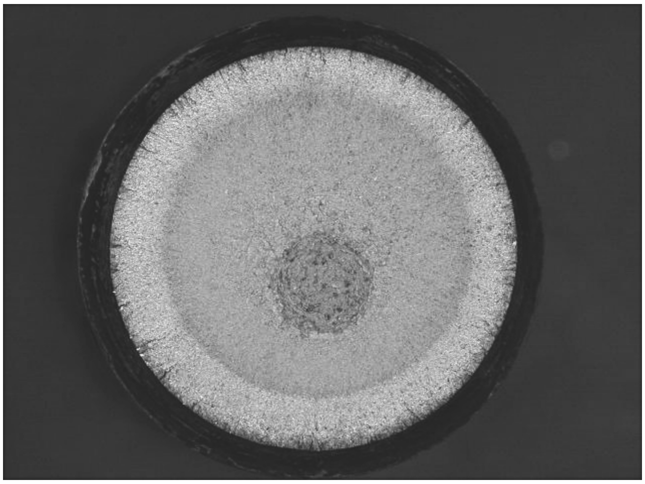

Fig. 17. Macro FS, spec. P22

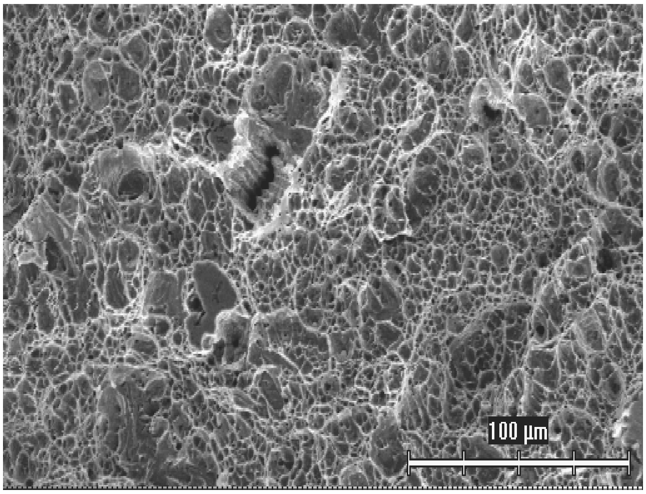

Fig. 15. Detail of finish fracture, spec. K23

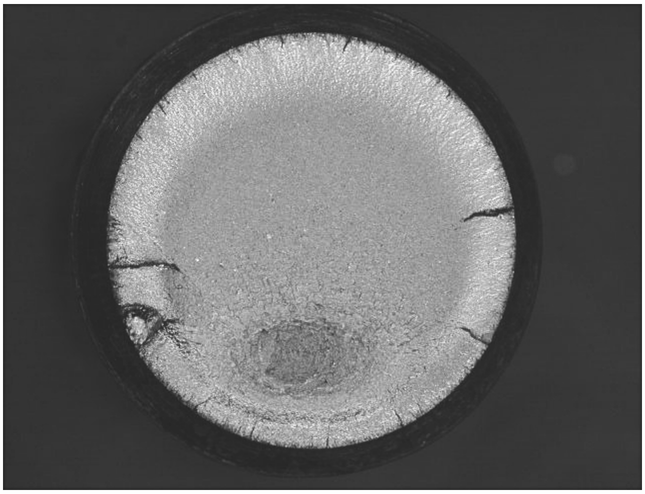

Fig. 18. Macro FS, spec. P40

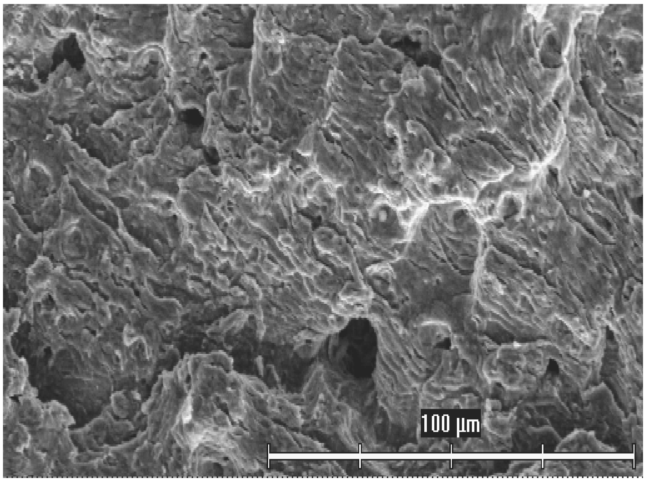

Fig. 19. Detail of fracture surface, spec. P22

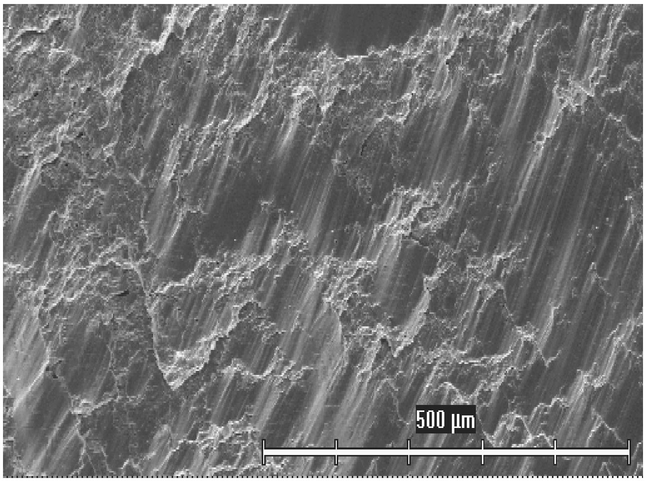

Fig. 20. Detail of fracture surface, spec. P37

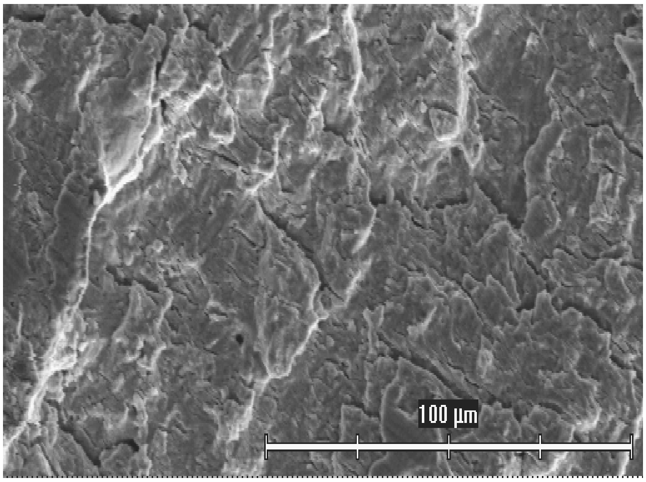

Fig. 21. Detail of fracture surface, spec. P37

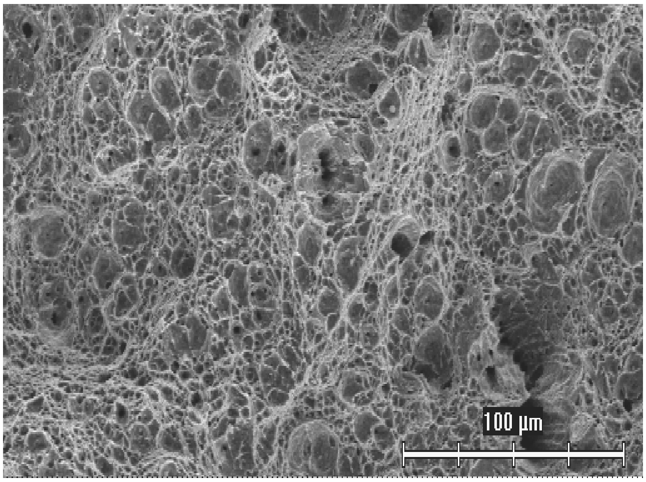

Fig. 22. Detail of finish fracture, spec. P37

4. Conclusions

The different heat treatment kinds employed contributed to the improvement of mechanical properties of the investigated alloy and contemporarily change its fatigue properties.

Results of fatigue testing at various stress levels for the samples in initial state and after the heat treatment mentioned above have confirmed that obtained values of cycles to rupture were at least 585 000 cycles. This value fulfils the requirements for production of high-strength fasteners.

It is obvious from described results that there has occurred change of fatigue properties in dependence on heat treatment of the used steel.

Fatigue properties after quenching and tempering were lower than in initial state. After tempering there are occurs their improvement in comparison with quenched state, although fatigue limit was increased only slightly. Results of fatigue tests had a considerable scatter, particularly in the samples in initial state.

Manifestations of fatigue damage were investigated on fracture surfaces of the samples. On all fracture surfaces there was found occurrence of radial surface cracks, very fine in case of low stress, medium and very thick in case of stress nearing of the limit fatigue, namely in the case of specimens – V – initial state.

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