UDK 621.78:620.178.3
Professional article/Strokovni članek

ISSN 1580-2949
MTAEC9, 48(6)959(2014)

FATIGUE-LIFE ENHANCEMENT OF SHEETS MADE OF 34CrNiMo6 STEEL

POVEČANJE ODPORNOSTI PROTI UTRUJANJU PLOČEVIN IZ JEKLA 34CrNiMo6

Jan Džugan, Zbyšek Nový, Martina Marešová
COMTES FHT Inc., Průmyslová 995, Dobřany, Czech Republic
jan.dzugan@comtesfht.cz

Prejem rokopisa – received: 2013-10-04; sprejem za objavo – accepted for publication: 2014-01-27

Currently available and well-known materials can obtain superior properties when treated with special procedures. Nowadays special treatment procedures are efficiently developed with the use of physical simulators. Physical simulators allow a treatment optimization for small-scale laboratory samples that can be subsequently transferred to real production processes. There is always a need for a successful transfer of knowledge from small-scale laboratory experiments to a real production of, for example, metal sheets. In the current paper the previously developed thermomechanical procedures for the 34CrNiMo6 steel under laboratory conditions are applied to the metal-sheet production. Very promising properties of the bulk-material samples processed in a physical simulator were obtained; the challenge was to obtain similar properties of real metal sheets by transferring the laboratory procedure to a metal-sheet production process. Several previously developed thermomechanical procedures were applied to the metal-sheet production. The sheets exhibit a very good combination of the tensile strength exceeding 1500 MPa and the elongation reaching 10 %. The fatigue strength was investigated in all the considered states and a comparison of the materials treated with various thermomechanical procedures was carried out.

Keywords: thermomechanical treatment, fatigue, steel, metal sheets

Razpoložljivi in dobro poznani materiali, obdelani s posebnimi postopki, lahko pridobijo posebne lastnosti. Ti postopki obdelave se danes razvijajo s fizikalnimi simulatorji, ki omogočajo optimiranje obdelave majhnih laboratorijskih vzorcev, rezultati pa se lahko kasneje prenesejo v realno proizvodnjo. Kljub temu vedno obstaja potreba po uspešnem prenosu iz laboratorijskih eksperimentov na majhnih vzorcih v realno proizvodnjo, kot je primer kovinskih pločevin. V tem primeru so bili predhodno laboratorijsko razviti termomehanski postopki za jeklo 34CrNiMo6, uporabljeni pri proizvodnji pločevine. S fizikalnim simulatorjem so bile dobljene zelo obetajoče lastnosti osnovnega materiala, izziv pa je bil dobiti podobne lastnosti realnih pločevin s prenosom laboratorijskih postopkov v proizvodnjo. Pri proizvodnji pločevin so bile uporabljene številne vrste predhodno razvite termomehanske obdelave. Pločevine imajo dobro kombinacijo natezne trdnosti nad 1500 MPa, raztezek pa dosega 10 %. Pri vseh upoštevanih stanjih je bila preizkušena odpornost proti utrujanju in opravljena je bila primerjava materialov po različnih termomehanskih obdelavah.

Ključne besede: termomehanska obdelava, utrujanje, jeklo, pločevine

1 INTRODUCTION

This work is a part of a currently running project dealing with the material-property improvement using a special treatment. The material of interest in the present case is the 34CrNiMo6 steel. The material investigated is widely used for heavily loaded parts such as rotors or crank shafts. This material is generally used in bulk form. Investigations leading to an optimization of the material properties for bulk applications were performed[1,2]. The results obtained were very good and thus the investigations are extended also to thin-sheet applications, where a high strength with a certain degree of available plastic deformation is of high demand at present[3,4]. The input material for the study included the sheets with a thickness of 1 mm rolled from a diameter bar 60 mm. Several heat-treatment procedures were applied and the resulting mechanical properties and microstructures were observed. Special consideration was given to the fatigue strength for the obtained material states in the current case.

2 HEAT TREATMENT

The material of interest underwent several heat treatments. Following the previous investigation, the influences of the two main parameters on the resulting material properties were investigated: the cooling rate during quenching and the impact of the subsequent annealing. Two cooling mediums were used, oil and nitrogen gas. The procedure of applying oil was performed with the use of a standard furnace. The procedure of applying nitrogen was carried out in a special vacuum furnace using nitrogen treatment. The nitrogen cooling was carried out at a pressure of 6 bar. The applied cooling rate for nitrogen was roughly between oil and air, thus slower than in the first case of cooling. The samples were quenched in both above-mentioned ways and a half of the each batch of the samples was subsequently annealed. Detailed information on the heat-treatment conditions can be found in **Table 1**.

3 TENSILE TESTS

Tensile tests according to CSN EN ISO 6892-1 were performed at room temperature. Standard flat specimens with a gauge-section width of 12.5 mm and a gauge length of 50 mm were tested. Three samples were tested for each material condition. Prior to the testing, the specimen dimensions were measured and the original gauge length for the elongation *A*5 determination was marked on each specimen. After the test, the yield stress $R_p = 0.2$ and tensile strength R_m were determined. The final gauge length was also measured after the test and the elongation after fracture *A*5 was evaluated as well as the uniform elongation at the tensile strength A_g and the cross-section reduction *Z*. The records of the tests can be found in **Figure 1**. The evaluated material properties are summarized in **Table 2**.

The samples quenched in oil generally exhibited slightly higher strength values than the samples treated in nitrogen. It can also be seen that there is a significant difference in the tensile-strength value between the nitrogen-quenched samples with and without annealing. The values for the annealed samples are lower by about 150 MPa, while the other tensile-test parameters are almost identical. In the case of the oil-treated samples, a very small decrease in the tensile strength is found between the annealed samples and the samples without annealing. The annealed samples exhibit an improvement in the other parameters. The yield stress is especially improved, by almost 150 MPa.

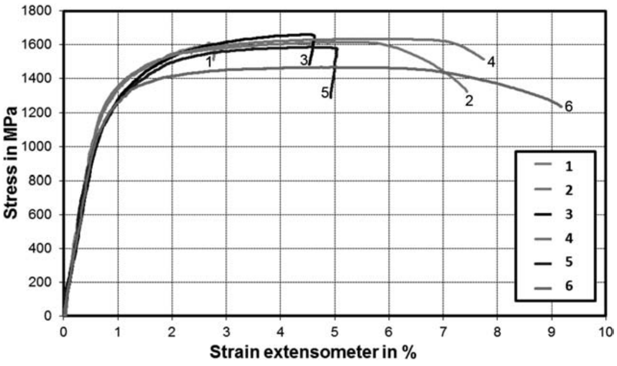

Figure 1: Examples of tensile-test records for the considered heat-treated states

Slika 1: Primeri krivulj pri nateznem preizkusu za uporabljena toplotno obdelana stanja

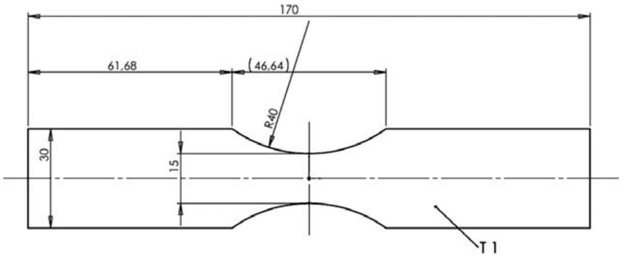

Figure 2: Specimen for fatigue tests

Slika 2: Vzorec za preizkus utrujanja

4 FATIGUE TESTS

High-cycle fatigue tests were performed on the experimental batches with a magnetoresonant testing machine. The tests were run in the force-control mode at room temperature. The geometry of a test piece is shown in **Figure 2**. The test frequencies were about 120 Hz. The fatigue strength was evaluated as the intersection of the line fitted to the measured data with the line representing $1 \cdot 10^7$.

The evaluated high-cycle fatigue-strength values are summarized in **Table 3**. The obtained fatigue curves are shown in **Figure 3**. The results obtained point out a significant difference in the fatigue strength between the

Table 1: Heat-treatment-regime overview

Tabela 1: Pregled uporabljenih vrst toplotne obdelave

Sample	Normalizing	Quenching			Annealing		
		°C	Hold	Cooling medium	°C	Hold	Cooling medium
1	860 °C/vermikulit	850	20 min	nitrogen	–	–	–
2	860 °C/vermikulit	850	20 min	nitrogen	200	120 min	air
3	860 °C/vermikulit	850	20 min	oil	–	–	–
4	860 °C/vermikulit	850	20 min	oil	200	120 min	air
5	860 °C/vermikulit	850	20 min	nitrogen	–	–	–
6	860 °C/vermikulit	850	20 min	nitrogen	200	120 min	air

Table 2: Tensile-test results

Tabela 2: Rezultati nateznih preizkusov

Treatment	$R_{p0.2}$ (MPa)	R_{eH} (MPa)	R_{eL} (MPa)	R_m (MPa)	A_g (%)	A_{50} (%)	*Z* (%)
1	1173.8	939.4	295.3	1615.9	3.4	4.3	32.8
2	1183.8	1208.7	283.8	1461.3	3.5	4.6	33.0
3	1164.8	1170.7	269.3	1665.0	3.9	5.1	10.8
4	1308.7	1272.0	275.2	1648.8	4.4	5.5	12.9
5	1193.2	946.4	305.6	1626.7	2.6	5.0	41.5
6	1226.8	606.3	273.0	1546.8	4.1	5.3	39.4

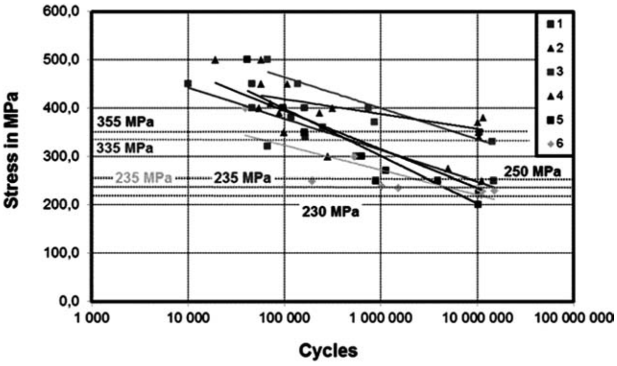

Figure 3: High-cycle fatigue curves for the materials investigated
Slika 3: Krivulje visokocikličnega utrujanja preiskovanih materialov

oil- and nitrogen-quenched samples. The difference is about 100 MPa in favor of the oil-treated samples. The difference between the samples with and without annealing is not significant in the cases of both sample treatments. The highest fatigue strength can be found for the annealed oil-treated samples.

Table 3: Results of high-cycle fatigue tests
Tabela 3: Rezultati preizkusov visokocikličnega utrujanja

Material	Fatigue strength (MPa)
1	235
2	250
3	335
4	355
5	230
6	235

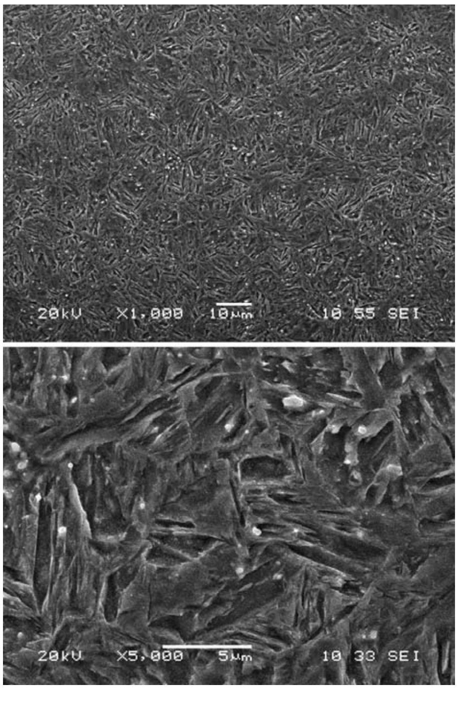

Figure 4: Microstructure after regime 1 (SEM)
Slika 4: Mikrostruktura po režimu 1 (SEM)

5 METALLOGRAPHY

Metallographic investigations were performed in order to assess the obtained microstructures for all the considered material states. The standard preparation of metallographic samples was done. The samples were observed with a light microscope and investigations at

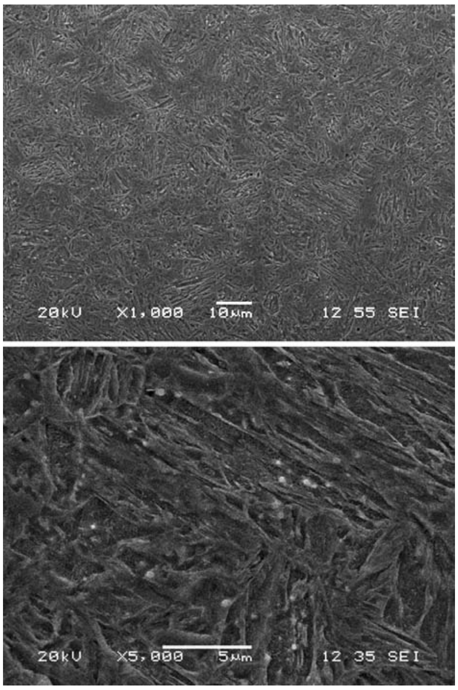

Figure 5: Microstructure after regime 2 (SEM)
Slika 5: Mikrostruktura po režimu 2 (SEM)

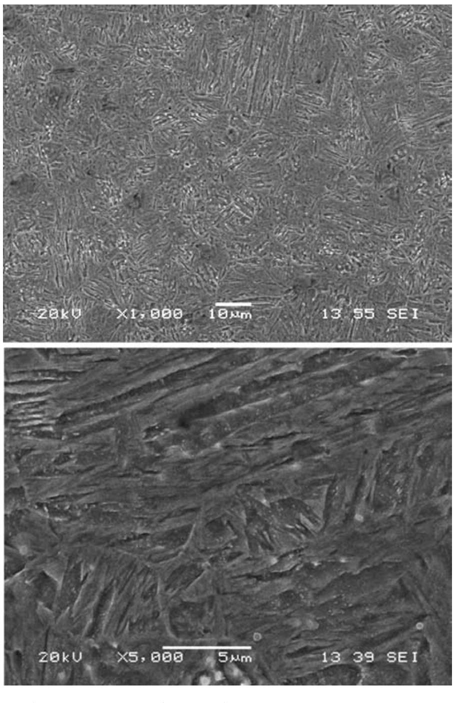

Figure 6: Microstructure after regime 3 (SEM)
Slika 6: Mikrostruktura po režimu 3 (SEM)

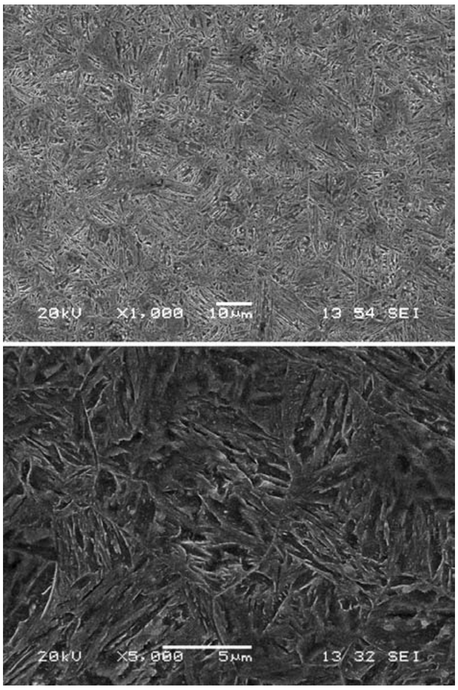

Figure 7: Microstructure after regime 4 (SEM)
Slika 7: Mikrostruktura po režimu 4 (SEM)

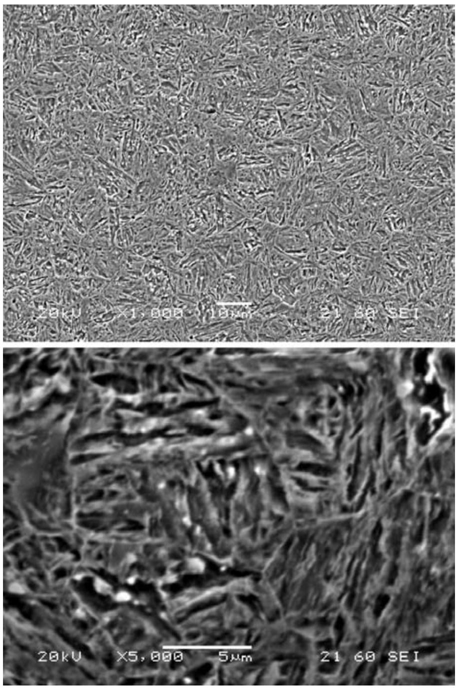

Figure 9: Microstructure after regime 6 (SEM)
Slika 9: Mikrostruktura po režimu 6 (SEM)

higher magnifications were carried out with a scanning electron microscope. The obtained microstructures for all the applied regimes are shown in **Figures 4** to **9**.

The microstructure of the sample that underwent quenching in nitrogen is shown in **Figure 4**. The microstructure consists of fine martensite with original carbides, which were not dissolved in austenite before the hardening, The length of the martensite plates seems to be between 5–10 µm. The average diameter of the undissolved carbides is about 0.4 µm. There is no fine-carbide dispersion precipitation in the microstructure after the hardening.

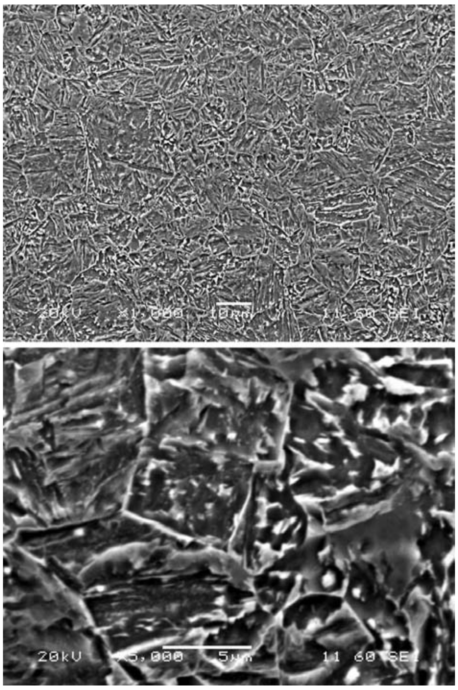

Figure 8: Microstructure after regime 5 (SEM)
Slika 8: Mikrostruktura po režimu 5 (SEM)

Figure 5 depicts the microstructure of the nitrogen-quenched and annealed sample. A microstructure very similar to that of the previous nitrogen-quenched sample can be found. It includes fine martensite und undissolved carbides. Additionally, very fine, needle-like carbide particles that almost create a network structure can be found.

The microstructure after oil quenching (regime 4), including martensitic needles without carbides is shown in **Figure 6**.

A very fine precipitate seems to be present in the oil-quenched sample after quenching followed by annealing. This microstructure is depicted in **Figure 7**.

Fine martensitic grains with fine needle-like particles that almost create a network structure around the original austenitic grains after the treatment with regime 5 are shown in **Figure 8**. The average diameter of the undissolved carbides is 0.5 µm.

A very fine-grained martensitic microstructure with a very low presence of undissolved carbides obtained after the treatment with regime 6 can be seen in **Figure 9**.

6 RESULTS AND DISCUSSION

Sheets with a thickness of 1 mm were rolled from a diameter bar 60 mm. Normalizing, quenching and tempering processes were consequently performed on the sheets. Two variants of quenching were performed, hardening in oil and hardening in nitrogen gas under a pressure of 6 bar. A metallographic analysis, quasistatic tensile tests and high-cycle fatigue tests were realized on the experimental material.

The metallographic analysis shows that quenching in oil is faster than in pressure nitrogen gas 6 bar. The mixture of martenzite and bainite occurred after the quenching in nitrogen, while pure fine martensite is visible after the oil quenching. The annealing after both variants of quenching caused a precipitation of very fine, needle-like carbides. The samples after the quenching in oil exhibit higher yield strength, higher tensile strength and higher fatigue strength in comparison with the samples after the quenching in nitrogen. This result is expected as the martensitic samples after the oil quenching have higher strength properties. A drop in the tensile strength was found after the annealing at 200 °C for the samples quenched in nitrogen. On the other hand, the oil-quenched samples exhibited no drop in the tensile strength after the annealing, and their yield strength increased by almost 150 MPa. The fatigue strength was also found to be higher for the oil-quenched samples than for the nitrogen-quenched ones.

7 CONCLUSION

A laboratory preparation of ultra-high-strength sheets from the 34CrNiMo6 steel was achieved. The sheets with a thickness of 1 mm, a tensile strength above 1650 MPa and fatigue strength of 350 MPa were produced. A standard phenomenon was observed when the tensile-test properties and the fatigue strength obtained after the mild quenching in nitrogen were lower than in the case of the faster oil quenching. The tempering at 200 °C caused a further enhancement of both the yield strength and the elongation of the oil-treated material. Excellent attained properties of the investigated sheets allow further possibilities for a mass reduction of the heavy-loaded sheet constructions, for example, in the automotive industry.

Acknowledgment

This paper includes the results obtained within project ED2.1.00/03.0077 - West-Bohemian Centre of Materials and Metallurgy (2011-2014, MSM/ED).

8 REFERENCES

[1] J. Džugan, Z. Nový, P. Konopík, P. Motyčka, Improvement of fatigue properties of 34CrNiMo6 steel by controlled thermomechanical treatment, Proc. of the conference Metal 2010, Roznov pod Radhostem, Czech Republic, 2010, 421–426

[2] J. Džugan, Z. Nový, M. Sosnová, Improvement of fatigue life of 34CrNiMo steel by thermomechanical treatment, Advanced Materials Research, 264–265 (**2011**), 1725–1730

[3] Z. Nový, J. Džugan, P. Motyčka, M. Donátová, J. Dlouhý, Fatigue life improvement of metal sheets made of 34CrNiMo6 steel with the use of physical simulator, Proc. of the conference Metal 2011, Brno, Czech Republic, 2011

[4] J. Džugan, Z. Nový, P. Motyčka, J. Martínková, P. Martínek, Mechanical properties optimization of metal bars and sheets made of 34CrNiMo6 steel, Journal of Iron and Steel Research (International), (**2011**) S1, 956–960