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ANALYZING THE HEAT-TREATMENT EFFECT ON THE MECHANICAL PROPERTIES OF FREE-CUTTING STEELS

ANALIZA VPLIVA TOPLOTNE OBDELAVE NA MEHANSKE LASTNOSTI AVTOMATNIH JEKEL

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In this research, the heat-treatment effect on the mechanical properties of free-cutting steels was investigated. Free-cutting steels (FCSs) are used where high degrees of machining are required as they increase the machining speed and reduce the tool wear. The effect of heat treatment on mechanical properties was identified using tensile and fatigue tests, and microstructure images taken with a scanning electron microscope (SEM). The studied material included commercially available AISI 12L14 cylindrical bars of free-cutting steel. FCS was heated to 900 °C and held at this temperature for different time spans. The degradation of the mechanical properties of free-cutting steel due to the elevated temperature was assessed. At a microscopic level, more mechanical damage was observed between the steel matrix and the second phase of the heat-affected specimens.

Keywords: fatigue, tensile strength, free-cutting steel, heat treatment

V prispevku je bil raziskan vpliv toplotne obdelave na mehanske lastnosti avtomatnih jekel. Avtomatna jekla (FCS) se uporabljajo v primerih, ko so zahtevane velike stopnje obdelave, saj dopuščajo večje hitrosti rezanja ob manjši obrabi orodja. Vpliv toplotne obdelave na mehanske lastnosti je bil določen z rezultati nateznega preizkusa in preizkusa utrujenosti. Z vrstičnim elektronskim mikroskopom (SEM) so bili narejeni posnetki mikrostrukture. Preiskovane so bile komercialno dosegljive palice iz avtomatnega jekla AISI 12L14. FCS je bil segret na 900 °C in različno dolgo zadržan na tej temperaturi. Določeno je bilo zmanjšanje mehanskih lastnosti avtomatnega jekla zaradi povišane temperature. V toplotno obdelanih vzorcih je bilo z mikroskopom opaženih več mehanskih poškodb.

Ključne besede: utrujenost, nateg, avtomatna jekla, toplotna obdelava

1 INTRODUCTION

A significant increase in mechanical-machining costs has led to a reappraisal of the importance of steel machinability.[1] In order to achieve higher automation and cost competitiveness, a series of steels commonly known as free-cutting steels (an S minimum of 0.10 %) are being increasingly used. Special lead-containing steels differ from the normal structural, quenched-and-tempered and case-hardened steels because of the presence of Pb (approximately 0.15–0.35 %) in order to improve their machinability. These steels allow an excellent chip removal and they are particularly suitable for large productions.[2,3] Lead has a very good lubricating effect and, combined with the heating produced by the tools, breaks the chips, thus allowing for a higher productivity resulting in more advantageous production runs. It also guarantees a lower tool wear.

Free-cutting steels are used where high degrees of machining are required as they increase the machining speed and reduce the tool wear. These steels contain manganese, lead, sulphur and phosphorous, which improve the machining performance. The additives reduce the coefficient of friction between the tool and chip, thereby reducing the cutting force, the temperature and the built-up edge formation, allowing higher feeds and/or speeds.[4–6] Free-cutting steels are preferred in manufacturing mechanical components for their improved machinability.[6–8]

AISI 12L14 is a Pb-added low-carbon resulphurised free-cutting steel containing 0.3 % Pb and 0.3 % S. It is used in large quantities in automotive applications such as transmission oil hydraulic control valves and oil hydraulic hose connectors, in printer shafts and other parts of office automation equipment. Lead is insoluble in free-cutting steel and during the cutting process lead particles are sheared and smeared over the tool-chip interface.[9,10] Lead improves the machinability with little effect on mechanical properties. Due to its low shear strength, lead acts as a solid lubricant. Manganese and sulphides assist the chip formation and reduce the friction and wear of a cutting tool. Free-cutting steels are used where high degrees of machining are required as they increase the machining speed and reduce the tool wear.

Table 1: Chemical composition of free-cutting steel (AISI 12L14) in mass fractions, (*w*/%)
Tabela 1: Kemijska sestava avtomatnega jekla (AISI 12L14) v masnih deležih, (*w*/%)

C	Si	Mn	P	S	Cr	Mo	Ni	Cu	Pb	Fe
0.074	0.005	1.203	0.045	0.294	0.04	0.02	0.08	0.12	0.30	balance

In this study, the heat-treatment effect on the mechanical properties of FCS was investigated. FCS was heated to 900 °C and held at this temperature for different time spans. Degradation of the mechanical properties of the free-cutting steel due to the elevated temperature was assessed. The effect of heat treatment on mechanical properties was investigated using tensile and fatigue test results, and microstructure images taken with a scanning electron microscope (SEM).

2 EXPERIMENTAL PROCEDURE

The studied material included commercially available AISI 12L14 cylindrical bars of free-cutting steel with a diameter of 12 mm. The bars were machined into tensile and fatigue specimens with dimensions as shown in **Figure 1**. After the machining, the specimens were grinded with 4000 emery paper. Two samples were used for each stress level and the results were averaged for the as-received specimens and the specimens exposed to 900 °C for (3, 6, 9, 12 and 15) h. The percent chemical composition (% of mass fractions) and mechanical properties of the FCS are given in **Tables 1** and **2**, respectively. Tensile-test specimens were machined according to EN ISO 6892-1 standard. Fatigue tests were conducted on an R. R. Moore type rotating-beam fatigue-testing machine with a frequency of 25 Hz. Microstructural changes in the FCS exposed to high temperature were investigated using SEM images. Tensile tests were conducted to investigate the heat-treatment effect on the ultimate tensile strength (R_m), the yield strength (R_e), the ductility and the toughness. FCS specimens were heated to 900 °C and held at this temperature for different time spans. Degradation of the mechanical properties of free-cutting steel due to elevated temperature was investigated. More mechanical damage was observed between the steel matrix and the phase in the heat-affected specimens at a microscopic level. The effect of heat treatment on the mechanical properties was investigated using tensile and fatigue tests, and microstructure images taken with SEM. The R_m and R_e values of the FCS decreased as the toughness and ductility increased due to the effect of elevated heat.

Table 2: Mechanical properties of free-cutting steel (AISI 12L14)
Tabela 2: Mehanske lastnosti avtomatnega jekla (AISI 12L14)

Yield strength (MPa)	Tensile strength (MPa)	Elongation (%)	Brinell hardness (HB) (10 mm steel ball and 500 kg load)
465	587	12	150

3 RESULTS AND DISCUSSION

Fatigue test results for the FCS specimens with different dwell times and the as-received specimens are given in **Figure 2**. From this figure, it is seen that the fatigue strength of the FCS exposed to elevated temperature decreased. There was a limited effect of the time span affecting the fatigue strength of the tested specimens. Under the cyclic load of 300 MPa, the heat-affected and as-received specimens fractured at 50,000 and 300,000 cycles, respectively. The fatigue strength of the FCS reduced in the ratio of 83 % because of the effect of high temperature. The regression lines of the fatigue strength given in **Figure 2** are expressed as:

$$y = -a \ln(x) + b \qquad (1)$$

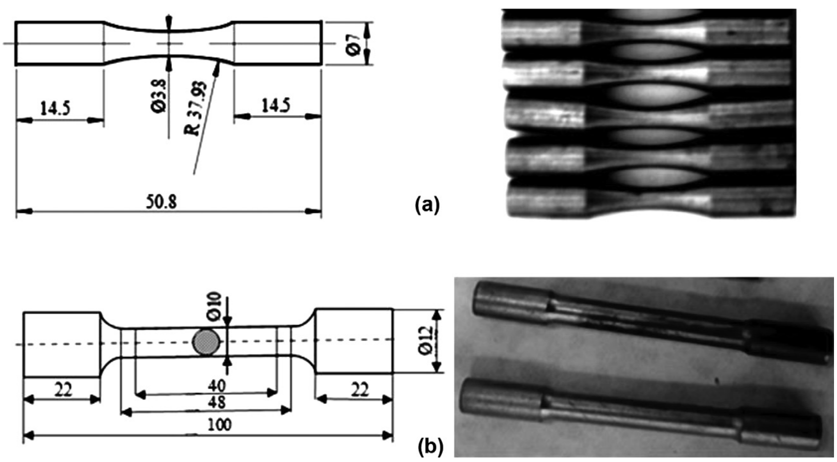

Figure 1: Dimensions and images of test specimens: a) fatigue, b) tensile test
Slika 1: Mere in posnetki preizkušancev: a) utrujanje, b) natezni preizkus

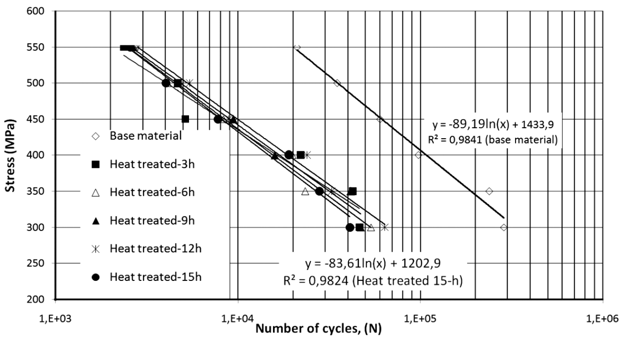

Figure 2: Effect of the heat exposure and time on the fatigue test results for FCS

Slika 2: Vpliv časa ogrevanja na rezultate utrujenostnega preizkusa FCS

where *y* is the loaded stress range, *x* is the number of cycles to failure, *a* and *b* are the fitting constants. The constants of the equations of regression lines, the *R*-square, which indicates how well data points fit a statistical model (the coefficient of determination: R^2) and the residual variance (R_v), which is a measure of the variation of the *y* values about the regression line ($R_v = 1 - R^2$) of the fatigue tests are given in **Table 3**.

Table 3: R-square, residual variance and fitting constants of the tests

Tabela 3: R-kvadrat, preostale variance in ustrezne konstante preizkusov

Experimental variables	Fitting constants of regression lines		*R*-square (R^2)	Residual variance ($R_v = 1 - R^2$)
	a	b		
Base material	–89.19	1433.9	0.9841	0.0159
Heat treated: 15h	–83.61	1202.9	0.9824	0.0176
Heat treated: 12h	–78.819	1176.1	0.9885	0.0115
Heat treated: 9h	–79.957	1178.6	0.9805	0.0195
Heat treated: 6h	–81.643	1188.4	0.9816	0.0184
Heat treated: 3h	–71.404	1093.6	0.9367	0.0633

The reduction in the fatigue strength of the specimens exposed to high temperature can be explained with microstructural changes. The grain size of the base material and the heat-affected specimens were measured as 10 μm and 25 μm, respectively, as seen from **Figure 3**. From this figure, it is seen that the grain size of the FCS increased by 250 % with the heat effect and 3–15 h time spans. The grain growth reduced the load-carrying capacity of the specimens. At the elevated temperature of 900 °C and under a long dwell time, the precipitated phase coalesced and grew in the microstructure as seen in **Figure 3**. Kalpakjian states that the grain growth reduces the grain boundaries per volume unit of a grain.[11,12] Smaller grains have a higher strength and a higher contact surface area.

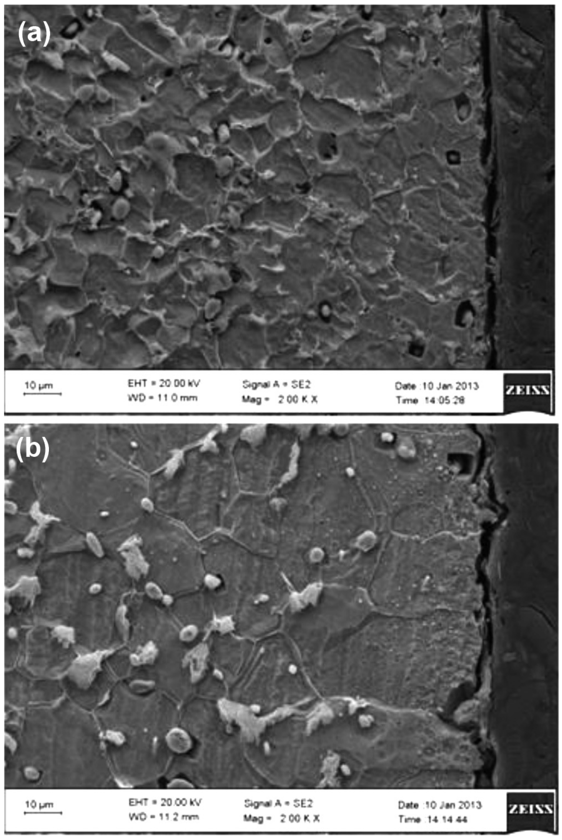

Figure 3: SEM images of grains: a) as received and b) heat treated at 900 °C for 15 h

Slika 3: SEM-posnetek zrn: a) stanje ob dobavi in b) žarjena 15 h na 900 °C

The increase in the size of the grains reduced the fatigue strength of the FCS. The ultimate tensile strength (R_m) and the yield strength (R_e) of the heat-effected FCS were reduced as seen in **Figure 4**. The toughness of the heat-affected FCS specimens was calculated with the following Equation (2):

$$\text{Toughness} = \frac{R_e + R_m}{2} \cdot e \tag{2}$$

where R_e and R_m are the yield and tensile strengths, respectively, and *e* is the engineering strain. The R_e and R_m values of the initial FCS specimens were 616 MPa and 512 MPa, respectively. For the specimens heat-treated at 900 °C for 3 h, these values were reduced to 441 MPa and 318 MPa. The reduction in R_m and R_e was 28.4 and 37.8 %, respectively. The amounts of energy per volume (toughness) that the FCS absorbed before rupturing were 100.51 MPa and 143.67 MPa for the specimens in the as-received state and heat treated at 900 °C for 15 h, respectively, as seen in **Figure 4**. The toughness of the FCS increased in the ratio of 42.94 % due to the effects of heat and time. This increase in the toughness of FCS can be explained with the disposal of the residual stress induced during manufacturing stages. The ductility of the FCS specimens was determined

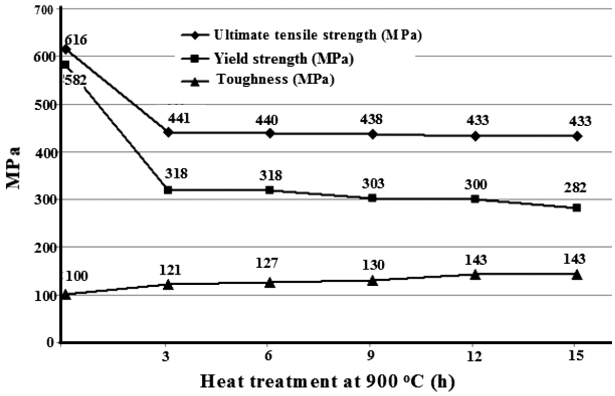

Figure 4: Effect of heat treatment on ultimate tensile strength (R_m), yield strength (R_e) and toughness of FCS
Slika 4: Vpliv žarjenja na natezno trdnost (R_m), mejo plastičnosti (R_e) in žilavost FCS

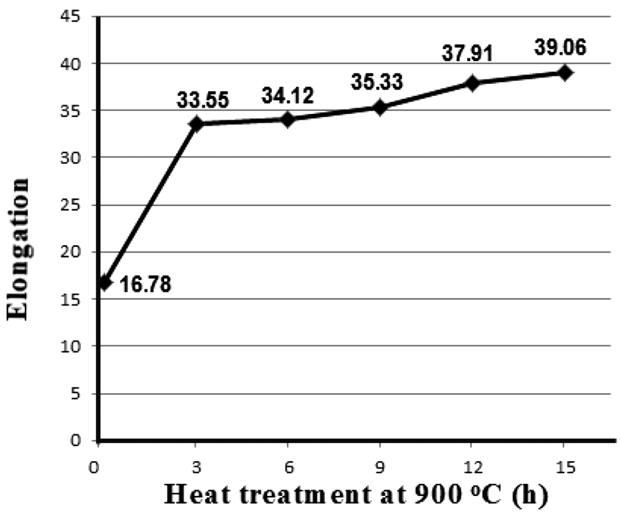

Figure 5: Heat-treatment effect on the elongation of free-cutting steel
Slika 5: Vpliv žarjenja na raztezek avtomatnega jekla

with the elongation calculated with the following Equation (3):

$$\text{Elongation} = \frac{l_f + l_0}{l_0} \cdot 100 \qquad (3)$$

where l_0 and l_f are the gage lengths of the original and fractured sample, respectively. The ductility of the FCS changed with the effect of heat treatment, as shown in **Figure 5**. The ductility was 16.78 % and 39.06 % for the as-received specimens and the specimens heat-treated at 900 °C for 15 h, respectively. SEM images of the fatigue-fractured surfaces of the as-received and heat-affected specimens are given in **Figure 6**. The heat effect increased the voids between the matrix and the second phase of the FCS under cyclic load during the fatigue test, as seen in **Figure 6**. From this figure, it is clearly seen that the voids between the matrix and the

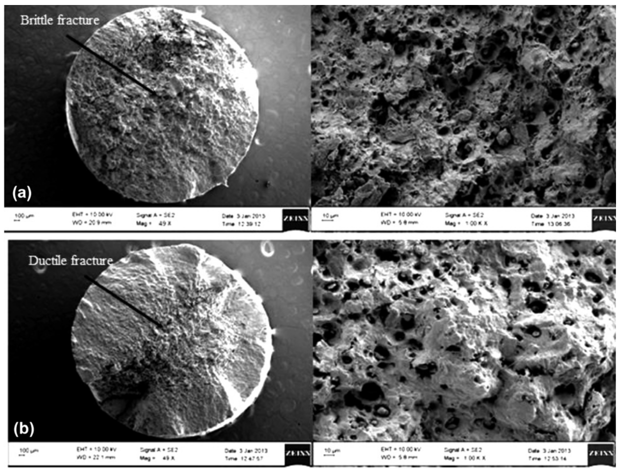

Figure 7: Macrostructures (49X) and microstructures (1000X) of fractured specimens: a) as received and b) heat treated at 900 °C for 15 h
Slika 7: Makrostruktura in mikrostruktura prelomljenega vzorca: a) dobavljeno in b) žarjeno 15 ur na 900 °C

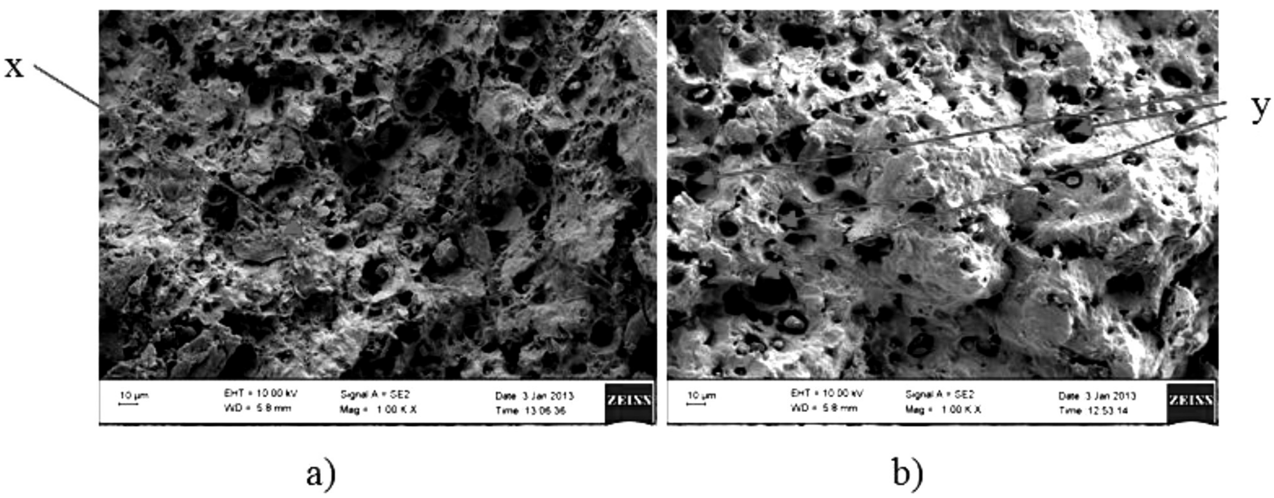

Figure 6: SEM images of fatigue-fractured surfaces of FCS: a) as received, b) heat treated at 900 °C for 15 h (*x* and *y* are voids)
Slika 6: SEM-posnetek površine utrujenostnega loma FCS: a) stanje ob dobavi, b) žarjeno 15 h na temperaturi 900 °C (*x* in *y* so praznine)

second phase are larger in the structure of the heat-affected specimens (**Figure 6b**). The heat-treatment effect made the material more ductile and, as a result, the bonding between the matrix and the second phase was weakened, while the fatigue and tensile strengths of the FCS decreased as well.

Macro- and microstructure images of the fractured specimens in the as-received and heat-affected states are given in **Figures 7a** and **7b**, respectively. The base material exhibited brittle fracture, while the heat-treated specimens exhibited ductile fracture. The fatigue values, R_m and R_e, of the base material were higher than those of the heat-treated FCS, as seen in **Figures 2** and **4**. This situation can be explained with the residual stress included in the as-received specimens. The grain growth due to the heat treatment of the FCS material also reduced these values.

4 CONCLUSION

From the above results, the following conclusions can be drawn:

- The heat effect made the material more ductile and weakened the bonding between the matrix and the second phase.
- The microstructure of the FCS changed at 900 °C. The elevated temperature and a long dwell time resulted in the grain growth and precipitation, which caused a decrease in the fatigue and tensile strengths.
- The grain size of the FCS increased by up to 250 % with the heat treatment at 900 °C and a dwell time of 15 h. The grain growth reduced the load-carrying capacity of the specimens.
- The fatigue strength of the FCS was reduced in the ratio of 83 % due to the effect of the high temperature and long dwell time.
- The heat treatment at 900 °C, for a period of less than 3 h reduced R_m and R_e in the ratio of 28.4 and 37.8 %, respectively, when compared to the base material.
- The toughness of the FCS increased in the ratio of 42.94 % due to the effect of heat treatment and dwell time.
- The heat effect led to increased ductility and larger voids between the matrix and the second phase of the FCS under a cyclic load. At a microscopic level, more mechanical damage was observed between the steel matrix and the second phase of the heat-affected specimens.
- The effect of time on the fatigue strength of the tested specimens is less significant.

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