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CREEP PROPERTIES OF MICROALLOYED STEELS

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Paper analyses the properties of microalloyed steels quality of S315 MC and S460 MC and carbon heat resistance steel of quality St.45.8 at higher temperatures in the creep conditions. The higher values of stress-rupture strength of microalloyed steels in the creep conditions (400 - 500 °C), which are comparable to stress-rupture strength of low alloyed steels, are mainly the result of the precipitation hardening.

Key words: *microalloyed steel, strength properties, creep, fracture*

Svojstva puzanja mikrolegiranih čelika. U ovom radu se analiziraju svojstva mikrolegiranih čelika kvalitete S315 MC i S46O MC i otpor na zagrijavanje ugljičnog čelika St45.8 pri višim temperaturama u uvjetima puzanja. Veća trajna čvrstoća mikrolegiranih čelika u stanju puzanja (400 - 500 °C), koja se može usporediti s trajnom čvrstoćom niskolegiranih čelika, je uglavnom rezultat očvršćavanja precipitacijom.

Ključne riječi: *mikrolegirani čelik, čvrstoća, puzanje, prijelom*

INTRODUCTION

The significant increase of strength properties of commercial consumption steels brings the production of microalloyed steels. The increase of strength properties of traditional carbon steels was potential only by the next increase either carbon or manganese content in steel what caused expressive decrease of brittle fracture and technological properties (weldability, flexibility). Alloying of low carbon steels, mainly by the Nb, V, Ti (up to 0.15 %) or other elements in combination with the thermomechanical processing, enables to obtain for microalloyed steels especially by the grains and precipitation hardening the high values of yield stress (up to 600 MPa), whereas mechanical and technological properties are the same or even better [1-3].

Temperature, as a external factor has a significant influence at steel properties and its behaviour during the service. Generally said, with the temperature increase the strength properties of steel decreased and at the long time service creep of materials [4-5] is realised. All these changes are dependent, besides on temperature and time, also on steel structure. The increasing of creep properties of carbon heat resistance steels by the carbon content increase happens to be of low effectiveness. Therefore, must low alloyed steels (Mo, Mo-Cr) be used for the higher exploitation temperatures (400 - 430 °C). The literature sources [6-8] points out that it is possible to use the microalloyed steels also like the heat resistance steels, mainly due to the presence of precipitates in ferrite matrix of these steels.

The main purpose of this paper is to analyse behaviour of the new developed hot rolled microalloyed steels quality of S and MC in creep conditions. Analysed steels have a low content of Si, C and the minor elements and are suitable for cold forming [9]. These steels have also high resistance to fatigue and brittle fracture and excellent weldability.

EXPERIMENTAL PROGRAMME

Experimental programme was realised on specimens machined out from the hot rolled microalloyed steel sheets, 8 mm thick and 1400 mm wide, quality S315 MC and S460 MC and on specimens obtained from the carbon heat resistance pipe quality St.45.8. Chemical composition of tested steels is given in Table 1..

From testing specimens were made testing rods in the rolling direction for tensile tests and stress-rupture strength test with dimensions of d_0 = 6 mm, L_0 = 30 mm and for notch toughness tests with dimensions of 10x8x55 mm with V-notch shape. Tensile tests were realised in the tempera-

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Table 1. **Chemical composition of tested steels**
Tablica 1. **Kemijski sastav testiranih čelika**

Steel	C	Mn	Si	Al	P
S315 MC	0.05	0.87	0.02	0.042	0.011
S460 MC	0.07	1.533	0.02	0.050	0.011
St.45.8	0.17	0.65	0.25	-	0.030
	S	Nb	V	Ti	
S315 MC	0.007	0.042	-	0.011	
S460 MC	0.004	0.051	0.082	0.015	
St.45.8	0.010	-	-	-	

ture range from 20 °C to 500 °C, notch toughness tests from 20 °C to 80 °C and stress-rupture strength tests at temperatures 400 °C, 450 °C and 500 °C for rupture time from the range 100 up to 8 000 hours. The optical and electron microscopy were used for structure analysis of initial and exposed material.

RESULTS AND DISCUSSION

The initial microstructure of tested steels is formed by ferrite and pearlite, Figure 1. and Figure 3.. There is considerable difference in the grain size, pearlite content as well as in the size, type and amount of precipitates distributed in

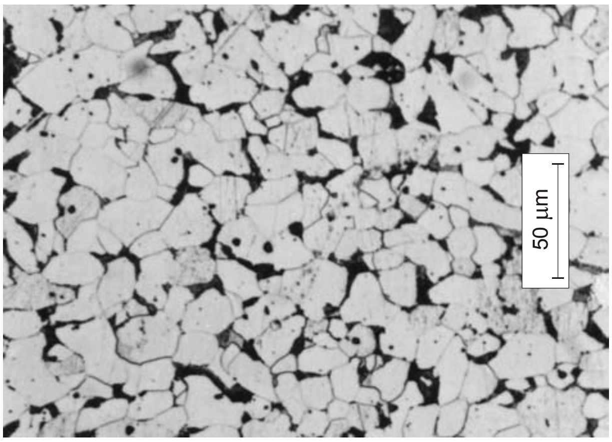

Figure 1. **Microstructure of steel quality of St.45.8**
Slika 1. **Mikrostruktura čelika St.45.8**

the matrix. The basic structural parameters of tested steels and the basic mechanical properties obtained by tensile tests and notch toughness tests at 20 °C are given in Table 2..

Microalloyed steels have pronounced higher yield stress comparing to steel of quality St.45.8 about 30 % (S315 MC) or 85 % (S460 MC), and ultimate tensile strength about 19 % and 45 %, respectively. Yield stress of tested steels as a function of temperature is presented in Figure 4.. From the diagram it is implied that with the temperature increase the yield stress decreases. This tendency depends on quality of tested steel. The sensitivity of steel on the higher temperatures during the tensile test represents better the temperature dependency of ratio yield stress at given temperature (R_{eT}) and yield stress at temperature 20 °C (R_e) which is

Table 2. **Basic mechanical properties, structural parameters and calculated contribution of hardening of tested steels**
Tablica 2. **Osnovna mehanička svojstva, strukturalni parametri i proračunati doprinos očvršćavanja testiranih čelika**

Steel	Yield stress R_e[MPa]	Ultimate tensile stress R_m [MPa]	Elongation A_5 [%]	Redukction of area Z [%]	Notch tough. KCV [Jcm^{-2}]	Grain size d [µm]	Pearlite content [%]	R_r [MPa]
S315 MC	350	485	27	77	273	9	5	46
S460 MC	500	590	28	70	232	6	1	88
St.45.8	270	407	35	67	158	20	20	53
	R_Z [MPa]	R_p [MPa]	R_{PR} [MPa]	R_Z/R_e [%]	R_r/R_e [%]	R_p/R_e [%]	R_{PR}/R_e [%]	
S315 MC	211	28	9	60	13	8	2	
S460 MC	258	120	3	52	18	24	0	
St.45.8	126	0	60	47	20	0	22	

given in Figure 5.. In the temperature range from 300 to 500 °C it is possible to describe the temperature dependency R_{eT}/R_e by the equation:

$$R_{eT}/R_e = R_e \cdot 300°C/R_e - k \cdot (T\text{-}300) \tag{1}$$

where T is testing temperature and k is constant which represents sensitivity of tested steel on temperature. The values of constant k for tested steels as well as for another carbon heat resistant steels are summarised in Table 3..

Table 3. **Material constants of tested and selected steels**
Tablica 3. **Konstante materijala testiranih i odabranih čelika**

Steel	St.45.8	S315 MC	S460 MC	St.35.8	HIV
C[wt.%]	0.17	0.05	0.07	0.07-0.15	max. 0.22
Mn[wt.%]	0.65	0.87	1.53	0.35-0.60	min. 0.70
Si[wt.%]	0.25	0.02	0.02	0.17-0.35	max. 0.35
$k10^{-3}$[1/°C]	1.68	1.20	0.92	1.7	1.6
R_r/R_e[%]	20	13	18	~14	~20

Connection between yield stress R_e and the structure of microalloyed steel at 20 °C is given in equations (2, 3)

$$R_e = 40 + R_Z + R_r + R_P + 3 \cdot PR \tag{2}$$
$$R_r = 80 \cdot Si\ [\%] + 50 \cdot Mn\ [\%], \tag{3}$$

where $R_Z = 20 \cdot d^{-1/2}$ is the hardening by grain boundaries in MPa, d is grain size in mm, PR is portion of pearlite in the structure in %, R_P is precipitation hardening calculated from the equation (2). In the Table 2. are summarised individual types of hardening and their contribution to the yield stress. In the Table 3. is given approximately contribution of solid solution hardening (R_r/R_e) of steels St 35.8 and HIV. It is implied that solid solution hardening by Mn and Si, and hardening by pearlite in the structure of carbon heat

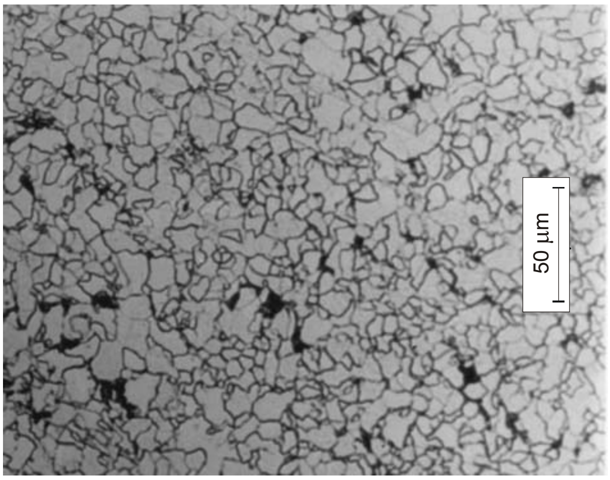

Figure 2. **Microstructure of steel quality of S315 MC**
Slika 2. **Mikrostruktura čelika S315 MC**

resistant steels do not affected the sensitivity of yield stress on the temperature. The evidence of that fact is practically the same value of constant k for the carbon steels. The de-

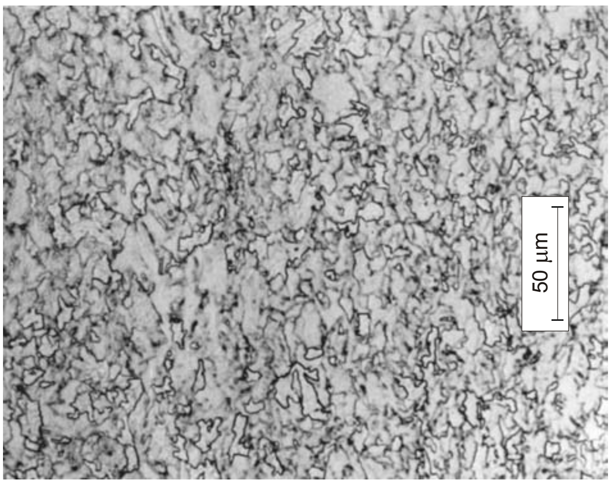

Figure 3. **Microstructure of steel quality of S460 MC**
Slika 3. **Mikrostruktura čelika S460 MC**

crease of sensitivity of microalloyed steels on temperature (lower value of *k* constant) is possibly related to the precipitation hardening. Generally said, with the portion of precipitation hardening increase, the value of *k* constant is decreased. The contribution of grain size hardening is possibly supposed to be independent of temperature.

The purpose of the paper is to analyse the properties of tested steels in creep conditions. Figure 6. shows experimental results of dependency of nominal stress - time

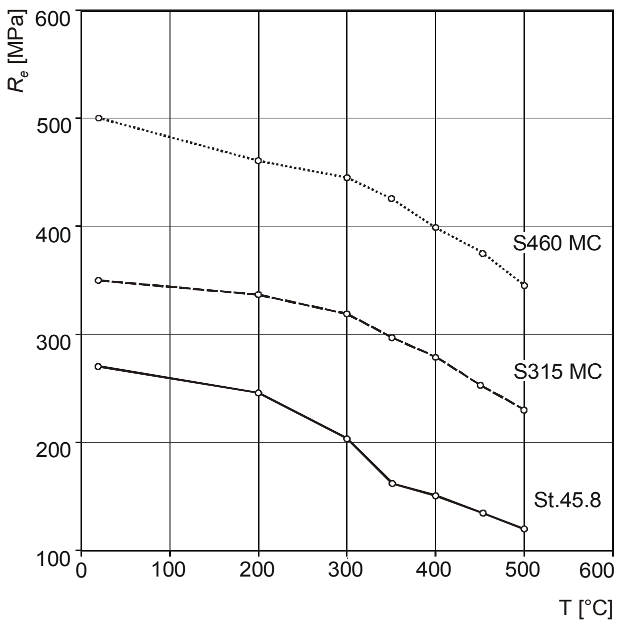

Figure 4. **Yield stress of tested steels as a function of temperature**
Slika 4. **Granica razvlačenja testiranih čelika kao funkcija temperature**

to rupture at 450 °C. From this diagram were appointed values of stress-rupture strength for 10^4 hours ($R_{mT}10^4$). Values of $R_{mT}10^4$ of tested steels at temperatures 400 °C, 450 °C and 500 °C and selected carbon heat resistant steels (St.35.8, HIV obtained from the Slovak standard) are presented on Figure 7.. The ratios of these values to ultimate

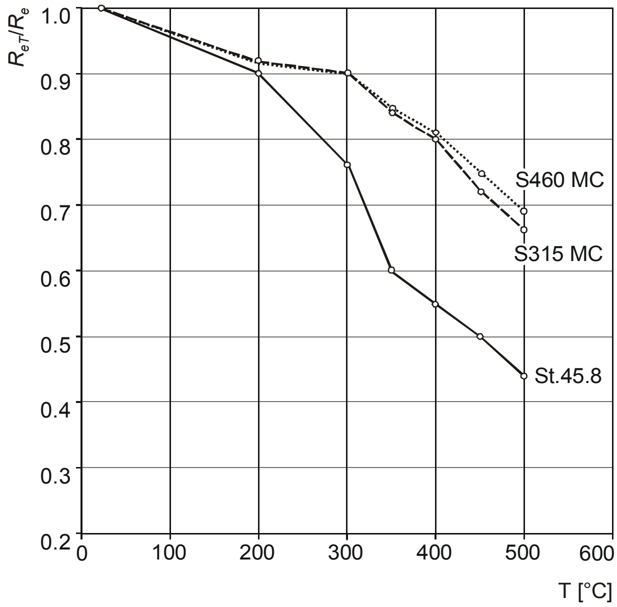

Figure 5. **Ratio of yield stress at given temperature (R_{eT}) and yield stress at temperature 20 °C (R_e) as a function of temperature**
Slika 5. **Omjer granice razvlačenja pri zadanoj temperaturi (R_{eT}) i granice razvlačenja pri temperaturi 20 °C (R_e) kao funkcije temperature**

tensile strength R_m are given on Figure 8.. Obtained results confirmed that the carbon content increases in carbon heat resistant steels (Table 3.) and Mn and Si have no effect on the increase of creep characteristics. Tested

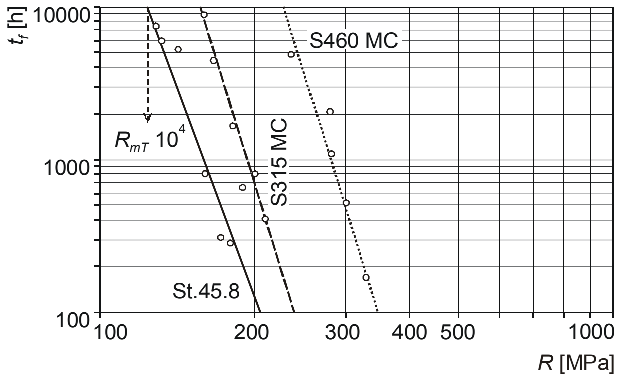

Figure 6. **Relationship between fracture time t_f and nominal stress R**
Slika 6. **Odnos između vremena prijeloma t_f i nominalnog naprezanja R**

microalloyed steels with lower carbon content, but with some portion of precipitation hardening at yield stress have expressively higher increase of creep properties. Ratio R_{mT}/R_m, which characterised the resistance of steel to creep, is for steel S315 MC at 400°C about 8% higher comparing

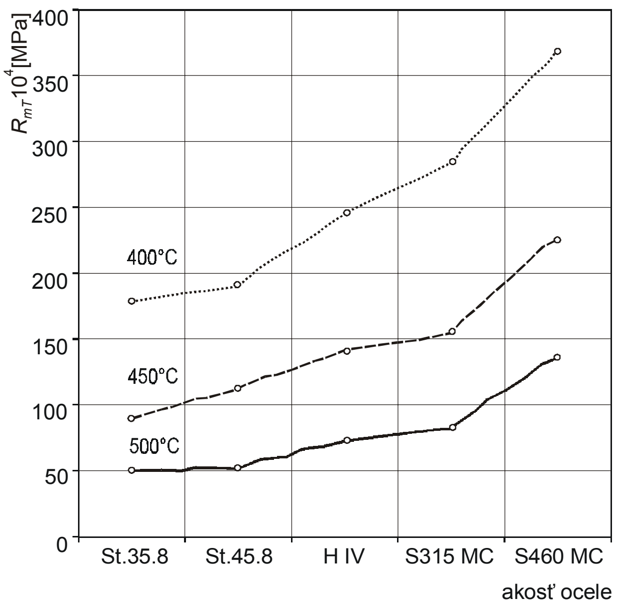

Figure 7. **Comparison of stress-rupture strength $R_{mT}10^4$ of tested and some selected carbon heat resistance steels**
Slika 7. **Usporedba trajne čvrstoće $R_{mT}10^4$ testiranih i nekih odabranih ugljičnih čelika otpornih na toplinu**

to the heat resistant steel of the best quality mark of HIV, at temperature 450 °C about 14 % and at temperature 500 °C about 20 % higher. For the steel quality S460 MC it is about 28 %, 40 % and 58 % higher values, respectively. It is implied that the precipitation hardening has crucial effect for microalloyed steels on their creep resistance. As precipitation hardening and testing temperature are higher, the discussed influence is more expressive.

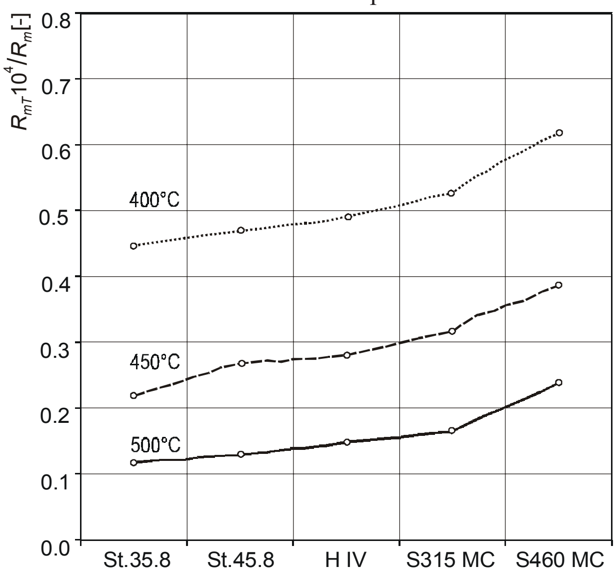

Figure 8. **Ratio of stress-rupture strength R_{mT} and ultimate tensile stress R_m of tested and some selected carbon heat resistance steels**
Slika 8. **Omjer trajne čvrstoće R_{mT} i čvrstoće na vlak R_m testiranih i nekih odabranih ugljičnih čelika otpornih na toplinu**

Attention was given also to the analysis of test conditions on type of fracture of the tested steels. Reduction of area Z and fracture stress σ_f were calculated from the fractured testing rods. On the Figure 9. and Figure 10. are given

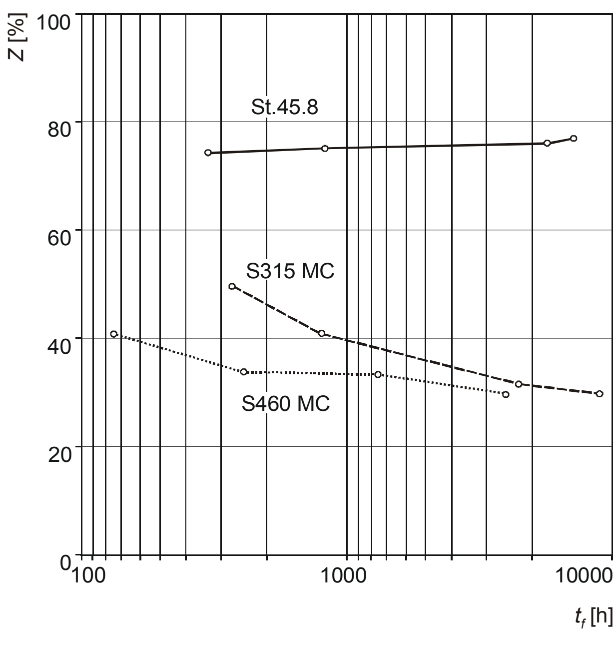

Figure 9. **Relationship between reduction of area Z and fracture time t_f at temperature 450 °C**
Slika 9. **Odnos između redukcije površine Z i vremena prijeloma t_f pri temperaturi od 450 °C**

relationships of reduction of area Z and fracture stress σ_f on fracture time at 450 °C. It is implied from Figure 7. that reduction of area Z of steel quality St.45.8 in creeping conditions of is comparing to the reduction of area Z = 71 % obtained from the tensile test a little different. With the frac-

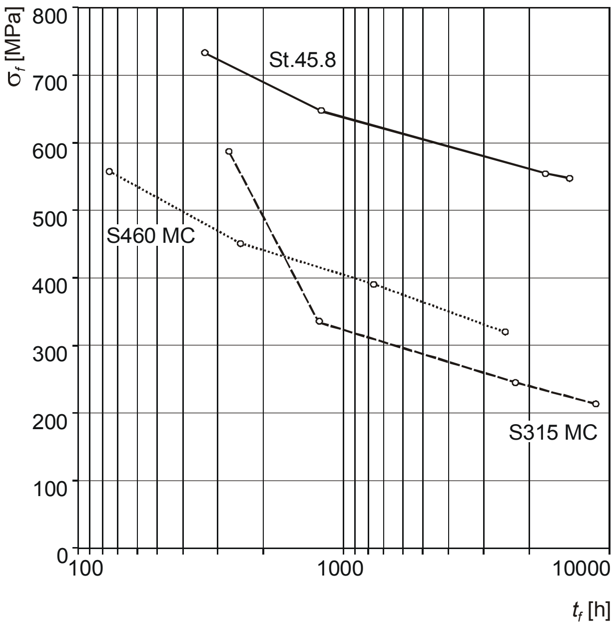

Figure 10. **Relationship between fracture stress σ_f and fracture time t_f at temperature 450 °C**
Slika 10. **Odnos između naprezanja pri prijelomu σ_f i vrijeme prijeloma t_f pri temperaturi 450 °C**

ture time increasing the reduction of area meekly increased (at fracture time 7 120 hrs is Z = 76.7 %). The reduction of area of microalloyed steels in creep conditions with the in-

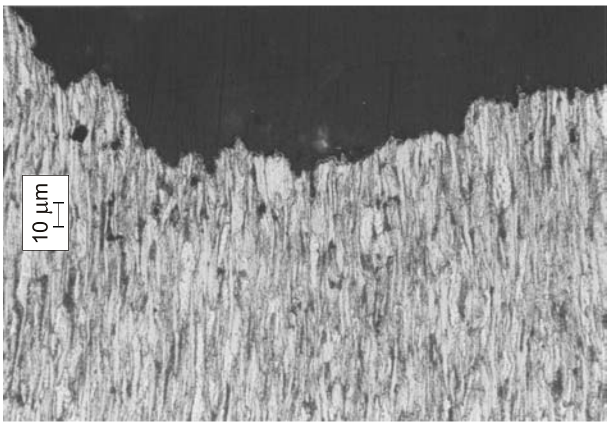

Figure 11. **Microstructure of steel quality of St.45.8 close to fracture line; temperature 450 °C, fracture time 7120 hours**
Slika 11. **Mikrostruktura čelika St.45.8 blizu crte prijeloma; temperatura 450 °C, vrijeme preloma 7120 sati**

creasing fracture time is expressively decreased. In conditions of tensile test (450°C) the reduction of area Z for steel quality S315 MC is 78 % and for steel quality S460 MC 74%. In the creep conditions the reduction of area Z is decreased to 49 or 40 % until the fracture time of 400 hours and with the followed fracture time the reduction of area is decreased. The reduction of area value affects also creep fracture stress, Figure 10. It is implied from the relationship σ_f - t_f that the value of σ_f is for steel St.45.8 expressively higher than the yield stress or ultimate tensile strength at 450 °C (Figure 4.). The value of fracture stress of low alloyed steels is after fracture time of about 4 000 hours (steel S315 MC) and 2 000 hours (steel S460 MC) lower than value R_e 450 °C. This fact is related to fracture behaviour of steel. Fig-

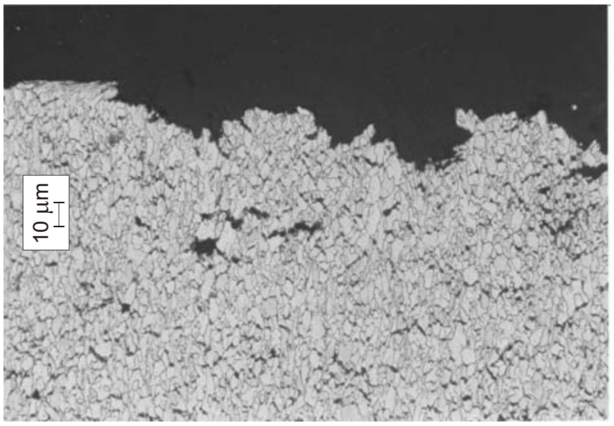

Figure 12. **Microstructure of steel quality of S315 MC close to fracture line; temperature 450 °C, fracture time 8930 hours**
Slika 12. **Mikrostruktura čelika S315 MC blizu crte prijeloma; temperatura 450 °C, vrijeme preloma 8930 sati**

ures 11 and 13 showed microstructures of tested steels close to fracture line. It can be concluded from the fracture line and from the microstructure in fracture vicinity that fracture mode of steel St.45.8 is transcrystalline (Figure 11.). The structure shows a high grade of plastic deformation without microscopic in homogeneities. Figures 12. and 13. showed

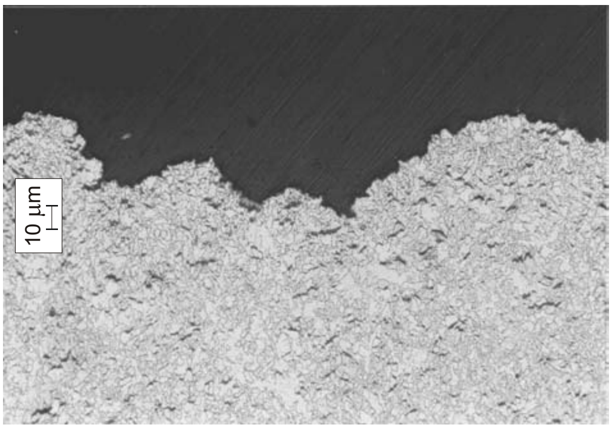

Figure 13. **Microstructure of steel quality of M460 MC close to fracture line; temperature 450 °C, fracture time 2830 hours**
Slika 13. **Mikrostruktura čelika M460 MC blizu crte prijeloma; temperatura 450 °C, vrijeme preloma 2830 sati**

that the fractures of microalloyed steels are either inter-crystalline or mixed intercrystalline - creep, grade of plastic deformation close to fracture line is expressively lower comparing to steel St.45.8 and in the structure were observed either cracks on the grain boundaries (wedge cracks) or secondary cracks.

On the basis of metallographic analysis, it can be concluded that the fracture behaviour of carbon heat resistant steel St.45.8 at temperatures 400 °C up to 500 °C during fracture time 10 000 hours in creep conditions is the equal to the conditions of tensile test. This fact is valid also for microalloyed steel but it must by fulfilled that at a given temperature fracture stress will be higher up to reach the ultimate tensile strength R_m. When the fracture stress is lower than R_m, the fracture mode starts to change and if $\sigma_f < R_e$ the fracture will be intercrystalline - creep. If the matrix of microalloyed steel is more strengthened, especially by precipitates (steel S460 MC), condition $\sigma_f < R_e$ is fulfilled for the lower values of fracture times.

CONCLUSIONS

The main aim of paper was to analyse creep properties of selected microalloyed steels quality of S315 MC and S460 MC which have excellent cold formability and to compare behaviour of these steels with the carbon heat resistant steels at higher temperatures in the creep conditions. Experimental programme resulted in these conclusions:

- microalloyed steels keep the high yield stress up to 500 °C and are less sensitive to temperature than carbon heat resistant steels. This effect is more expressive if there is a higher portion of precipitation hardening on yield stress;
- stress-rupture strength $R_{mT}10^4$ of tested microalloyed steels at temperatures 400 - 500 °C is higher comparing to carbon heat resistant steels and this difference at value of yield point increased with the temperature and precipitation hardening increase. Stress-rupture strength of microalloyed steels is at temperature 500 °C higher for about 55 % (steel S315 MC) or 150 % (steel S460 MC) comparing to carbon heat resistant steel;
- the increase for about 0.1 % of carbon content in carbon heat resistant steel caused only fractional increase of heat resistant effect (ratio $R_{mT}10^4/R_m$ is higher for about 8 %). The similar effect shows also the increase of Mn and Si. The influence of heat resistance of microalloyed steels is expressively higher and is affected by precipitation hardening. It was found out that for 8 % fraction of precipitation hardening on yield stress R_e (S315 MC) was ratio $R_{mT}10^4/R_m$ for about 18 % higher comparing to steel St.35.8 (temperature 400 °C) and 30 % (temperature 500°C), respectively. For steel S460 SC with 8% fraction of precipitation hardening ratio was higher about 40 - 100 %;
- hardening by the grain boundaries, which represented the crucial contribution of hardening of microalloyed steels at higher temperatures up to 500 °C, has an effect only in the short time loading. In the creep conditions the effect of this hardening on stress-rupture strength is neglected. Crucial influence on heat resistance of micro-alloyed steels has the contribution of precipitation hardening;
- in the creep conditions at temperatures 400 - 500 °C and time to fracture of max. 10 000 hours were testing rods from steel St.35.8 fractured by ductile fracture with the higher reduction of area comparing to tensile test. In the case that fracture stress was lower than yield stress, testing rods from steels S315 MC and S460 MC were fractured by intergranular-creep fracture.

The paper shows that microalloyed steels S315 MC and S460 MC have a higher yield stress even at higher temperatures and a higher stress-rupture strength than the carbon heat resistant steels of the best quality. Steel of quality S460 MC due to its excellent properties can up to temperature of 500 °C displace also the low alloyed heat resistant steels. It must be also noted that steels of quality S and MC have the higher resistance to brittle and fatigue fracture, better weldability and formability comparing to carbon and low alloyed heat resistant steels. It is possible to expect utilization of these materials for construction, reparation and reconstruction of boiler systems and other energetic equipment.

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