

## Effect of strain rate on hot ductility of C-Mn-B steel

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Received 21.03.2010; published in revised form 01.07.2010

### Materials

#### ABSTRACT

**Purpose:** The aim of the paper is to determine the influence of hot deformation conditions on hot ductility and  $\sigma$ - $\epsilon$  curves of C-Mn-B steel.

**Design/methodology/approach:** The force – energetic parameters of hot – working were determined in hot tensile tests performed in a temperature range of 700 to 1200°C by the use of Gleeble 3800 thermo – mechanical simulator with strain rate 0.01 s<sup>-1</sup> and 6.5 s<sup>-1</sup>. After rupture the contractions of samples were measured. Samples were taken from columnar and equiaxed grains zone of continuously cast billet.

**Findings:** Hot ductility curves as a measure of contraction in function of temperature of deformation for given strain rate and shape of the grains were established. At strain rate 6.5 s<sup>-1</sup> there was no minimum of hot ductility for columnar grains and for equiaxed grains minimum of hot ductility was temperature 800 – 850°C (40%). At strain rate 0.01 s<sup>-1</sup> and equiaxed grains minimum of the hot ductility (23%) was between 800 – 900°C and for columnar grains between 850-950°C at about 40%. Minimum of the hot ductility was usually in the vicinity of A<sub>3</sub> temperature.

**Research limitations/implications:** To determine in detail the hot ductility behaviour of C-Mn-B steel, a SEM investigations of rupture should be done.

**Practical implications:** The obtained stress-strain curves can be useful in determination of power-force parameters of hot-rolling.

**Originality/value:** The hot ductility behaviour of new-developed low carbon steel containing Boron microaddition was investigated.

**Keywords:** Low carbon C-Mn-B steel; Hot-working; Hot ductility; Flow curve; Rheological equation

#### Reference to this paper should be given in the following way:

A. Lis, J. Lis, C. Kolan, M. Knapieński, Effect of strain rate on hot ductility of C-Mn-B steel, Journal of Achievements in Materials and Manufacturing Engineering 41/1-2 (2010) 26-33.

### 1. Introduction

Critical parameters influencing hot ductility of steel are chemical composition, temperature, austenite grain size, volume

fraction and dispersion degree of nonmetallic inclusions and precipitates and strain rate [1-3]. An improvement of hot ductility caused by increased deformation rate was presented in papers [3, 4]. Hot ductility is influenced also by precipitates at austenite

grain boundaries, which postpone dynamic recrystallization and facilitates grain boundary slip. Boron in amount of 0.002-0.005% is intentionally added to many grades of steel. In austenitic steels boron improves hot ductility [5]. In low carbon low alloyed steels, the effect of boron on phase transformations and hardenability depends on the type of its existence in solid solution or as precipitates [6]. The composition of the primary precipitates of the boron compounds and their dispersion may differ upon chemical composition and conditions of crystallization. They have a great effect on hot working of steels. Stability of the primary boron precipitates depends on chemical composition of the steel mainly on carbide forming elements. The smallest primary segregation of boron was determined for low alloyed steels [2]. During hot working fragmentation and partly dissolution of primary boron compounds takes place. Boron may inhibit dynamic recrystallization of austenite during hot working. Temperature for recrystallization start and finish usually increases with the increase of boron content above 5 ppm [7, 8]. Below 5 ppm of boron the effect on the kinetic of recrystallization process was not observed [9]. Microstructure investigation of low carbon steel after hot deformation were presented in [10-15].

## 2. Experimental

In present paper low carbon steel with 60 ppm of boron was tested to evaluate hot ductility in the temperature range 700-1200°C using Gleeble 3800 thermomechanical simulator. The following chemical composition of the investigated steel in mass percent was presented in Table 1.

Table 1.  
Chemical composition of the investigated steel in mass percent

C	Mn	Si	P	S	Cr	Ni
0.08	0.46	0.1	0.013	0.016	0.06	0.11
Cu	Al	Mo	Sn	B	N <sub>2</sub>	
0.22	0.003	0.02	0.015	0.006	0.009	

Steel was continuously cast in square billets 105 x 105 mm. Cylindrical tensile test specimens 10 mm in diameter and 120 mm in length were cut from billets in parallel to casting direction from area at the surface which corresponds to columnar grains and from interior area of the equiaxed crystals. The parameters of the hot working experiments are schematically shown in Fig. 1.

The specimen was heated to 1300°C at heating rate 20°C/s then soaked 60 s and cooled down to tensile testing temperature at 10°C/s and shortly soaked 5 s at deformation temperature 700-1200°C, ruptured and cooled to room temperature. Temperature was controlled by spot welded thermoelements PtRh-Pt to the specimen surface. Hot ductility tests were run at two different strain rates: 0.01 s<sup>-1</sup> which simulated deformation during continuous casting process and 6.5 s<sup>-1</sup> which was characteristic for hot rolling. After rupture contraction of each sample was measured. The critical temperatures for phase transformations at heating rate 20°C/s and cooling rate 10°C/s were determined from dilatometric investigations. These temperatures were A<sub>c3</sub> = 983°C, A<sub>c1</sub> = 692°C, A<sub>r3</sub> = 833°C, A<sub>r1</sub> = 590°C. During

thermomechanical working the austenite grain size has substantial effect on recrystallization processes and progress of phase transformations after deformation. For the investigation steel experiments of austenite grain growth were realized according to PN-EN ISO 643. Estimation was done in 6 different areas of observation and total amount of determined grains was greater than 250. The austenite grain size was also established with scale of standards included in PN-EN ISO 643. Results of the investigations are shown in Table 2.

Table 2.  
Austenite grain size characterized by PN-EN ISO 643

Temperature [°C]	Diameter $\bar{d}$ [mm]	Standard deviation	Standard G
800	0.01249	0.00336	9-10
850	0.01597	0.00131	9-8
900	0.02165	0.00282	8-7
950	0.04597	0.02318	7-6-5
1000	0.05697	0.03839	5-4-3
1050	0.06272	0.02025	3-4-5
1200	0.11050	0.02010	3-4
1300	0.2035	0.02151	1-2-3

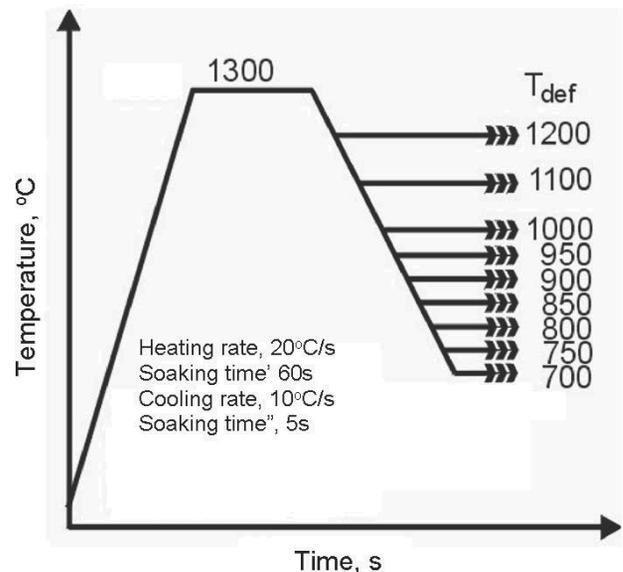


Fig. 1. Parameters of the hot working

## 3. Results of the hot ductility

Results of the measured contractions of the specimens ruptured at temperatures 700-1200°C at strain rate 0.01 s<sup>-1</sup> and 6.5 s<sup>-1</sup> which were representative for columnar and equiaxed grains are shown in Fig. 2.

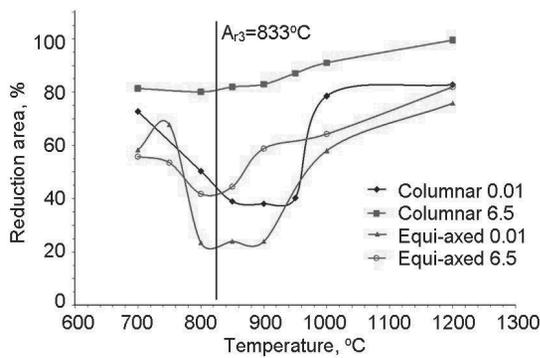


Fig. 2. Hot ductility curves for specimens from columnar grains and equiaxed grains regions which were deformed at strain rates  $0.01 \text{ s}^{-1}$  and  $6.5 \text{ s}^{-1}$

For samples taken from columnar grains region which were deformed at strain rate  $6.5 \text{ s}^{-1}$  there was no minimum of ductility. Values of the contractions were increasing with temperature increase. At  $700^\circ\text{C}$  contraction of samples from columnar grains zone was around 75-80% at strain rate  $0.01 \text{ s}^{-1}$  and  $6.5 \text{ s}^{-1}$  and 56% for equiaxed grains. Refinement of the microstructure as a result of  $\gamma \rightarrow \alpha$  phase transformation was also responsible for high values of contraction at that temperature. Local decrease of the hot ductility to 40% was observed at  $850\text{-}950^\circ\text{C}$  for "columnar" samples deformed at strain rate  $0.01 \text{ s}^{-1}$ . At the same strain rate decrease in hot ductility to 23% was observed between  $800\text{-}900^\circ\text{C}$  for specimens with equiaxed grains. At higher strain rate  $6.5 \text{ s}^{-1}$  minimum of hot ductility was narrower at  $800^\circ\text{C}\text{-}850^\circ\text{C}$  and about 40% contraction. Above  $1000^\circ\text{C}$  for all cases hot ductility was higher than 50%. Thus lowering of hot ductility was usually in the vicinity of  $A_{r3}$  temperature and increase above  $A_{c3}$  temperature. The lowest contractions were observed in the region of coexistence of ferrite and austenite. Well below  $A_{r3}$  temperature ( $833^\circ\text{C}$ ) when volume fraction of austenite was lowered ductility of the steel rose again due to increase in ferrite content. Unusual correlation of ductility and austenite grain size was observed. For minimum contraction (40%) at temperature  $850\text{-}950^\circ\text{C}$  the average austenite grain size  $\bar{d}_\gamma$  was  $0.0149\text{-}0.048 \text{ mm}$  while with increase in ductility above  $1000^\circ\text{C}$   $\bar{d}_\gamma$  was in the range  $0.05\text{-}0.11 \text{ mm}$  (Table 2).

#### 4. Determination of flow curves

System Gleeble is using equations (1) and (2) to calculate true stress and true strain from measured parameters of experiment as force and the change of the elongation of the specimen with extensometer.

$$\sigma = \frac{F}{\frac{\pi d_o^2}{4} L_o} \frac{L_o}{L_o + \Delta L} \quad (1)$$

$$\varepsilon = \ln \frac{L_o + \Delta L}{L_o} \quad (2)$$

where:

F - force measured by heads of the tensile machine,

$d_o$  - initial diameter of the sample (10 mm),

$L_o$  - initial length of the sample (12 mm) - distance which is heated up,

$\Delta L$  - change in the length of the specimen measured by extensometer.

The determined values of the stress and strain are shown in Figs. 3-6. The stresses which were observed in Figs. 3 and 4 were pronouncedly lower at strain rate  $0.01 \text{ s}^{-1}$  than those registered at strain rate  $6.5 \text{ s}^{-1}$  in Figs. 5 and 6. It was caused by annihilation of dislocation during slow deformation process. However at higher strain rate the increase in hardening was greater which caused significant growth of stresses for all deformation temperatures. It was also observed that greater true strain values were measured at higher true stresses. Probably the limited time for boron segregation towards grain boundaries and reduced possibility of boron compounds precipitation gave effect of increased plasticity.

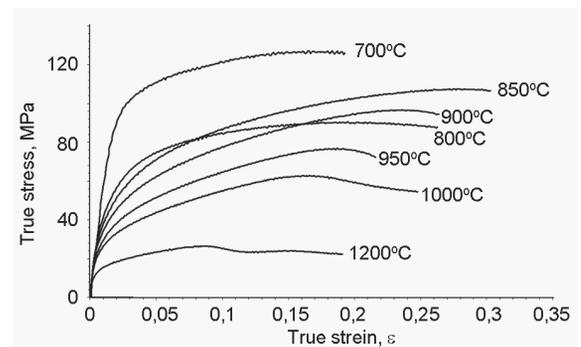


Fig. 3. True stress - true strain curves for specimens from columnar grains region which were deformed with strain rate  $0.01 \text{ s}^{-1}$

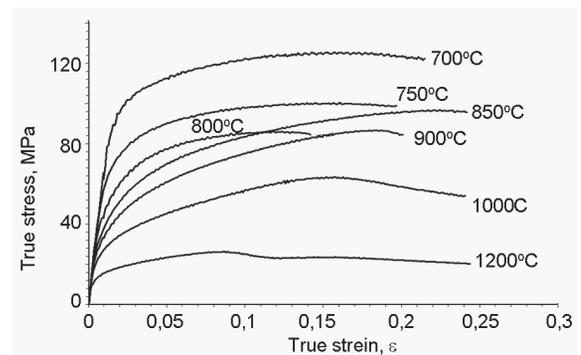


Fig. 4. True stress - true strain curves for specimens from equiaxed grains region which were deformed with strain rate  $0.01 \text{ s}^{-1}$

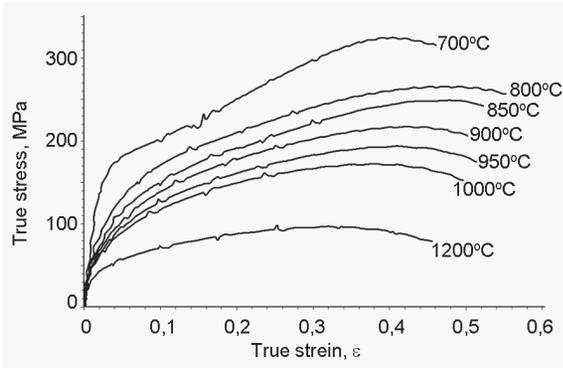


Fig. 5. True stress - true strain curves for specimens from columnar grains region which were deformed with strain rate  $6.5 \text{ s}^{-1}$

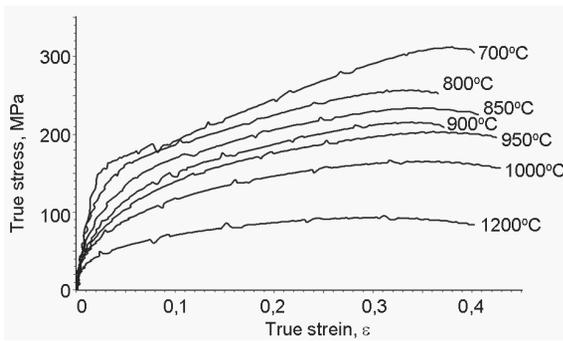


Fig. 6. True stress - true strain curves for specimens from equiaxed grains region which were deformed with strain rate  $6.5 \text{ s}^{-1}$

From analysis of the flow curves shown in Figs. 3-6 it is obvious that flow stress depends on temperature and strain rate. For lower strain rate  $0.01 \text{ s}^{-1}$  lower stresses were obtained for both specimens with columnar or equiaxed grains. At strain rate  $6.5 \text{ s}^{-1}$  flow stresses are higher. The increase in temperature of deformation caused lower stresses for both strain rates. For deformation temperatures higher than  $900^\circ\text{C}$  maximum of the stress was observed on the curves, which means that dynamic recrystallization process would occur.

At assumption of stable cross section of the samples  $S_0 = \text{const}$  tensile strength was calculated and compared to maximum tensile stress for all investigated conditions of hot working (Table 3).

The results for specimens with columnar and equiaxed grains are similar. Also shape of the curves for the same deformation temperature and strain rate are similar, thus characteristics of deformation are independent on the place from which samples were taken. For obtained results dependence of stress from strain in the form of rheological equation was established:

$$\sigma = a_1 \cdot \varepsilon^{a_2} \cdot \exp(a_3 \cdot \varepsilon) \cdot \dot{\varepsilon}^{a_4} \cdot \exp(a_5 \cdot T) \quad (3)$$

It follows from the given equation 3 that considerable effect of straining on the increase in true stress is higher than influence of strain rate. Enhancement in temperature caused exponentially lowering of stresses according to coefficient  $a_5$ . The calculated values from equation 3 are generalization of measured maximum stresses which are given in Table 3.

In Table 4 values of coefficients in equation 3 are given.

Table 3. Tensile strength and maximum true stress from flow curves

Temperature/ strain rate [ $^\circ\text{C}/\text{s}^{-1}$ ]	Columnar grains		Equiaxed grains	
	UTS [MPa]	Max $\sigma$ [MPa]	UTS [MPa]	Max $\sigma$ [MPa]
700 / 0.01	110	127	111	126
750 / 0.01	-	-	89	100
800 / 0.01	77	90	78	86
850 / 0.01	84	108	79	97
900 / 0.01	78	97	73	87
950 / 0.01	64	77	-	-
1000 / 0.01	54	63	54	64
1200 / 0.01	24	26	24	26
700 / 6.5	223	325	217	312
750 / 6.5	-	-	189	257
800 / 6.5	179	266	173	234
850 / 6.5	167	249	160	216
900 / 6.5	151	218	149	203
950 / 6.5	136	194	-	-
1000 / 6.5	127	173	123	167
1200 / 6.5	76	98	72	93

UTS –Ultimate Tensile Strength; MAX  $\sigma$  - max. True stress

Table 4. Values of coefficients used in equation 3

$a_1$	3853.539
$a_2$	0.47672
$a_3$	-1.21136
$a_4$	0.10533
$a_5$	-0.002521

## 5. Metallographic analysis of microstructures after hot rupture

After reheating the steel at  $1300^\circ\text{C}/60\text{s}$  the average austenite grain diameter was  $203.5 \mu\text{m}$  and maximum diameter was  $250 \mu\text{m}$ .

The cooling rate from 1300°C was 10°C/s. Rupture temperature 700°C was the lowest for ( $\alpha+\gamma$ ) temperature range. The higher temperatures of the investigations in the  $A_{c1}$  -  $A_{c3}$  region were 750°C and 800°C. After deformation at 700°C the achieved microstructure was ferrite-pearlite (Fig. 7). Different morphological features of ferrite were observed. Elongated grains of ferrite were formed from unrecrystallized austenite and fine polygonal grains of ferrite underwent recrystallization process. Finer ferrite grains were achieved in the steel ruptured at tensile strain rate 6.5 s<sup>-1</sup> than at 0.01 s<sup>-1</sup>.

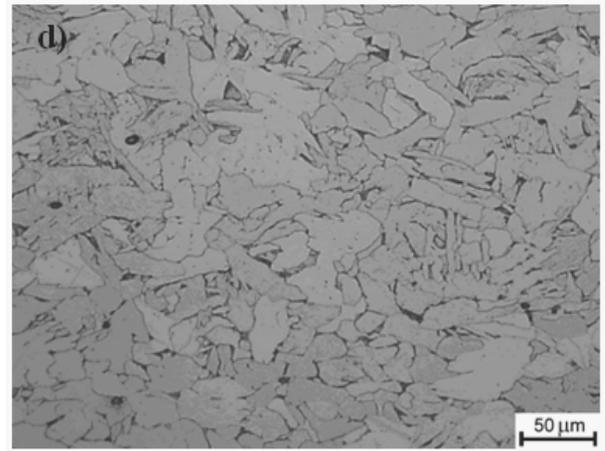
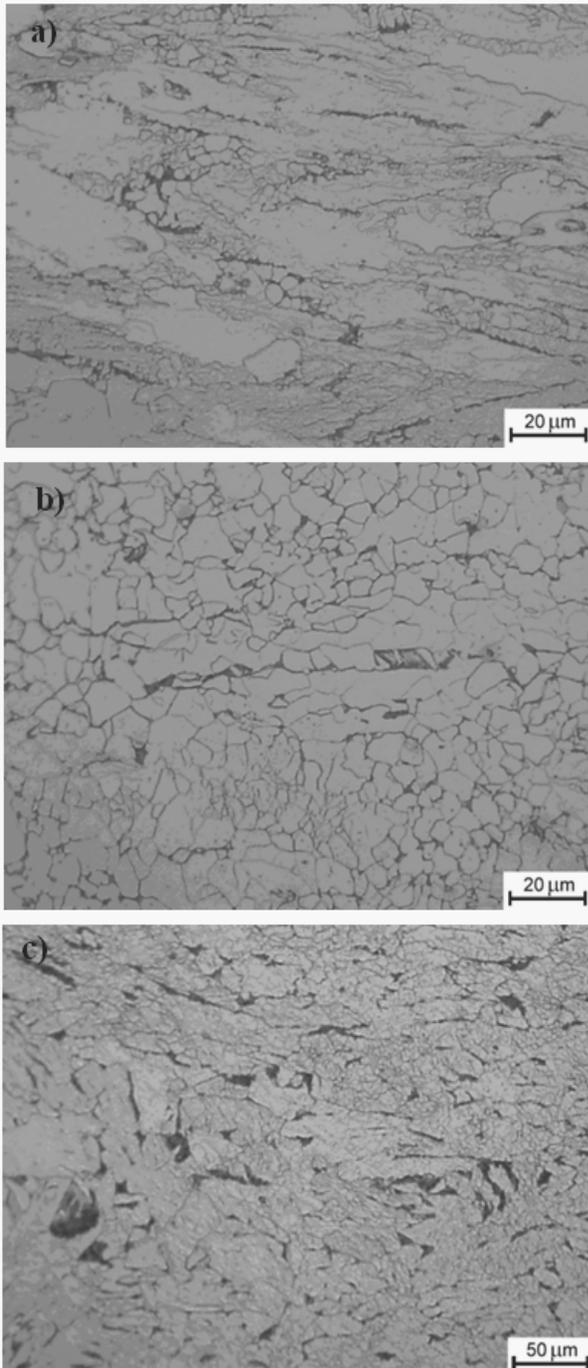
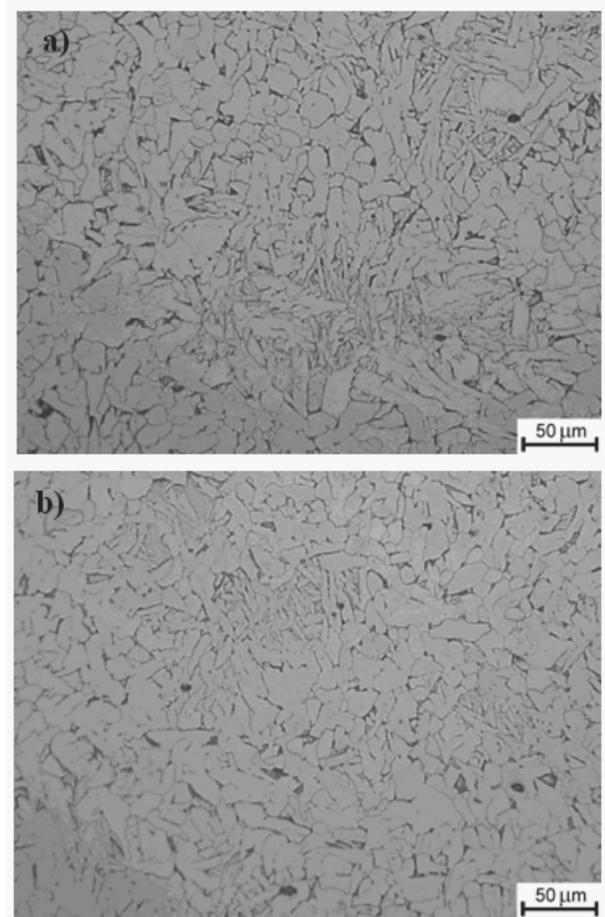


Fig. 7. Microstructure of the investigated steel after hot ductility testing at temperature 700°C at strain rate 0.01 s<sup>-1</sup> (columnar (a) and equiaxial (b) grain region) and 6.5 s<sup>-1</sup> (columnar (c) and equiaxial (d) grain region)



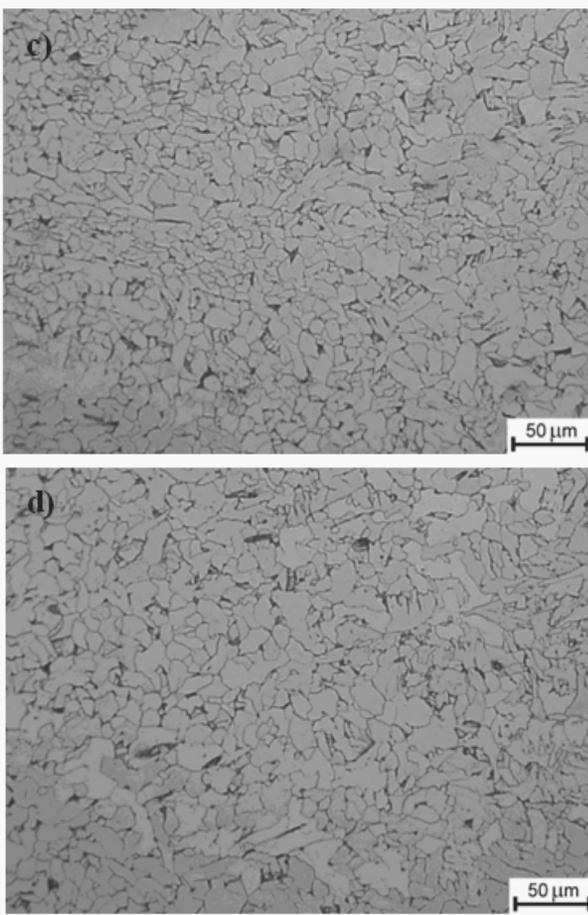


Fig. 8. Microstructure of the investigated steel after hot ductility testing at temperature 800°C at strain rate  $0.01 \text{ s}^{-1}$  (columnar (a) and equiaxial (b) grain region) and  $6.5 \text{ s}^{-1}$  (columnar (c) and equiaxial (d) grain region)

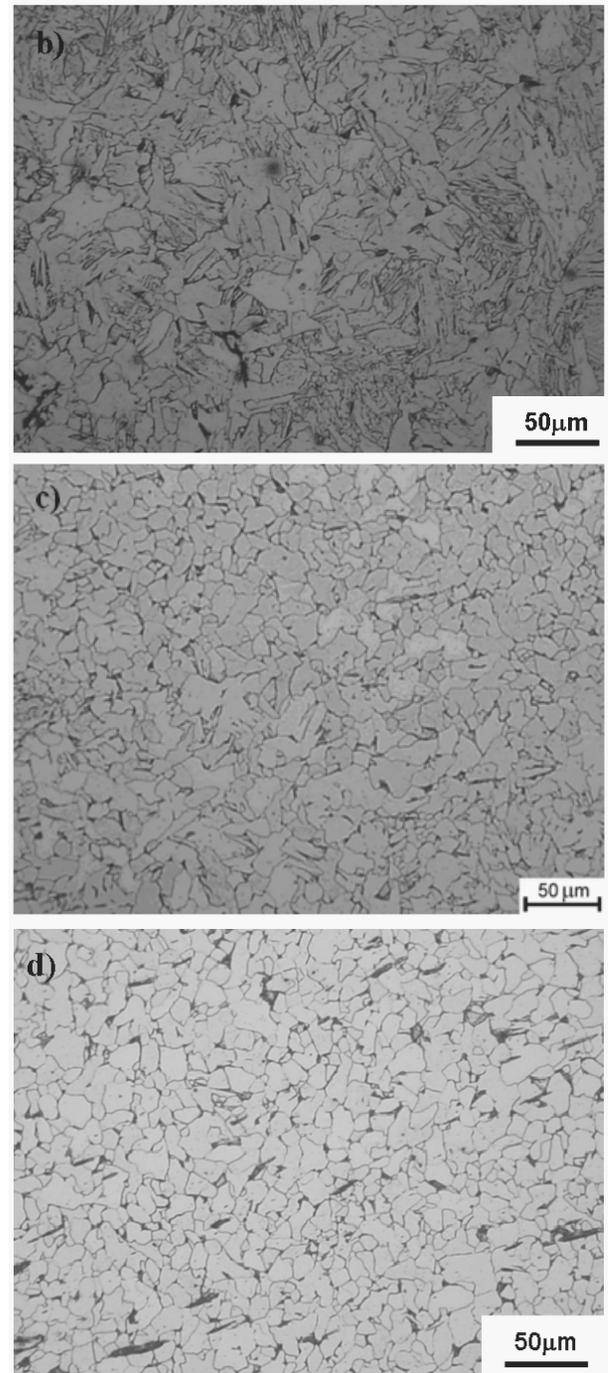
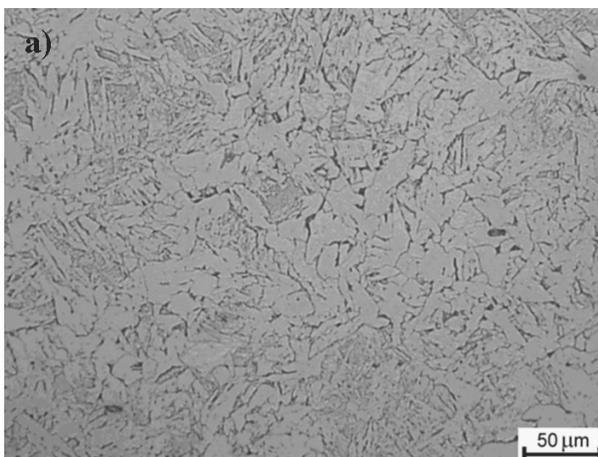


Fig. 9. Microstructure of the investigated steel after hot ductility testing at temperature 950°C at strain rate  $0.01 \text{ s}^{-1}$  (columnar (a) and equiaxial (b) grain region) and  $6.5 \text{ s}^{-1}$  (columnar (c) and equiaxial (d) grain region)



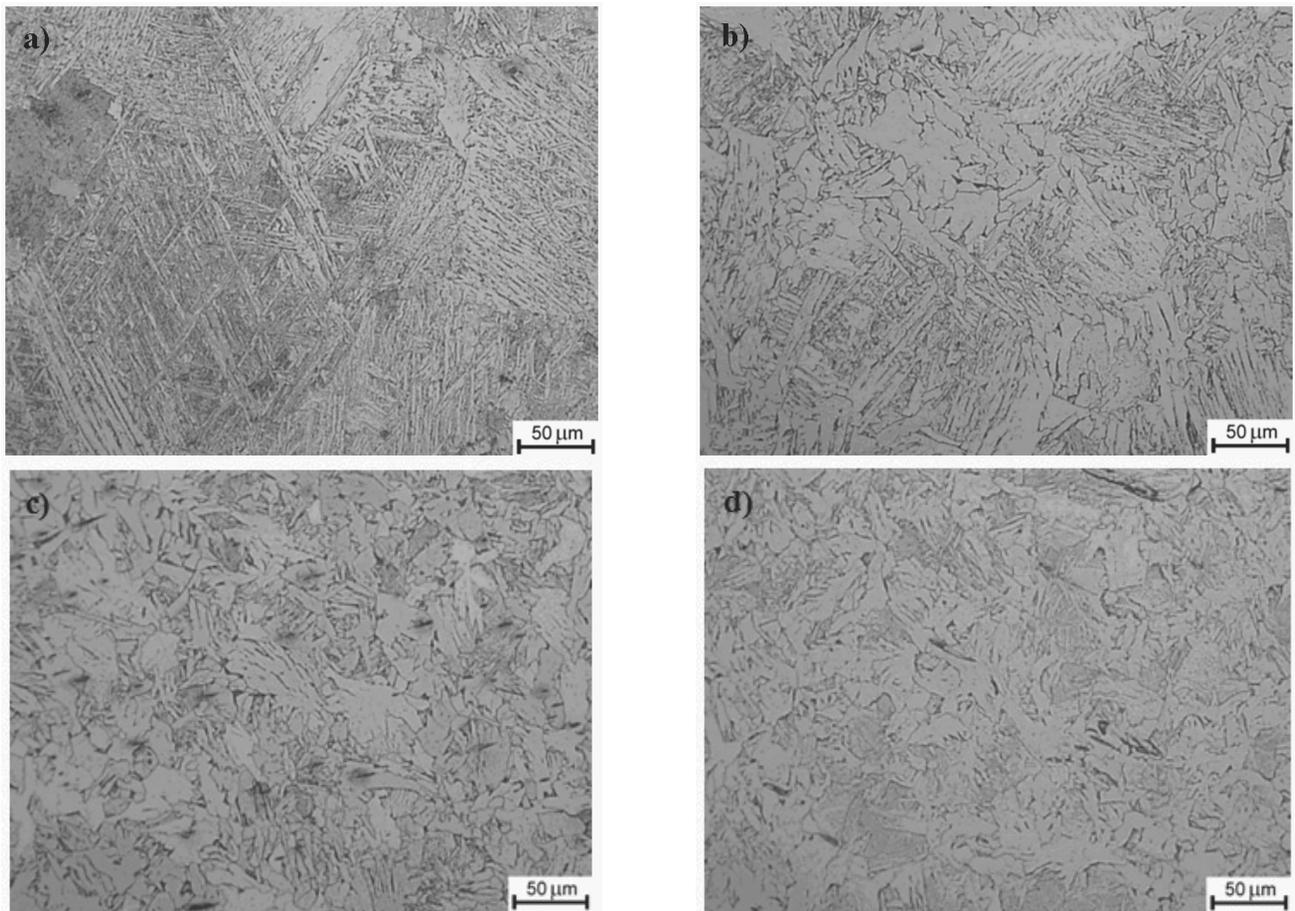


Fig. 10. Microstructure of the investigated steel after hot ductility testing at temperature 1200°C at strain rate 0.01s<sup>-1</sup> (columnar (a) and equiaxial (b) grain region) and 6.5 s<sup>-1</sup> (columnar (c) and equiaxial (d) grain region)

The very similar microstructures were formed at temperature 750°C for both deformation rates. After testing at 800°C microstructure constituencies were more dispersed than those at deformation temperatures 700 and 750°C. At temperature 800°C the austenite to ferrite transformation was accelerated thus there was less regions of formerly unrecrystallized austenite grains before transformation. After deformation straining 0.01 s<sup>-1</sup> and 6.5 s<sup>-1</sup> more refined ferrite and pearlite grains and some bainite areas were observed. The increase of deformation temperature to 850°C caused greater refinement of microstructural components of polygonal ferrite, acicular ferrite, pearlite and bainite. Smaller grains were observed in the steel deformed at 6.5 s<sup>-1</sup> strain rate (Fig. 8). At temperatures 900, 950 and 1000°C there were less pearlite regions in the microstructure. Acicular and polygonal small ferrite grains and some bainite areas were present in the microstructure (Fig. 9). After hot deformation at 950°C and at rate 6.5 s<sup>-1</sup> the achieved ferrite was more uniform than after deformation at the rate 0.01 s<sup>-1</sup> (Fig. 9b). It was assumed that dynamic recrystallization has taken place at temperature 950°C and above. After hot rupture at 1200°C there was very small amount of pearlite in the microstructure (Fig. 10), which was in the vicinity of former austenite grain boundaries independently

of deformation rate applied. There were mainly bainite and ferrite grains of different shape due to higher cooling rate after deformation.

## 6. Conclusions

- Hot ductility of low carbon C-Mn-B steel which was determined as contraction of tensile specimen ruptured at strain rate 6.5 s<sup>-1</sup> and 0.01 s<sup>-1</sup> depends on temperature strain rate and the place from which sample was taken from continuously cast billet (zone of columnar or equiaxed grains).
- In low carbon C-Mn-B steel the increase of temperature of deformation or decrease of strain rate generate lowering of stress. More pronounced effect in lowering the stress has an increase in temperature of testing.
- The rheological equation for C-Mn-B steel was established for temperatures in the range 700-1200°C

$$\sigma = a_1 \cdot \varepsilon^{a_2} \cdot \exp(a_3 \cdot \varepsilon) \cdot \dot{\varepsilon}^{a_4} \cdot \exp(a_5 \cdot T)$$

- Morphology of the microstructure of the steel after rupture at ( $\alpha+\gamma$ ) temperature range was dependent on austenite grain size, advancement of recrystallization process and amount of ferrite formed before deformation process.
- Microstructure of the steel deformed above 850°C was dependent on the occurrence of austenite recrystallization process during deformation and to the same extent on the grain growth and cooling speed after rupture.
- The cooling rate was greater after higher deformation temperature of rupture.

## Acknowledgements

Scientific work was financed from the science funds in a period of 2006-2008 in the framework of project No 3 T 08B 019 30.

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