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HOT FORMING OF AISI A2 TOOL STEEL

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For further increase of economy of production of AISI A2 tool steel a study of possibility of expanding the hot working range and better prediction of flow stress has been carried out. By employing hot compression tests it was proved, that initial microstructures have influence on the lower limit and chemical composition on upper limit of hot working range. A CAE Neural Networks was applied to predict the flow stresses for intermediate values of strain rates and temperatures. For optimization purposes the activation energies and constants of the hyperbolic sine function for two temperatures ranges (850-1000°C and 1000-1150°C) were calculated.

Key words: A2 tool steel, hot workability, activation energy, CAE neural networks

Vruća prerada AISI A2 alatnog čelika. Za postizanje više gospodarnosti proizvodnje AISI A2 alatnog čelika potrebni su koraci istraživanja vezani na postizanja tehnološke plastičnosti i uspješno predvidjanje krivulja tečenja. Sa metodom CAE neuralnih mreža bile su predviđene krivulje tečenja i za odgovarajuća temperaturna stanja i brzine deformacija. Pomoću pokusa vrućeg sabijanja utvrđeno je, da ulazna mikrostruktura utječe na donju temperaturnu granicu, a kemijski sastav na gornju temperaturnu granicu radnog područja s obzirom na granicu plastičnosti materijala. Sa namjerom optimiziranja procesa izračunate su aktivacijske energije i odredjene su konstante sinus hiperbolne funkcije za dva temperaturna područja (850-1000°C i 1000-1150°C).

Ključne riječi: A2 alatni čelik, vruća prerada, aktivacijska energija, CAE neuralne mreže

INTRODUCTION

In order to optimize the hot forming process of tool steels, further improvement of flow stress prediction and additional knowledge on hot deformability, especially at lower and upper limits of the hot working range, are required. The hot working ranges for these steels are very narrow as a consequence of the role of alloying elements, which form carbides. Carbides improve tool steel's hardenability, strength, hardness, etc. but at the same time decrease hot deformability. The lower limit of the hot working range is determined by the shape, size and type of the carbides which precipitate in grain interior and on grain boundaries. On the other hand, the upper limit is determined by the occurrence of incipient melting of eutectic carbides and by segregation of Cu, Sn, Se or their phases with low melting point on grain boundaries [1-7].

At present time hot forming (rolling) of AISI A2 tool steel is becoming more and more oriented towards larger initial dimensions of roll-pieces and towards smaller outlet dimensions (below ϕ=10 mm) which consequently require lower final deformation temperatures (below 900°C). For an achieving of optimal cross-section reductions the accuracy of prediction of flow stress should be within 5% range [8]. For tool steels, such accuracy can not be obtained using various empirical and semi-empirical models, because of complex role of carbides [9-13]. Neural networks are nowadays used at solving of such complex systems [14-18]. In the past BP NN have been already used for the prediction of flow curves but the authors [17-19] did not present the flow curves for intermediate values of strain rates and temperatures simultaneously. On the other hand this has been done in [20-21] but the accuracy was questionable or the NN were too clumsy. Therefore the aims of the present contribution are firstly to apply advanced adaptive methods which are suitable for handling complex systems, and secondly to study the possibility of expanding of hot working area.

EXPERIMENTAL

The specimens dimensions ϕ=8 x 12 mm for our investigation were cut from surface layer and from the centre of the billet of soft annealed material with ϕ=128. The chemical composition (in mass %) of specimens was 0,99 C, 0,28 Si, 0,48 Mn, 0,022 P, 0,011 S, 4,95 Cr, 0,94 Mo, 0,15 Ni, 0,18 V, 0,08 Cu, 0,08 W, 0,004 Sn and 0,007 Al. The initial microstructure from the surface layer of billet consists of spheroidal perlite, secondary carbides, and

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primary carbides (see Figure 1a). Due to stronger segregation which takes place during the process of solidification the amount of primary carbides in the billet centre is higher and are distributed in short bands (see Figure 1b). By employing the hot compression testing on GLEEBLE 1500D in range between 1220-1170°C the upper soaking temperature for both specimens have been assessed. The criterion was the appearance of cracks on the specimen's surface at strain of 0,9. In order to find the optimal soaking temperature another kind of tests were employed. Beside the occurrence of cracks, the appropriate microstructure was additional criterion. The examined range was 1220-1170°C and the samples have been deformed at 800 and 850°C, respectively. The soaking temperature can influence the processes of dissolution of fine carbides, coagulation and growth of coarse carbides, and in consequence it can also influence the lower limit of temperature range [22]. Flow curves were determined for the range 850-1150°C, and for strain rates of 0,001-10 s^{-1}.

CONDITIONAL AVERAGE ESTIMATOR NEURAL NETWORKS

CAE neural networks used in this study was first presented and introduced by Grabec and Sachse [23] and so far were applied in many engineering applications [15-16, 24-25]. For the detailed description of the CAE NN the interested reader is referred to [23-24]. Here only the main ideas behind the method are given. The output variable corresponding to the vector under consideration, (i.e. a vector with known input variables and output variables to be predicted) can be estimated by the formulae:

$$\hat{\sigma} = \sum_{n=1}^{N} C_n \cdot \sigma_n, \;\; C_n = c_n \Big/ \sum_{j=1}^{N} c_j$$

$$c_n = \exp\left[-\sum_{i=1}^{L} (p_i = p_{ni})^2 / 2w^2 \right] \qquad (1)$$

Here $\hat{\sigma}$ is the estimated (predicted) k-th output variable (e.g. *stress*), σ_n is the same output variable corresponding to the n-th vector in the data base, N is the number of vectors in the data base, p_{ni} is the i-th input variable of the n-th vector in the data base (e.g. *temperature, strain, strain rate*), p_i is the i-th input variable corresponding to the vector under consideration, and L is the number of input variables. To estimate quantitatively the accuracy of the CAE method for predicting the flow curves, the equation, which calculates the root mean sum of the squared deviations (RMSSD [20]) for each deformation condition was used.

RESULTS AND DISCUSSION

According to the selected criterion the temperature of 1210°C was determined as upper soaking temperature for samples taken from both mentioned places of the billet. At temperatures of 1220 and 1215°C the occurrence of decohesion of grain boundaries has been observed (Figure 2a). As can be concluded from Figure 2b that incipient melting occurs in the regions of positive segregation, where before the heating primary carbides were precipitated. For comparison for the samples with higher content of C, S, Mo, etc. the soaking temperature of approx. 1200°C was obtained. It was further found that at soaking temperature of 1170°C all carbides dissolve and the microstructure of the tool steel consists of austenite grains. Thus higher soaking temperature does not influence on the stronger precipitation of carbides on lower limit (cca 850°C) of the working range.

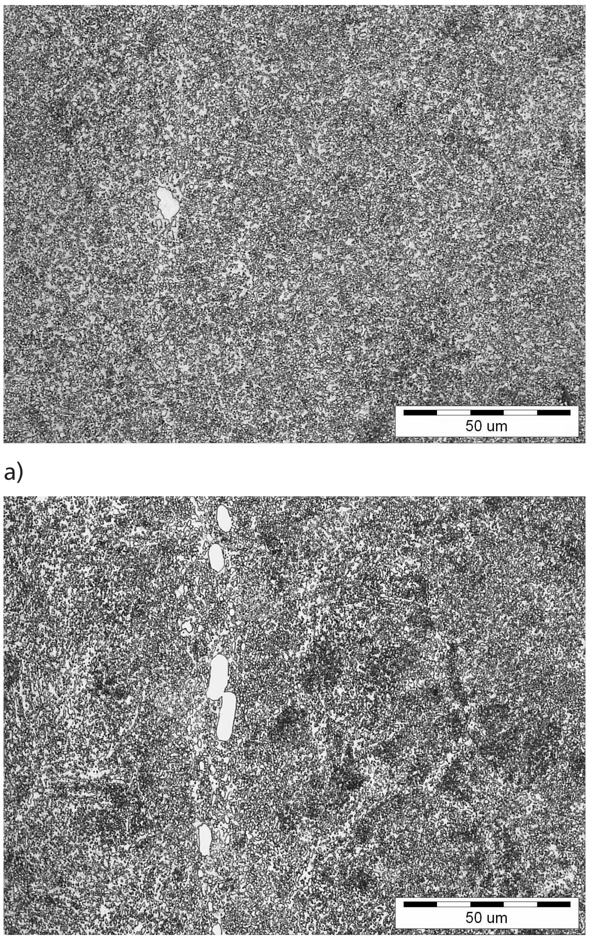


Figure 1. Initial billet microstructures of A2 tool steel, under surface of billet (a), billet centre (b).

The shape of flow curves (Figure 3) and obtained microstructures indicate that dynamic recrystallization DRX has taken place. In order to obtain better prediction of flow curves for intermediate values of strain rates and temperatures the logarithmic scaling of strain rates was used in CAE NN modeling. Note that results for A2 tool steel exhibit good agreement between the experimental and predicted results when a non-constant smoothing parameter ($w_\varepsilon = w_T = 0{,}03$; $w_{\varepsilon(\varepsilon=0{,}02)} = 0{,}01$, $w_{\varepsilon(\varepsilon=0{,}52)} = 0{,}03$) is used (see Figure 3). The mean error (RMSSD) of 2,2 % with the training data and within 3 % for predicted data

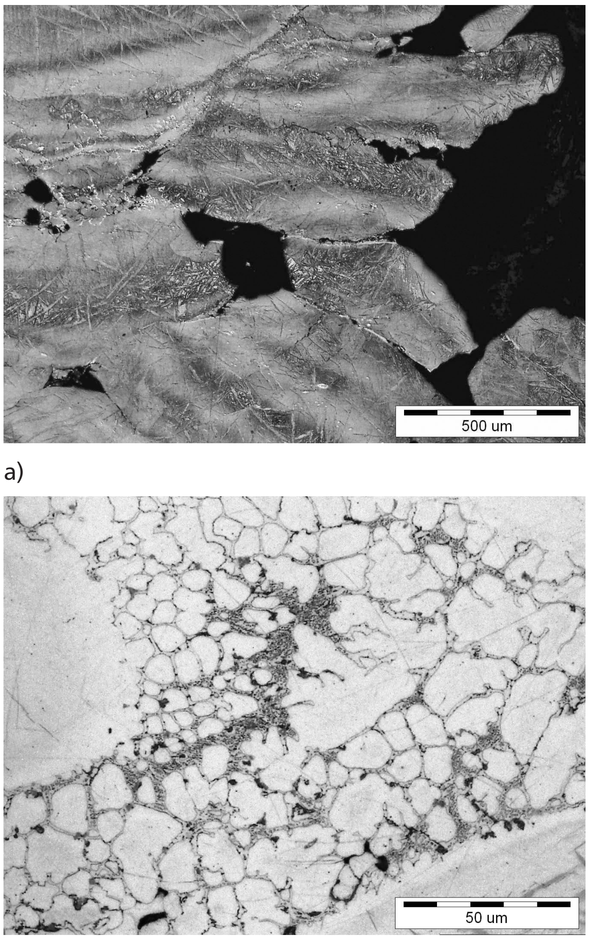


Figure 2. Occurrence of decohesion of grain boundaries (a) and incipient melting with occurrence of newly formed eutectic in positive segregation (on grain boundaries) at 1215°C (b).

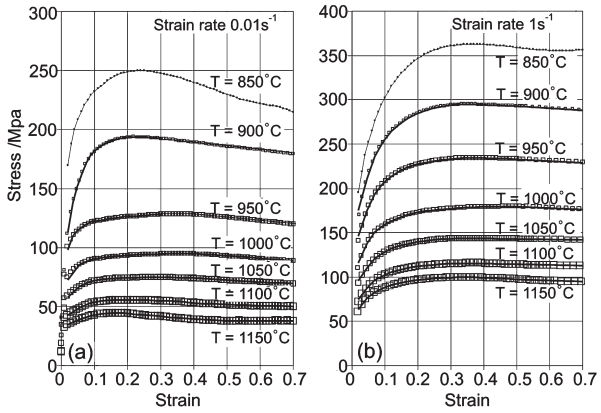


Figure 3. Flow curves for A2 tool steel – experimental (□) and CAE predicted results (–).

were obtained. Thus the obtained errors are within the required accuracy limit of 5% [8]. The advantage of the proposed method for prediction of flow curves can be clearly recognized from the prediction of the intermediate values of the input parameters especially for strain rates where the existing experimental data are given only for each decade. Figure 4a shows the predicted flow stress as a function of logarithm of strain rate for two different strains and temperatures as obtained by single interpolation method. Double interpolation method was applied for prediction of flow stress for intermediate strain rates and temperatures. The results are very encouraging and are shown on Figure 4b. Figure 4c shows predicted flow curve for strain rate 1s^{-1} and T=975°C ($w_{\varepsilon'}$ = 0,1, w_T = 0,05, $w_{\varepsilon(\varepsilon=0.02)}$=0,01, $w_{\varepsilon(\varepsilon=0,52)}$=0,03).

The amount of precipitated carbides on grain boundaries and on twins depends on the initial microstructures (see Figure 1). For the samples that had been cut from the centre of the billet where initial microstructure is more segregated and contains more primary carbides (Figure 1b), the amount of the precipitated carbides during deformation at 850°C is also higher and carbides are coarser (Figure 5a). Note that the shape of these carbides (irregular shaped) differs from the primary carbides (spheroidal) in initial microstructure. This clearly indicates that they precipitated during the cooling and deformation. Their amount and shape have detrimental influence on hot deformability at lower limit of the working range since this leads to the occurrence of micro- and macro-cracks on triple points and along the grain boundaries. On the other hand the material can be safely deformed, without any appearance of micro- and macro-cracks, at 850°C for more homogeneous initial microstructure (Figure 1a) that leads to lower precipitation of carbides during deformation (Figure 5b). From the analysis of microstructures of specimens deformed at temperatures above 1000°C it

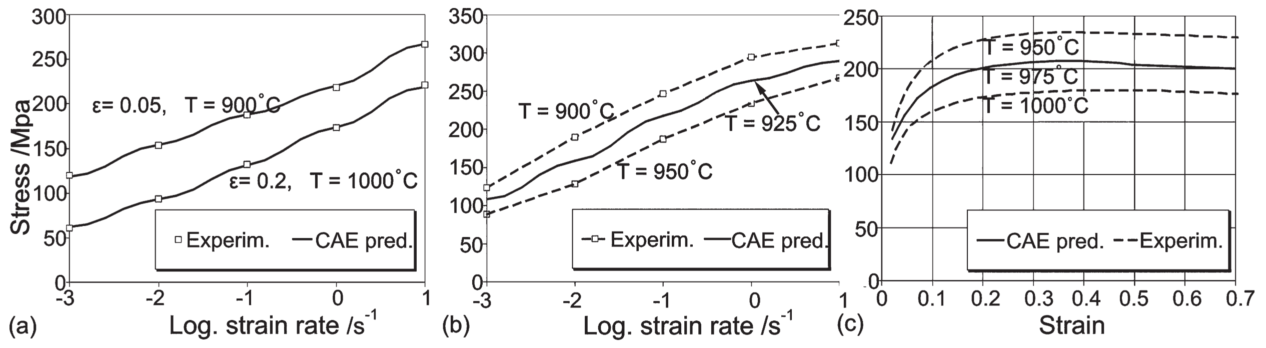
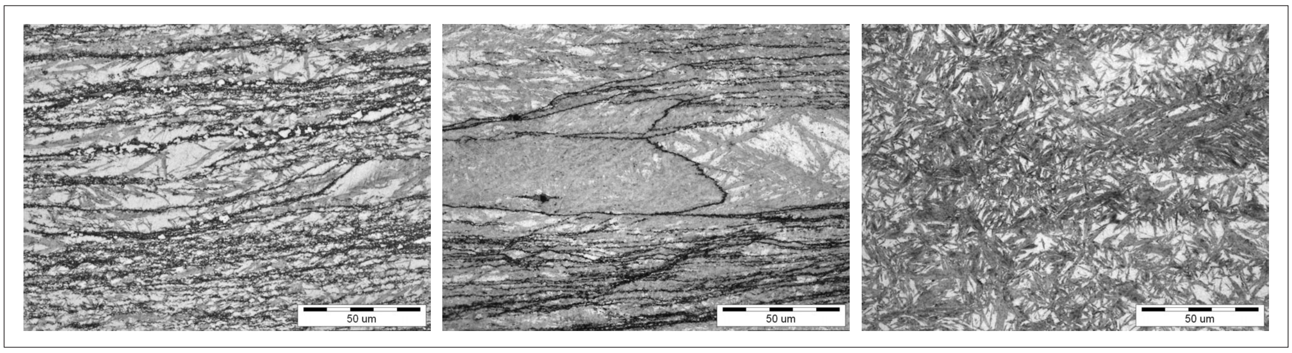


Figure 4. Prediction of hot flow curves for A2 tool steel as function of strain rate for ε=0,05, T=900°C and ε=0,2, T=1000°C (a), for T=925°C at ε=0,4 (b), and for T=975°C at strain rate 1 s^{-1} (c).



a) b) c)

Figure 5. Microstructures of samples from billet centre and deformed at 850°C (a), from billet surface and deformed at 850°C (b), and of samples deformed above 1000°C (c).

was found that almost no precipitation of carbides occurs (Figure 5c). On the other hand for samples deformed below 1000°C, the precipitation of secondary carbides on grain boundaries which are mainly of type $M_{23}C_6$ [1], is clearly seen on Figure 5a-b. Therefore the activation energy for deformation, Q, which is the indicator of operating microstructural mechanism during hot deformation, can not be the same for entire examined range (850-1150°C).

Flow stress maximums collected from the experimental flow curves have been used for determination of activation energies and constants of the hyperbolic sine equation:

$$Z = \varepsilon \exp(Q / RT) = A(\sin \alpha\sigma)^n \qquad (2)$$

for temperature ranges 850-1000°C and 1000-1150°C. The procedure of determination of activation energy and other constants is given in [26] and the results are selected in Table 1. For comparison the values which were obtained by Imbert et all [1] with torsion testing for range 900-1150°C at strain rates of 0,1, 1, and 4 s^{-1} are given together with values calculated from present experimental data for the same range. The comparison between measured and calculated dependence of peak stresses on temperature for different strain rates are shown on Figure 6; very good agreement was obtained.

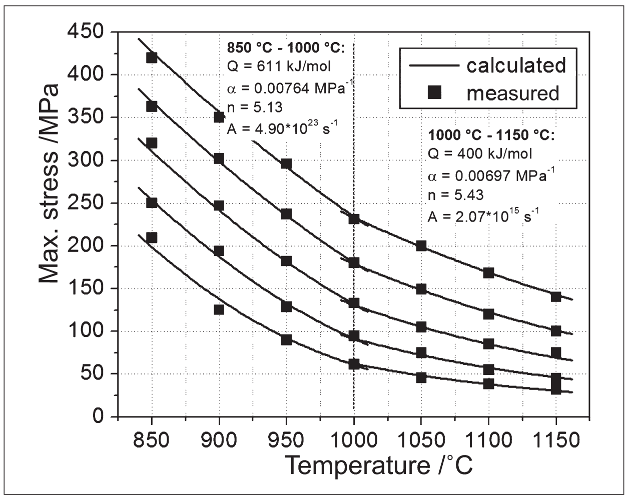


Figure 6. Comparison between measured and calculated peak-stress.

Table 1. **Activation energies and constants of the hyperbolic sine equation.**

Temperature range /°C	Q /kJ/mol	α/MPa^{-1}	n	A /s^{-1}
850-1000 (present investigation)	611	0.00764	5.13	$4.90 \cdot 10^{23}$
1000-1150 (present investigation)	400	0.00697	5.43	$2.07 \cdot 10^{15}$
900-1150 (present investigation)	497.5	0.0056	6.0	$2.5 \cdot 10^{15}$
900-1150 (Imbert et all. [1])	399	0.012	3.6	$7.06 \cdot 10^{19}$

CONCLUSIONS

Hot compression tests over a wide temperature range (850-1220°C) were carried out to obtain the upper soaking temperature (i.e. cca 1170-1210°C) and also lower temperature limit of the working range. The soaking temperature has no influence on precipitation of carbides on grain boundary at lower limit of the working range, T=850°C. On the other hand both initial microstructures influences the hot deformability at lower limit of the working range. Furthermore it was also observed that chemical composition influence the upper limit of the working range. Flow stresses were determined in temperature range 850-1150°C and strain rates 0,001-10 s^{-1}. Since increased precipitation of carbides bellow 1000°C was observed, the temperature interval for hyperbolic sine function analyses was divided into two ranges, i.e. 850-1000°C and 1000-1150°C. Activation energies for lower and higher temperature range are 611 kJ mol^{-1} and 400 kJ mol^{-1}, respectively. New approach based on CAE Neural Networks with double interpolation was developed. For predicted data the mean error of 3 % was obtained.

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Note: Author T. Večko Pirtovšek is responsible for English language.