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HIGH TEMPERATURE MECHANICAL PROPERTIES OF THE AS-CAST LOW CARBON STEELS AND THEIR PREDICTION

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High temperature properties of as-cast material, as reduction of area and strength, were tested in a temperature interval from 850 °C up to the melting temperature on measuring equipment provided with high frequency heating. The software for prediction of the high temperature plasticity development based on physical metallurgical and regression analyses was elaborated for the cast state of low carbon steels. The program was verified by using experimentally estimated values.

Key words: *low carbon steels, high temperature testing, prediction*

Mehanička svojstva na visokoj temperaturi lijevanih niskougljičnih čelika i predmnijevanje tih svojstva. Materijal u lijevanom stanju i njegova svojstva na visokoj temperaturi kao što su redukcija područja i čvrstoće, ispitivan je mjernim instrumentima opremljenim uređajima za visokofrekventno zagrijavanje na temperaturnim intervalima od 850 °C pa sve do temperature taljenja. Izrađen je softver za planiranje razvoja plastičnosti na visokim temperaturama koji se zasniva na fizičkoj metalurgiji i regresivnim analizama a namijenjen je niskougljičnim čelicima i lijevanom stanju. Program je potvrđen uporabom eksperimentalno utvrđenih vrijednosti.

Ključne riječi: *niskougljični čelici, ispitivanje na visokim temperaturama, predmnijevanje*

INTRODUCTION

Steel undergoes multiple phase transformations during casting and various forces of technological origin affect a slab in the casting machine. As a consequence of these influences, various types of defects arise during the casting process [1 - 5]. The slab surface quality is a crucial factor for quality of the end products, especially of the flat ones. Plasticity of the steel is a further, very important parameter influencing the slab surface quality. A high plasticity enables relaxation of various stresses and therefore causes minimum changes in the surface relief, without formation of crack like defects.

Temperature course of plasticity evaluated by the reduction of area values in the temperature range from about 900 °C up to the maximum solidus temperatures is for some of the investigated steels schematically depicted in Figure 1. The plasticity decrease regions under the t_x as well as above the t_h temperatures are critical for formation of defects, Figure 1.

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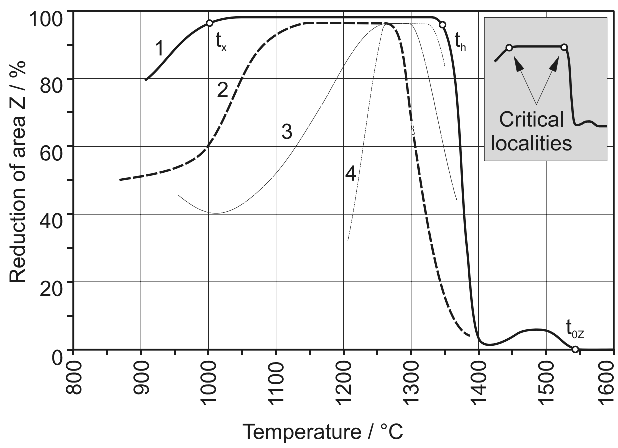

Chemical composition / wt. %							
Steel	C	Mn	Si	P	S	As	
1	0,04	0,15	-	0,014	0,007	0,050	
2	0,07	0,60	0,02	0,016	0,007	0,011+ Ti, Nb	
3	0,03	0,39	1,37	0,050	0,009	0,006+	0,36Sn
4	0,04	0,18	0,01	0,014	0,011		

Figure 1. **Temperature course of the reduction of area values**
Slika 1. **Tok temperature pri redukciji vrijednosti područja**

The plasticity decrease at lower testing temperatures is connected with formation of a proeutectoide ferrite network on the austenite grain boundaries [6 - 8]. Various factors controlling morphological as well as qualitative properties of ferrite can have an influence on the plasticity degradation temperature and on the intensity of its decrease [9 - 12]. In addition to these factors, plasticity is negatively influenced also by grain boundary strength weakening caused by a selective diffusion of trace elements [13, 14].

The high-temperature properties in laboratory conditions are measured by various methods, applying several heating and loading regimes. Even if there exists a testing possibility after remelting the material, the testing conditions always more or less differ from the working ones. Various testing conditions limit possibilities of a mutual comparison of the achieved results. In spite of this, the testing of high-temperature properties gives some information, which can be applied at optimization of the cast technology can remarkably contribute to minimizing the occurrence of surface defects.

The present contribution deals with investigation of the phenomena influencing high temperature plasticity and with possibilities for the prediction of the high-temperature properties of low carbon steels in the as-cast state.

EXPERIMENTAL MATERIALS AND TESTING METHODS

Equipment used for high-temperature properties testing consisted of a high frequency generator, tensile testing machine, and a time-temperature regulation of heating.

The experiments were realized on 24 low carbon commercially produced steels. Specimens with a diameter of about 6 mm were used. Specimens were high-frequency heat-ed in protecting atmosphere of argon. Standardized testing conditions and heating time-temperature regimes, 60 s holding time at 1350 °C and 60 s holding time on testing temperature as well as loading velocity of 0,047 s^{-1} were used. Strength (R_{ht}) and reduction of area (Z) were evaluated after testing and fractographic and metallographic analyses were made on the specimens. Both evaluated parameters, strength and plasticity, are quantities of conventional nature.

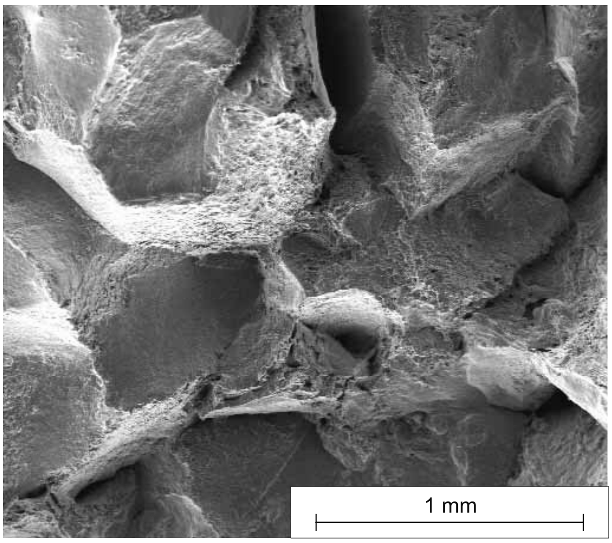

Figure 2. **Intercrystalline fracture - region of the t_x temperatures**
Slika 2. **Međukristalni prelom - područje temperatura t_x**

MORPHOLOGY OF THE HIGH TEMPERATURE FRACTURES

Intercrystalline ductile fractures, e.g., Figure 2. usually arise at lower testing temperatures. The main cause of plasticity degradation is in this case precipitation of ferritic envelopes on the austenite grain boundaries.

Ductile transcrystalline fractures with high values of the reduction of area arise in one phase austenite region, Figure 3. In some cases intercrystalline fractures also arise in this region, as a consequence of grain boundary weakening by diffusion of impurities as, e.g., in steels 3 and 4, Figure 1.

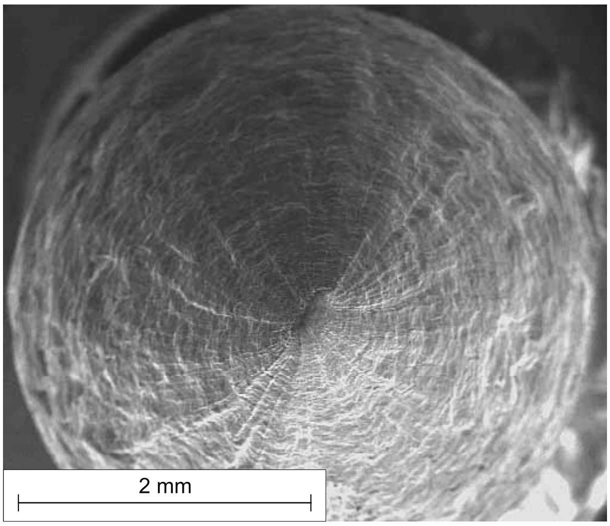

Figure 3. **Ductile transcrystalline fracture in the high plasticity region**
Slika 3. **Međukristalni prelom žilavog materijala u području visoke plastičnosti**

Fractures originating at the highest temperatures are intercrystalline with variable morphology. Besides intercrystalline fractures of typical appearance, Figure 4., other fracture morphologies were also observed. These specific morphologies were present not only in regions of the coexistence of austenite and delta ferrite phases, but also in austenite.

HIGH TEMPERATURE PROPERTIES

Analyses of high-temperature reduction of area values showed a preferred influence of As on the t_x temperature. This effect is substantially higher, chiefly at As contents

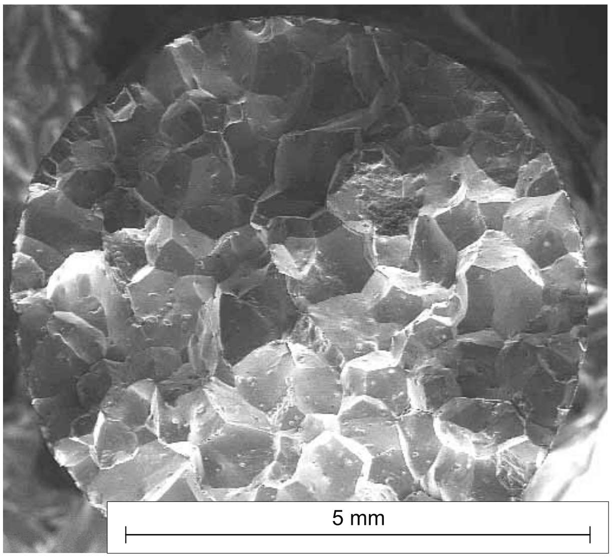

Figure 4. **Intercrystalline fracture originated at the highest testing temperatures in δ-ferrite**
Slika 4. **Međukristalni prelom nastao na najvišim ispitnim tem-**

above app. 0,010 %. In steels with a lower content of A_s the "fracture unit size", *dz*, estimated on the intercrystalline fracture surfaces or on specially etched metallographic cross sections, had the greatest influence on the reduction of area values, Figure 5.

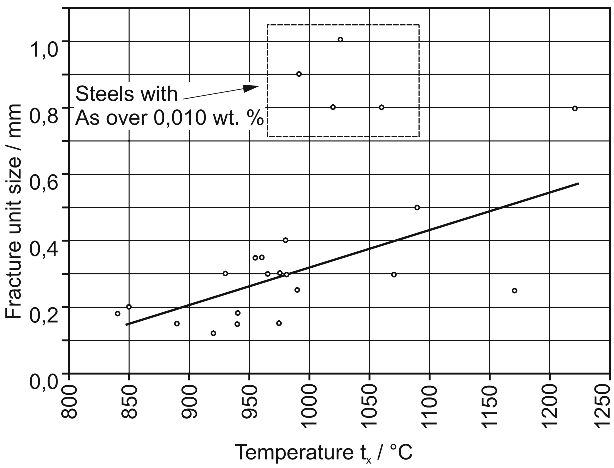

Figure 5. **The influence of fracture unit size on the temperature t_x**
Slika 5. **Utjecaj veličine jedinice prijeloma na temperaturu t_x**

At investigation of the temperature t_h unambiguously was determined only the influence of phosphorus. This evidently negative influence takes place above about 1320 °C. The t_h temperature is most probably influenced also by the grain size. Because the t_h temperatures intervene in the gamma - delta phase changes, some dependence could be determined only for individual steel groups.

The high-temperature plasticity is also influenced by other chemical elements, which are usually, or casually present in low carbon steels, often only in trace contents. Their effect was in the set of tested steels lower then the above mentioned influences.

PREDICTION OF THE HIGH TEMPERATURE PROPERTIES

From the analysis of the high-temperature properties it followed that these are influenced by a number of variables, their partial effects are temperature dependent, and a mutual interaction is taking place between them. The prediction of high-temperature properties was investigated by linear regression analysis in several steps. Regression models were chosen and optimized in the first step. Temperatures t_h and t_x, Figure 1., were chosen as characteristic ones for plasticity prediction, as well as analogous temperatures t_{x90} and t_{h90} on 90 % level of the reduction of area values. The analyses were completed also for the temperature t_{0Z}, i.e., the minimal temperature at which the reduction of area value dropped to an immeasurable one. For comparison the theoretical transformation temperatures γ - α (t_{xteor}) and the maximal solidus temperature (t_{hteor}) were also figured out. Temperatures in a range from 900 up to 1500 °C with a step of 50 and 100 °C, resp., were chosen for strength. Then the corresponding equations, some of them selectively established for individual steel groups, were elaborated into computer software. It concerns about 80 equations.

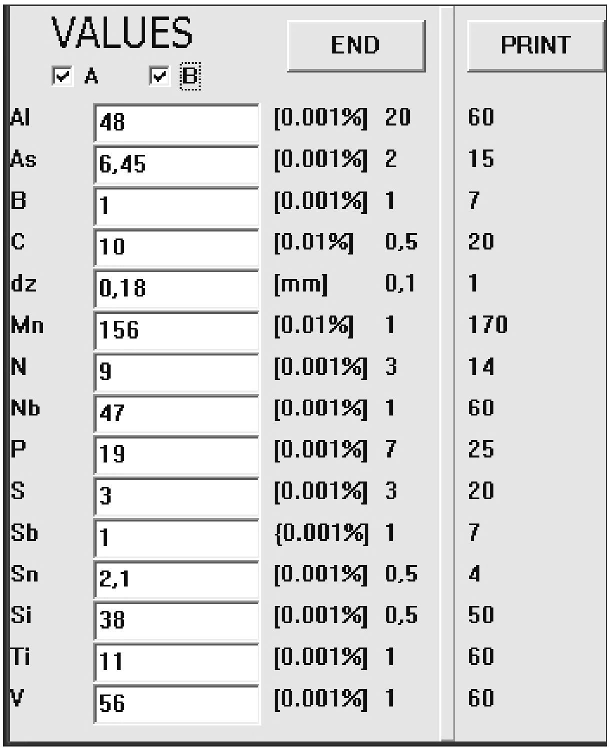

Figure 6. **The input values, the prediction software screen**
Slika 6. **Ulazne vrijednosti, ekran sa softverom za planiranje vrijednosti**

The input parameters and their extent are evident from Figure 6. Besides the multiple parameters of chemical composition the fracture unit size (*dz*) is also included to the input parameters. This parameter is calculated from several equations as a function of S, P, B, Mn, and Sn contents, variant for characteristic steel groups according to their chemical composition. Accuracy of the *dz* parameter prediction was for the set of investigated steels quite good, the *r* coefficients were in a range from 0,81 up to 0,85. An example of output in the numeric as well as graphic form is in Figure 7.

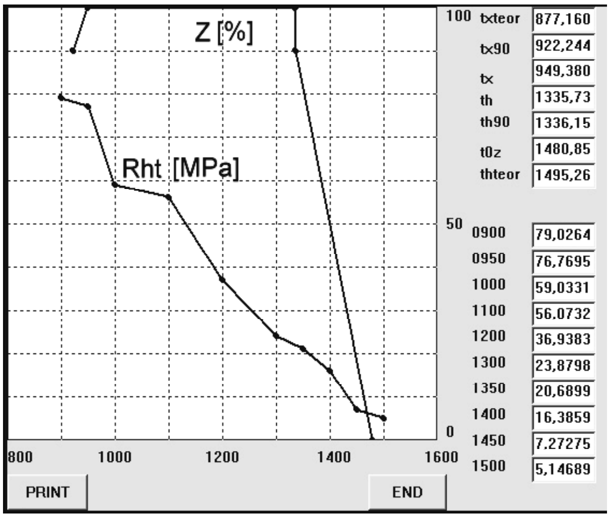

Figure 7. **The calculated values, the prediction software screen**
Slika 7. **Izračunate vrijednosti, ekran sa softverom za planiranje vrijednosti**

DISCUSSION

The verification of the program was realized by comparing experimentally determined values with calculated ones for all steels involved into investigation.

In case of characteristic points on the reduction of area course an increase of the corresponding coefficients was taking place as a consequence of an alternative way of calculation. For the temperature t_x, at which the prediction equations had high correlation coefficient values, about 0,92, only a moderate improvement of this coefficient, on the value of 0,93, was established. For the temperature t_h a considerable increase of the correlation coefficient was achieved, from the level of about 0,70 to 0,82.

The strength prediction was best at 900 °C, in this case the correlation coefficient increased from 0,75 to 0,88. The accuracy of the strength prediction at higher temperatures gradually decreases and above app. 1300 °C we cannot speak any more about dependency. But in such case the strength values are very low, under 30 MPa.

The values of the characteristic temperatures of plasticity course are of conventional character. At any change of testing conditions, as deformation rate, specimens' geometry, or notching the specimens the determined values will be different. The plasticity and strength values will also be influenced by the steel structure. Besides the influence of grain size, which is already experimentally proved, the high temperature plasticity will be probably also influenced by the matrix state, e.g., by qualitative and quantitative parameters of the secondary phases.

CONCLUSIONS

Based on physical and metallurgical investigation of the influence of chemical composition and microstructure on the high temperature properties prediction software for reduction of area and strength values in the temperature interval from 850 °C up to the melting temperature was elaborated. The contents of Al, As, B, C, Mn, N, Nb, P. S, Sb, Sn, Si, Ti and V are input data of the software. The grain size, which significantly influences the degradation temperature at lower testing temperatures - t_x, is determined as a function of S, P, B, Mn, and Sn content.

The program was verified by experimentally measured values. The accuracy of the prediction of plasticity degradation at lower testing temperatures, the t_x temperature, has a high correlation coefficient r = 0,93. This temperature is controlled chiefly by the arsene content and grain size, measured as fracture unit size.

The accuracy of the prediction of plasticity degradation at the highest testing temperatures, t_h, which is significantly influenced by the phosphorus content, is on a level of r = 0,82. The lower prediction accuracy in comparison with the t_x temperature is probably caused by grain size changes in steels which undergo γ -δ transformation.

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