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PLASTOMETRIC STUDY OF HOT FORMABILITY OF HYPEREUTECTOID C – Mn – Cr – V STEEL

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Formability of hypereutectoid C-Mn-Cr-V steel in hot condition was investigated with use of plastometric methods. A wide range of deformation temperatures 1 300 - 640 °C for hot tensile tests was proposed with use of nil-strength temperature (NST), determined by special plastometric method, and as well as with use of the calculated temperatures of phase transformations during heating of the investigated steel. Ultimate tensile strength of the investigated steel was increasing exponentially with the decreasing deformation temperature. Ductility of the investigated steel in hot condition increased with the increasing deformation temperature up to the temperatures ranging from 1 150 to 1 250 °C, after which a sharp decline of formability took place in investigated material.

Key words: hypereutectoid steel, deformation, hot formability, mechanical properties in hot condition.

INTRODUCTION

Formability is the ability of the body to get plastically deformed under certain conditions forming till failure of its consistency (till formation of critical cracks, or to fracture). Investigation of formability, or of deformation behaviour of steel in hot condition uses mainly laboratory physical modelling on tensile or on torsion plastometers [1-5]. Tests by uniaxial pressure are not suitable for this purpose due to compressive stresses acting on the deformed material [6,7]. The universal plastometers Gleeble make it possible for example to use high temperature tensile tests for investigation of the problems connected with cracking of materials during their casting [8,9]. The studied parameters of hot tensile tests are usually particularly material strength and ductility [10,11]. For determination of technological formability it is then possible to use a well-tried method of laboratory rolling of wedge samples [12].

This paper deals with research of formability of hyper-eutectoid C – Mn – Cr – V steel in hot condition, designated for subsequent drawing. All experimental works were performed on plastometer Gleeble 3 800, which is installed in the laboratory of the VSB - Technical University of Ostrava, and which is characterised by big universality of testing possibilities [13,14].

EXPERIMENTAL PROCEDURE

Chemical composition of the investigated steel is presented in Table 1.

Table 1 **Chemical composition / wt. %**

C	Mn	Si	Cr
0,83	0,67	0,22	0,22
V	Ti	B	N
0,077	0,0011	0,0003	0,0031

Experimental works were divided into two stages. The nil-strength temperature of the investigated steel, which provides important information for selection of the maximum forming temperatures, etc., was determined by special plastometric tests.

Cylindrical bars with a diameter of 6 and length of 81 mm were prepared from the investigated steel for the tests designed to determine the nil-strength temperature. The nil-strength temperature was determined by special method, comprised of the controlled two-step high-temperature electric resistance heating in combination with very small constant tensile force applied on the test bar heated by resistance heating. In the temperature range from 0 to 1 300 °C a heating rate of 22 $°C \cdot s^{-1}$ was applied to the test bar, and in the temperature range from 1 300 to 1 500 °C a heating rate of 2 $°C \cdot s^{-1}$was applied.

The nil-strength temperature *NST* / °C lies between the solidus and liquidus temperatures and it corresponds to the highest value of the registered temperature at the moment of loss of material consistency under action of very low force (rupture of test bar and a sudden deep drop in temperature) [15]. Altogether three such tests were performed - see Figure 1 and mean nil-strength temperature is recognised as the result of them. Table 2 presents experimentally obtained and statistically processed results.

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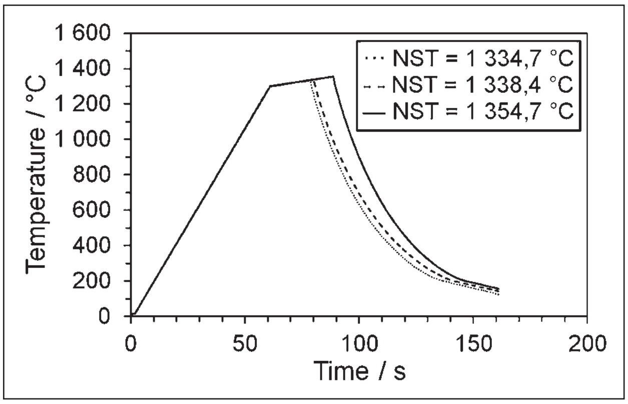

Figure 1 Evolution of temperature during nil-strength temperature tests

Table 2 **Results of nil-strength of the investigated steel**

	NST / °C
1st test	1 338,4
2nd test	1 354,7
3rd test	1 334,7
mean value	1 342,6
standard deviation	8,7

Temperatures of phase transformations of the investigated steel during its heating were also calculated. The temperature Ac_1 = 728 °C was calculated using the equations given in [16] and the temperature Ac_m = 749 °C was calculated using the equation published in [17].

Test bars with diameter of 10 mm and length of 116,5 mm were prepared from investigated steel for hot tensile tests. The prepared test bars were on the plastometer Gleeble 3 800 heated by electric resistance at the rate of 10 °C·s^{-1} at the selected deformation temperature followed by a 30 second dwell at this temperature. This was followed by drawing of individual bars at investigated temperatures and at selected drawing rates.

With respect to the mean nil-strength temperature and to the phase transformation temperatures at heating of the investigated steel deformation temperatures were proposed for tensile tests in order to ensure deformation in the austenite, pearlitic and two-phase region of the investigated steel: 1 300, 1 250, 1 150, 1 050, 950, 900, 850, 780, 738, 690 and 640 °C. For this experiment the drawing rates of 1 000, 20, 0,4 and 0,01 mm·s^{-1} were chosen.

The tested specimens were clamped in the jaws made of AISI304 stainless steel, the contact length of which with the sample was only 4,25 mm. Thanks to their design and thermal properties they are characterised by the measured length of the heated zone of the test bar of 20 mm.

DISCUSSION OF RESULTS

From the data were, for all the broken test bars, designed the maximum values of the force F_{max} / kN were determined for all the ruptured test bars from the measured data, which were used, together with the initial cross-section of the test bars S_0 / mm, for calculation of the ultimate tensile strength R_m / MPa of the investigated material in hot condition:

$$R_m = \frac{F_{max} \cdot 1000}{S_0} \qquad (1)$$

Apart from that a ductility (relative elongation) A / % of the investigated steel in hot condition was determined from the values of elongation to rupture:

$$A = \frac{\Delta L}{L_0} \cdot 100 \qquad (2)$$

where ΔL / mm is elongation to rupture and L_0 is the measured length, which was in the case of used clamps made of stainless steel equal to 20 mm.

On the basis of the results obtained by hot tensile tests using jaws made of stainless steel 3D maps of ultimate tensile strength or of ductility in hot condition in dependence on the deformation temperature and strain rate were constructed - see Figures 2 and 3. The strain rate was determined from the intensity of deformation and from the drawing rate for conditions of uniform deformation, i.e. till formation of a neck during drawing. Strain rates ranging from 9,5·10^{-4} to 8,4·10^{1} s^{-1} corresponded to the applied drawing rates.

Ultimate tensile strength of the investigated steel increases exponentially with the decreasing deformation temperature. The contractual strength increases linearly with the increasing strain rate. Deformation at temperatures below 800 °C, resulted in a steep increase in strength, which can be explained by change of structure of the investigated steel.

Ductility of the investigated steel in hot condition increases with the increasing drawing temperature up to the certain maximum, varying in dependence on the strain rate within the temperature range from 1 150 to 1 250 °C, and then it steeply decreases.

With use of thermodynamic-kinetic software (IDS Solidification Analysis Package) [18] the solidus temperature of the investigated steel of 1 331 °C was determined for equilibrium conditions. The IDS has

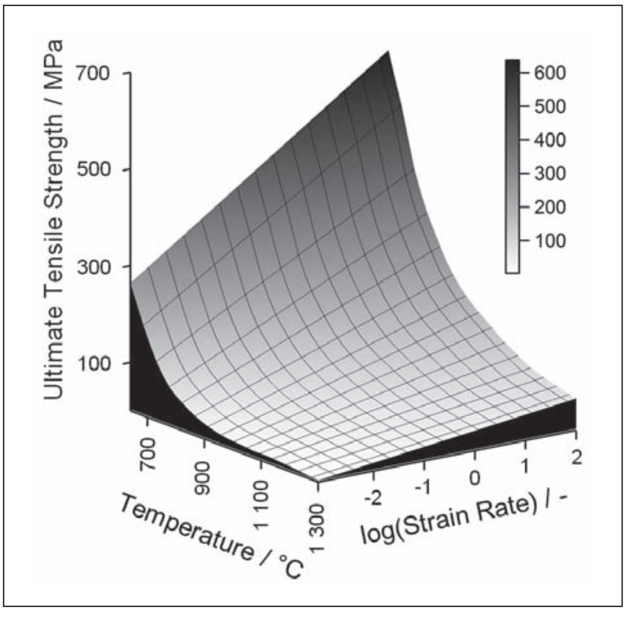

Figure 2 3D map of ultimate tensile strength in hot condition

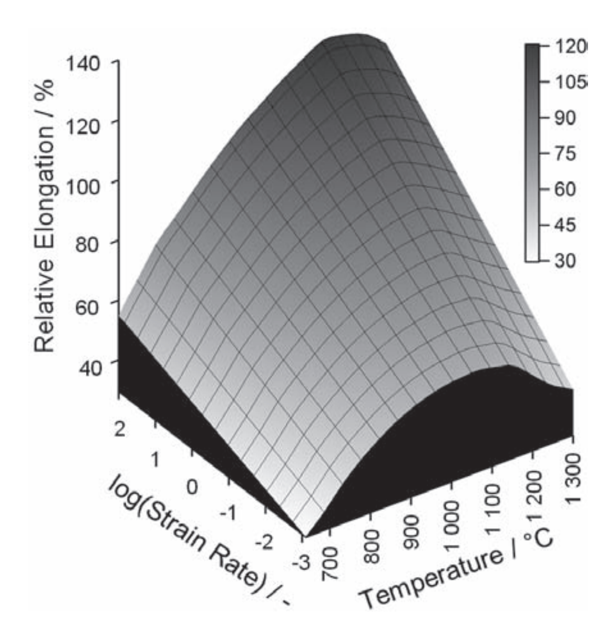

Figure 3 3D map of ductility in hot condition

been developed to simulate phase changes and solute distribution during solidification of steel. It is therefore evident that decrease of ductility was not caused by the manner of melting of the investigated steel. In addition it was also found by calculation in the IDS program that at the temperature of 1 230 °C the TiN particles should be dissolved in material, and at the temperature of 1 245 °C the BN particles should be dissolved. Owing to the chemical composition of the investigated steel the influence of the TiN and BN particles on the evolution of formability should be negligible.

The ascertained drop of ductility was thus apparently caused by overheating of the investigated steel or by an abnormal grain coarsening during heating to the high temperature.

SUMMARY

With use of the universal plastometer Gleeble 3 800 a formability of the hypereutectoid C-Mn-Cr-V steel, deformed in a wide range of temperatures from 1 300 to 600 °C and at the strain rate from $9{,}5 \cdot 10^{-4}$ to $8{,}4 \cdot 10^{1}$ s^{-1}, was investigated.

The deformation temperatures were chosen with respect to plastometrically determined nil-strength temperature and to calculated temperatures of phase transformations during heating of the investigated steel.

3D maps of ultimate tensile strength and ductility of the examined steels after in hot condition in dependence on the strain rate and deformation temperature were created from the results of tensile tests performed with use of clamps made of stainless steel.

Evolution of ultimate tensile strength in hot condition was fundamentally influenced by deformation temperature or by deformation in a two-phase area and in single phase pearlitic area. The ultimate tensile strength of the investigated steel increased with the decreasing deformation temperature.

What concerns ductility a significant influence of deformation temperature was also observed. Ductility of the investigated steel in hot condition increased with the increasing deformation temperature up to the temperature range from 1 150 to 1 250 °C, after which a sharp drop of ductility took place in the investigated material, caused by overheating of the investigated steel.

Small scatter of experimental data confirmed the high reproducibility of the results obtained in a very wide range of strain rates and deformation temperatures.

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REFERENCES

[1] B-H. Chen, H. Yu, Hot ductility behavior of V-N and V-Nb microalloyed steels, International Journal of Minerals Metallurgy and Materials 19 (2012) 6, 525-529. DOI: 10.1007/s12613-012-0590-6

[2] S. Grosseiber, S. Ilie, C. Poletti, B. Harrer, H.P. Degischer, Influence of strain rate on hot ductility of a Vmicroalloyed steel slab, Steel Research International 83 (2012) 5, 445-455. DOI: 10.1002/srin.201100335

[3] R. Pernis, J. Kasala, J. Bořuta, Hot torsion tests of cartridge brass MS70, Acta Metallurgica Slovaca 15 (2009) 1, 5-14.

[4] V. Kurka, P. Machovcak, K. Michalek, P. Unucka, Evaluation of production and properties of the forged bar made of super-duplex austenitic-ferritic steeel, Conference Proceedings, 20th International Conference on Metallurgy and Materials Metal 2011, Brno, 2011, Ostrava: Tanger Ltd, pp. 180-186.

[5] R.S. Lee, Y.K. Lin, T.W. Chien, Experimental and theoretical studies on formability of 22MnB5 at elevated temperatures by Gleeble simulator, Procedia Engineering 81 (2014), 1682-1688. DOI: 10.1016/j.proeng.2014.10.213

[6] A.Y. Churyumov, M.G. Khomutov, A.N. Solonin, A.V. Pozdniakov, T.A. Churyumova, B.F. Minyaylo, Hot deformation behaviour and fracture of 10CrMoWNb ferritic-martensitic steel, Materials and Design 74 (2015), 44-54. DOI: 10.1016/j.matdes.2015.02.023

[7] D.N. Zou, K. Wu, Y. Han, W. Zhang, B. Cheng, G.J. Qiao, Deformation characteristics and prediction of flow stress for as-cast 21Cr economical duplex stainless steel under hot compression, Materials and Design 51 (2013), 975-982. DOI: 10.1016/j.matdes.2013.04.065

[8] K.M. Banks, A. Tuling, B. Mintz, Influence of thermal history on hot ductility of steel and its relationship to the problem of cracking in continuous casting, Materials Science and Technology 28 (2012) 5, 536-542. DOI: 10.1179/1743284711Y.0000000094

[9] S.T. Mandziej, Physical simulation of metallurgical processes, Materials and Technology 44 (2010) 3, 105-119.

[10] G.Q. Hou, L. Zhu, Influence of strain rate on hot ductility of austenitic stainless steel slab, Materials Science and Technology 29 (2013) 5, 568-572. DOI: 10.1179/1743284712Y.0000000182

[11] K.M. Banks, A. Tuling, B. Mintz, Influence of V and Ti on hot ductility of Nb containing steels of peritectic C contents, Materials Science and Technology 27 (2011) 8, 1309-1314. DOI: 10.1179/026708309X12584564052139
[12] I. Schindler, P. Suchanek, S. Rusz, P. Kubecka, J. Sojka, M. Heger, M. Liska, M. Hlisnikovsky, Hot-cracking of high-alloyed steels evaluated by wedge rolling test, Strength of Materials 40 (2008) 1, 52-55.
DOI: 10.1007/s11223-008-0014-z
[13] R. Kawulok, I. Schindler, P. Kawulok, S. Rusz, P. Opěla, Z. Solowski, K.M. Čmiel, Effect of deformation on the CCT diagram of steel 32CrB4, Metalurgija 54 (2015) 3, 473-476.
[14] P. Kawulok, R. Kawulok, I. Schindler, S. Rusz, J. Kliber, P. Unucka, K.M. Čmiel, Credibility of various plastometric methods in simulation of hot rolling of the steel round bar, Metalurgija 53 (2014) 3, 299-302.
[15] L. Kuzsella, J. Lukács, K. Szücs, Nil-strength temperature and hot tensile tests on S960QL high-strength low-alloy steel, Production Processes and Systems 6 (2013) 1, 67-87.
[16] O.G. Kasatkin, B.B. Vinokur, V.L. Pilyushenko, Calculation models for determination the critical points of steel, Metal Science and Heat Treatment, 26 (1984) 1, 2731.
[17] S.J. Lee, Y.K Lee, Thermodynamic formula for the A_{cm} temperature of low alloy steels, ISIJ International 47 (2007) 5, 769-771.
[18] M. Zaludova, B. Smetana, S. Zla, J. Dobrovska, V. Vodarek, K. Konecna, V. Matejka, P. Matejkova, Experimental study of Fe-C-O based system below 1 000 degrees C, Journal of Thermal Analysis and Calorimetry 111 (2013) 2, 1203-1210. DOI: 10.1007/s10973-012-2346-y.

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