PLASTIC PROPERTIES OF STEEL AISI 4140 INFLUENCED BY STRAIN RATE AND TEMPERATURE

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Abstract

Deformation behavior of continuously cast steel with 0.43 % C, 1.01 % Cr and 0.19 % Mo was studied in the austenite region. Its solidus temperature was calculated as 1435 °C and the nil strength temperature at heating was determined as 1402 °C using a special testing method. Hot ductility was measured by means of the uniaxial tensile tests in wide range of mean strain rate (0.00074 – 63 s^{-1}) and temperature (800 – 1375 °C). At medium strain rate of 0.65 s^{-1}, formability steadily increased to a temperature of approx. 1335 °C and then sharply dropped as a result of overheating and burning of the steel. The nil ductility temperature was determined as 1365 °C in this case. Influence of strain rate on formability was evaluated at two temperature values corresponding to relatively poor and/or good plastic properties. At a temperature of 900 °C, ductility increased rather moderately with the increasing strain rate. At a temperature of 1280 °C, the growth of ductility at increasing strain rate was sharper and both dependencies intersected at a strain rate of approx. 0.008 s^{-1}. Formability was improved by higher temperature at high strain rates and deteriorated at very low strain rates, which is a quite unique result. It was not possible to determine the value of the strain rate corresponding to the local maximum of ductility, even if applying the strain rate range of 6 orders. SEM analysis of the broken samples confirmed the expected influence of microstructure development on hot formability.

Keywords: Uniaxial tensile test, mean strain rate, ductility

1. INTRODUCTION

Influence of strain rate on steel hot formability is an interesting issue but less intensively investigated across the world than, for example, influence of the forming temperature. The reason is mainly experimental demandingness (necessity of achievement of a sufficiently wide interval of strain rate, and not each laboratory device can easily achieve it) and considerable complexity of the issue resulting from a varied chemical composition of steel and different material aspects of their deformation behavior. Not always fully compatible knowledge of different researchers also complies with it [1-7]. An appreciatory type of material for the given investigations are austenitic corrosion-resistant steels; structural analyses of the fractured samples are not complicated by their phase transformations proceeding during cooling from the testing temperature [8-10]. Formability of material is influenced by a change of strain rate $\dot{e}$ (s^{-1}) at a continuous deformation up to a fracture due to different factors: structural composition, initial grain size, strength and clearness of the grain borders, kinetics of dynamic recrystallization, influence of deformation heat, deformation-induced precipitation, etc. High-temperature formability is improved by the course of dynamic recrystallization, which releases tensional concentrations and displaces borders of the grains out of the existing cracks, by which it is prevented from their progress. A key knowledge is that hot formability depends more on microstructure development influenced by strain rate than on strain rate itself, i.e. its effect is, first of all, indirect, mediated [11].

2. DESCRIPTION OF EXPERIMENT

The aim of the paper was to determine - on the basis of laboratory tests - laboratory conditions, at which formability of medium-carbon low-alloyed Cr-Mo steel is the highest. The investigated steel was delivered in a cast state and had the following chemical composition: 0.43 C - 0.80 Mn - 0.27 Si - 0.012 P - 0.011 S - 1.01 Cr - 0.19 Mo - 0.029 Al - 0.0044 N. Cylindrical samples for testing by single-axes tension with a diameter of 10 mm and threats at both ends were withdrawn from the area of columnar crystals, in parallel with the direction of continual blank casting. Testing went on in the Gleeble 3800 simulator after resistive heating of the sample with a rate of 10 °C/s and resting at the temperature for 300 s. Applied jaws for sample gripping of „hot grips“ type were made from austenitic corrosion-resistant steel, and they ensured a heated (measured) length of 20 mm. As the first, influence of temperature to hot ductility was investigated (respectively relative elongation up to fracture) A_T (%) at constant crossbeam speed of 20 mm/s. The temperature range was chosen in an interval from 800 °C up to the nil ductility temperature. On the basis of the obtained results, two temperature levels were chosen for the determination of influence of strain rate to formability - 900 °C and 1280 °C. Tensile tests were applied at these temperatures at nominal crossbeam speeds of 0.02 - 0,2 - 2 - 200 - 2000 mm/s. A wide range of rates (5 orders) should enable possible localization of strain rate connected with the highest formability. After fracturing, all samples were cooled freely, without control of cooling rate or fixation of structural state by means of hardening with water nozzles.

2.1. Thermal dependence of formability

Figure 1 shows examples of results obtained at nominal rate of the transverse of 20 mm/s. The shot of the samples after fracturing and of dependence of force F (kN) on elongation ΔL (mm) documents different deformation behavior of the investigated steel at different temperatures. A specificity is a „two-stage“ form of several curves in **Figure 2**. Especially in the case of temperature of 1000 °C, a plateau of force exists at enormously big elongation, which can be described neither by mechanics of the test nor by manifestation of a significant yield point. A mean value of strain rate was simplistically calculated for each test with non-nil ductility as a share of the crossbeam speed and the mean length of the measured part of the rod; it included the initial length (20 mm) and the final length (20 mm + total elongation up to fracture). In dependence on concrete ductility, the so-defined values of strain rate are in the interval of 0.59 - 0.72 s^{-1}. Values of A_T were then calculated as a percentage share of ΔL and the measured sample length, respectively a contractual hot strength limit R_{mT} (MPa) as a share of the maximum measured force and the initial cross-section area of the sample with a diameter of 10 mm.

Figure 1 Shape of the tested samples

Monotonic course R_{mT} in **Figure 3** proves that the whole used temperature range corresponds with the austenitic area. Formability is gradually growing with temperature approximately up to 1335 °C and afterwards is vehemently dropped due to overheating and material burning. The nil ductility temperature is probably situated between 1360 and 1370 °C; the sample is cracked at temperature of 1375 °C already during heating.

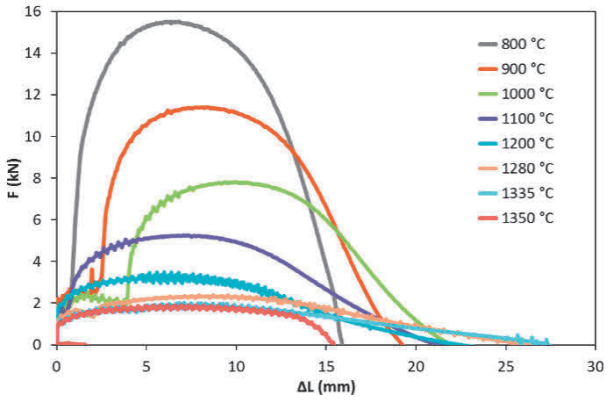


Figure 2 Deformation behavior influenced by temperature at tensile testing – crossbeam speed of 20 mm/s (force-elongation dependencies)

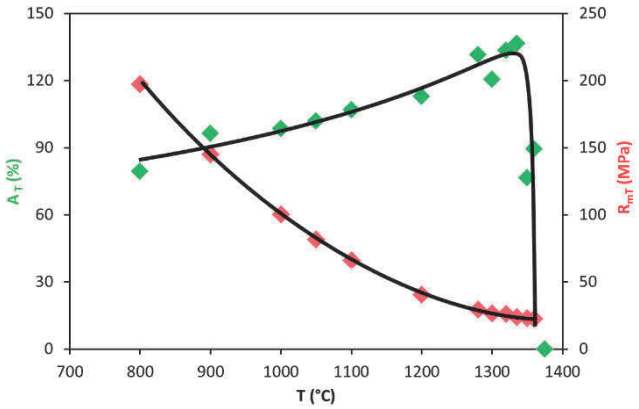


Figure 3 Temperature dependence of ductility and tensile strength at crossbeam speed of 20 mm/s

2.2. Influence of strain rate on formability

Figure 4 shows other relevant examples of a shape of the fractured samples and of dependence of force on elongation. As is clear from the figure, influence of strain rate on deformation behavior is in case of temperature of 900 °C more less significant than at temperature of 1280 °C. Mean values of strain rate were also calculated for this set of tests; they fluctuated in a range of 0.00074 - 63 s^{-1}.

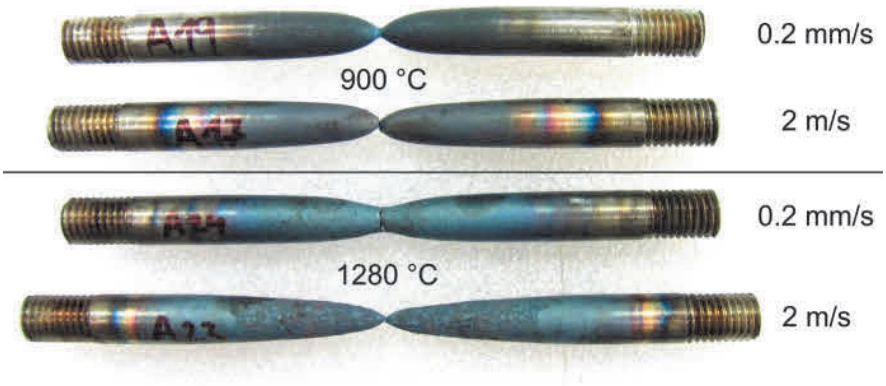


Figure 4 Shape of the samples after testing

The graph in **Figure 5** documents influence of strain rate on formability at the both temperature levels. At temperature of 900 °C, ductility grows with a growing strain rate linearly and relatively slightly. In the case of temperature of 1280 °C, the given dependence can be described with a good accuracy by a quadratic equation, whereas the growth of ductility with a growing strain rate is steeper than at low temperature. What is, however, interesting is that the both curves are intersected at $\dot{e} \approx 0.008\ s^{-1}$. Due to it, at $\dot{e} \approx 60\ s^{-1}$, ductility is dramatically more favorable (almost by 40 %) for temperature of 1280 °C, while for $\dot{e} \approx 0.00074\ s^{-1}$ material shows ductility higher by 40 % at temperature of 900 °C.

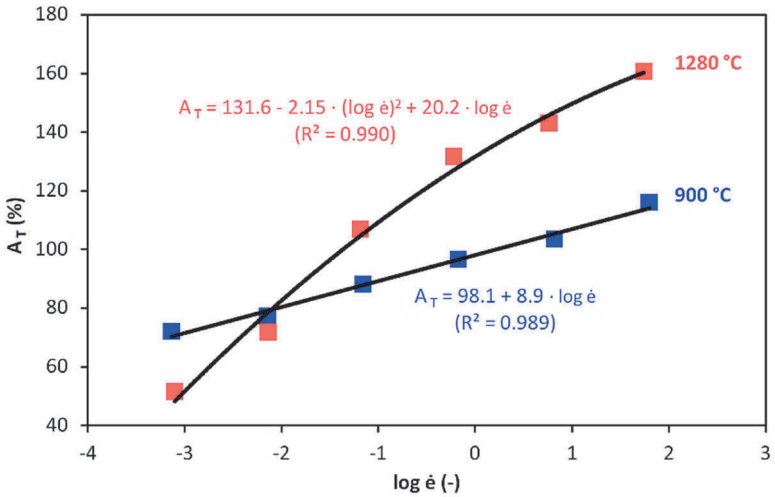


Figure 5 Ductility depending on strain rate at temperatures of 900 °C and 1280 °C

Generally higher strain rate leads to more homogeneous distribution of deformation, finer dynamically recrystallized grains and brakes restoration - it leads to the improvement of ductility. On the other hand, higher strain rate results in a lower range of dynamic recrystallization, which supports hot cracking. Influence of strain rate on formability, then, depends on microstructure development. If there is a balance between positive and negative impacts of these structural phenomena, or if changes of strain rate are too small, then influence of strain rate on formability is insignificant.

3. METALLOGRAPHICAL ANALYSES

Structural analyses were complicated by origination of hardening components during cooling of the fractured sample, which often made it impossible to obtain solid information on a grain size in the area near to the fracture of the sample. At any rate, it was manifested that at temperature of 900 °C the resulting structure was fine-grain after forming with low and high rate - see **Figure 6.** Fibrousness of the structure is probably consequence of casting segregations. The structure of the samples tested at temperature of 1280 °C is significantly more coarse-grainer, but probably originated thanks to sufficient deformation from recrystallized austenite - see, for example, **Figure 7**.

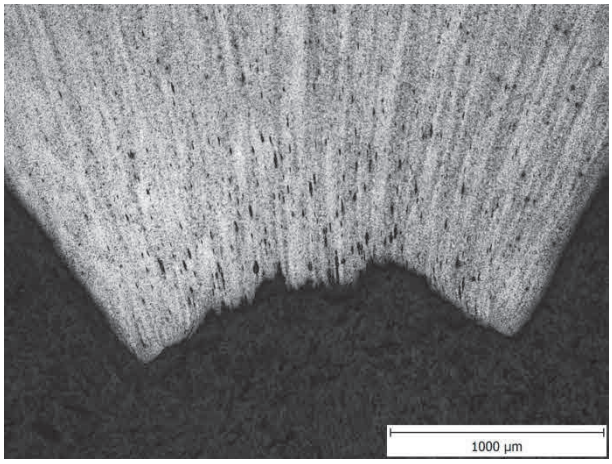


Figure 6 Micrograph of sample deformed at temperature of 900 °C (crossbeam speed 2 m/s)

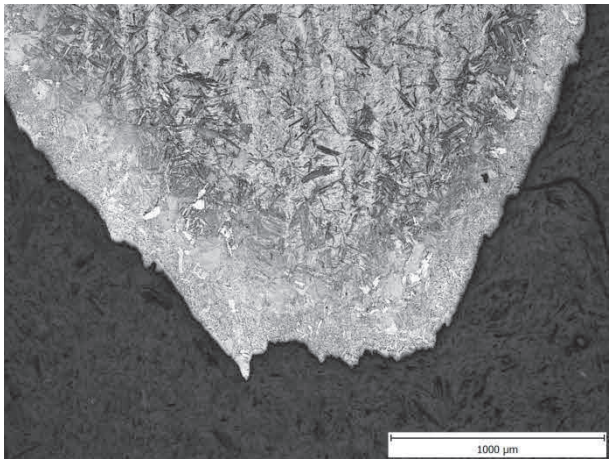
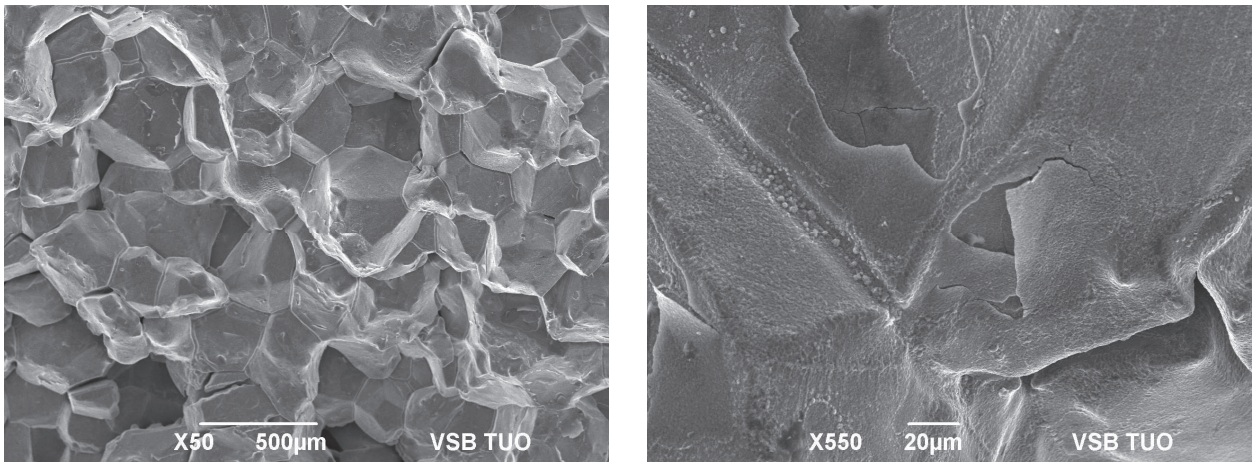


Figure 7 Micrograph of the sample deformed at temperature of 1280 °C (crossbeam speed of 2 m/s)

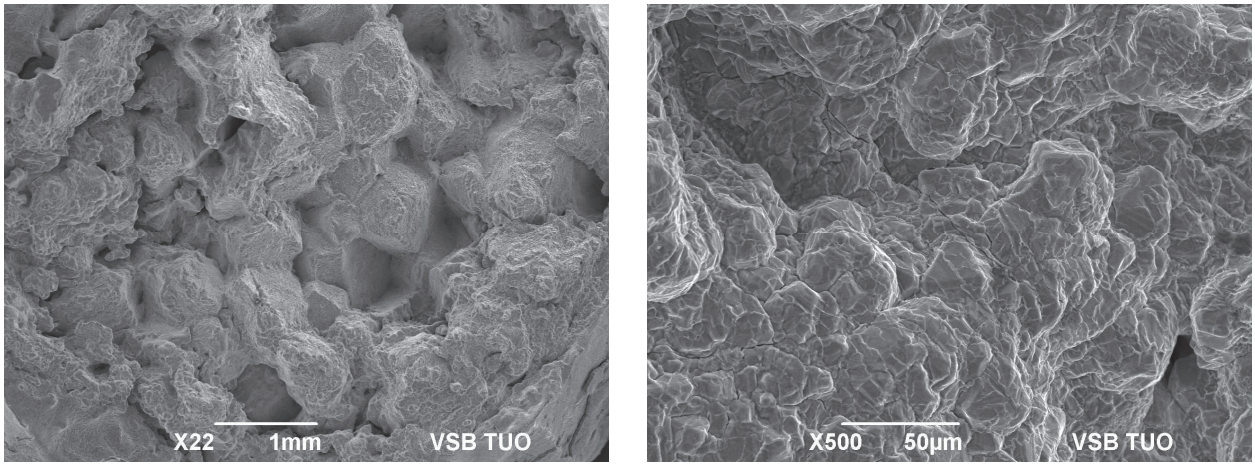
4. SEM ANALYSIS OF SELECTED FRACTURES

Samples with sufficiently big fracture surfaces were investigated on a scanning electronic microscope. After heating to temperature of 1375 °C, fracture occurred already at a nil deformation, and that is due to significant grain coarsening and material burning - see **Figure 8**. It is clear that grains on the surface of the intercrystalline fracture were covered by two thin layers of oxide, which are delaminated and peeled. The bottom layer probably originated during heating of the sample to the forming temperature; the upper layer not earlier than during cooling after sample fracturing. Temperature decreasing to 1350 °C led to the origination of mixed fractures - with more expressive relief looking in the macro-view like a ductile fracture (**Figure 9**). The fracture surface at higher magnification shows mostly intercrystalline character, coarse in the central part, very fine in the edge areas, with transversal secondary cracks. Expressive oxidation of the surface as well as of the fracture area manifested itself here.



a) intergranular brittle fracture b) detail of oxide layers on the grain surfaces

Figure 8 Fracture surface of the sample elongated by speed of 20 mm/s at temperature of 1375 °C



a) signs of brittle and tough fracture b) intergranular and transgranular cracks

Figure 9 Fracture surface of the sample elongated by speed of 20 mm/s at temperature of 1350 °C

5. CONCLUSION

Formability of fluently-casted medium-carbon steel low-alloyed by chromium and molybdenum was investigated by single-axes tensile test in a range of temperatures of 800 - 1375 °C and mean strain rates of 0.0074 - 63 s^{-1}. Ductility is gradually growing with temperature approximately up to 1335 °C and afterwards is

vehemently dropped due to overheating and material burning. The nil ductility temperature is probably situated in an interval between 1360 and 1370 °C.

At temperature of 900 °C, ductility grows with a growing strain rate linearly and relatively slightly. In the case of temperature of 1280 °C, the given dependence can be described with a second degree polynomial, whereas the growth of ductility with a growing strain rate is steeper than at low temperature.

Metallographical analyses and SEM of the fracture areas confirmed that relation between strain rate and the course of dynamic recrystallization of austenite played an important role in the experiment. Unfavorable influence of grain coarsening at high temperatures (up to 1335 °C) was compensated by a natural growth of formability with growing temperature. A local transformation of the dendritic structure and non-traditional mixed fracture were registered at combination of high temperature and low forming rate. It evokes considerations about possible influence of creep mechanism under certain deformation conditions.

Neither in the applied range of 5 orders, a value of strain rate corresponding to the theoretically assumed maximum of formability was determined; it can be possible to expect in the case of the given steel and only in case of very high temperatures from strain rates with even higher orders, which are not achievable with the used plastometer.

ACKNOWLEDGEMENTS

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REFERENCES

[1] NORSTÖM, L. and JOHANSON, B. Hot Ductility - a Matter of Strain Rate. *Scandinavian Journal of Metallurgy*. 1982. vol. 11, no. 2, pp. 139-142.

[2] SUZUKI, G., NISHIMURA, S. and YAMAGUCHI, S. Characteristics of Hot Ductility in Steels Subjected. *Transactions ISIJ*. 1982. vol. 22, no. 1, pp. 48-56.

[3] ARIKAN, M. Hot ductility Behavior of a Peritectic Dteel during Continous Casting. *Metals*. 2015. vol. 5, no. 2, pp. 986-999.

[4] CROWTHER, D. N. and MINTZ, B. Influence of grain size on hot ductility of plain C-Mn steels. *Materials Science and Technology*. 1986. vol. 2, no. 9, pp. 951-955.

[5] KAWULOK, P., SCHINDLER, I., KAWULOK, R., RUSZ, S., OPĚLA, P., KLIBER, J., KAWULOKOVÁ, M., SOLOWSKI, Z. and ČMIEL, K.M. Plastometric study of hot formability of hypereutectoid C - Mn - Cr - V steel. *Metalurgija*. 2016. vol. 55, no. 3, pp. 365-368.

[6] HURTADO-DELGADO, E. and MORALES, R.D. Hot ductility and fracture mechanisms of C-Mn-Al Steels. *Metallurgical and Materials Transactions B*. 2001. vol. 32, no. 5, pp. 919-927.

[7] HE, J., CUI, Z., CHEN, F., XIAO, Y. and RUAN, L. The new ductile fracture criterion for 30Cr2Ni4MoV ultra-super-critical rotor steel at elevated temperatures. *Materials & Design*. 2013. vol. 52, no. 2, pp. 547-555.

[8] TAN, S., WANG, Z., CHENG, S. and FU, W. Processing maps and hot workability of Super304H austenitic heat-resistant stainless steel. *Materials Science and Engineering: A*. 2009. vol. 512, no. 1-2, pp. 312-315.

[9] DUAN, X. W. and LIU, J. S. Research on damage evolution and damage model of 316LN steel during forging. *Materials Science and Engineering: A*. 2013. vol. 588, no. 2, pp. 265-271.

[10] HOU, G. Q. and ZHU, L. Influence of strain rate on hot ductility of austenitic stainless steel slab. *Materials Science and Technology*. 2013. vol. 29, no. 5, pp. 568-572.

[11] WANG, Z., MENG, Q., QU, M. and FU, W. Effect of Strain Rate on Hot Ductility Behavior of a High Nitrogen Cr-Mn Austenitic Steel. *Metallurgical and Materials Transactions A*. 2016. vol. 47, no. 3, pp. 1268-1279.