THE INFLUENCE OF GRAIN SIZE ON HOT FORMABILITY OF STEEL C45

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Abstract

With using of tension tests, which were performed on universal plastometer Gleeble 3800, the influence of grain size on hot formability medium-carbon steel was investigated. From investigated steel were prepared 2 sets of samples, while the booth sets were made from the same melt. The first set of samples was made from hot rolled bars. The second set of samples was made from the subsurface area of the continuously cast billet. It can be assumed that the samples prepared from a cast billet should have a relatively coarse grain structure, whereas samples made from hot rolled bars should have relatively homogenous fine grain structure. The samples with the initial deformed structural state were heated directly to the selected deformation temperatures, whereas samples with initial cast structural state were uniformly austenitized by temperature 1300 °C and then were controlled cooled down to selected deformation temperatures. All hot tensile tests were performed at uniform tension rate 1000 mm·s^{-1}. The samples from initial deformed structural state exhibited, with a comparison of samples from initial cast structural state, the higher hot ultimate tension strength and smaller hot ductility. The interesting results of hot ductility were obtained in the two-phase low-temperature region. In the case of samples from initial cast structural state, the ductility at low-temperature two-phase area decreased, whereas in the case of a sample from the initial deformed structural state the ductility unexpectedly increase.

Keywords: Grain size, hot formability, tension test, mechanical properties in hot condition

1. INTRODUCTION

Several types of tests can be used to investigate the basic plastic properties of steels in hot condition [1, 2], while the most simple one is a uniaxial tensile test, which is very sensitive to the workability of the materials due to the predominant tensile stress during the test [3, 4]. Several works, in which the steel is used in the initial cast or formed state can be encountered in the literature, and its strength and plastic properties during hot forming should, therefore, be affected by the initial grain size [5 - 7]. The formability of the cast steel should be moreover negatively affected by structural and chemical inhomogeneity, weakening of grain boundaries, internal tension and occurrence of casting defects [3, 8].

The main objective of this work was to compare the influence of the structural state, or of the grain size on formability of the medium-carbon steel C45. For this purpose, hot tensile tests were used, which were carried out over a wide range of deformation temperatures on the universal plastometer Gleeble 3800, which is installed in the Laboratory of the Regional Materials Science and Technology Centre [4].

2. EXPERIMENT DESCRIPTION

We used for this experiment an unalloyed medium-carbon steel C45, the standard chemical composition of which (in wt.%) is the following: 0.40 - 0.52 C, max. 0.43 Si, 0.46 Mn, max. 0.035 P, max. 0.04 S, max. 0.45 Cr, max. 0.13 Mo, max. 0.45 Ni [9].

The investigated steel was delivered for the purposes of this experiment in two initial structural states, i.e. in the form of hot-rolled bars of 12 mm in diameter and in the form of continuously cast billet with a cross-section of 150 x 150 mm. This different initial structural state of the samples and the chosen mode of heating should affect the size of the initial austenitic grain during uniaxial tension tests. Cylindrical samples of 10 mm diameter and length of 116.5 mm, which were threaded at the ends, were prepared from these supplied bars, or from continuously cast billets for tensile tests. First, a 10 mm thick layer was removed from the continuously cast billets, which consisted of strand shell. After that longitudinal bars of a square cross-section (14 mm square side) were cut out from thus the cut continuously cast billet, from which cylindrical samples were made for tensile tests.

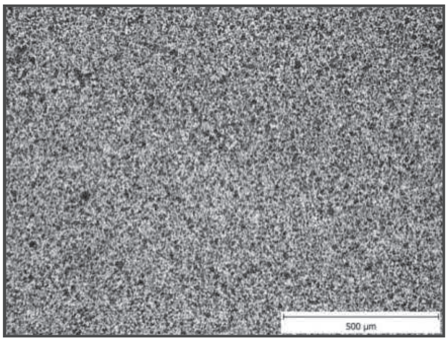


Figure 1 Microstructure of hot rolled products

The microstructure of the samples made from hot-rolled bars consisted of a fine-grained homogeneous mixture of ferrite and pearlite - see **Figure 1**. Contrary to that, the structure of samples made from continuously cast billets consisted of coarse pearlite blocks, which were lined with relatively fine ferrite mesh - see **Figure 2**.

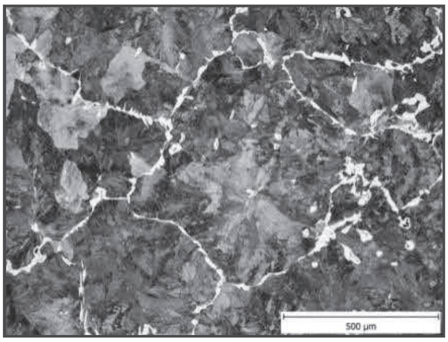


Figure 2 Structure of continusously cast billet

Temperatures of phase transformations of Ac_1 and Ac_3 (°C) (see **Table 1**), were determined even before the uniaxial tensile tests using the QTSteel 3.2 software and the Kasatkin [10] equations. Based on the evaluation of these temperatures, the deformation temperatures for uniaxial tensile tests were determined in a way to perform individual tests in a single-phase austenitic region, in a two-phase austenitic-ferritic region or below the temperature Ac_1, i.e. in the ferritic-pearlite region.

Table 1 Temperatures of phase transformations during heating of investigated steel

Temperature of phase transformation	Calculation Methods		Average value	Standard deviation
	QTSteel	Kasatkin		
Ac_1 (°C)	729	734	731.5	2.5
Ac_3 (°C)	780	792	786	6

Prepared samples made from the initial hot-rolled bars were heated by electrical resistance heating at a rate of 10 °C·s^{-1} directly to the selected deformation temperatures, at which they were held for 30 seconds. This heating mode was selected in order to suppress grain roughening during dwell at the deformation temperature. For this purpose, the deformation temperatures were chosen from 1400 °C to 675 °C.

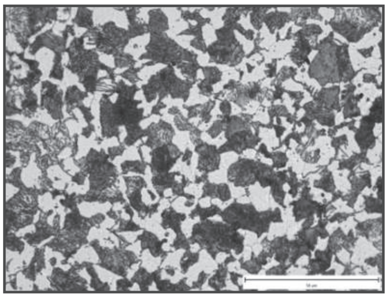
The samples made from the continuously cast billet were uniformly preheated to a temperature of 1300 °C and they were held at this temperature for 3 minutes while trying to form in the investigated material a coarse austenitic grain. The samples were then cooled down by controlled cooling at a rate of 5 °C·s^{-1} to the chosen deformation temperatures, followed by a short 10 s dwell for temperature homogenization. For this part of the experiment, deformation temperatures were selected in the range from 1300 °C to 650 °C. Since at a deformation temperature of 1300 °C no significant decrease of the maximum force and elongation to rupture took place, compared to other samples from the same set, two further tests were performed with heating of the samples directly to the deformation temperatures of 1320 °C and 1340 °C. The dwell at these temperature was again 3 minutes.

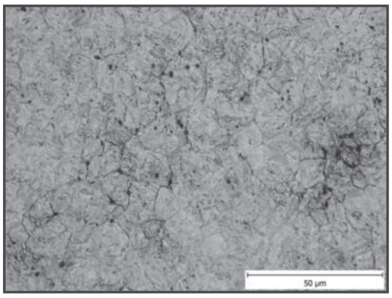
All the samples were subjected to tensile stretching at a uniform tension speed of 1000 mm·s^{-1}.

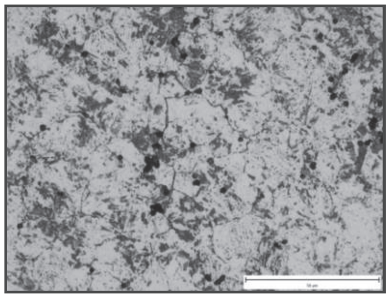
For the purposes of determining the mean diameter of the initial grain after heating of the investigated steel to the selected deformation temperatures, the samples of 10 mm in diameter and 15 mm in length were made from both initial structural states. They were placed into an electric canthal furnace heated to the selected temperatures, and after 7 minutes of dwell time, they were quenched in water. Samples from the initial formed structure were heated to 700 °C, 775 °C, 900 °C, 1200 °C, 1340 °C and 1370 °C. In the case of samples from the initial cast structure, only the heating temperature of 1300 °C was chosen because at the tensile tests the samples made from a continuously cast billet were uniformly heated to this temperature. Subsequently, these samples were subjected to metallographic analyses aimed at etching the boundaries of the original austenitic grain.

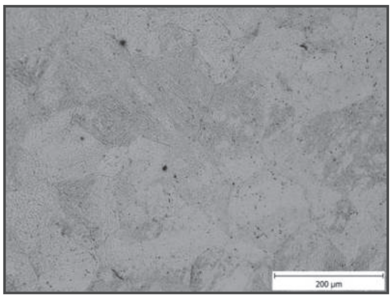
3. DISCUSSION OF RESULTS

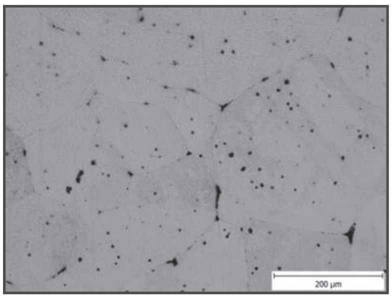
Metallographic analyses were performed using conventional optical microscopy. In the case of samples from the initial formed state of the steel C45, the heating temperature of 700 °C did not result in austenitization of the sample (see **Figure 3a**) and the microstructure was formed by a fairly even mixture of ferrite and pearlite. At the heating temperature of 775 °C, a partial austenitization of the structure already occurred (see **Figure 3b**). Higher heating temperatures resulted in complete austenitization of the samples (see **Figures 3c - 3e**). In a sample heated to 1370 °C (see **Figure 3e**) it is possible to see black formations inside the grains and also at their boundaries, which evidently indicate the presence of inclusions, which cause hot brittleness after segregation at the grain boundaries. In the case of a sample from the initial cast state, a complete austenitization also took place (see **Figure 3f**) and the initial austenitic grain was very coarse.


a) heating temperature of 700 °C (initial formed state)


b) heating temperature of 775 °C (initial formed state)


c) heating temperature of 900 °C (initial formed state)


d) heating temperature of 1200 °C (initial formed state)


e) heating temperature of 1370 °C (initial formed state)

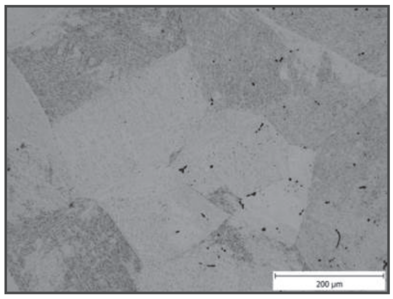

f) heating temperature of 1300 °C (initial cast state)

Figure 3 Photo documentation of initial grains after various heating temperatures of investigated steel

The mean diameter of the initial austenitic grain d_{mean} (µm) or of the ferritic grain and pearlitic blocks of the heat treated samples was determined using the linear straight line method according to EN ISO 643 [11]. In the case of samples from the initial formed state, the mean diameter of the austenitic grain increased exponentially with the increasing temperature, as documented graphically in **Figure 4**. In the case of a sample from the initial cast structure, a mean austenitic grain size of 223.2 μm was achieved.

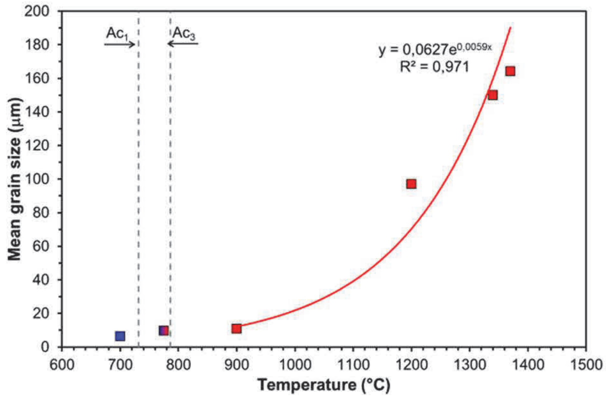


Figure 4 The average diameter of the grain of the investigated steel in its initial formed state

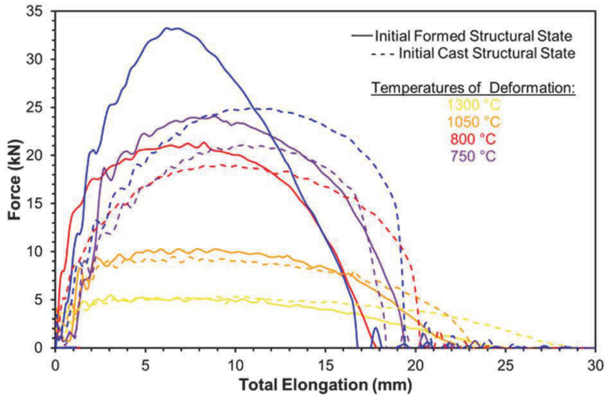


Figure 5 Tension diagrams - comparison of the initial formed and cast state

The maximum force values $F_{max.}$ (kN). and the total elongation to fracture ΔL (mm) were determined from the measured data from the uniaxial tensile tests, see **Figure 5** documenting the dependence of the measured force and the total elongation of the selected test samples from the initial formed and cast structure. These values were then used to calculate the contractual hot ultimate tensile strength UTS_H (MPa) and hot ductility A_H (%) of all ruptured test bars:

$$UTS_H = \frac{F_{max.} \cdot 1000}{S_0} \tag{1}$$

$$A_H = \frac{\Delta L}{L_0} \cdot 100 \tag{2}$$

where S_0 (mm) is the initial cross-sectional area of the test bars and L_0 (mm) is the initial measured length, which was 20 mm for used stainless steel jaws. Evolution of these strength and plastic properties in dependence on the deformation temperature is graphically documented in **Figure 6** and **Figure 7**.

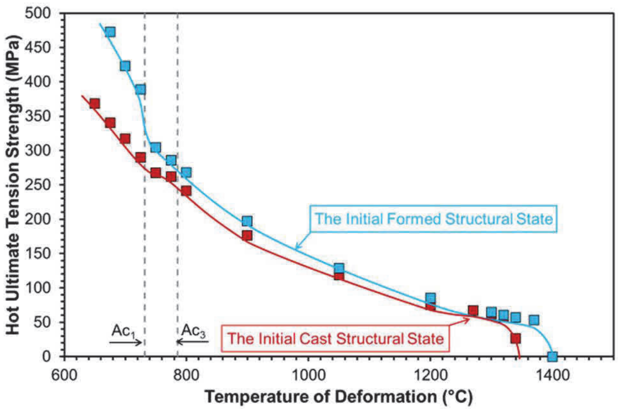


Figure 6 Dependence of the hot strength on the deformation temperature

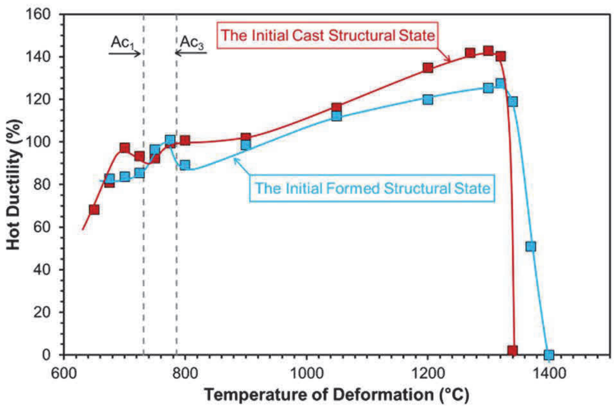


Figure 7 Dependence of the hot ductility on the deformation temperature for both structures

With increasing deformation temperature, the material flow stress and thus its strength decreased (see **Figure 6**). Higher values of contractual hot strength were achieved on the samples made from the initial fine-grained formed material. At a deformation temperature of 1270 °C and higher, the differences between the values of the contractual hot strength for both sets of samples were negligible, naturally with the exception of the cases influenced by practically zero formability. Interestingly, the effect of the phase composition was at low temperatures (below 725 °C) manifested only in the case of a formed state.

The initial coarse-grained casting structure was expected to negatively affect the workability of the investigated steel in comparison to its fine-grained state, as it should relatively decelerate the nucleation phase of the recrystallization and contribute to the fragile inter-crystalline fracture [3]. This assumption, however, was surprisingly fulfilled only at the highest temperatures of exceeding approx. 1320 °C, when the cast structure showed an earlier and steeper decrease in plastic properties probably due to overheating and burning of the material - see **Figure 7**. This corresponds to the results of metallographic analyses showing that the samples from the initial cast state and heated at a temperature of 1300 °C, have a coarser initial austenitic grain than the samples from an initial state heated to 1370 °C. At lower deformation temperatures, however, the cast state showed practically always slightly higher ductility.

It is known that the refining of the initial grain increases the steel formability only at high temperatures - by limiting the development of inter-crystalline cracks connected even with slip along grain boundaries, and by accelerating the dynamic recrystallization process [12, 13]. On the other hand, under the cold conditions, the more ductile steel are usually more coarse-grained [3], when moving dislocations travel along a longer free path before they encounter an impassable obstacle, i.e. the grain boundary. It is also true that only very significant differences in grain size really affect the formability of metallic materials - see e.g. [7]. Another complication consists in the fact that ductility of metallic materials is mostly investigated in laboratories at very low strain rates [5, 6, 14], where the kinetics of dynamic recrystallization plays a key role. In contrast to that, the tensile tests of the steel C45 were carried out at a constant drawing speed of 1000 $mm \cdot s^{-1}$, corresponding to a mean strain rate of approx. 50 s^{-1}. Given the known dependence of the strain value necessary to initiate dynamic recrystallization on the Zener-Hollomon parameter [3], it can be questioned whether under the given experimental conditions, dynamic recrystallization could be at all achieved, or what impact it would have on formability. The grain boundaries are repeatedly changed and possible micro-cracks are moved from the grain boundaries to the grain volume by recrystallization. This inter-granular position then considerably reduces conditions for their propagation.

It is further evident from the graph in **Figure 7** that the two-phase ferritic-austenitic region (manifested by a change in the temperature-elongation curve) is in the case of samples with an initial casting structure shifted relatively to lower temperatures. This corresponds to the assumptions about the influence of the size of the austenitic grain on the evolution of the phase transformations [15].

In the ferritic-austenitic area, even a slight increase in plastic properties took place, which disagrees with the general opinion on the deterioration of the formability in the two-phase structure. This phenomenon has already been observed in the works [5, 14] and it could be explained by a deformation occurring preferably in a more ductile ferritic phase.

4. CONCLUSIONS

With decreasing deformation temperatures, the strength properties of the investigated steel increased in both initial structural states. The initial coarse-grained cast structure exhibited lower strength properties across the whole range of applied deformation temperatures than the initial finer formed structure.

Surprising results were found regarding the plastic properties. Better hot ductility was exhibited at high temperatures by the samples from the initial coarse-grained cast structure, contrary to the samples from the initial fine-grained formed structure. The chosen drawing speed of 1000 $mm \cdot s^{-1}$, or high strain rate of 50 s^{-1}, apparently did not lead to the initiation of dynamic recrystallization, which subsequently affected the formability of the investigated material. In addition, in the two-phase ferritic-austenitic region, the samples from the initial formed state exhibited increased hot ductility, which was evidently caused by a deformation occurring preferably in the ferritic phase. Deformation temperatures above 1300 °C, in the cases of the samples from the initial as-cast state, or 1320 °C in the case of an initial formed state, as a result of overheating and burning of the material probably led to a significant decrease in formability.

Given the achieved results of the plastic properties, it would be appropriate to examine the influence of the initial structural state of the investigated steel on the formability at lower applied tension speeds.

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