DEFORMATION BEHAVIOUR OF SURFACE LAYERS OF CONTINUOUSLY CAST BLANKS FROM C-Mn-Cr STEEL

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Abstract

Due to heterogeneity of structure and to casting defects contained in surface layers of continuously cast blanks with large cross sections the study of their deformation behaviour, and namely of their hot formability is a highly demanding task. Exact plastometric methods in the case of taking of the samples from surface areas do not provide acceptable results, since due to their small sizes they cannot express sufficiently the present structure heterogeneity. Surface layers of material, in which it is possible to expect the biggest occurrence of defects that expand at the subsequent forming till they achieve character of critical cracks, are then removed from the samples by machining. For these reasons the wedge rolling test, performed in partly non-machined samples, proved to be successful for investigation of these continuously cast blanks. One of the freely spreading side surfaces of the sample corresponds to the raw surface of the casting and it is then possible to use it then from efficient investigation of effects of reduced technological formability. This approach was used for investigation of deformation behaviour of low alloyed steels of the type C-Mn-Cr, microalloyed by vanadium or niobium. The heating temperature (1150 to 1340 °C) and rolling temperature (950 to 1150 °C) were the changed parameters. The obtained results were supported by metallographic analyses in non-etched and etched states, by TEM and SEM analyses of present particles (inclusions and precipitates).

Keywords: wedge rolling test, metallographic analyses, TEM, SEM

1. INTRODUCTION

The formability tests on specially prepared samples comprise also the wedge rolling test. Its objective, similarly as in the case of other technological tests of formability, consists in determination of the maximal degree of deformation to rupture of material and also in assessment of the progress of the restoration processes during forming at various temperatures. At present, the input shape of the sample took the form of a wedge. These samples are then rolled on smooth rolls with a preset gap between the rolls, which gives us with together with the variable height of the sample various types of loads and therefore of deformation of the sample [1-3].

At rolling of the wedge sample the degree of deformation continuously increases up to the selected maximum. A triaxial state of deformation is induced in material. A compressive deformation is induced in the direction of the force applied from the working rolls. The components of deformation in both transverse directions are tensile. To study the formability of the boundary conditions in the zone of deformation main The direction of propagation is the most important for investigation of boundary conditions of formability, because tensile stress acts on the sample surface and tensile deformation takes place. This combination of tensile deformation components causes material failure after excess of the limit state [4].
A number of wedge shapes [5] or of their modifications [6] exists. For example new modified shape of the wedge sample, that is of the sample with the notches cut in advance on one of its side walls. This modification makes the applied method much more sensitive and it should be therefore used for materials with very high material toughness.

2. EXPERIMENTAL PROCEDURES

Microstructure and technological formability of continuously cast blanks with a diameter of 410 mm from 3 melts of steel were examined, namely on their surface area. The wedge rolling test [7] was used in order to enable investigation of the raw, i.e. non-machined surface area of the continuously cast blank with its possible defects. The supplied melts had the following chemical composition - see Table 1.

Table 1 Contents of selected elements of investigated melts in wt. %

<table>
<thead>
<tr>
<th>melt</th>
<th>C</th>
<th>Mn</th>
<th>Si</th>
<th>Cr</th>
<th>Mo</th>
<th>V</th>
<th>Nb</th>
</tr>
</thead>
<tbody>
<tr>
<td>3</td>
<td>0.166</td>
<td>1.14</td>
<td>0.199</td>
<td>0.18</td>
<td>0.008</td>
<td>0.04</td>
<td>0.002</td>
</tr>
<tr>
<td>8</td>
<td>0.152</td>
<td>1.14</td>
<td>0.188</td>
<td>0.15</td>
<td>0.006</td>
<td>0.005</td>
<td>0.028</td>
</tr>
<tr>
<td>9</td>
<td>0.173</td>
<td>1.16</td>
<td>0.191</td>
<td>0.18</td>
<td>0.009</td>
<td>0.003</td>
<td>0.025</td>
</tr>
</tbody>
</table>

Wedge-shaped samples with length of 150 mm, height from 3.8 to 15.2 mm and width of 15 mm were made always from the surface area of the supplied materials. The longitudinal axis of the sample coincided with the longitudinal axis of the continuously cast blanks. Formability was studied in freely moving side (originally trapezoidal) area, which remained non-machined which thus corresponded to the surface of the given blank. The samples were after re-heating to the required temperature (for 20 min) rolled in one pass at different temperature; Tab. 2 demonstrates plan of the experiment:

Table 2 Temperatures of heating and rolling of individual samples

<table>
<thead>
<tr>
<th>heating</th>
<th>temperature of deformation</th>
</tr>
</thead>
<tbody>
<tr>
<td>1340 °C</td>
<td>1150 °C (A)</td>
</tr>
<tr>
<td>1290 °C</td>
<td>1150 °C (B) 1100 °C (C)</td>
</tr>
<tr>
<td>1240 °C</td>
<td>1100 °C (D) 1050 °C (E)</td>
</tr>
<tr>
<td>1200 °C</td>
<td>1050 °C (H) 1000 °C (M)</td>
</tr>
<tr>
<td>1150 °C</td>
<td>1000 °C (P) 950 °C (R)</td>
</tr>
</tbody>
</table>

Marking of each sample consisted of the number identifying the melt (i.e., 3, 8, 9) and from the letters A through R, corresponding to the temperature mode of the test. The wedges were rolled on the laboratory rolling mill K350 in the two-high configuration (i.e. with rolls diameter of 150 mm), and at the rotational speed of the rolls 70 min⁻¹ [8]. Rolling of the wedge was followed by free cooling of the material on air. Ground areas of the selected rolled products were scanned (Fig. 1), which enabled the calculations of deformation and of strain rate along their length using special software KLIN [9, 10], working on the basis of computer image analysis.

It is possible to deduce from the ground areas of the rolled products and from the following resulting graph (e.g. Fig. 2), that spreading increases and elongation of the rolled samples decreases with the decreasing temperature of deformation, and irregularity of spreading increases with the increasing temperature (which may be caused by greater scaling of the sample during heating). Identical deformations were achieved in different samples with different lengths of the rolled product. Thanks to these calculations it was possible to determine for each rolled product the place corresponding to the vertical deformation of 75%, and to take samples from this place for next analyses.
Fig. 1 Example of ground area shapes of the rolled products. Melt 9, finish-rolling temperature of 1150°C (A) or 950°C (R)

Fig. 2 Deformation relations along the length of the selected laboratory rolled products. Melt 9, finish-rolling temperature of 1150°C (A) or 950°C (R)

3. DISCUSSION OF EXPERIMENTAL RESULT

3.1 Microstructure of laboratory rolled products

Vertical longitudinal sections were analysed by metallography. Microstructure of the samples from the melt 3 was composed of ferrite, pearlite and acicular ferrite, or of upper bainite. The amount of acicular ferrite and bainite decreased with the decreasing temperature of deformation. While at the highest temperature of deformation the share of the components, at creation of which the shear mechanism of several tens of percent was applied (Fig. 3), from the temperature of deformation of 1050 °C and less their occurrence was only sporadic. It is possible to deduce from the nature of the structure that with the decreasing temperature of deformation the size of austenite grains also decreased.

The microstructure of the samples from the melt 8 differed from those from the melt 3 mainly from the quantitative perspective. At the highest temperature of deformation upper bainite, or acicular ferrite prevailed in the structure, and also occurred usual allotriomorphous ferrite was present. The share of pearlite was very low. With the decrease of the temperature of deformation decreases the upper bainite and acicular ferrite, but their share was always higher than that for the samples from the melt 3 deformed at the same temperature. At the same time a slight increase of the share of pearlite took place. At the temperature of deformation of 1000 °C occurrence of non uni-axial areas of bainite was observed in a limited extent in the
samples, which suggests that at this temperature full recrystallization of austenite was not accomplished. A much higher share of non uni-axial areas of bainite, indicating only a partial recrystallization of austenite, was observed in the sample with the temperature of deformation of 950 °C. The microstructure of the sample from the melt 9 was very similar to that from the melt 8. However, higher share of upper bainite or of acicular ferrite was observed in the melt 9 in comparison with the analogous samples from the melt 8 (deformed at the same temperature) (Fig. 4). For the temperatures of deformation of 1000 and 950 °C in the samples from the melt 9 a higher occurrence of non uni-axial regions of bainite was observed, which means that the share of non-cry stallised austenite was in the melt 9 higher at these higher temperatures.

3.2 Surface defects of laboratory rolled products

After cutting off of the clippings flat to the half of the rolled product thickness occurrence of cracks and of other defects on the original surface of continuously cast blanks was examined. Character of the surface of wedge tests was similar for all three melts, at least from the qualitative point of view. On the surface of the samples, which was predominantly scaled, recessions were present, as well as relatively shallow cracks (tearings) filled or at least lined with scale. Under continuous layer of scale fine discrete particles of oxides were present (probably mainly on the basis of Mn with respect to the relatively low Si content).

The frequency of occurrence of defects was lower in the melt 3, in principle for all temperatures. In all melts the lowest occurrence of defects was observed at both extreme temperatures of deformation, i.e. at the temperature of 1150 °C and the temperature of 950 °C. Higher occurrence of defects was observed for the temperature of deformation of 1100 °C. The highest occurrence of defects was observed for the temperature of deformation of 1050 °C and for the temperature of deformation of 1000 °C, but here only at higher temperature of heating - 1200 °C. Cracks reached the depth of max. 0.1 mm below the surface (only rarely – in the sample 8H a crack was observed extending to the depth of 0.15 mm - Fig 5).

In the case of melt 3 after etching the samples we failed to find a clear structural relationship with the occurrence of cracks. In the case of the melts 8 and 9 it was proven, that the cracks formation occurred preferentially at the boundaries of austenite grains (as it can be seen in Fig 6).
3.3 Results of SEM analyses
Size of the observed and analysed particles ranged from 30 nm to approx. 15 µm – it means that they were inclusions and precipitates. Inclusions are characterised by considerable diversity in their shape (see Fig. 7). It is evident from the obtained images (see, e.g. Fig. 8) that distribution of particles in all the samples was random, so no connection of the distribution of particles with the grain boundaries was therefore established. The distance between individual particles is in the range of approx. 0.5 - 10 µm.

3.4 Results of TEM analyses
Due to the fact that the samples were made of sub-eutectoid carbon steels, which were ferromagnetic, the TEM analysis of the samples was much more difficult (minimum possibility of tilting in the beam). The results of observations and analyses showed that all the samples were made from the mixture of ferritic and pearlitic areas. In pearlitic areas cementite lamellae Fe₃C grow from the boundaries of ferritic grains (Fig. 9). Grain boundaries in all the samples are generally clean and free of particles of foreign phases (Fig. 10). Only two types of small particles were detected, and only in ferritic grains: the melt 3 contained only Fe₃C particles of approximately spherical or cubic shape with dimensions of 20-40 nm, and the melts 8 and 9 we proved the presence, in addition to the same particles as in the melt 3 were, also of disk-shaped particles of niobium carbide with a diameter of approx. 40 nm and a thickness of approx. 10 nm.
4. SUMMARY

This experiment has confirmed that the wedge rolling test is a source of reliable results for evaluation of formability, complemented by structural analyses performed with use of SEM and TEM. The main advantages of the wedge rolling test is the similarity of its state of stress with the state of stress at industrial rolling. The experiment was carried with use of the low-alloyed C-Mn-Cr steels, micro-alloyed with vanadium or niobium. Thanks to the fact that part of the samples was not machined, we were able to study efficiently the impaired formability on the raw surface of the continuously cast blank, which is very beneficial for industrial practice.

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LITERATURE