SELECTED PROPERTIES OF MINES SUPPORTS

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Abstract
The work deals with four steel types of mine supports. Two steel types are on the basis of C-Mn and the other two are micro-alloyed steels with addition of vanadium, niobium and nitrogen. Both strength and plastic and impact properties in as-rolled condition and after subsequent straightening and ageing are compared in the work. Confrontation of all steel types with microstructural and micro-fractographic analysis and explanation of reasons of some in-homogeneous results of strength and especially impact values are part of solution. In frame of work flange of mines supports were investigated. The conclusions serve for followed mine supports development with higher mechanical parameters.

Keywords: support of mines, strength, impact energy, microstructure, fracture surface

1. INTRODUCTION
Conventional steels types used for supports of mines belong to the group of low and/or middle carbon steels. The supports has been exploiting in mines for a long time. During that period rock loading and mine atmospheres permanently influence the supports of mines. This is also reason why to study the aging processes, including both the natural ageing and the artificial ageing, on those supports. The aging can be first of all connected with the sick Cottrel’s or sparse Maxwell’s and/or Snoeck’s atmosphere [1-3]. Ageing is firstly characteristic for materials with low carbon content, resp. generally for interstitial elements. With increasing carbon content the ageing influences are not so important and at 0.25-0.30 wt. % of carbon the aging effect becomes insignificant because the higher pearlite content superposes changes in ferrite [4]. Materials being only on the basis of carbon show after rolling lower yield strength even when the plasticity complies with requirements. Higher strengthening could be reached using subsequent quenching and tempering after rolling process however any heat treatment does not represent an economical trend. In order to secure required higher mechanical properties of supports including yield stress, tensile strength and also plasticity, resp. the impact energy, micro-alloyed materials must be used. These steel types are able to eliminate ageing processes, resp. the micro-alloyed elements, are able to bind to carbon and especially to nitride, which is from point of view of ageing much more dangerous. Nitrides or carbides and/or carbon-nitrides are formed. Among those elements belong titanium, niobium, vanadium, boron and also aluminium [5]. Niobium forms very fine precipitates at the temperature close to 1100°C, which are able to refine the primary austenite grains and also to strengthen the basic matrix. Moreover, the niobium nitrides suppress static recrystallization of matrix after hot deformation. Regarding vanadium that forms carbon-nitrides under the temperature of 900°C and these predominantly make the matrix more strength. Some nitrides can be also formed thanks the presence of aluminium. Titanium is not too suitable for an application because of its ability to form unstable precipitates at high temperature, close to 1200°C, which have a tendency to grow coarse during cooling process and to degrade toughness of the matrix [6]. In case of presence of titanium and as well as niobium, both elements are able to form, approximately at 1050°C, complex TiNb(CN) particles, where the niobium, thanks its kinetic, prevents enormous growth of the titanium precipitates [7, 8]. Naturally, niobium can also form a complex precipitates of the NbV(CN) type [6].
Target of the presented work was to show differences in materials used for supports of mines on both the conventional C-Mn basis and the micro-alloyed materials with addition of vanadium, niobium and nitride ensuring non-ageing steels.

Table 1 Chemical composition of used material [wt. %]

<table>
<thead>
<tr>
<th>Steel</th>
<th>C</th>
<th>Mn</th>
<th>Si</th>
<th>P</th>
<th>S</th>
<th>Al</th>
<th>V</th>
<th>Nb</th>
<th>N</th>
</tr>
</thead>
<tbody>
<tr>
<td>A</td>
<td>0.33</td>
<td>0.94</td>
<td>0.39</td>
<td>0.020</td>
<td>0.018</td>
<td>0.036</td>
<td>-</td>
<td>-</td>
<td>0.0050</td>
</tr>
<tr>
<td>B</td>
<td>0.30</td>
<td>1.05</td>
<td>0.42</td>
<td>0.011</td>
<td>0.008</td>
<td>0.012</td>
<td>-</td>
<td>-</td>
<td>0.0045</td>
</tr>
<tr>
<td>C</td>
<td>0.18</td>
<td>1.31</td>
<td>0.36</td>
<td>0.011</td>
<td>0.009</td>
<td>0.030</td>
<td>0.088</td>
<td>0.048</td>
<td>0.0107</td>
</tr>
<tr>
<td>D</td>
<td>0.48</td>
<td>1.40</td>
<td>0.39</td>
<td>0.015</td>
<td>0.007</td>
<td>0.017</td>
<td>0.106</td>
<td>0.036</td>
<td>0.0112</td>
</tr>
</tbody>
</table>

2. EXPERIMENTAL PROCEDURE

For investigation four steel types of TH 29 profile were used and its chemical composition Table 1 summarises. Steel A represents a convention variant of the supports of mines and was tested in as-rolled state and after deformation artificial ageing unlike the steel B which was tested in as-quenched and subsequently tempered state (exact data were not given) and after artificial deformation ageing. The steels C and D were studied after rolling (finishing rolling temperature corresponded to 980°C) and subsequent strengthening. All heats as well as the supports of mines were industrially manufactured. In accord with ČSN EN ISO and ČSN ISO 148-1 Standards tensile tests using tensile machine ZWICK and Charpy KU3 tests by use of the PSW 300AF machine were realised. In frame of metallographic study cleanliness was evaluated in accord with ČSN ISO 4967 Standard, further grain size (ČSN EN ISO 643), banding evaluation (ČSN 420469) and volume fraction of presented phases were evaluated using the light microscope OLYMPUS X70 with the IMAGE PLUS programme allowing e.g. measurement of phases volume fraction. Microfractographic investigation of the fracture surfaces of the notch toughness tests was part of solution. This investigation was realised by use of SEM JEOL JSM-6490 LV equipped with a X-ray EDA analyser. Samples for tests were taken out from flanges.

Table 2 Mechanical properties and impact energies of the investigated materials

<table>
<thead>
<tr>
<th>Steel</th>
<th>A</th>
<th>B</th>
<th>C</th>
<th>D</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>State</td>
<td>as-rolled</td>
<td>ageing</td>
<td>as-rolled</td>
</tr>
<tr>
<td>YS [MPa]</td>
<td>413</td>
<td>414</td>
<td>620</td>
<td>551</td>
</tr>
<tr>
<td>TS [MPa]</td>
<td>667</td>
<td>666</td>
<td>815</td>
<td>764</td>
</tr>
<tr>
<td>El. [%]</td>
<td>24.9</td>
<td>24.6</td>
<td>20.9</td>
<td>23.3</td>
</tr>
<tr>
<td>CU3 [J]</td>
<td>79.3</td>
<td>35.7</td>
<td>165.7</td>
<td>110.5</td>
</tr>
</tbody>
</table>

YS = yield strength, TS = tensile strength, El. = elongation and CU3 = impact energy with 3 mm notch

3. RESULTS AND DISCUSSION

Results of mechanical properties and impact energies are summarised in Table 2. In accord with Standard the yield strength and tensile strength of the flange should reach the minimal level of 480 MPa and 650 MPa whereas elongation should be higher than 20 %. From the Table 2 follows the worst results showed the steel A and the best and much more balanced the steel D. Material of the steel A was not able to reach required yield strength values. The yield strength was by 67 MPa under the minimal level of 480 MPa, whereas in case of the steel D reserve of 97 MPa and 101 MPa in the yield strength and tensile strength was reached. In plasticity 4.5 % reserve was recorded. The influence of ageing was not convincing. After ageing the yield strength was higher only in case of the steel D, however without any loss of plasticity. It is true with the exception of the steel B carbon contents were too high and moreover the steel B was quenched and tempered. After the second mentioned operation some dislocation had to be annihilated after tempering. The
microstructures of all steels after rolling as well as after artificial ageing are presented in Fig. 1a, b and Fig. 2 a, b.

For the steel A ferrite-pearlite microstructure with coarser grains, thinner allotriomorphic ferrite decoration as an expression of slow cooling process from the higher temperatures and higher carbon content (0.33 wt. %) matrix was typical [9]. Microstructure was not banded thanks rolling at higher temperatures and subsequent slower cooling process. The average grain size corresponded to 68.2 μm, however among grain sizes partial in-homogeneities were observed as it is seen in Fig. 1a. In microstructure 42.7 % of ferrite was detected which was also reason of the lowest strength level and a high plasticity of the steel A in frame of the four compared steels. Mixed microstructure formed the steel B. Beside bainite and pearlite, allotriomorphic ferrite decorating the primary austenite grains with Widmanstätten ferrite were observed as the Fig. 1b demonstrates. It is again evidence of slower cooling from the quenching temperature and/or lower temperature of quenching, because pearlite, allotriomorphic ferrite are reconstructive products and Widmanstätten ferrite is formed above the upper bainite temperatures [9, 10]. The average grain size of the steel B was 24 μm and it is an evidence of generally faster cooling process than corresponds to slower cooling on the air after rolling as it was realised in case of the steel A. Ferrite matrix corresponded to 20.7 % and the strengthening also reached the highest value. Un-cleanness of the steel A was on basis of oxide-
sulphides (grade A1.5-2.5) and oxides (grade D1.5-2 and coarser particles of DS1 grade), whereas in case of the steel B it was predominantly on the basis of silicates (grade C1-1.5) and oxide-sulphides (grade D1-2).

The steel C showed the lowest carbon content (see Table 1), even when the vanadium and niobium addition was only 1.044 times lower than in case of the steel D. This was also reason of lower strength values in comparison with the steel D as Table 2 shows. After ageing, the yield strength differences of both steels corresponded to 87 MPa. The higher carbon and partially manganese contents of the steel D (by 0.39 wt. % higher unlike the steel C) as well as the higher addition of both micro-alloyed elements, being 1.044 times higher than in steel C, and nitrogen, being 1.047 times higher than in the steel C, led to finer microstructure that contributed to the higher strengthening with more balanced favourable toughness as it is obvious from differences presented in Table 2. Elongation of the steel D was by 1 % higher than in the steel C and the impact energy reached after ageing 35.5 J. The steel C reached maximal impact energy values (approximately 48 J on average), however to the exclusion of strengthening as it Table 2 demonstrates. In steel C in-homogeneities in form of coarser pearlite blocks were detected unlike the steel D as it follows from dissimilarities of the both steel types (see Fig. 2). The grain sizes of the steel C and D corresponded to 36 μm and 28 μm and reflected the microalloying influence. Un-cleanness of the steel C was on basis of oxidesulphides (grade A1.5-2) and oxides (grade D2), whereas in case of the steel D it was also on the basis of silicates (grade C1-1.5) and oxide-sulphides (grade D2-2.5 and coarser DS1). The same inclusions types were also revealed by use of the X-ray EDX analyser on the fracture surfaces of the notch toughness samples. The segregated banding of the steel C and D was at level of the grade 2B2 and 2B/3 (given in sequence). Unfortunately, the thermo-mechanical control process with subsequent accelerated cooling was not used from the finishing rolling temperature which could be able to eliminate the harmful banding and simultaneously to support favourable acicular ferrite formation during the accelerated cooling process which would be effective both for the strengthening increase and for plasticity increase [11-13]. In microstructure with acicular ferrite, carbon is soluble in acicular ferrite matrix and thanks the displacive mechanism of acicular ferrite formation high dislocation density is typical phenomenon as well as the high angle misorientation among the acicular ferrite laths/plates [14]

Thanks the higher manganese and especially carbon contents more noticeable banding, even when very narrow, as a segregation expression was developed in the steel D. It is generally known, the microstructures showing any banding is connected with carbon atoms heterogeneity, also at the cooling rate of 0.5-1°C.s⁻¹. Presented high manganese content also shows strong segregation activity corresponding to 50 % of local increase and consequently in areas with dissimilar segregation of mentioned elements, 50°C and more a difference in the Ar3 temperature can be registered. Already, at cooling rate of 0.5°C.s⁻¹ this difference corresponds to time shift of the austenite transformations approximately by 100 s [15].

The Figs. 3 and 4 demonstrate fracture surfaces of the realised notch toughness samples in central areas at normal temperature. Fracture surface of the steel A showed trans-crystalline cleavage character in case of the steel B it was only partially, with ductile ridges mostly decorating the cleavage and/or quasi-cleavage facets. The coarsest facets (size corresponded to 50 μm on average) were revealed in the steel A, where also rivers were observed in minority unlike the steel B, where practically quasi-cleavage facets were 13 μm in diameter on average and also thicker and numerous ductile ridges were observed here as it from Fig.3 b, used heat treatment and results of the Table 2 follows.

In case of the steel C facets size corresponded to 35 μm on average and for the steel D it was 32 μm. In comparison with the steels A and B the fracture surfaces of the steel C and especially of the steel D were more jagged and showed fine cleavage facets with longer ductile ridges. It is interesting, the steel C showed slightly higher impact energy values than the steel D, even when the elongation as well as the grain size of the microstructure were more favourable in case of the steel D (see Fig. 2). Simultaneously, the more noticeable finer banding of the microstructure should be for the cleavage crack propagation more important obstacle and the coarser pearlite blocks of the steel C should support lower impact energy. Hence, the impact energy results of the steel D could reflect the mentioned facts, because all notch toughness bars
were taken in rolling direction. Maybe slight worse cleanness of the steel D could be an elucidation of the observed disproportion.

![Fracture surface image after ageing of the a) steel A, b) steel B](image)

**Fig. 3** Fracture surface image after ageing of the a) steel A, b) steel B

![Fracture surface image after ageing of the a) steel C, b) steel D](image)

**Fig. 4** Fracture surface image after ageing of the a) steel C, b) steel D

### 4. CONCLUSIONS

Four types of mines supports in flange were compared. Steel A and B were on the basis of C-Mn. Both steels were rolled conventionally, the steel B was subsequently quenched and tempered. The other two steels variants were microalloyed on the basis of vanadium, niobium and nitrogen especially differing in carbon and manganese contents. In the steel C was 1.49 wt.% of carbon with manganese unlike the steel D which showed by 0.39 wt.% higher carbon and manganese content. The cleanness of all steel types was practically at comparable level.

The results showed that for conventional rolling process the microalloying effect was favourable. The influence of ageing was not convincing. All steel types had higher carbon contents and the microalloying suppressed the possible negative influence of free interstitial elements.

The worst results showed the steel A which not reached the required yield strength and tensile strength levels. The grain size was the coarsest in frame of the investigated steel types and in microstructure a high volume fraction of ferrite, predominantly of allotriomorphic ferrite was detected. The steel B showed slight reserve in elongation as well as the steel C where coarser pearlite blocks were observed. In case of the steel...
D yield strength reached 577 MPa on average, the tensile strength 751 MPa, elongation 24.5 % and the impact energy corresponded to 35.5 J. Those results satisfied requirements for the mines supports flange.

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