EM study of precipitation-strengthening process in ultra low carbon steel with copper addition
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Abstract
Effect of ageing parameters on the microstructure evolution and the precipitation-strengthening yield strength increase of HN3M1.5Cu steel with 1.4% Cu addition was investigated. The microstructure of the steel after water quenching and ageing at temperature 913K during 0.6 to 100 hours was observed with optical, transmission and scanning electron microscopy. EDS combined with STEM and SEM technique was used to analyze chemical composition of the precipitates. The aim of the study was to describe the role of copper in precipitation process, and to make use of copper to precipitation hardening. The quantitative determination of the average diameter of precipitates and interparticle spacing was studied to calculate the precipitation effect on yield strength according to modified equation of Orowan- Ashby's type. Time - temperature parameters for the optimum mechanical properties of the investigated ultra low carbon bainitic steel were established. That steel belongs to a new group of advanced structural steels, which are going to be applied for constructions working at low temperatures. That grade of steel is used for special applications in U. S. Navy.

INTRODUCTION
Ultra low carbon bainitic steels recently have been used for pressure vessels and heavy plate hull section of ships and for structures working at low temperature severe applications. HSLA 100 steel is a typical example of the ULCB steel family with YS=690 MPa and guaranteed Charpy V notch impact transmission temperature ITT = 189 K at the minimum impact energy of 80 Joules after quenching and tempering [1]. New grade of ULCB- Ni steel was developed to meet HSLA 100 criteria [2,3].

MATERIAL AND EXPERIMENTS
The chemical composition of the investigated HN3MCu1.5 steel is given in Table 1. The water quenched process of 16mm plates from temperature 1173 K has been performed [4,5] The ageing process of plates involved annealing at temperature 913 K during 0,6 to 100 hours.

Table 1
<table>
<thead>
<tr>
<th>Grade</th>
<th>C</th>
<th>Mn</th>
<th>Si</th>
<th>Ni</th>
<th>Cr</th>
<th>Mo</th>
<th>Cu</th>
<th>Nb</th>
<th>Al</th>
<th>N</th>
<th>P</th>
<th>S</th>
</tr>
</thead>
<tbody>
<tr>
<td>HN3MCu1.5</td>
<td>0.03</td>
<td>1.0</td>
<td>0.23</td>
<td>3.56</td>
<td>0.61</td>
<td>0.59</td>
<td>1.41</td>
<td>0.034</td>
<td>0.024</td>
<td>0.010</td>
<td>0.010</td>
<td>0.005</td>
</tr>
</tbody>
</table>

RESULTS
The mechanical properties and impact strength of as aged plates after WQ were determined. The general aspects of the microstructure were studied by SEM and the fine details by TEM. During study of morphology it has been shown, that the small areas of the former M-A islands ware presented in annealed microstructure as tempered bainite- martensite islands with carbides and ε_Cu particles redistributed uniformly within annealed ferrite matrix. This bainitic type of microstructure observed by optical microscopy was preserved also after 10 hours of annealing at 913 K. Typical microstructures of examined steel, after WQ (a) and ageing (b, 913 K/100 hrs) with SEM, are shown in Figure 1.

Figure 1. Structure of steel HN3M1.5Cu after: a)WQ, and b) WQ + ageing 913K/100hrs;
Typical martensite-bainite morphology was confirmed with optical microscopy and special colorant etching developed by Prof. Beraha. It was shown by quantitative metallography examination that after water quenching there was 60% of martensite, 37% of bainite and 3% of other phases like residual austenite, carbides and ε Cu phase in microstructure. After ageing we can see occurrence recrystallization and precipitation processes. The characteristic precipitates in the microstructure after WQ and ageing are shown in Figure 2a, and corresponding mapping of Cu element investigated by means of STEM-EDS spectrometer is shown in Figure 2b.

![Figure 2. STEM-EDS copper element map of steel HN3M1.5Cu after WQ + ageing 913K/100hrs.](image)

Diameter of precipitates and mean free path between the particles were measured using bright and dark field techniques on thin foil in STEM. Special attention was paid to study ε Cu precipitates. Based on a single diffusion mechanism, where the thermal stability of a specific class of particles is of particular concern, the following formula (1) to predict the size of a spherical ε Cu precipitates was used [6]:

\[
R = Z(D_{Cu} \cdot t)^{1/2}
\]

Where R is the radius of spherical precipitate, \(D_{Cu}\) represented the coefficient of cooper diffusion in ferrite, t is the ageing time and Z- parabolic rate constant, here = 0.1. Based on the Gibbs-Thomson equation (2) it is then possible to obtain an explicit expression for the critical radius \(R^*\) of a particle that neither will grow nor dissolve [7]:

\[
R^* = \frac{2\gamma M V_m}{RT} \left(\ln\left(\frac{C}{C_0}\right)\right)^{-1}
\]

where \(\gamma\) is the particle/matrix interfacial energy and \(V_m\) is the molecular volume of the precipitates. Both diameter results (calculated and measured) and mean free path were used to calculation increase Yield Strength investigated steel according to modified equation (3) of Orowan- Ashby's type [8]:

\[
\Delta \sigma_p = \frac{0.84 Mg b}{2 \pi (1-\nu)^{0.5} (\lambda - 2r)} \ln \frac{r}{b}
\]

where: M is the Taylor factor, G is the shear modulus of matrix, b is the Burger vector, r is the particle radius, \(\nu\)- Poisson's ratio, \(\lambda\)- mean free path between particles.

All results will be presented in the poster.

REFERENCES