SIMILAR AND DISSIMILAR WELD JOINTS
OF CREEP-RESISTING STEELS

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Abstract
One of critical parts of structural device in power industry is a weld joint, similar or dissimilar. In comparison to the base metal, the mechanical and structure characteristics of as-welded and after post weld heat treatment (PWHT) weld metal are different, i.e. hardness values of weld metal are significantly higher. Moreover, the heat-affected zone (HAZ) induces even structure differences comparing to the unaffected base metal.

In a long-term service, materials properties of whole weld joint degrade. Unfortunately, each zone of weld joint degrades specifically that leads to profoundly different properties of weld zones and disallows to reliable predict a behaviour of the weld as a whole. Therefore, it is very important to determine possible degradation processes occurring in the weld joint inducing the properties changes during long-term service and to study the behaviour of each zone of the weld joint in these service conditions.

The paper deals with the study of materials properties of similar and dissimilar weld joins of creep-resisting steels. Creep-resisting 9Cr steels marked P91, P92 and a low-alloyed CrMoVW steel marked T23 as experimental materials were used. The structure and mechanical including creep behaviour of each zone of the weld joint during a long-term isothermal exploitation at 650 degrees of Celsius in air atmosphere was observed. For this reason, the light microscopy (LM), transmission electron microscopy (TEM), X-ray diffraction (XRD), and CALPHAD approach were used. Finally, all theoretical and experimental data were discussed with respect to the choice of weld metal, welding method, and PWHT.

Keywords: similar/dissimilar weld joints, creep-resisting steels, microstructure, mechanical tests, creep tests
1. INTRODUCTION

A behaviour and suitability of creep-resisting steels for power and chemical industry is widely studied focused on to develop materials of new generation for super-critical power plants. So far achieved knowledge on long-term behaviour of creep-resisting steels is mostly based on testing of just base metals, although real structural components of power plants are heavily welded and bended. And just these welded and bended places become most critical parts of entire construction. Therefore, a necessary condition for suitability assessment for super-critical plants is to study the behaviour of welded and/or bended as-treated as well as as-exposed creep-resisting material.

In this paper a main research is focused on similar and dissimilar weld joints of low-alloyed bainitic creep-resisting 2.25Cr-0.25V-1.6W steel (T23), and two middle-alloyed martensitic creep-resisting 9Cr steels (P91, P92).

2. EXPERIMENTAL MATERIALS

2.1 Base metals

T23 steel is a modification of known low-alloyed bainitic creep-resisting 2.25Cr-1Mo steel. Increased creep properties of as-treated steel similar to 9 wt.% of Cr steels P91, P92 have been achieved by alloying with 0.04 wt.% of V and substituting 0.90 wt.% of Mo by 1.49 wt.% of W (the steel contains just 0.10 wt.% of Mo). Furthermore, an addition of 0.005 wt.% of B contributes to improve a weldability of this steel. The microstructure of as-treated T23 steel (normalised and tempered) is formed with upper bainite with carbides of $M_23C_6$ type and carbon-nitrides of MX type. A long-term service exposure induces a progressive coarsening of carbide particles on grain boundaries and partial precipitation of new particles in grains. $M_{23}C_6$ carbides rich on chromium are substituting by $M_6C$ particles (containing tungsten) resulting in decrease in substitution strengthening of solid solution (see Fig. 1). Therefore, the creep resistance level of steel T23 falls during an isothermal exploitation to a level of classical 2.25Cr-1Mo steel.

P91 steel is well known ferritic-martensitic 9 wt.% of Cr steel alloyed with 1 wt.% of Mo, 0.20 wt.% of V, 0.08 wt.% of Nb, and 0.05 wt.% of N. Due to its extended strength and creep properties at elevated temperature P91 steel is used as boiler tubes in superheaters and as steam pipes for power industry. The microstructure of as-treated steel (normalised and tempered) is formed with upper martensitic, and ferritic grains with dispersed carbides/carbon-nitrides of $M_{23}C_6$, MX type, respectively, in grains and/or on their boundaries. During a long-term isothermal exposure at high temperature (620 - 650 degrees of Celsius), martensitic plates are dissolving and carbide $M_{23}C_6$ particles are coarsening (see Fig. 2).
P92 steel is a modification of P91 steel, mentioned above, in addition alloyed with 1.7 wt.% of W dissolved in a matrix to obtain more extended creep resistance by a substitution strengthening. The microstructure of as-treated steel is formed with tempered martensite grains with dispersed M$_{23}$C$_6$ carbides and MX carbon-nitrides. During the same long-term isothermal exposure at high temperature, martensitic plates are too dissolving and carbide M$_{23}$C$_6$ particles are coarsening. In contrary to P91 steel, the long-term exposure leads to a precipitation of Laves phase rich on tungsten and molybdenum (see Fig. 3) that weakens the solid solution.

![Fig. 2. Phase diagram of P91 steel](image1)

![Fig. 3. Phase diagram of P92 steel](image2)

The chemical composition of T23 steel (normalised 1 045 degrees of Celsius/ 10 min/ air and tempered 770 degrees of Celsius/ 60 min/ air), P91 steel (normalised 1 060 degrees of Celsius/ 60 min/ air) and P92 steel (normalised 1 050 degrees of Celsius/ 60 min/ air and tempered 780 degrees of Celsius/ 120 min/ air), used as experimental materials for making similar and dissimilar weldments, is to see in a table 1.

<table>
<thead>
<tr>
<th>Materials</th>
<th>C</th>
<th>Mn</th>
<th>Si</th>
<th>P</th>
<th>S</th>
<th>Cr</th>
<th>Ni</th>
<th>Mo</th>
<th>V</th>
<th>Nb</th>
<th>N</th>
<th>W</th>
<th>Others</th>
</tr>
</thead>
<tbody>
<tr>
<td>T23 steel</td>
<td>0.06</td>
<td>0.29</td>
<td>0.21</td>
<td>0.014</td>
<td>0.004</td>
<td>2.25</td>
<td>0.10</td>
<td>0.240</td>
<td>0.040</td>
<td>0.006</td>
<td>1.49</td>
<td>1.72</td>
<td>B 0.005, Al 0.013</td>
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<tr>
<td>P91 steel</td>
<td>0.09</td>
<td>0.56</td>
<td>0.20</td>
<td>0.021</td>
<td>0.009</td>
<td>8.36</td>
<td>0.46</td>
<td>0.86</td>
<td>0.200</td>
<td>0.060</td>
<td>0.065</td>
<td>Al 0.007</td>
<td></td>
</tr>
<tr>
<td>P92 steel</td>
<td>0.11</td>
<td>0.48</td>
<td>0.37</td>
<td>0.013</td>
<td>0.005</td>
<td>8.58</td>
<td>0.09</td>
<td>0.33</td>
<td>0.227</td>
<td>0.058</td>
<td>0.037</td>
<td>1.62</td>
<td>B 0.0015, Al 0.017</td>
</tr>
<tr>
<td>Union I</td>
<td>0.08</td>
<td>0.56</td>
<td>0.006</td>
<td>0.001</td>
<td>2.23</td>
<td></td>
<td></td>
<td></td>
<td>0.220</td>
<td></td>
<td></td>
<td>1.72</td>
<td></td>
</tr>
<tr>
<td>Thermanit</td>
<td>0.11</td>
<td>0.46</td>
<td>0.38</td>
<td>0.008</td>
<td>0.001</td>
<td>8.76</td>
<td>0.53</td>
<td>0.40</td>
<td>0.201</td>
<td>0.060</td>
<td>0.044</td>
<td>1.55</td>
<td>Cu 0.05</td>
</tr>
</tbody>
</table>

**Table 1. Chemical composition of base and weld metals**

### 2.2 Filler metals
Preparing similar and/or dissimilar weldments, filler metals Union I Cr2WV (see Fig. 4) for T23 steel, and Thermanit MTS 616 (see Fig. 5) for P91, P92 steels were
used. A chemical composition of Union I Cr2WV filler metal is similar to T23 steel, especially considering a volume of chromium, see table 1. Likewise, a filler metal Thermanit MTS 616 contains 9 wt.% of Cr, so it is suitable for welding of martensitic steels with a similar volume of chromium.

![Fig. 4. Phase diagram of weld metal Union I Cr2WV](image1)

![Fig. 5. Phase diagram of weld metal Thermanit MTS 616](image2)

In case of a dissimilar weldment of different materials (so-called transition welds), a choice of a suitable filler metal is an issue, especially considering a carburised or decarburised zone occurring after welding. For example, welding of low-alloyed T23 steel and 9Cr P91 steel requires some filler metal with an ideal 6 wt.% Cr, which is, unfortunately, rarely available on market. Therefore, you can choose filler metals with 2.25 or 9 wt.% of Cr, only, and you are supposed to pay attention to diffusion processes controlling a quality and following behaviour of weld joints.

2.3 Weld joints

**Thick-walled boiler tubes of T23 steel** with a diameter OD 38x8mm were delivered after following heat treatment (HT): normalisation 1 045 degrees of Celsius for 10 min (cooled in air), tempering 770 degrees of Celsius for 1 hour. Similar butt W weld joints were prepared by TIG (in argon) in co-operation with Alstom Power, s.r.o Brno Company. Three technological versions were used (as-welded structures see in Fig. 6):

1. Version A – no preheating, no PWHT
2. Version B – preheated at 150 degrees of Celsius, no PWHT

**Thin-walled pipes of P92 steel** with a diameter OD 350x39mm were delivered after HT: normalisation 1 050 degrees of Celsius (cooled in air), tempering 780 degrees of Celsius. Similar weld joint were prepared by TIG (in argon) for the root pass and MMA for filler and cap passes in co-operation with Company Modřanská potrubní, a.s. The butt welds were preheated at 200 degrees of Celsius
with an interpass temperature 200 – 250 degrees of Celsius and PWHT 760 degrees of Celsius for 2 hours cooled in air.

_Dissimilar weld joint of P92-P91 steels_ was prepared on pipes with a diameter ID 350x39mm (P91) and ID 350x80mm (P92). In this case, welding method TIG (in argon) for the root pass and MMA for filler and cap passes. PWHT was 750 degrees of Celsius for 3 hours cooled in air followed by 700 degrees of Celsius for 2 hours cooled air, again.

All weldments were welded in position PF.

3. RESULTS OF STRUCTURE ANALYSES

For evaluation of microstructure of all as-treated and as-exposed steels, many assessment methods were used, i.e. the light microscopy (LM), transmission electron microscopy (TEM), X-ray diffraction (XRD). In the same time, CALPHAD approach was used to simulation of real weld joints. The main results are mentioned here:

Various initial states of _similar weld joints of T23 steel_ based on technological procedure (preheating, PWHT) influenced achieved microstructure of each weld joint. In macroscopic point of view, a big difference between versions A, B, and C can be observed mainly comparing a width of HAZ, be specific, HAZ of version C is half-width. Then, in microscopic point of view, despite a higher density of precipitates of version B than version A, microstructures of both versions are very similar. In contrast, a microstructure of version C shows already in the initial state a rare

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_Fig. 6. Weldments of T23 steel_  
_Fig. 7. Weld of P92 steel_  
_Fig. 8. Dissimilar weld of P91-P92_
precipitation of carbide particles. However, in all versions, the microstructure is formed with high tempered bainite with coarse $M_{23}C_6$ and fine $M_4C_3$ particles, an average ferritic grain size is 6.5 (base metal), 4.5 (fusion zone) respectively. During a thermal degradation at 650 degrees of Celsius primary precipitated coarse carbides, first of all, on grain boundaries keep coarsening (transformation $M_{23}C_6$ to $M_6C$) and new carbides in grains precipitate and grow. Moreover, a CALPHAD simulation of behaviour of weld joints under those degradation conditions predicted a presence of $M_7C_3$ (see Fig. 9) and Laves phase (just in case of temperatures about 550 degrees of Celsius).

As a remarkable change of microstructure, we must assume an increasing coarsening of fine-grained zone spreading from both surfaces of tubes to the middle part of wall thickness. This phenomenon is most significant in version C, where the fine-grained zone is except the actually middle part coarse across entire wall thickness (see Fig. 10). In agreement, values of hardness vary from 140 HV10 (in the middle of fine-grained zone, non-affected) to 112HV10 (coarse area).

The microstructure of similar weld joint of P92 steel is homogeneous formed by tempered martensite with dispersed carbide particles of $M_{23}C_6$ and MX type. HAZ is very narrow (2-3 mm) – see Fig. 7 – and with no defects. Comparing the microstructure of base metal, HAZ has no remarkable microstructure differences including non-significant coarsening on fusion line, too. And to be precision, the hardness of weld metal varies between 235 and 255 HV10, HAZ has values of hardness lying between 220 to 260 HV10 and an average hardness of base metal is 225 HV10.

![Fig. 9. Phase profile cross weld C](image)

![Fig. 10. Fine-grained zone of exposed weld (type C)](image)
The microstructure of dissimilar weld joint of P92 and P91 steels is formed by tempered martensite with particles of M_23C_6 and MX carbides, carbon-nitrides respectively.

Characterising all zones of weld, the microstructure of root, filler and cap passes is formed by tempered martensite, too, with no significant structure changes across a wall thickness of the welded tube. The average hardness of weld metal is 292 HV10 (306 HV10 for the root pass).

HAZ, comparing a similar weld of P92 steel, is very narrow (2-3 mm), too, and homogeneous across the wall thickness. Then, more significant fusion zone can be observed just in P91 steel (see Fig. 12). The average values of hardness are 255 HV10 (P91 steel) and 268 HV10 (P92 steel), respectively.

But, in base metal near external surface of both tubes, very large coarse-grain area occurs (see Fig. 13). However large and remarkable structure area it is, its
hardness is practically the same considering remnant non-affected base metal, 231 HV10 (P91 steel) and 217 HV10 (P92 steel), respectively.

The influence of PWHT on change of microstructure properties of similar and dissimilar weld joints of P92 steel induced by following isothermal degradation at 650 degrees of Celsius (laboratory testing) are still running.

4. RESULTS OF MECHANICAL TESTS

Tensile tests proofed a significant influence of applied post-weld heat treatment on mechanical properties of weld joints. After a long-term isothermal degradation loading, this influence is more powerful. For example, mechanical properties of weld joint of T23 steel – type C (without preheating, with PWHT) decrease more rapidly than the other two types (with/without preheating, without PWHT).

5. RESULTS OF CREEP TESTS

Creep tests of weldments were carried out at Laboratory of Institute of Physics of Materials of Academy of Science of the Czech Republic. As testing parameters, uniaxial tensile isothermal loading and with cyclic temperature, respectively, were set. Comparing creep behaviour of welded and non-welded steels, the results led to expected conclusion: a level of creep resistance of weld joints is lower, in general.

6. CONCLUSIONS

Presented paper deals with similar and dissimilar weld joints of low-alloyed steel (2.25Cr-0.25V-1.6W) marked T23 and 9 wt.% of Cr steels marked P91, P92 respectively. For evaluation of as-treated and as-exposed steels, many assessment methods were used, i.e. the light microscopy (LM), transmission electron microscopy (TEM), X-ray diffraction (XRD), and CALPHAD approach. In addition, mechanical tests including creep were taken.

REFERENCES


ACKNOWLEDGEMENT

Authors want to thank to Ministry of Industry and Trade of the Czech Republic for their financial support within programmes “TANDEM” (project no. FT-TA2/038), and “TRVALÁ PROSPERITA” (project no. 2A-1TP1/057).