CREEP CRACKING OF SIMILAR AND DISSIMILAR T92 STEEL WELDMENTS

L. Falat, P. Ševc, L. Čiripová

Abstract
This paper deals with the characterization of creep cracking types occurring in similar T92/T92 and dissimilar T92/TP316H welded joints produced by tungsten inert gas (TIG) welding. Both martensitic/martensitic and martensitic/austenitic weldments types were post-weld heat treated by tempering at 760 °C. Moreover, one separate series of T92/TP316H weldments was subjected to re-quenching from 1060°C into water and subsequent tempering at 760 °C. Afterwards, all the weldments were subjected to creep testing at 625 °C and 650 °C using initial applied stresses ranging from 80 MPa to 160 MPa. Depending on PWHT and creep testing conditions used, several failure modes have been observed, including cracking in T92 base material (T92 BM), type IV cracking in fine-grained intercritical heat-affected zone (HAZ), type III cracking in the fusion zone at the interface between T92 steel and Ni-based weld metal (Ni WM), over-load cracking at T92/Ni WM interface and cracking in over-tempered T92 BM relating to subcritical HAZ failure. Performed fracture path analyses combined with morphological observations of creep cracks and cavities in microstructures beneath fracture surfaces of creep-exposed specimens were essential for fracture mechanism determination.

Keywords: T92 and TP316H steels, welded joints, creep cracking, fracture mechanism

INTRODUCTION
Since power plant boilers consist of many steam-line circuits heated up to different operation temperatures, wide variety of creep-resistant steels with respect to the alloying and microstructural concept are used for their fabrication [1]. The individual construction parts of these boilers are joined together with conventional fusion welding techniques inducing relatively great heat input into the welded base materials. Thus, the welded joints represent most critical construction parts within the energetic boiler equipment [2]. It generally holds that the microstructure of individual regions of weldments, namely weld metal (WM), fusion zone (FZ), heat-affected zone (HAZ) and typical cracking types, occurrence depend on the location (distance from weld center-line) and reached a peak temperature during welding (see Fig.1a). Due to the presence of phase transformations in steels, their HAZ additionally consists of several microstructural sub-regions, namely coarse-grained HAZ (CGHAZ), fine-grained HAZ (FGHAZ), intercritical HAZ (ICHAZ), and subcritical HAZ (SCHAZ). With regard to the great microstructural heterogeneity of HAZ related to welding-metallurgical reasons (e.g. weld metal dilution, dendritic segregation, etc.) and subsequent degradation processes during creep loading in service or

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laboratory conditions, four basic cracking types may occur in weldments leading to their integrity loss and failure (see Fig.1b) [3].

Fig.1. Schematic dependence of microstructures and weld cracks formation on reached peak temperature during welding (a) and Schüller's classification of cracks types in welds (b) [3].

Type I and type II cracks are directly related to the welding process (level of impurities in welding consumables). They appear as intergranular, so-called “hot cracks” formed during weld solidification. Type III cracking refers to reheat or stress relief cracking which is defined as intergranular cracking in HAZ or WM. Brett [4] additionally defined the type IIIa cracking as a failure mode occurring in soft decarburised CGHAZ close to the weld FZ. Type IV cracking is generally considered to be a life-limiting factor of ferritic steels welded joints. Generally, the type IV cracking is related to the occurrence of soft microstructural zones (ICHAZ and/or FGHAZ) with degraded creep strength surrounded by the zones with higher creep resistance. Study by Abe et al. [5] indicated significant creep-strength improvement of newly developed martensitic steels and their welds by boron
alloying which has been the challenge for continuation in basic investigations of Fe-based model alloys with boron [6,7].

Our previous studies [8-10] were dealing with detailed characterization of microstructures, creep behaviour and weld metal interface phenomena of dissimilar welded joints between boron-containing T92 martensitic steel and TP316H austenitic steel. The present work is particularly focused on characterization of creep cracking and related failure modes of similar and dissimilar weldments of the T92 martensitic steel.

**EXPERIMENTAL PROCEDURE**

Similar T92/T92 and dissimilar T92/TP316H welds were produced by tungsten inert gas (TIG) welding procedure using Thermanit MTS 616 and Nirod 600 filler metals, respectively. All experimental details regarding geometry and dimensions of the welded materials and welding conditions were given in [8-11]. Chemical compositions of used base materials and filler metals are shown in Tables 1 and 2, respectively. Both martensitic/martensitic (T92/T92) and martensitic/austenitic (T92/TP316H) weldments types were post-weld heat treated by tempering at 760°C. In addition, one separate series of T92/TP316H welded joints was subjected to re-quenching from 1060°C into water followed by tempering at 760°C.

| Tab.1. Chemical composition in wt.% of base materials of studied weldments. |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| C | N | Si | Mn | Cr | Mo | W | B | Ni | Al | V | Nb | Fe |
| T92 | 0.11 | 0.056 | 0.38 | 0.49 | 9.08 | 0.31 | 1.57 | 0.0023 | 0.33 | 0.014 | 0.2 | 0.069 | rest |
| TP316H | 0.052 | - | 0.51 | 1.77 | 16.76 | 2.05 | - | - | 11.13 | - | - | - | rest |

| Tab.2. Chemical composition in wt.% of filler metals of studied weldments. |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| C | Si | Mn | N | Cr | Mo | W | Ni | V | Nb | Ti | Cu | Fe |
| Thermanit MTS 616 | 0.11 | 0.22 | 0.6 | 0.04 | 8.6 | 0.45 | 1.6 | 0.6 | 0.2 | 0.06 | - | - | rest |
| Nirod 600 | 0.05 | 0.3 | 3.0 | - | 20.0 | - | - | rest | - | 2.0 | - | - | 2.0 |

Afterwards, all the weldments were tested in creep at 625°C and 650°C using initial applied stresses ranging from 80 MPa to 160 MPa. Cylindrical tensile specimens with M6 thread head, 40 mm of body length and 4 mm in body diameter were used for the creep tests. Creep cracking and related failure modes of investigating weldments were evaluated by observation of broken creep samples counter-parts using conventional light optical metallography.

**RESULTS AND DISCUSSION**

**Creep cracking of similar T92/T92 welded joint**

Figure 2 shows a profile view on sub-fracture microstructures of two counterparts of broken creep specimen tested at 625°C, 120 MPa. The creep fracture location within fine-grained ICHAZ corresponds obviously to type IV cracking failure mode. In Figure 3 the sub-fracture microstructures of the ICHAZ regions are shown in more detail.

Fracture path analysis in Fig.3 indicates intergranular dimple tearing to be the major creep fracture mechanism in the case of type IV cracking failure of T92/T92 similar welded joint.
Fig. 3. Fracture path and creep cavities in sub-fracture ICHAZ microstructures of two counter-parts of similar T92/T92 welded joint ruptured after 1546 h of the creep test at 625°C, 120 MPa.

**Creep cracking of dissimilar T92/TP316H welded joint**

Figure 4 shows a failure by cracking in over-tempered T92 BM (i.e. cracking in SCHAZ) of T92/TP316H weldment after conventional tempering PWHT and subsequent creep testing at 650°C, 120 MPa for 55 h.

Fig. 4. Light optical microstructures of two counter-parts of conventionally tempered T92/TP316H weldment ruptured by “cracking in over-tempered T92 BM” after creep testing for 55 h at 650°C, 120 MPa.
Due to very high local deformation beneath creep fracture (Fig.4), the positions of SCHAZ, ICHAZ, and FGHAZ are only roughly estimated. However, in accordance with other studies [12,13] the cracking in over-tempered T92 BM can be indicated by high reduction of the area at fracture rather than microstructural characterization. Remarkable necking at the fracture area in this case suggests significant participation of dynamic recrystallization in the creep deformation process. Figure 5 shows the detailed profile view on the sub-fracture microstructures revealing typical features of fracture path and creep cavities. Figure 5 indicates that the creep fracture mechanism corresponding to the failure in over-tempered BM is characterized by ductile dimple tearing.

Fig.5. Fracture path and creep cavities in microstructures of broken sample counter-parts of tempered T92/TP316H weldment after 55 h of creep testing at 650 °C, 120 MPa.

Fig.6. Overload interfacial failure of conventionally tempered T92/TP316H weldment after 62 h of creep test at 625°C, 160 MPa.

Figure 6 shows over-load failure by cracking along the T92/Ni WM interface of conventionally tempered T92/TP316H weldment after 62 h of the creep test at 625°C, 160 MPa. Although a major part of the over-load failure can be regarded as totally brittle (interfacial decohesion), a certain part of the fracture extending to the CGHAZ of T92 steel exhibits still some plastic deformation (see detail in the right portion of Fig.6).

Figure 7 shows a failure by cracking in T92 BM of the re-quenched T92/TP316H weldment after creep test at 650 °C, 120 MPa with rupture time of 644 h. The overall appearance of the failure by cracking in T92 BM (Fig.7) strongly resembles the failure by cracking in over-tempered T92 BM (Fig.4). Significant necking at the fracture area
suggests the participation of dynamic recrystallization during creep deformation process. The microstructures beneath fracture surfaces are refined due to high local deformation (Fig.8).

Fig.7. Light optical microstructures of two counter-parts of the re-quenched and tempered T92/TP316H weldment ruptured by cracking in T92 BM after 644 h of creep test at 650°C, 120 MPa.

Fig.8. Fracture path and creep damage features in sub-fracture microstructures of two counter-parts of re-quenched and tempered T92/TP316H weldment ruptured after 644 h of creep test at 650°C, 120 MPa.

Figure 9 shows a failure by type III interfacial decohesion cracking at T92/Ni WM interface of the re-quenched and tempered T92/TP316H weldment after 2303 h of creep at 650 °C, 100 MPa. It can be seen that the interfacial creep fracture is partially extending to the T92 steel. Since interfacial creep damage in this region is well-developed (see the right portion of Fig.9), such fracture appearance may rather be caused by local stress state conditions (reflecting V-groove geometry of Ni WM) than by microstructural factors.
SUMMARY AND CONCLUSIONS

Table 3 summarizes the occurrence of individual creep cracking (failure modes) of studied similar (T92/T92) and dissimilar (T92/TP316H) weldments independence of PWHT and creep conditions used.

Tab.3. Summary of failure modes occurrence in T92/T92 and T92/TP316H weldments.

<table>
<thead>
<tr>
<th>Weldment</th>
<th>T92/T92</th>
<th>T92/TP316H</th>
</tr>
</thead>
<tbody>
<tr>
<td>PWHT</td>
<td>tempering only</td>
<td>tempering only</td>
</tr>
<tr>
<td>$\downarrow \sigma_{\text{appl}}$</td>
<td>$T_c$</td>
<td>$\sigma_{\text{appl}}$</td>
</tr>
<tr>
<td>80 MPa</td>
<td>type IV (ICHAZ)</td>
<td>type IV (ICHAZ)</td>
</tr>
<tr>
<td>100 MPa</td>
<td>type IV (ICHAZ)</td>
<td>type IV (ICHAZ)</td>
</tr>
<tr>
<td>120 MPa</td>
<td>type IV (ICHAZ)</td>
<td>OT BM (SCHAZ)</td>
</tr>
<tr>
<td>140 MPa</td>
<td>type IV (ICHAZ)</td>
<td>OT BM (SCHAZ)</td>
</tr>
<tr>
<td>160 MPa</td>
<td>n.d.</td>
<td>n.d.</td>
</tr>
</tbody>
</table>

$\sigma_{\text{appl}}$ – applied stress

$T_c$ – creep temperature

n.d. – not determined (Creep test was not performed.)

OT BM – over-tempered base material cracking

OL IF – over-load interfacial cracking

- Similar martensitic/martensitic (T92/T92) and dissimilar martensitic/austenitic (T92/TP316H) weldments subjected to classical tempering PWHT and subsequent creep testing show qualitatively the same creep failure behaviour characterized either by type IV cracking or over-tempered base material cracking. Thus the T92 part of
dissimilar tempered only T92/TP316H weldments always represented their weakest region in used (only tempering) PWHT and creep conditions.

- The use of re-quenching and tempering PWHT of dissimilar T92/TP316H weldments prior to creep testing resulted in significant changes in their creep cracking characteristics compared to the same weldments subjected only to classical tempering. Compared to tempering only PWHT, transitions from type IV cracking to type III cracking and from over-tempered base material cracking to only base material cracking were observed after application of re-quenching and tempering PWHT.

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