Investigation of Materials from the Decommissioned Reactor Pressure Vessel of Gundremmingen Unit A Power Plant

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ABSTRACT

Trepans were taken from the reactor pressure vessel of the decommissioned nuclear power plant Gundremmingen, unit A (KRB-A) in Germany to determine the actual material state of base material, weld and cladding in comparison with surveillance specimens and irradiated archive material. Irradiation experiments with archive and trepan material were performed in test reactors and the thermal annealing behavior was studied.

1 INTRODUCTION

According to the Code requirements, the material state of the reactor pressure vessel (RPV) is determined from surveillance specimens. To validate this procedure mainly with regard to neutron spectra and dose rate effects, trepans were taken from vessel shells and welds of the RPV of the nuclear power plant Gundremmingen, unit A, decommissioned after 10 years of operation [1]. The post-service material state of trepans from one of the vessel shells and the circumferential weld of the core belt-line region is compared with that of corresponding archive material - unirradiated and irradiated in test reactors -, surveillance specimens and trepans taken from a vessel shell at the top of the vessel for which no irradiation damage has to be assumed. The neutron dose at the trepan location in the core-belt line region (cladding/ferrite interface) amounts to about 3 to 6 \( \cdot 10^{18} \text{cm}^{-2} \), whereas the surveillance specimens cover a range from 3 \( \cdot 10^{16} \) to 97 \( \cdot 10^{18} \text{cm}^{-2} \) and include additional specimens which were only exposed to operating temperature. Since toughness data of the austenitic stainless steel cladding are important considering small defects, the investigation of the trepans was also directed to the cladding. Because of the limited thickness of the cladding, only subsize impact specimens (KLS1) can be tested. A correlation was established to evaluate data adequate to Charpy specimens.

2 PROPERTIES OF ARCHIVE AND RPV MATERIAL

Archive base material was only available from one of the core belt-line vessel shells. The Charpy impact results of transverse (T-L) and longitudinal (L-T) specimens show an upper shelf energy (USE) of 105 J (T-L) and 145 J (L-T), respectively, Fig. 1. Although this forging was


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manufactured in 1965 these toughness values are in accordance with today's requirements. The chemical composition, however, exceeds the present specification with regard to Cu, P and S in case of the base material and Cu in case of the weld, Table 1.

Table 1: Chemical composition of base material and weld

<table>
<thead>
<tr>
<th></th>
<th>C</th>
<th>P</th>
<th>S</th>
<th>Cu</th>
<th>Wt</th>
</tr>
</thead>
<tbody>
<tr>
<td>archive base material</td>
<td>.23</td>
<td>.014</td>
<td>.019</td>
<td>.17</td>
<td>.77</td>
</tr>
<tr>
<td>trepan base material (low toughness)</td>
<td>.24</td>
<td>.015</td>
<td>.027</td>
<td>.17</td>
<td>.79</td>
</tr>
<tr>
<td>trepan base material (high toughness)</td>
<td>.21</td>
<td>.009</td>
<td>.007</td>
<td>.13</td>
<td>.75</td>
</tr>
<tr>
<td>circumferential weld</td>
<td>.08</td>
<td>.009</td>
<td>.010</td>
<td>.25</td>
<td>.20</td>
</tr>
</tbody>
</table>

Fig. 1: Charpy energy of unirradiated archive base material

Fig. 2: Charpy energy of irradiated trepan base material

For one of the vessel shells of the core belt-line region the USE of the Charpy specimens machined from the trepan material remains still at a high level of 135 J for the L-T orientation, while the USE of the T-L specimens was found to be 60 J at the inner side of the vessel wall, Fig. 2, converging to the level of the archive material at the outer side, Fig. 3.

The reduction in area determined with tensile specimens (T-orientation) shows similar behavior. This is the only tensile test parameter which was found to correlate with the upper shelf energy in Charpy tests, while yield and ultimate strength vary only little across the wall and compared with the unirradiated archive material.

Besides the fact that the USE of the transverse specimens is below the limit of 63 J required by the Code, the change in USE - compared with the unirradiated archive material - is significantly higher than that predicted by the U.S. Reg.Guide 1.89 Rev. 2, Fig. 4.
In addition, the shift in transition temperature of the T-L specimens is high and exceeds that of the mean curve of the Code prediction (U.S. Reg. Guide 1.99 Rev. 2). When the previous Reg. Guide 1.99 Rev. 1 is used for comparison, which supposes Cu and P as dominant for the material susceptibility to irradiation damage, the transition temperature shift exceeds the prediction curve significantly. The behavior of the longitudinal specimens (L-T), however, is conservatively covered by the existing Code. The general agreement of the L-T specimens with the prediction curves was already seen from surveillance specimens. According to surveillance practice at the time when the reactor was built, only longitudinal specimens were used to monitor in-service degradation. However, the missing information on transverse USE data cannot be derived reliably from longitudinal data.

Specimens of a second vessel shell of the core belt-line region show high post-service USE for both orientations (T-L 150 J / L-T 180 J). The USE of the circumferential weld, of which only T-L specimens had been tested, dropped from 180 J to 150 J. Despite of the high copper content the toughness is still high after irradiation and is in accordance with the Code prediction.

3 APPLICATION OF EB-COMPOUND TECHNIQUE FOR SURVEILLANCE SPECIMENS

For the assessment of toughness data from transverse specimens of the surveillance program an electron beam (EB) weld technique was applied to reconstitute specimens using a weld-in piece of 10 x 10 x 10 mm³ which was machined from broken halves of Charpy specimens. On this basis, results of specimens from the surveillance program of both orientations could directly be compared, Fig 5. The USE of the reconstituted T-L specimens is in the range of 90 J even with a 50% higher fluence than those specimens from the vessel trapan which showed an USE of only 60 J. Thus no agreement exists between surveillance specimens and vessel wall material.

4 THERMAL ANNEALING OF IRRADIATION DAMAGE

Specimens from base material trapanes were thermally annealed at 450°C for 188 h. in some cases up to 520°C, to investigate the recovery behavior and
assess the initial material state. Hardness measurements, Charpy and tensile tests were performed after annealing. All results show that the material cannot be restored to the level of the unirradiated archive material and a significant toughness gradient remains from the inner to the outer surface of the vessel wall, as shown in Fig. 5. Even after applying a complete new heat treatment - austenitizing, quenching and tempering - the upper shelf energy does not improve more than due to annealing at 450°C. Moreover, the line established for the "as-irradiated condition" matches with the predicted initial material state when the U.S. Reg. Guide 1.99 Rev. 2 is applied to the irradiated tritium material in the opposite way. It may be assumed that an initial toughness gradient existed already in the pre-service condition resulting from manufacturing.

Fig. 5: Charpy energy of L-T surveillance specimens and reconstituted T-L compound specimens

Fig. 6: Effect of heat treatment on upper shelf energy of irradiated tritium material

5 TEST REACTOR IRRADIATION

Irradiation experiments were performed under high neutron flux in test reactors in the U.S., the UK and in Germany. Although the irradiation
conditions varied in a wide range, the results with regard to flux and neutron energy spectrum were found to be in one scatter band. The decrease in USE of the T-L specimens was similar to that of the reconstituted surveillance compound specimens, Fig 7, and thus much less than that of the vessel wall material. In addition to these experiments, Charpy specimens were machined from the vessel outer region ($\Phi = 0.8 \cdot 10^{18} \text{cm}^{-2}$) and irradiated to a fluence corresponding to the vessel inner surface [2]. The susceptibility of this material to neutron irradiation is well predicted by the slope of the U.S. Reg. Guide curve and the low USE of the vessel inner side material is not nearly reached.

6 CHARACTERIZATION OF THE AUSTENITIC CLADDING WITH SUBSIZE SPECIMENS

The RPV was cladded using a two layer wire overlay procedure. The thickness of the cladding is too small to obtain Charpy specimens. For this reason subsize specimens (KLST) were used according to the German Standard DIN 50 115. Due to geometric constraint effects the results of KLST specimens cannot easily be converted into Charpy size results. A correlation has been established covering materials with Charpy USE from 40 to 190 J including data from literature [3] and an austenitic stainless steel cladding (USE = 80 J) representing present technology, Fig 8.

![Fig. 8: Correlation between USE of Charpy and subsize (KLST) specimens](image1)

![Fig. 9: Subsize impact energy of irradiated austenitic cladding material](image2)

The correlation procedure comprises USE transformation according to Fig 8 and index temperature correlation as a function of USE ratio, e.g.

$$T_{41 \text{J}} \ (\text{KLST}) = 41 \text{ J} \cdot \frac{\text{USE}_{\text{KLST}}}{\text{USE} (\text{CHARPY})}$$

The results of the original KRB-A cladding show a wide scatter in transition temperature and in particular in upper shelf energy, Fig 9. When converted to Charpy values, the USE of the first layer is about 145 J, that of the second (outer) layer is spread into two regimes of 80 J for one set and less than 40 J for the other set of specimens. Investigations of the microstructure are under way to find the causes for the great differences in toughness.
CONCLUSION

Charpy impact test on RPV base material (transverse specimens) have shown low upper shelf Charpy energy at the inner side of one core belt-line vessel shell. Since heat treatment was not successful to restore the material toughness it cannot be excluded that the low toughness results only partially from neutron irradiation. Another contribution may come from an initial gradient across the wall thickness resulting from manufacturing. It is not very likely that only irradiation and other in-service conditions are responsible for the low toughness results, because the second vessel shell in the core region and the weld, as well, do not show any unexpected effects. Otherwise this would suppose an extreme susceptibility to irradiation of this special vessel shell material. The relatively high sulfur content (0.027 %) of the vessel shell of concern together with the forging procedure might have contributed to the strong anisotropy, the low toughness level in general and to an supposed toughness gradient of the initial material state. Indications for this were obtained from analysing the size distribution of manganese sulfides over the wall thickness that are mainly reasonable for directionality effects. With regard to the small irradiation response of thearchive material in test reactors and in the surveillance program which did not lead to the low toughness of the vessel wall and considering the uniform properties of archive material across the wall, it might be possible that both materials were manufactured independently. Although basing from the same melt, differences in ingot size and hot forming procedure may have cause differences in mechanical properties. This indicates the problems involved in providing sufficient test and archive material representative for the whole vessel.

The stainless steel cladding shows great differences in USE depending on local microstructure. Since similar results were found on 308/309 stainless steel cladding [4] it has to be checked whether this behavior represents common cladding practice or has only to be assumed for specific fabrication procedures. The effect of the low toughness on the initiation of small cracks under pressurized thermal shock loading has to be considered.

The investigations are being continued on both areas, the base material and the cladding behavior.

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