Application of Reconstitution Technique on Performance Evaluation of Anchor Bolts

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Abstract. The impact property of a high-strength grade 42CrMoE alloy steel was investigated under varied insert lengths using reconstitution method. A new full-field strain measurement method was employed to explore the plastic deformation region of the steel. Meanwhile, in order to quantitatively examine the insert length influence, an instrumented impact method was proposed to analysis the impact property. The results have successfully demonstrated that inserts equal to or larger than 20 mm can be used to obtain valid data for 42CrMoE.

Introduction

In nuclear power plants (NPPs), many vessels are fixed by the anchor bolts with concrete consolidation which is difficult to replace. Considering that the integrity of the vessels is a major issue of plant life management in NPPs, and the bolts are important components to ensure a tight connection between vessels’ pedestal and the skirt [1], thus the quality of anchor bolts may affect the structural integrity of vessels during the operation of NPPs.

In recent years, many problems of such anchor bolts were exposed in China. More attention is being paid on the toughness and strength which may cause a great threat to the vessels that undergo accident conditions, such as earthquake. However, as shown in Fig.1, limited by bolt exposed end is too short to process a standard specimen size. Therefore, the assurance of safe exploitation of anchor bolts through the verification test using advanced techniques is urgent.

The reconstitution technique creates the possibility to construct specimens from small quantities of material [2, 3]. This technique consists in welding extensions to the piece of material of interest (the insert) so to prepare a test specimen of standard dimensions, thus to
overcome the lack of test specimens from plants. As far as now, a number of reconstitution techniques such as arc stud welding (ASW) [3], laser and electron beam welding (EBW) [4-6], projection welding methods were studied [7]. ASTM E1253 provides a guideline for the reconstituted original size Charpy specimen used in reactor pressure vessel (RPV) [2]. Work to date has indicated successful results with above methods for a suitable weld quality with narrow weld and heating area zone (HAZ) thickness. Especially for the electron beam welding method, it provides a high energy density achievable means that narrow welds and heat-affected zones can be created.

In the present study, we design an experimental method to quantitatively compare the impact behavior of a high-strength anchor bolt material 42CrMoE low alloy steel with electron beam welding reconstitution technique. The minimum insert length and influence on the impact property are further discussed in the context.

Material and Specimens

The material tested in this study is a high-strength grade 42CrMoE alloy steel that is widely used for anchor bolts in the PWR nuclear power plants. The bolt size is M68×1140mm. The main chemical composition of the steel is C:0.400; Si:0.230; Mn:0.780; P:0.019; S:0.010; Cr:0.890; Mo:0.200 and balance Fe.

To verify the minimum suitable insert length, a number of reconstituted specimens with different length of insert were studied. The specimens with dimensions 10mm×10mm×55 mm were machined from at a quarter thicknesses from the inner surfaces of the anchor bolt in the axial direction, a schematic diagram of this process is shown in Fig. 2.

Experiment Design

Electron Beam Welding

The welding experiments were carried out on Leybold – Heraeus electron beam welding equipment ESW300/60-15. During the welding, the end studs and inserts were carefully machined at exact size and positioned in a special designed rig as shown in Fig.3. Slices were placed between specimens so to avoid material flow at the edges. Besides, in view of the carbon content of material is slightly higher, a preheat process with a maximum 230°C was introduced before welding so to avoid thermal crack.
Reconstitution Evaluation

In ASTM E1253, it is prescribed that the minimum length of the specimen insert shall be 18 mm. International research on reconstitution of Charpy-sized specimens for RPV steel concluded that the effect of reconstitution is not negligible in general when the insert length is short [2]. Therefore, five types of reconstituted specimens with different length of insert (12mm, 14mm, 16mm, 18mm and 20mm) and end stud were designed so to determine the suitable minimum insert length for 42CrMoE steel. Based on the previous results [6, 8, 9], it is seen that the minimum insert length generally depends on the toughness level of the insert and welding conditions whether the reconstitution affects it or not, and it can be expressed as the following formula [10],

$$W_a \geq W_{loss} + 2(W_{pm} + W_{HAZ})$$

(1)

Where $W_a$ is the insert length, $W_{loss}$ is material loss caused by welding, $W_{HAZ}$ is the hardened heat affected distance from the weld center depending on the welding procedure and welding condition, and $W_{pm}$ is plastic deformation width as shown in Fig.4.

In order to acquire $W_{pm}$, a full-field strain measurement through DIC (digital image correlation) system was used. Meanwhile the $W_{HAZ}$ can be determined according to the hardness distribution measurement and micro-structural examination. Considering that the EBW method does not need any weld material during welding, thus the $W_{loss}$ can be
considered as none. In the meantime, the instrumented impact results can be used to quantitatively examine the insert length influence. Therefore, the whole evaluation process can be illustrated as Fig.5.

![Evaluation Plan for the Min Insert Length.](image)

Figure 5. Evaluation Plan for the Min Insert Length.

(1) Plastic strain width W_{pm}
Conventionally, the Vickers hardness distributions of the tested Charpy impact specimens were measured so to define W_{pm}. This technique can only provide limit information for one or a few points on the broken specimens. In this paper, non-contact optical method provides a new way to experimentally study dynamic strain distribution which is shown in Fig.6. Full-field DIC is a non-contact optical method where digital images of an object are captured and analyzed to extract full field shape, deformation and/or motion measurements [11]. Thus, an optical non-contact 2D displacement measuring system (ARAMIS HR) manufactured by GOM connected with Photron (Tokyo, Japan) SA 1.1 high speed video (HSV) camera have been used to determine the strain field in the notch region of specimens in the impact test. The cameras operated at a resolution of 1024 pixels × 1024 pixels, recording at a frame rate of 250fps and a minimum shutter speed of 1/5000s, so to obtain a high resolution of data points on a surface of interest with relative ease.

![View of the HSV DIC Experimental Setup.](image)

Figure 6. View of the HSV DIC Experimental Setup.

(2) HAZ width WHAZ
Metallographic study of the welded joint was carried out on optical microscope ZEISS AXIOVERT 200 MAT. For determined the micro-hardness of the base metal, HAZ and weld metal was used 402MVD Micro-hardness Tester, with range 100N and displacement interval 0.3mm.
(3) Impact property

Impact tests were carried out at room temperature according to ASTM E23 (ASTM, 2009) with Zwick RKP 450 instrumented impact testing machine. The load-deflection data obtained from the impact tests as shown in Fig. 7 were utilized to investigate the insert size effect on the dynamic ultimate load $F_m$, the crack initiation energy $W_i$, the crack propagation energy $W_p$, and the total impact energy $W_t$.

![Figure 7. Typical Load-deflection Curves of Charpy Specimens for 42CrMoE.](image)

Results and Discussion

Welding Quality

The micro-structural of the EBW specimen, including the weldment and HAZ is shown in Fig.8, it can be seen that the weld width varies along the depth of the welded joint, and the weld width is about 3.0mm in the middle centerline of weldment. Fig. 9 shows micro-hardness distribution along the reconstructed specimen - in base metal, HAZ and weld. Sudden change of micro-hardness is closely connected with microstructural transformations as a result of thermal cycle of welding.

![Figure 8. Typical Micro-structural of the EBW Specimen.](image)
Figure 9. Micro-hardness Distribution along Reconstructed Specimens.

**Full-field Strain Mapping**

Strain evolution during the impact deformation of the virgin specimen is shown in Fig.10. It is proved that plastic deformation is mainly concentrated in the notch region, and there is also a high strain region opposite the notch where the bending strains are concentrated due to the nature of the constraint. Thus, the sequence of the inhomogeneous deformation occurring during the impact deformation is clearly revealed. From any strain map after localized plastic deformation, one can easily determine the deformation range by selecting the strain of a facet adjacent to the top surface of the specimen, the results indicate that the plastic deformation region is generally limited about 12mm no matter which stage the impact process.
As refer to the reconstitution specimens, the strain field maps for different insert length cases are shown in Fig. 11, and the comparison of the plastic deformation region is also listed in Table 1. It can be found that there is no obvious difference between the virgin and reconstitution specimens.
Table 1. Comparison on the Plastic Deformation Region for Different inserts Cases.

<table>
<thead>
<tr>
<th>Insert length (mm)</th>
<th>0 (Virgin)</th>
<th>12</th>
<th>16</th>
<th>20</th>
</tr>
</thead>
<tbody>
<tr>
<td>$W_{pm}$ (mm)</td>
<td>12</td>
<td>11</td>
<td>12</td>
<td>12</td>
</tr>
</tbody>
</table>

**Impact Property**

Fig.12 compares typical instrumented signals obtained from EBW and virgin specimens. It is seen that the reconstitution under the conditions investigated alters the features of the load–deflection curves. An increase of the overall deformation and a decrease of the ultimate loading level are caused by the increase of insert length. Apparently, the general yield load, $P_{gy}$, is not affected by reconstitution in all cases. However, the peak load $P_m$ point is slightly affected when the insert length is short, such as 12mm, 14mm. It seems that $P_m$ decreases with the extension of insert length as shown in Fig.13.
As shown in Fig.14, there are typical increases for the crack initiation energy, the crack propagation energy and the total impact energy with the increment of the insert length during reconstitution. The loss of absorbed energy for the reconstitution specimens is due to the constraint of plastic deformation at the hardened region (weldment and HAZ). However, there is nearly no difference before and after reconstitution in the signals from specimens with 20mm inserts.
Reconstitution Evaluation

As stated above, Wa can be determined in Eq.(1) with parameter $W_{\text{loss}}=0$, $2W_{\text{mp}}=12\text{mm}$ and $WHAZ=3\text{mm}$, thus Wa should be larger than $18\text{mm}$ at least. This value is same as required in ASTM E1253 which suitable for RPV material.

However, reconsidering the insert length effect on the impact property, including $F_{\text{m}}$, $W_{\text{i}}$, $W_{\text{p}}$, $W_{\text{t}}$, it recommends that only when the insert length greater than $20\text{mm}$, the reconstitution can provide accurate and reliable data compared with the virgin material.

Summary

The effects of reconstitution of a Charpy impact specimen for high-strength grade 42CrMoE alloy steel which used as anchor bolts material in NPPs were examined and analyzed. Based on the test results, the following conclusions were made.

1. Electron beam welding can be successful applied for the reconstitution of Charpy test specimens on high-strength grade 42CrMoE alloy steel.

2. The full-field stain measurement results indicate that the plastic deformation region for Charpy test specimens is generally limited about $12\text{mm}$, there is no obvious difference between the virgin and reconstitution specimens when the insert length is greater than $12\text{mm}$.

3. With the increment of insert length, it leads an increase of the overall deformation and a decrease of the ultimate loading level and impact energy until the insert length reaches $20\text{mm}$.

Based on an overall consideration of various factors, it recommends that inserts equal to or larger than $20\text{mm}$ can be used so that reconstitution can provide accurate and reliable data for 42CrMoE alloy steel.

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References


