Hot crack assessment of LTT welds using μCT

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Abstract

Investigations on weldability often deal with hot cracking, as one of the most popular failure during weld fabrication. The modified varestraint transvarestraint hot cracking test (MVT) is well known for the assessment of the hot cracking susceptibility of materials [1, 2]. The shortcoming of this approach is that the information is only from the very near surface region, which inhibits access to the characteristic of the hot crack network in the bulk. Here, we report about a new approach, illustrated in the example of low transformation temperature (LTT) weld filler materials, to monitor the entire 3D hot crack network after welding by means of microfocus X-ray computer tomography (μCT).

Keywords: LTT weld filler materials, hot cracking, welding, μCT-analysis, Varestraint testing

1 Introduction

The aim to satisfy lightweight demands and higher load capacities of steel constructions at the same time leads to an increased use of low-alloyed high-strength steels. To exploit their full strength potential, welding these components at their own level of strength is a major challenge. Therefore, the residual stress state in the weld joint is of great importance as it strongly affects the cold cracking risk and fatigue life of the welded components.

Two main mechanisms usually lead to the final residual stress state after welding. Due to the cold surrounding base material the thermal contraction during cooling down of the weld joint is restrained. This effect leads to the formation of tensile residual stresses. The second effect is that the phase transformation from austenite to martensite is accompanied by a volume expansion of the weld volume, which is also constrained by the ambient base material. This counteracts the restrained thermal shrinkage of the weld and results in compressive residual stresses. These two mechanisms superimpose and lead to the resulting residual stress state, which is tensile if the restrained thermal shrinkage is the dominating effect. Since tensile residual stresses favour early crack initiation and propagation there is the aim to minimize tensile residual stresses or ideally to induce compressive residual stresses in the weld by post weld heat treatments or post weld mechanical surface treatments as e.g. shot peening or hammering. However, these techniques are either time consuming or cost intensive and sometimes hard to apply e.g. in case of large-scale components. Hence, it is preferable to reduce tensile residual stresses in the weld line without postweld treatments, but during the welding process itself.

Using low transformation temperature (LTT) weld filler materials is an innovative method to mitigate welding induced tensile residual stresses directly during weld fabrication. This is achieved by the addition of alloying elements like e.g. nickel or manganese, which results in a delayed martensite transformation compared to conventional weld filler materials. The volume expansion during martensite formation is more pronounced at lower temperatures due to the higher coefficient of thermal expansion (CTE) for austenite compared to martensite. In-situ analysis using high energy synchrotron X-ray diffraction during realistic MAG welding showed a significantly higher decrease of residual strain due to the hindered volume expansion for an LTT weld filler material compared to a conventional weld filler material [3, 4]. The subsequent residual stress analysis using the contour method, which gives an entire two-dimensional residual stress map normal to the cut face through the component, revealed a higher compressive residual stress level for the investigated LTT filler materials compared to a conventional weld filler material [5].

However, LTT fillers are high alloyed materials, and therefore prone to hot cracks, depending on their chemical composition. Hot cracks are formed at high temperatures during the solidification of the weld pool or during reheating (e.g. multipass welding). They are intergranular or interdendritic defects since mostly low melting phases at the grain boundaries are involved during hot crack formation. Dynamically loaded components are particularly at risk of component failure during operation due to hot cracks.

As an appropriate approach to assess hot cracking, the standardized modified varestraint transvarestraint hot cracking test (MVT) was developed [1]. By means of this test, different base or filler materials can be easily evaluated during welding, as specimens are bent at a certain point in longitudinal or transversal direction to the weld line using defined bending rates. Tungsten inert gas (TIG) welding is used to simulate the weld fabrication. After welding, the total length of all detectable
cracks at the specimen surface is added up and the investigated weld filler material is ranked in regard to its hot crack susceptibility.

Although the highest strain during MVT testing is present on the sample surface, cracking may also occur in the bulk of the sample. These cracks are not covered by the standard evaluation. And valuable information for appropriate characterization of the hot crack network is disregarded. Hence, for accurate assessment of the hot cracking susceptibility, the volume crack information shall also be considered. Therefore, microfocus X-ray computer tomography (µCT) was applied. In this paper we report about an evaluation strategy to determine the hot cracking susceptibility, illustrated in the example of LTT weld filler materials, under consideration of the entire 3D hot crack network.

2 Hot cracking theories

There is a range of existing hot cracking theories based on different assumptions. An overview concerning theoretical approaches can be found for example in the study of Lippold et al. [6]. One of the most common approaches to describe the hot crack formation is the strain based hot crack model following Prokhorov [7]. It describes a material specific hot crack critical temperature range (Brittleness Temperature Range). The Brittleness Temperature Range (BTR) starts below the liquidus temperature at $T_{BTR,max}$ and extents to $T_{BTR,min}$ below the nominal solidus temperature (Figure 1). Below $T_{BTR,min}$ the shrinkage of the melt during solidification in the interdentritic zones is no longer fully compensated by a replenishing flow of melt [8]. Below $T_{BTR,min}$ the grain boundary strength is high enough to resist the thermal and mechanical strains.

Within the BTR, hot crack formation is possible if a critical strain is exceeded. The critical strain is material-specific and is defined by Prokhorov as a temperature dependent function $P(T)$. The acting strain in the material can be caused by external reasons $\varepsilon_{ext}$ (e.g. mechanical load) or by internal reasons $\varepsilon_{int}$ (e.g. hindered volume shrinkage during cooling down). Hot cracks form if $\varepsilon_{tot} = \varepsilon_{ext} + \varepsilon_{int}$ is greater than $P(T)$ within the BTR.

![Figure 1: Hot crack model following Prokhorov [7]. Hot cracks form if the total strain $\varepsilon_{tot}$ exceeds the critical strain function $P(T)$ within the Brittleness Temperature Range (BTR).](image)

3 Modified Varestraint Transvarestraint (MVT) hot cracking test

One of the most commonly used hot cracking tests is the MVT test (Figure 2) which is described in ISO TR 17641-3 [1]. For the MVT test, standardized specimens with dimensions 100 x 40 x 10 mm³ are used. In case of testing weld filler materials, a U-shaped groove with a depth of 5 mm and a width of 20 mm is milled into the blank specimen in longitudinal direction. The investigated weld filler material is then deposited into the groove by automated gas metal arc welding using several layers. Afterwards the specimen is finished to the standardized MVT dimensions. During the MVT tests the weld filler material is remelted by an automated TIG welding process with a defined heat input. When the welding torch reaches the specimen center, the specimen is bent over a die with defined radius - either in longitudinal (Varestraint) or transverse (Transvarestraint) strain direction (Figure 2). Thereby, hot cracks are formed locally wherever the applied strain exceeds the critical strain $P(T)$ within the critical temperature range BTR. Standard evaluation is carried out with an optical light microscope and the cumulated total crack length is plotted in a special MVT diagram. Depending on the curve progression in the diagram, the investigated weld filler material is ranked with regard to its hot cracking susceptibility.
4 Experimental (µCT approach)

µCT was applied at the Karlsruhe Institute of Technology (KIT) using the High-Resolution Cone-Beam CT system type Yxlon Y.CT Precision with fine focus twin head FXE 225.99. The scans were performed at a high voltage of 190 kV and 0.3 mA. To determine the location of the hot crack network, the whole MVT specimen is scanned (Figure 3a). As shown in Figure 3b the MVT specimen is cut in the next step into a smaller cuboid (about 10 x 40 x 10 mm$^3$) to provide a sufficiently high resolution (cone beam geometry) and to reduce X-ray absorption (uncut specimens ~ 25 µm voxel size, cut specimen ~ 7 µm voxel size). It is ensured that the complete 3D crack network is situated within the cuboid. The procedure presented in this contribution is exemplarily performed on a high alloyed LTT weld filler material with a chromium content of 8 wt. % and a nickel content of 6 wt. %. The corresponding chemical composition, welding and MVT parameters are shown in Table 1.
<table>
<thead>
<tr>
<th>Material</th>
<th>Chemical composition in wt. %</th>
<th>Welding parameters</th>
<th>MVT parameter</th>
</tr>
</thead>
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<tr>
<td></td>
<td>C</td>
<td>Cr</td>
<td>Ni</td>
</tr>
<tr>
<td>LTT weld filler</td>
<td>0.045</td>
<td>8</td>
<td>6</td>
</tr>
</tbody>
</table>

4.1 Segmentation

Despite of cutting the specimens, the obtained quality of the reconstructed images is not good enough for a reliable and fast segmentation of the cracks. In particular, high grey value fluctuations and measurement artifacts prevent a global threshold based segmentation. Consequently, a two-step segmentation strategy was implemented using MATLAB©.

In the first step, an adaptive thresholding algorithm (described in [9]) was applied. Here, the 3D image is partitioned in small cubes with defined edge length. Within the cuboids, a mean local grey value is calculated. If the grey value of a voxel is below a certain threshold of the mean grey value (e.g. 10 %), this voxel is detected as a crack. The adaptive thresholding algorithm allows handling the large grey scale value fluctuations within the reconstructed 3D specimen volume. In the second step, the segmented voxels from the first step are used as so called “seeds” for a region growing algorithm [10]. This segmentation strategy examines neighboring voxels of the initial “seeds” and determines whether they should be added to the crack region or not, by means of a second threshold. Using the region growing algorithm allows the growing or shrinking of cracks to their final size.

Additionally, micrographs at defined depths from the weld surface were prepared and analysed with an optical microscope using a magnification of 12.5 x. In order to determine the best suited threshold, each segmented slice from the µCT scan was compared to the micrographs and the Pearson’s Correlation coefficient was calculated. To every micrograph, the µCT slice with the highest correlation coefficient was assigned. Afterwards, the segmentation threshold was varied. Figure 4a illustrates the course of the correlation coefficient as a function of the percentage grey value ΔThreshold. For all studied depths, a plateau can be observed where the correlation coefficient varies less than 5 % to the maximum value for 16 % < ΔThreshold < 19 % (Figure 4b). As a consequence, the selected value for ΔThreshold was 17 % for the segmentation of this specimen.

Subsequently, the segmented binary images can be analyzed statistically and quantitatively.

![Figure 4](image_url)

Figure 4: Pearson’s Correlation coefficient as a function of the used threshold for segmentation at the weld surface. Between thresholds of 16 to 19 % below the mean local grey value, a plateau exists where the correlation coefficient varies less than 5 % to the maximum value (a). For all studied depths, the plateau is located between 16 % < ΔThreshold < 19 % (b).
4.2 Evaluation of µCT data in regards to hot cracking susceptibility

4.2.1 Crack orientation

To determine the crack orientation, a polynomial fit of degree 2 is performed on each individual crack in each slice. The crack orientation as a function of distance to the weld centerline shows that the cracks on or near the centerline are oriented approximately 0° to the longitudinal axis, while with increasing distance to the centerline the orientation rises up to 90° at the fusion boundary (Figure 5a). Under assumption of an elliptical weld pool, this crack orientation dependency can be explained by the solidification direction during the welding process. As hot cracks are intergranular defects, they are oriented in the direction of solidification. In Figure 5b it is shown that the solidification rate $v_{\text{sol}}$ and the crystallisation direction are orthogonal to the liquid-solid interface of the weld pool [6]. Among other things, this makes it possible to reconstruct the 3D weld pool and the crystallisation direction from the slopes of the cracks. Hot crack formation and its characteristics depend on numerous secondary influence factors e.g. weld pool geometry. A lot of these factors can be further examined using the gathered µCT data. Evaluation of 3D hot crack networks therefore allows for significant enhancement of MVT specimen analysis. This can become important for the comparison of total crack lengths of two weld filler materials with significantly different melting temperatures (different weld pool size at constant heat input).

![Figure 5](image)

**Figure 5:** Crack orientation as a function of the distance to weld centerline (a). Crystallisation direction for an elliptical weld pool (b).

4.2.1 BTR range

Based on the hot crack model following Prokhorov, the cracks can form between $T_{\text{BTR,min}}$ and $T_{\text{BTR,max}}$ during the bending of the specimen. When looking at the 2D slices, the isotherms of $T_{\text{BTR,min}}$ and $T_{\text{BTR,max}}$ form ellipses around the weld pool. This is shown in Figure 6 for the top view. However, the 3D temperature distribution during the welding process is not accessible without great experimental or numerical effort. As the strain at the surface of the MVT specimen is high, it is assumed that the crack length corresponds to the distance of the isothermes $T_{\text{BTR,max}}$ and $T_{\text{BTR,min}}$. Consequently, the hot cracking susceptibility determined by the conventional MVT test is proportional to the extent of the BTR. Therefore, a qualitative comparison of different weld filler materials can be made in the form of rankings. However, the susceptibility to strain is not taken into account here. Consideration of the complete 3D hot crack network provides additional information about $P_{\text{min}}$ from the hot crack model following Prokhorov. Like the 3D temperature distribution, the 3D strain distribution during bending is also not accessible without great effort. But as the strain decreases with increasing distance to the surface, the maximum crack depth $D_{\text{max}}$ is proportional to the minimum critical strain as illustrated in Figure 7. As a result, using the 3D crack information gives a significant additional benefit over the standard evaluation of the MVT test. Furthermore, using this approach it becomes possible not only to rank weld filler materials in regards to their extent of BTR, but also in regards to their strain susceptibility.
5 Conclusion

µCT analysis is used to evaluate the hot cracking susceptibility of MVT specimens for the example of LTT weld filler materials. The following conclusions can be drawn regarding the application of this new approach:

- A two step segmentation strategy using an adaptive threshold and region growing algorithm has proved to be suitable for the segmentation of the hot cracks.
- The hot crack orientation as a function of the distance to the weld center line shows that the cracks are oriented in solidification direction. This allows reconstructing the 3D weld pool and the crystallisation direction from the slopes of the cracks. Additional information about the formation of hot cracks can be obtained by analyzing the 3D weld pool geometry.
• The µCT studies show that the evaluation of the 3D hot crack network results in a much better basis for the assessment of the hot cracking susceptibility than the standard MVT analysis procedure, which only focuses on surface information. The standard evaluation strategy is solely a measure for the extent of the BTR. The volume analysis additionally considers the critical strain $P_{\text{min}}$, which is proportional to the maximum depth $D_{\text{max}}$ of the crack network.

5 Acknowledgement

Financial support by the German Research Foundation (DFG) in the project GI376/8-2 is gratefully acknowledged.

References