Digital image correlation for the characterization of fatigue damage evolution in brazed steel joints

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Abstract

In this work, the fatigue behavior of brazed steel joints in different heat treatments and geometries was investigated and compared with the behavior of the steel substrate. Cyclic loading experiments were performed on a servo-hydraulic testing facility at R = 0.1. The results showed that brazed round specimens exhibit higher plastic strains and lower fatigue lifetimes at similar loading amplitudes when compared with their substrate material. Furthermore, the S,N-curves show that heat treatments which are performed after brazing significantly influence the fatigue lifetime and the defect tolerance of the brazed specimens. To investigate the local effects of the thin braze layer, digital image correlations (DIC) were performed with a high speed camera. The results show the complex interactions of a braze layer with the surrounding material and lead to a better understanding of the fatigue behavior of brazed steel joints.

Keywords: Fatigue; braze; steel; strain; digital image correlation

Nomenclature

<table>
<thead>
<tr>
<th>Abbreviation</th>
<th>Description</th>
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<tbody>
<tr>
<td>DIC</td>
<td>Digital image correlation</td>
</tr>
<tr>
<td>HTM 1/2</td>
<td>Heat treatment (procedure 1 or 2)</td>
</tr>
<tr>
<td>R</td>
<td>Load ratio</td>
</tr>
</tbody>
</table>

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1. Introduction

Today, brazing is used as a promising joining technology for many seminal applications in mechanical engineering, as e.g. for energy production, tool fabrication or space applications (Boretius, 2006). It allows joining a broad range of materials combinations (as e.g. ceramics to metals) and small geometries at fast processing times. Generally, brazing is performed by placing a filler metal between two plates of base material(s) and heating of the assembly above the melting point of the filler metal. The filler metal melts, wets the joining surfaces and fills the joint gap. Cooling of the assembly leads to solidification of the filler metal, and a joint is produced by material closure. A wide range of materials can be combined and custom tailored for the application. With the use of advanced brazing technologies such as high-temperature furnace brazing in vacuum or with a shielding gas, especially the brazing of steel components has become very cost efficient (Nowacki and Swider, 2003). Since diffusion processes can significantly influence the joint strength, subsequent heat treatments are often performed after brazing.

From a microstructural point of view, brazed joints consist of base material, filler metal and diffusion zone. Due to a mismatch of elastic-plastic properties of base material and filler metal, brazed joints form heterogeneous systems and their behavior under mechanical loading significantly varies from the ones of the materials in their bulk form. Under uniaxial loading, a constraining effect between base material and filler metal leads to a three dimensional stress state in the proximity of the braze layer that significantly influences the joint strength. The constraining effect depends on different parameters, as e.g. the elastic-plastic properties of base material and filler metal and the thickness of the braze layer (Schindler and Leinenbach, 2012). Especially defects that can occur during brazing strongly influence the stress distribution and consequently the joint strength. It has been shown that for the material combination investigated in the scope of this work, certain defect assessment procedure can be used to estimate the influence of brazing defects on the integrity of braze joints under static loading (Lis et al., 2012). Concerning the fatigue behavior of brazed joints only little information is available in the literature (Yang et al., 2011, Schindler and Leinenbach, 2012). Preliminary fatigue experiments have shown brazed specimens showed lower fatigue lifetimes in comparison with the substrate material in its bulk form (Koster et al., 2013). The findings correlate with FE-calculations, showing increased strains and higher loads in the proximity of the braze layer in the substrate material.

In this work, fatigue experiments were performed with brazed specimen of a soft martensitic steel and with the substrate material. Besides different specimen geometries, also the influences of heat treatment and defects on the fatigue behavior were considered. The evolution of fatigue induced damage was investigated by digital image correlation (DIC). Furthermore, DIC and SEM investigations were performed to investigate crack initiation and of crack propagation due to cyclic loading.

2. Test materials and experimental setup

For the cyclic loading experiments, brazed specimens were produced from the steel AISI CA 6NM (X3CrNiMo 13-4) as base material and with AuNi18 as a filler metal. Due to its soft martensitic microstructure, the base material provides high strength and strain at fracture. The filler metal has a melting point of 955 °C and is characterized by good corrosion resistance and wetting behavior.

Brazing was performed in an industry furnace with H₂ as a shielding gas. Subsequent heat treatments were performed after brazing to adjust the mechanical properties of the steel joints with regard to potential applications, as e.g. the transport of aggressive media containing H₂S. In this work, two different heat treatments (designated HTM 1 and HTM 2) were compared regarding their influence on the fatigue lifetime. HTM 1 is characterized by two annealing steps at high temperatures; HTM 2 consists of one annealing step at a comparable low temperature.
different heat treatments lead to different mechanical properties, as listed in Table 1. In the experiments, round specimen and T-joint specimens are investigated (Figure 1a). They are produced from pre-shaped steel plates with the dimensions 300 x 100 x 22 mm³.

Figure 1: Specimen (a) and defect (b) geometries

T-joint specimens are designed with respect to the original geometry of a compressor impeller and are characterized by an abrupt change of the cross sections. To investigate the influence of defects on the fatigue lifetime, experiments are performed with T-joint specimens containing artificial straight defects with a size of a = 2 mm. The defects were introduced by electric discharge machining in the braze layer (Figure 1b). The results of tensile tests (Lis et al., 2012) indicate the significant influence of heat and defects on the quasi-static properties (Table 1). Due to the specimen geometries, the determination of Young modulus and yield strength was limited to round specimen.

Table 1: Results of tensile tests (Leinenbach et al., 2012)

<table>
<thead>
<tr>
<th>Specimen geometry</th>
<th>Heat-Treatment</th>
<th>Young Modulus [MPa]</th>
<th>σ_y [MPa]</th>
<th>σ_UTS [MPa]</th>
</tr>
</thead>
<tbody>
<tr>
<td>Round, base material</td>
<td>HTM 1</td>
<td>203</td>
<td>726</td>
<td>844</td>
</tr>
<tr>
<td>Round, braze joint</td>
<td></td>
<td>200</td>
<td>725</td>
<td>841</td>
</tr>
<tr>
<td>T-joint, defect-free</td>
<td></td>
<td></td>
<td></td>
<td>847</td>
</tr>
<tr>
<td>T-joint with defect</td>
<td></td>
<td></td>
<td></td>
<td>614</td>
</tr>
<tr>
<td>Round, base material</td>
<td>HTM 2</td>
<td>204</td>
<td>1017</td>
<td>1224</td>
</tr>
<tr>
<td>Round, braze joint</td>
<td></td>
<td>203</td>
<td>1020</td>
<td>1220</td>
</tr>
<tr>
<td>T-joint, defect-free</td>
<td></td>
<td></td>
<td></td>
<td>1120</td>
</tr>
<tr>
<td>T-joint with defect</td>
<td></td>
<td></td>
<td></td>
<td>453</td>
</tr>
</tbody>
</table>

The results in Table 1 show that HTM 2 provides a higher σ_UTS for defect-free T-joints and round specimens compared to HTM 1. Furthermore, it can be seen that defects generally lead to a decrease of the ultimate tensile strength because of the stress concentration ahead of the defect. Interestingly, the decrease is more pronounced for specimens after HTM 2 compared to HTM 1. To study the influence of heat treatment and defects on the fatigue behavior of brazed specimens, stress-controlled fatigue experiments were performed at R = 0.1 on a servo-hydraulic testing facility at a frequency of 5 Hz. DIC was performed to monitor the local strains with a sufficient lateral resolution during the cyclic loading experiments. The measurements are performed with the high-speed camera model MotionXtra HG-100K by Redlake at a recording speed of 500 Hz with an aperture time of 100 μs. A black speckle pattern was applied on a white base coating by airbrush with an average speckle size of 45 μm. DIC was performed using the software Moiree Analysis V0.950©. The camera’s ring buffer allows post-triggering and therefore determining the strains during crack propagation.
3. Results

Generally, the fatigue behavior of materials can be investigated using two different approaches. For the lifetime oriented approach, the main results are summarized in S,N-curves by plotting the number of cycles to fracture as a function of the maximum applied nominal stress amplitude (i.e. assuming a defect-free cross section). The event-oriented approach allows achieving more detailed information about the materials reactions, as e.g. the strain distribution, in a defined fatigue state. In this work, the strains were analyzed by DIC by correlating \( F_{\text{min}} \) with \( F_{\text{max}} \) in the same loading cycle. The results of the fatigue experiments based on the lifetime oriented approach are shown in Figure 2.

![Figure 2: S,N-curves for brazed specimens and base material](image)

The S,N-curves show a significant decrease of the fatigue lifetimes for brazed joints in comparison with the lifetimes of the substrate material. Comparing the specimens with the same heat treatment, the substrate material generally provides the highest fatigue strength, followed by brazed round specimens and by T-joint specimens. Due to the combined influence of the specimen geometry and local stress concentration, the defect containing T-joints provide the lowest lifetimes, as could be expected. Furthermore, the S,N-curves can be used to estimate the defect tolerance of specimens after the different heat treatments. While the substrate material after HTM 2 provides higher fatigue strengths compared to HTM 1, the introduction of a braze layer leads to very similar S,N-curves for brazed defect-free specimens regardless the heat treatment if the maximum loadings remain below the yield strength of the base material. When a defect is present, HTM 1 generally provides a better fatigue strength compared to HTM 2. An explanation for this cannot be given based on lifetime oriented investigations only.

To obtain more detailed information about the strain distribution after cyclic loading in the vicinity of the braze layer DIC were performed. Figure 3 shows the results of the DIC for defect containing specimens with different heat treatments. At \( \sigma_{\text{max}} = 250 \text{ MPa} \), failure occurred after 11419 cycles for the specimen with HTM 1 (Figure 3a-c) and after 4909 cycles for the specimen with HTM 2 (Figure 3d-f). DIC is performed at defined fatigue states: in the cycle before fracture occurs (Figure 3c and f), 10 cycles (Figure 3b and e) and 200 cycles (Figure 3a and d) prior to fracture, respectively.

The DIC analysis 200 cycles before fracture shows that for HTM 1, a propagating crack can be already observed (Figure 3a), whereas HTM 2 does not show any increased strains around the defect (Figure 3d). 10 cycles before fracture, strain localization and crack growth can be observed for both heat treatments, whereas the crack length is considerably longer for HTM 1, compared to HTM 2.
In the cycle before fracture, the results of the DIC show that a crack with a length of approx. 2 mm has formed in the specimen with HTM 1 (Figure 3c), whereas for HTM 2 the crack length in the cycle before fracture is significantly smaller (≈ 0.5 mm) (Figure 3f). Generally, the results of DIC show that the strains are distributed over a larger area in HTM 1 compared to HTM 2. They clearly exceed the braze layer and reach into the base material. It should be mentioned that DIC allows the determination of strains only on the optical accessible surface. If a crack starts elsewhere, e.g. in the interior of a specimen, it does not necessarily lead to highest strains at the specimen surface. Therefore, an analysis of the fracture surface is necessary to interpret the results correctly. In the present case, the DIC measurements agree with the overall analysis of the fracture surface. The total amount of the fatigue fracture is 43% and 28% for HTM 1 and for HTM 2, respectively.

To obtain further information about the mechanisms of crack initiation and growth, SEM investigations are performed. The use of a BSE detector allows distinguishing between elements with a high atomic number as Au (bright) and lighter elements such as Fe and Cr (dark). The results of the SEM investigations show that the underlying mechanisms of crack initiation are comparable, whereas crack propagation changes for the different heat treatments (Figure 4). For both heat treatments, the cracks initiate in the base material and grow towards the braze
layer. It could be further observed for HTM 1 that cracks propagate over the whole width and for a comparable long distance in the base material (Figure 4 a), while for HTM2 the cracks grow only shortly in the base material. Furthermore, crack initiation occurred locally for HTM 2 (Figure 4 b). On its path through the base material, the cracks generally grow towards the brazing zone. Then they proceed in the gold-rich zone along the interface between brazing zone and base material - until fast fracture occurs.

4. Conclusions and Outlook

The results of the cyclic loading experiments show that the heat treatment of brazed specimens has a significant influence on the fatigue damage evolution, especially under the influence of defects. Experiments with brazed defect-free specimens show that both heat treatments lead to comparable fatigue strengths for cyclic stresses below the yield strength of the base material. Under the influence of defects, brazed specimens with a better ductility provided higher fatigue lifetimes. For a more profound analysis of the cyclic deformation behavior, Digital Image Correlations (DIC) were performed to determine the strain distribution in the vicinity of the brazed layer before fracture occurs. The results show that HTM1 leads to a wider and more homogeneous distribution of the accumulating strains in the substrate material of the specimen. In correlation with the DIC results, SEM investigations show that the mechanisms for crack initiation are comparable for both heat treatments: the cracks generally initiate in the base material or in the brazing fillet and grow inside the gold rich phase of the braze layer, until fast fracture occurs. Considerable differences can be observed during the crack growth phase. The fracture surfaces for the specimen in HTM 1 shows a higher amount of fatigue damage and a significantly longer crack length before fast fracture occurs. Furthermore, crack growth through the base material is much more pronounced for HTM 1, whereas for HTM 2, crack initiation in the base material occurs only locally and the cracks grow directly into the braze layer. These experiments allow a defect tolerant design of brazed components under cyclic loading- with special regard to the heat treatment. Further experiments with simultaneous DIC and extensometer measurements will be performed to quantify the strain accumulation due to cyclic loading and to achieve a better understanding of the failure mechanisms of brazed steel joints.

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References