Influence of brazing process and gap size on the fatigue strength of shear and peel specimen

A. Jöckel1 · J. Baumgartner1 · W. Tillmann2 · J. Bültena2 · K. Bobzin3 · H. Heinemann3 · J. Hebing3 · M. Erck3

Received: 19 January 2022 / Accepted: 21 April 2022 / Published online: 4 May 2022
© The Author(s) 2022

Abstract
Brazing is a joining technique used in many industries for components that consist of many individual parts. Many of these components are cyclically loaded during service. For this reason, reliable approaches to assess the service life must be developed. For this purpose, it is necessary to gain knowledge about factors influencing the fatigue strength and the damage behavior. In this paper induction, vacuum- and continuous furnace brazed shear and peel specimen with different brazing gap widths are analyzed. Therefore, the specimens were characterized, measuring the geometry of the specimens and surface condition of the brazing radii, and tested under load control using constant amplitudes. It is found that the manufacturing process and the parameters used have a significant influence on the mechanical properties of the brazing material, the surface condition and the profile of the fillet radii. These properties have again an influence on the damage behavior and the fatigue strength. In particular crack-like defects of varying severity, which can extend deep into the brazing material, that are located in highly stressed areas of the fillet radii have a significant influence on the fatigue strength. It is also found that, regardless of the brazing process used, there is a tendency in the area of the brazing gap width for the number and size of defects to increase with increasing gap size, which can negatively affect fatigue strength depending on the damage behavior.

Keywords Brazing process · Brazing gap size · Fatigue strength · Damage behavior

Abbreviations

| Symbol | Definition |
|--------|------------|
| t      | Sheet thickness, mm |
| l      | Overall length (specimen), mm |
| lₙ     | Sheet length, mm |
| w      | Sheet width, mm |
| R      | Sheet end radius, mm |
| l₀     | Overlap, mm |
| r      | Bending radius, mm |
| h      | Sheet height (peel specimen), mm |
| m      | Specific mass, g |
| rₜₜ    | Radius of the fillet, mm |
| rₜ₁    | Radius of the fillet (application side), mm |
| rₜ₂    | Radius of the fillet (opposite side), mm |
| b      | Brazing gap width, mm |
| d      | Brazing free gap height, mm |
| α      | Angular distortion,° |
| Rₚₚ    | Load ratio, - |
| f      | Test frequencies, Hz |
| Fₚₚ    | Test amplitude, N |
| Nₚₚ    | Cycles to total fracture, - |
| Nₙₙ    | Number of cycles to first tech. crack on the surface, - |
| Mₚₚ    | Secondary bending moment, Nmm |
| W      | Moment of resistance, mm³ |
| F      | Force, N |
| A      | Cross section surface, mm² |
| ε      | Eccentricity, mm |
| σₚₚ    | Bending stress, MPa |
| σₙₙ    | Nominal stress, MPa |
| kₚₚ    | Cyclic stiffness, N/mm |
| xₚₚ    | Displacement amplitude of the cylinder, mm |
| ω      | Mass fraction, wt% |
| a      | Crack length on the surface, mm |

Recommended for publication by Commission XVII - Brazing, Soldering and Diffusion Bonding

✉ A. Jöckel
andre.joeckel@lbf.fraunhofer.de

1 Fraunhofer Institute for Structural Durability and System Reliability LBF, Darmstadt, Germany
2 Institute of Materials Engineering (LWT) TU Dortmund University, Dortmund, Germany
3 Surface Engineering Institute (IOT) RWTH Aachen University, Aachen, Germany

DIV Springer
1 Introduction

Today, brazing is used as the favored joining technique for components that consist of many individual parts in many application areas, for example for manufacturing of heating and cooling systems, heat exchangers and for common-rail systems for direct fuel injection. Cyclically loaded fuel-carrying components in particular must be designed to be safe and reliable during their service life. Such components can be manufactured using a variety of joining processes, including induction brazing, vacuum brazing and brazing in a continuous furnace under a hydrogen atmosphere. Brazing is a thermal joining method that uses a molten brazing filler metal to create a metallurgical bonding between two or more base materials. Thereby, the process temperature must be above $T = 450\,^\circ\mathrm{C}$, at which the filler metal has reached its liquidus temperature and the base material is still in a solid state (ISO 857–2, [1]). During the joining process, the liquid brazing alloy wets the base material and flows through the brazing gap due to the capillary effect. Thereby, diffusion processes take place between the base material and the brazing filler metal, resulting in the formation of a brazing alloy with new mechanical properties [2]. This new alloy is referred to as the brazing material. Due to physical effects, fillet radii form at the edge areas.

The metallurgical and geometrical conditions resulting from the brazing process can have a significant influence on the fatigue life, particularly in real components, e.g. due to the geometry, defects and surface topology [3]. For this reason, it is necessary to identify as many influencing factors as possible in order to create a basis for subsequent computer-aided fatigue life estimates. In some papers, the influence of the brazing conditions and the seam geometry has been investigated sporadically. In [4], round shaped specimens and T joints made from AISI 316 C-NM and brazed with AuNi18 filler metal were manufactured and differently heat treated. Defined defects were introduced into some specimens to investigate their influence on the fatigue strength. It could be shown that the influence of the defects was much greater compared to the influence of the heat treatment. The failure mechanisms of stress controlled fatigue tested specimens of the steel AISI CA 6-NM brazed with AuNi18 under $\mathrm{H}_2$ atmosphere in a shielding gas furnace have been investigated in [5]. The results show that fatigue and residual fracture occurred always in the interface of the brazing zone. The crack path is characterized by interfacial jumps, accompanied by ductile deformation features. In [6], quality-related brazing parameters for cyclic loaded steel specimens manufactured by arc-brazing were investigated. By varying the shielding gas in the process, the heat input as well as the formation of the seam could be influenced which also had a great impact of the fatigue strength.

Compared to welded joints, there has been little work in the field of brazing technology, which deals with the analysis of the fatigue strength of brazed joints. The existing research work usually focus on the experimental determination of different specimen geometry in which the fillet of the brazed joint is mechanically removed. By removing the fillet, the geometric notch is neglected and only the metallurgical notch caused by the brazed joint is investigated [7]. A superimposed consideration of the geometric and metallurgical notch of fatigue tested brazed joints has hardly been investigated, especially for vacuum brazed components. From an industrial point of view, an evaluation of both influencing parameters combined is extremely valuable, since in many applications, such as common rail systems for direct fuel injection, the fillets are not machined after brazing process.

In this work, fatigue tests are performed on shear and peel specimens, where the fillet radii are not machined and where the specimen shapes represent the global stress states shear and peel predominantly encountered in structural components. Through the fatigue tests, influences such as the brazing process used, the geometry and the surface condition of the fillet are investigated. In addition, an analysis of crack initiation and crack propagation is performed, which is made possible by the correlation between photomicrographs and recorded specimen stiffness.

2 Manufacturing of the specimens

The study investigates the influence of three different brazing processes, induction, vacuum and continuous furnace brazing, on the seam quality and the fatigue strength of specimens with various gap widths. Therefore, two specimen types have been developed, inspired by brazed joints of rails for direct fuel injection from the automotive industry [3]. These are the shear and peel specimen, which represent two typical joint geometries in rails with different fracture mechanisms, Fig. 1.

The base material for both types of specimens is the austenitic steel 1.4301 (X5CrNi18-10, AISI 304) with a sheet thickness of $t = 3\,\mathrm{mm}$. The specimens were cut out of sheet metal material by using a waterjet. The waterjet cutting was chosen to exclude any heat influence on the base material while cutting the semi-finished products. The shear specimens were manufactured by two identical semi-finished products with a length of $l_s = 82\,\mathrm{mm}$ and a width of $w = 30\,\mathrm{mm}$. Both sheet ends on the brazing side have a radius of $R = 60\,\mathrm{mm}$ in order to obtain a stress concentration in the center of the brazing seam to trigger the crack initiation in this area while fatigue testing. The overlap was designed with $l_o = 14\,\mathrm{mm}$. The semi-finished products of the peel specimens were bent at a 90 degree angle with a bending radius of $r = 3\,\mathrm{mm}$. The height was designed with $h = 28\,\mathrm{mm}$ and a
width of d = 30 mm was used. The overall length of the peel specimens was l = 140 mm. To simplify the application of the filler metal, a chamfer was manufactured at the top front edge of the semi-finished products. The brazing gap widths of b = 50 µm, b = 100 µm or b = 200 µm of the shear and peel specimens were adjusted with a feeler gauge and fixed by WIG spot-welding of both semi-finished products. In order to avoid an influence on the fatigue strength, the spot was positioned as far as possible from location of crack initiation.

As brazing filler metal, Cu 110 according to ISO 17672 [8] was used. The brazing filler metal corresponds to copper with a purity of 99.90%. The filler metal was applied as a paste, made from Cu 110 powder mixed with 15% binder. The specimen specific amount m of paste is shown in Table 1.

Specimens of both types and with different brazing gap widths where manufactured by induction, vacuum- and continuous furnace brazing. The detailed brazing parameters are summarised in Table 2.

### 3 Specimen characterization

#### 3.1 Measured geometry

After the brazing process, the peel and shear specimens were characterized with respect to potential fatigue strength relevant parameters. For the peel specimens the radius of the fillet r_H, the brazing gap width b, the bending radii r_1, r_2 and the brazing free gap height d were determined, Fig. 2 (left). For the shear specimens radii of the fillet r_H1 and r_H2 on the brazing filler application side and the opposite side as well as the brazing gap width b were measured, Fig. 2 (right). In addition, the angular distortion α of the specimens was measured. The angular distortion varied in a range 1.3° ≤ α ≤ 3.2° (peel specimens) and 0.1° ≤ α ≤ 1.9° (shear specimens). All geometrical data was obtained with the digital microscope Leica (DVM6) and a 12.55× objective which allows image recording with depth information.

A three-dimensional top view of the fillet of each peel and shear specimen was generated, which was used to record the bending radii r, the fillet radii r_H and the brazing free gap height d. Since a shear specimen has two fillets (brazing application side and opposite side) two three-dimensional topography images were recorded for each of this specimen type. After recording a topography image, five defined profile curves over the entire specimen were extracted. These profile curves are located at the same position for each specimen. In the following, the characteristic geometrical values were measured based on the profile curves. The individual measured values of all five positions were averaged and used for further evaluations. Also another three-dimensional image of the left and right specimen side of each specimen type was recorded. These images were used to measure the brazing gap width b at five different locations. The total of ten values resulting from the left and right image acquisition of a specimen were also averaged and evaluated in the same manner as the results of measuring.

### Table 1 Applied brazing paste

| Mass [g] | 50 µm | 100 µm | 200 µm |
|----------|-------|-------|-------|
| Shear specimen | 0.25  | 0.50  | 1.00  |
| Peel specimen  | 1.13  | 2.25  | 4.50  |

### Table 2 Brazing parameters

| Parameter          | Conveyor belt furnace | Vacuum furnace | Induction brazing |
|--------------------|------------------------|----------------|-------------------|
| Brazing temperature [°C] | 1,120                  | 1,100          | 1,100             |
| Brazing time [min]  | 2                      | 5              | 1.5               |
| Cooling rate [K/min] | Free cooling (max. 35) | Free cooling (max. 35) | Free cooling (max. 35) |
| Atmosphere         | Hydrogen               | Vacuum/Argon   | Argon             |
3.2 Metallographic analysis of brazing filler metal

To characterize the microstructure of the brazing filler metal with regard to the influence of the brazing process and the brazing gap width $b$, shear specimens were prepared metallographically. The analyses were performed by means of the scanning electron microscope (SEM) with an energy dispersive x-ray spectroscopy (EDS) as well as the confocal laser scanning microscope (CLSM). Furthermore, hardness measurements were carried out in order to determine the hardness of the brazing filler metal. For this purpose, the Vickers hardness test is used, which is carried out according to DIN EN ISO 6507 [9] on a Micromet 1 from Bühler.

3.2.1 Influence of brazing process on the microstructure of the brazing

As shown in Fig. 3, the SEM image of the cross-section of the induction brazed shear specimen shows solid solutions with a dendritic structure (Fig. 3a) which are embedded into an almost pure copper matrix. The composition of the phases was detected by EDS-analysis and is summarized in Table 3. The point (EDS 1) is marked in Fig. 3a. The composition of the phases corresponds approximately to the composition of the base material with an additional proportion of copper. These are described in more detail in [10]. The appearance of this solid solutions suggests a strong dissolution of the base material in the brazed seam which indicates a significantly higher local temperature during the brazing process compared to vacuum brazed specimens.

The solid solutions in the vacuum brazed specimens (Fig. 3b and c) are smaller and primarily homogeneously distributed in the copper fillet. In addition, two different solid solutions can be found by EDS-analysis. On the one
hand, spherical solid solutions with a primary copper content of $\omega_{\text{Cu}} = 56.7$ wt%. On the other hand, there are smaller and darker solid solutions with a high amount of chromium ($\omega_{\text{Cr}} = 66.8$ wt%). The measuring points are marked in Fig. 3 and the mass fractions of the elements are summarized in Table 3. The different characteristics of the solid solution resulting from the brazing processes also lead to different mechanical properties such as strength and hardness of the brazing filler metal, which is caused by solid solution solidification [11].

3.2.2 Influence of gap size on the number and size of defects in the brazing

The area of the brazing gap width $b$ of vacuum and induction brazed specimens have been investigated by using a confocal laser scanning microscope. The images of various brazing gap widths $b$ are shown in Fig. 4. Regardless of the brazing process used, there is a tendency of increasing number and defect size with increasing brazing gap width $b$. A largely defect-free gap filling can only be observed with the brazing gap widths of $b = 50 \, \mu\text{m}$ and $b = 100 \, \mu\text{m}$ of the vacuum brazed specimens (see Fig. 4a and b). The vacuum brazed specimens with a brazing gap width of $b = 200 \, \mu\text{m}$, on the other hand, shows clear voids in the center of the brazing material, marked with a white arrow (Fig. 4c). Since a brazing gap width of $b = 200 \, \mu\text{m}$ represents the upper limit for good brazing quality, this corresponds to expectations [2].

In total, all vacuum brazed specimens show good wetting behavior.

Specimens brazed by induction (Fig. 4d, e and f) all show voids that increase in number and size with the brazing gap width $b$. Large defects as shown in Fig. 4e, suggest poor wetting behavior. The higher number of defects in induction brazed specimens is probably caused by a poorer quality of the atmosphere during brazing. In this case, stronger oxidation hinders the wetting of the base material by the brazing filler metal. These voids and wetting defects can have an influence on the fatigue life of the specimens by causing sharp notches and decreasing the amount of force transmitting area [12].

3.2.3 Hardness measurements

As seen in Fig. 3, the brazing process has an influence on the microstructure of the brazing filler metal, which is expressed in the form of different solid solutions. Therefore, a difference in the mechanical properties of the brazing filler metal is expected. To characterize these differences, hardness measurements were carried out in the area of the brazing gap width $b$. The results are shown in Table 4. Ten measurements were carried out in in the center and along the brazing gap in each case, from which a mean value was subsequently calculated. In addition, the tolerance is indicated. It can be seen that the filler metal of the vacuum brazed specimens has a 20% lower hardness in comparison to the induction brazing.
brazed specimens. As there is a correlation between the hardness of a metal and its static strength, investigated in [13] and in [14], it can be assumed that the induction brazed filler metal has better mechanical properties in terms of its strength.

4 Fatigue testing

4.1 Test setup

For the fatigue tests, 12 peel specimen (9 vacuum and 3 continuous furnace brazed specimen) and 18 shear specimen (9 vacuum, 3 continuous furnace and 6 induction brazed specimen) were tested at room temperature until total fracture. The influence of elevated temperatures or corrosive media, as they are present at rails, was not considered to reduce the overall complexity. The tests were carried out using a force-controlled servo-hydraulic testing machine with constant force amplitudes of $F_a = 1.6$ kN (peel specimen) and $F_a = 5.0$ kN (shear specimen), a load ratio of $R_F = 0$ and a test frequency of $f = 30$ Hz. The specimens were tested with existing angular distortion $\alpha$ and a clamping mechanism that avoids stresses due to the clamping process.

During the fatigue tests, photographs of the fillet radii $r_H$ were taken at defined intervals. In addition, the cyclic stiffness of the specimens was recorded. The correlation between the crack initiation resp. crack propagation behavior and the stiffness curves are used to define relevant failure criteria. These form the input for a mechanism-based fatigue strength evaluation. In the case of a force-controlled fatigue test, the cyclic stiffness $k_{cyc}$ can be used to describe which displacement amplitude of the cylinder $x_a$ results in order to generate the force amplitude $F_a$.

$$k_{cyc} = \frac{F_a}{x_a}$$

4.2 Results of peel specimen

4.2.1 Fatigue test results

The results of the fatigue tests (failure criterion total fracture) are shown in the statistical analysis, Fig. 5. Three specimens of each batch were used for this analysis. The black points mark the mean value of the achieved logarithmized number of cycles to total fracture $N_f$. In addition, the standard deviation is shown. In terms of the mean value, the highest number of cycles to total fracture $N_f$ was achieved with the vacuum brazed (Va) specimens with a brazing gap width of $b = 100$ µm. These specimens also show the lowest scatter. In contrast to that, vacuum brazed specimen with a brazing gap width of $b = 50$ µm result in the lowest number of cycles to total fracture $N_f$. The continuous furnace brazed (Fu) specimens show the highest scatter. The vacuum brazed specimens with a brazing gap width of $b = 200$ µm show a similarly high scatter. It is noticeable that the highest number of cycles to total fracture $N_f$ achieved with the continuous furnace and vacuum brazed specimens with a brazing gap width of $b = 200$ µm are close to the mean value of the vacuum brazed specimens with a brazing gap width of $b = 100$ µm. Thus, in the best case, a similar fatigue strength can also be achieved with these specimens. The cracks initiated always on the surface of the radius of the fillet $r_H$ and propagated in the brazing along the joint area. Thus, all specimens show a similar damage behavior. No clear correlation between the gap width $b$ and the fatigue strength can be observed.

4.2.2 Identified parameters influencing the fatigue strength

One reason for the large scatter of the results can be found in the geometry of the specimens, especially in the brazing free gap height $d$. A significant influence of the brazing free gap height $d$ on the fatigue strength can be seen, by correlating

| Table 4 Hardness measurements of brazing filler metal |
|-----------------------------------------------|
|                                | Vacuum brazed | Induction brazed |
| Vickers hardness              | 58.0 HV0.572.1 HV0.5 |
| Tolerance                     | ± 7.6         | ± 3.0            |
it to the number of cycles to total fracture $N_f$, Fig. 6. In this figure, two measured profiles are shown on the right side for illustration. It is noticeable that increasing the brazing free gap height $d$ reduces the fatigue life. The result can be explained by engineering mechanics. In addition to the nominal stress $\sigma_n$, which results from the quotient of force $F$ and cross-section surface $A$, a bending stress $\sigma_b$ is applied due to the eccentricity $e$ of the specimen geometry. The bending stress $\sigma_b$ is calculated from the secondary bending moment $M_b$ and the moment of resistance $W$. Increasing eccentricity $e$ leads to higher secondary bending moment $M_b = F \cdot e$ and thus to a higher bending stress $\sigma_b$.

The size of the radius of the fillet $r_{H}$ depends on the brazing free gap height $d$. The lower the brazing free gap height $d$, the greater the distance in the direction of loading between the sheets due to the bending radii $r$. Accordingly, the radius of the fillet $r_{H}$ increases with decreasing the brazing free gap height $d$. This leads to the correlation between the number of cycles to total fracture $N_f$ and the radius of the fillet $r_{H}$, which can be observed in Fig. 7. Decreasing the radius of the fillet $r_{H}$ reduces the fatigue strength. This is illustrated by the measured values on the right side of Fig. 7. Thus, the brazing geometry has a significant influence on the fatigue strengths. A differentiation between the individual influence of both values has not been possible in cause of this investigation.

4.2.3 Analysis of the damage behavior during fatigue testing

The correlation between crack initiation and propagation in comparison to relative cyclic stiffness was evaluated for the vacuum brazed (Fig. 8) and continuous furnace brazed specimen (Fig. 9). First cracks on the surface of peel specimens can already be seen after about 30% of the fatigue life. They start particularly from visible crack-like defects (solidification structures) at the surface of the radius of the fillet $r_{H}$. The size, position and number of these crack-like defects thus have a major influence on the fatigue strength and the damage behavior. Compared to the total service life an early crack initiation is shown by specimens which have a small radius of the fillet $r_{H} < 1$ mm and a large brazing free gap height $d > 4$ mm. These specimens also show a
significantly higher stiffness drop from the beginning and an earlier accelerated stiffness drop. This can be explained by high local stresses which, in addition to existing crack-like defects in the brazing geometry, lead to an early crack initiation. In contrast, first cracks on the surface of specimens with large radius of the fillet $r_H > 1$ mm and small brazing free gap height $d < 4$ mm can only be detected after about 80% of the fatigue life, Fig. 8. In this case, a linear and continuous decrease in stiffness can be seen until 60% – 80% of the fatigue life. After that, an accelerated stiffness decrease can be observed. It is noticeable that also in this example the first cracks start at the surface defects.
The continuous furnace brazed specimen (Fig. 9) shows a similar behavior as the vacuum brazed specimen shown in Fig. 8. However, the accelerated stiffness drop as well as the crack initiation starts slightly earlier, probably due to a smaller radius of the fillet $r_H$ and larger brazing free gap height $d$.

### 4.3 Results of shear specimen

#### 4.3.1 Fatigue test results

In general, the fatigue strength of a notched component decreases with decreasing radius due to the increase in local notch effect. In the course of the investigations, no clear correlation between geometrical parameters, like the size of the radius of the fillet $r_H$ or the gap width $b$, and the fatigue strength could be identified in the case of vacuum and continuous furnace brazed shear specimen. Depending on the manufacturing process and parameters used, variously pronounced crack-like defects are visible on the contact surfaces of the dendrites after the brazing material has solidified, which can extend deep into the brazing material. These defects result in high local stresses, which have a significant influence on crack initiation, crack propagation and, consequently, the fatigue strength. In particular, these crack-like defects on the surface of the radius of the fillet $r_H$ are observed in the case of vacuum and continuous furnace brazed specimen. In contrast, the radii of the fillet $r_H$ of induction brazed specimen show a more homogeneous profile and no crack-like defects on the surface, which leads to a different damage behavior. These show up in the form of different crack initiation and propagation during the fatigue tests, Fig. 10. Basically, two different damage behaviors can be observed. In the case of induction brazed specimen, the first cracks start in the area of the first third of the radius of the fillet $r_H$ and propagate through the sheet base material until total fracture of the specimen. In contrast, the first cracks of vacuum and continuous furnace brazed specimens start at crack-like defects in the central region or the first third of the radius of the fillet $r_H$ and changes the direction at the interface between the base material and the brazing and run parallel to it. In addition, cracks initiate in the base material and propagate through it, which leads to the total fracture of the specimen.

Figure 11 shows the statistical analysis of fatigue test results (failure criterion total fracture) of shear specimens. For this analysis, three specimens of each batch were used. Shown are the mean values of the logarithmized number of cycles to total fracture $N_f$ (black points) and the standard deviation to illustrate the scatter. Related to the mean value the highest number of cycles to total fracture $N_f$ is achieved with the vacuum brazed specimens with a gap width of $b = 50 \, \mu m$. The lowest number of cycles to total fracture $N_f$ results with the induction brazed (Ind) specimens with a gap width of $b = 50 \, \mu m$. In direct comparison with the peel specimens, the shear specimens show lower scatter and the number of cycles to total fracture $N_f$ achieved in the different batches are closer together.

**Fig. 10** Schematic illustration of crack initiation and propagation, shear specimen
In the case of induction brazed specimens, due to the homogeneous profile of the radius of the fillet \( r_H \) without crack-like defects on the surface, the fatigue strength decreases with decreasing the radius of the fillet \( r_H \) as the local notch effect increases, Fig. 12.

4.3.2 Analysis of cross-sections of cyclically tested specimens

The cross-section of a cyclically tested vacuum brazed specimen can be seen in Fig. 13. The specimen showed first crack initiation in the central region of the radius of the fillet \( r_H \) on the opposite side. The cracks start from the crack-like defects on the surface and subsequently propagate in the base material and partially in the brazing along the interface between the base material and the brazing. On the application side, a crack starting at the radius of the fillet \( r_H \) can be seen. The crack changes its directions and growth parallel to the gap in the interface between the base material and the brazing. This indicates that the resistance to crack propagation along the interface is less than the resistance through the base material for these specimens.

The cross-section of a cyclically tested continuous furnace brazed shear specimen, Fig. 14, shows that on the application side the cracks have propagated into the base material in the first third of the radius of the fillet \( r_H \). A cracked radius of the fillet \( r_H \) can be seen on the opposite side. The crack propagation runs along the interface between the base material and the brazing and thus shows an identical damage behavior as the vacuum brazed specimens on the opposite side. It is noticeable that the radius of the fillet \( r_H \) on the application side is very homogeneous and that there are no crack-like defects on the surface. In contrast, crack-like defects are visible on the opposite side, which influences the crack initiation and propagation and thus lead to a different damage behavior. It is assumed that the position of the crack initiation at the radius of the fillet \( r_H \) and the subsequent direction of the propagating crack have an influence on the damage behavior when it encounters the base material. Likewise, it is evident that local mechanical material properties, especially in the interface region, such as the strong dissolution of the base material in the case of the induction brazed specimens (Fig. 3a), have an influence on the damage behavior too.

Figure 15 shows the cross-section of a cyclically tested induction brazed specimen. The first cracks started in the area of the first third of the radius of the fillet \( r_H \) on the opposite side and propagated through the sheet base material. On the application side, cracks can also be observed at the radius of the fillet \( r_H \), which have already propagated into the base material. Both radii of the fillet \( r_H \) show a homogeneous profile and no crack-like defects on the surface. No crack propagation can be seen along the interface between the base material and the brazing. Thus, similar damage behavior can be seen on both sides as in the case of the continuous furnace brazed specimen on the application side. This suggests that the resistance to crack propagation through the
Fig. 13 Cross-section of a cyclically tested vacuum brazed shear specimen, Va 100 μm gap

Fig. 14 Cross-section of a cyclically tested continuous furnace brazed shear specimen, Fu 80 μm gap

Fig. 15 Cross-section of a cyclically tested induction brazed shear specimen, Ind 50 μm gap
sheet base material is much less than the resistance along the interface between the base material and the brazing for these specimens. In contrast to the other two brazing processes, significantly more voids can be seen along the joining area. However, since the crack on both sides only propagates through the base material, these have no influence on the fatigue strength.

4.3.3 Analysis of the damage behavior during fatigue testing

In the following, the crack initiation and propagation in comparison to relative cyclic stiffness for the vacuum brazed (Fig. 16) and induction brazed shear specimens (Fig. 17) are shown. All shear specimens show no significant decrease in stiffness until shortly before total fracture.
For the vacuum brazed specimen, the first cracks on the surface at the radius of the fillet $r_{H}$ can be seen after about 30% – 40% of the fatigue life, which leads to a long crack propagation phase of about 60% – 70%. In the example in Fig. 16, clearly visible cracks on the surface at the radius of the fillet $r_{H}$ are already present after 40% of the fatigue life. The long crack propagation phase can be explained by the crack propagation along the interface, i.e. between the base material and the brazing. The result is independent of the size of the radii of the fillet $r_{H1}$ and $r_{H2}$. This can be justified by the crack-like defects on the surface of the radius of the fillet $r_{H}$, where high local stresses occur, which leads to the early crack initiation in relation to the total service life.

In the case of continuous furnace brazed specimens, the first visible cracks appear on the surface at the radius of the fillet $r_{H}$ on the opposite side after about 60% – 70% of the fatigue life. On the application side, on the other hand, the first cracks can only be observed after about 80% – 90%. In the cross-section of a continuous furnace brazed shear specimen the different surface conditions of the radius of the fillet $r_{H}$ are shown, Fig. 14. Compared to the opposite side, the radius of the fillet $r_{H}$ on the application side is more homogeneous and there are almost no crack-like defects on the surface. In contrast, crack-like defects are visible on the opposite side, which influences the delay of crack initiation due to the resulting high local stresses.

The first cracks on the surface at the radius of the fillet $r_{H}$ of the induction brazed specimens can be observed after about 80% – 90% of the fatigue life, which can be seen in the example in Fig. 17. This means that the specimens have a significantly shorter crack propagation phase (about 10% – 20%) in comparison to vacuum brazed specimens, which can be explained by the different damage behavior. The homogeneous radii without crack-like defects lead to more homogeneous local stress distributions, which explain a long crack initiation phase. After the crack initiation on the surface of the base material, the crack grows through it very quickly. This can be explained by engineering mechanics. With increasing crack depth, the eccentricity $e$ and thus the secondary bending moment $M_b = F\cdot e$ increases. At the same time, the moment of resistance $W$ decreases due to the reduction in sheet thickness $t$. Since the sheet thickness is squared, this has a significant effect on the bending stress $\sigma_b$ component:

$$\sigma_b = \frac{M_b}{W} = \frac{F \cdot e}{w \cdot t}$$

In addition, the nominal stress component $\sigma_n$, which results from the quotient of force $F$ and cross-sectional surface $A$, increases due to the reduction of the cross-sectional area $A$. The increase of the stress components and the crack growth direction in the base material, which is almost orthogonal to the load direction, explains the short crack propagation phase.

For the failure criterion total fracture different damage states can be present, which makes a comparison of the fatigue strength difficult and needs some interpretation. For example, compared to the induction brazed specimens, the vacuum brazed specimens show significantly earlier crack initiation in relation to the total service life and crack propagation along the interface between the base material and the brazing. This additional damage behavior can lead to significantly later or, in extreme cases, no crack initiation through the sheet base material, which has a large influence on the sum of the achieved cycles to total fracture $N_f$. For this reason, the failure criterion number of cycles to first tech. crack on the surface $N_{crack}$ is evaluated, Fig. 18. Thus, the existing degree of damage of the different brazing processes can be compared with each other. In this investigation a crack length $a$ on the surface of $a \geq 1 \text{ mm}$ is assumed as a technical crack. Due to the irregular and microscopically crack-like surface of the radius of the fillet $r_{H}$ and multiple crack initiation areas, the assignment of an exact crack length on the surface is difficult. For this reason, the results should be treated with caution, as certain deviations are possible. The highest number of cycles to initiate a first crack on the surface ($N_{crack}$) is achieved with the induction brazed specimens. The results of the different gap width $b$ are close to each other. The lowest number of cycles to the first crack on the surface $N_{crack}$ results with the vacuum brazed specimens, in particular, specimens with a gap width of $b = 200 \mu \text{m}$. The continuous furnace brazed specimens settle between the
induction and vacuum brazed specimen, but tend to be closer to the results of the induction brazed specimens. This indicates that the crack-like defects are present in a less damaging form in the continuous furnace brazed specimens than in the vacuum brazed specimens.

5 Discussion

For the peel specimens, the brazing free gap height $d$, which determines the amount of the secondary bending moment $M_b$ and thus the local stresses at the radius of the fillet $r_H$, has the greatest influence on the fatigue strength, Fig. 6. This parameter depends to a large extent on the amount of the filler metal available and the brazing gap width $b$. In addition, the radius of the fillet $r_H$ depends on the brazing free gap height $d$, Fig. 7. This means that no reliable statement can be made as to whether the radius of the fillet $r_H$ alone also has an influence on the fatigue strength. This would theoretically be expected.

All peel specimen show a similar damage behavior during the fatigue tests. An early crack initiation is influenced in particular by specimens which have a small radius of the fillet $r_H$ and a large brazing free gap height $d$. This can be explained by high local stresses which, in addition to existing crack-like defects in the brazing geometry, lead to an early crack initiation. The cracks initiate and run particularly at the visible crack-like defects on the surface of the radius of the fillet $r_H$ and propagate in the brazing along the joint area. For this reason, it can be assumed that the surface condition of the fillet radii $r_H$ and consequently the fatigue strength can be positively influenced by brazing process optimization.

In the case of the shear specimens the surface condition of the radius of the fillet $r_H$, especially the size, position and number of crack-like defects (solidification structures), has the biggest influence on the fatigue strength and the damage behavior during fatigue testing.

The induction brazed specimens show homogeneous profiles and no crack-like defects on the surfaces of the radii of the fillet $r_H$ regardless of the brazing gap width $b$, Fig. 15. Therefore, since there is no influence of additional stress raiser, such as crack-like structures, the generally expected behavior of increasing fatigue strength with increasing the radii of the fillet $r_H$ can be seen, Fig. 12. The homogeneous radii of the fillet $r_H$ without crack-like defects lead to more homogeneous local stress distributions, which leads to a long crack initiation phase, Fig. 17. The first cracks start in the area of the maximum stress (first third of the radius of the fillet $r_H$, [3]) and propagated through the sheet base material, Fig. 15. A similar damage behavior can be seen on the application side of continuous furnace brazed specimen, Fig. 14. This suggests that a homogeneous radius of the fillet $r_H$ without crack-like defects on the surface tends to cause a long crack initiation phase.

In the case of vacuum and continuous furnace brazed shear specimen, crack-like defects on the surface of the radius of the fillet $r_H$ can be observed (Fig. 13 and Fig. 14), which leads to earlier crack initiation in relation to the total fatigue life and thus to a long crack propagation phase, Fig. 16. The fatigue strength is independent of the size of the radii of the fillet $r_H$, unlike as for the induction brazed specimens. This can be justified by the crack-like defects on the surface of the radii of the fillet $r_H$, where high local stresses occur, which leads to the early crack initiation.

For the vacuum and continuous furnace brazed shear specimen the cracks partially change direction at the interface between the base material and the brazing and run parallel to it, Fig. 13 and Fig. 14. This shows that the resistance to crack propagation along the interface must be much lower than the resistance through the base material. It is assumed that the position of the crack initiation at the radius of the fillet $r_H$ and the subsequent direction of the propagating crack, which are influenced by the direction of the maximum principal stress, have an influence on the damage behavior especially when it encounters the base material. Likewise, it is evident that local mechanical material properties, especially strong dissolution of the base material in the interface region (Fig. 3a), have an influence on the damage behavior. This explains, why no crack propagation along the interface was identified at the induction brazed shear specimens.

A crack propagation along the interface between the base material and the brazing can significantly delay the crack initiation and propagation through the sheet base material, which has a major influence on the sum of the cycles to total fracture $N_f$. For this reason, the failure criterion number of cycles to first tech. crack on the surface $N_{crack}$ is used, Fig. 18. Thus, the existing degree of damage of the different brazing processes can be compared with each other. The number of cycles to first tech. crack on the surface $N_{crack}$ of the induction brazed specimen is significantly higher than for the vacuum brazed specimen, which is due to the more homogeneous surface condition (no crack-like defects on the surfaces) of the radius of the fillet $r_H$. This leads to lower local stresses and consequently to later crack initiation in relation to the fatigue life.

6 Conclusions and outlook

The main conclusions can be drawn from the presented investigations:

- The surface condition of the radius of the fillet $r_H$, especially the size, position and number of crack-like defects
(solidification structures), has the biggest influence on the fatigue life and the damage behavior during fatigue testing.

- Regardless of the specimen type, a large homogeneous radius of fillet \( R_f \) without crack-like defects on the surface tends to result in a longer crack initiation phase than a small radius and therefore leads to a higher fatigue strength.

- It is evident that local mechanical material properties, especially like strong dissolution of the base material in the interface region, have an influence on the damage behavior and subsequently on the cycles to fracture.

- It is also found that there is a tendency in the area of the brazing gap width \( b \) for the number and size of defects to increase with increasing gap size, which can negatively affect the fatigue strength depending on the damage behavior.

- A clear influence of the brazing gap width \( b \) on the defects of the radius of the fillet \( R_f \) and thus on the fatigue strength could not be determined. Nevertheless, the brazing gap width \( b \) can influence the brazing geometry and thus the fatigue strength, especially in the case of the tested peel specimens.

Further investigation will be carried out in the future to identify the influencing parameters (brazing geometry, brazing gap size, angular misalignment, topography, roughness, waviness, etc.) on the mechanism-based fatigue strength of shear and peel specimen. In addition, a statistical design of experiment with vacuum brazed specimens (brazing gap widths of \( b = 100 \mu m \)) and three process parameters (brazing time, temperature and cooling rate) will be investigated to determine the extent to which the parameters affect the brazing geometry and surface condition, especially the size, position and number of crack-like defects. Also a 3D-scan and reverse engineering of real brazing geometry is in work to identify realistic stress distribution. Furthermore, local mechanical properties as well as material analyses of the brazed joint are to be investigated in order to reach conclusions regarding the formation of solid solutions.

**Funding** Open Access funding enabled and organized by Projekt DEAL. The presented investigations were supported by financial funding from the Federal Ministry of Economics and Technology BMWi by the AiF e.V. (Arbeitgemeinschaft industrieller Forschungsvereinigungen “Otto von Guericke” eV) under grant 20.370 N. Technical and scientific support during the project was given by the Research Association for Combustion Engines (FVV eV) and an industrial steering committee.

**Statements and Declarations** The authors declare that they have no conflict of interest.

**Open Access** This article is licensed under a Creative Commons Attribution 4.0 International License, which permits use, sharing, adaptation, distribution and reproduction in any medium or format, as long as you give appropriate credit to the original author(s) and the source, provide a link to the Creative Commons licence, and indicate if changes were made. The images or other third party material in this article are included in the article’s Creative Commons licence, unless indicated otherwise in a credit line to the material. If material is not included in the article’s Creative Commons licence and your intended use is not permitted by statutory regulation or exceeds the permitted use, you will need to obtain permission directly from the copyright holder. To view a copy of this licence, visit http://creativecommons.org/licenses/by/4.0/.

**References**

1. ISO D (2007) 857-2: 2007-03: Welding and allied processes – Vocabulary – Part 2: Soldering and brazing processes and related terms (ISO 857-2:2005)
2. AWS C3 Committee on Brazing and Soldering (2007) Brazing Handbook, 5th edn. ISBN 13: 9780871710468, American Welding Society
3. Baumgartner J, Tillmann W, Bobzin K, Ote M, Wiesner S, Sievers N (2020) Fatigue of brazed joints made of X5CrNi18-10 and Cu110 and derivation of reliable assessment approaches. Weld World 64(4):707–719. https://doi.org/10.1007/s40194-020-00850-1
4. Leinenbach C, Koster M, Kenel C, Lee W (2015) Influence of substrate properties on fatigue performance of brazed steel joints
5. Koster M, Kenel C, Stutz A, Lee WJ, Lis A, Affolter C, Leinenbach C (2013) Fatigue and cyclic deformation behavior of brazed steel joints. Mater Sci Eng A 581:90–97
6. Wesiing V, Schram M, Kessler M (2010) Low heat joining – manufacturing and fatigue strength of brazed, locally hardened structures. Adv Mater Res 137:347–374
7. Otto JL et al (2020) Effect of phase formation due to holding time of vacuum brazed AISI 304/LNiCrSiB joints on corrosion fatigue properties. J Mater Res Technol 9(5):10550–10558. https://doi.org/10.1016/j.jmatre.2020.07.047
8. ISO EN, D (2017) 17672:2017-01: Brazing – Filler metals (ISO 17672:2016)
9. Norm DIN (2018) Metallische Werkstoffe-Härteprüfung nach Vickers-Teil 1: Prüfverfahren (ISO 6507-1: 2018); Deutsche Fassung EN ISO 6507-1: 2018. Berlin, Beuth
10. Dreval LA, Turchanin MA, Abdulov AR, Bondar AA (2010) Thermodynamic assessment of the Cu–Fe–Cr phase diagram. Chemistry of metals and alloys (3,№ 3-4), 132–139
11. Bellini C, Brozzi A, Di Cocco V, Felli F, Iacovelli F, Pilone D (2020) Fatigue crack propagation mechanisms in C70250 and CuCrZr copper alloys. Procedia Struct Integr 26(2019):330–335. https://doi.org/10.1016/j.proint.2020.06.042
12. Li Y, Zhang X, Parfitt D, Jones S, Chen B (2019) Characterisation of microstructure, defect and high-cycle-fatigue behaviour in a stainless steel joint processed by brazing. Mater Charact 151(January):542–552. https://doi.org/10.1016/j.matchar.2019.03.042
13. Hashemi SH (2011) Strength-hardness statistical correlation in API X65 steel. Mater Sci Eng A 528(3):1648–1655. https://doi.org/10.1016/j.msea.2010.10.089
14. Khodabakhshi F, Gerlich AP (2020) On the correlation between indentation hardness and tensile strength in friction stir processed materials. Mater Sci Eng A 789:139682

**Publisher’s note** Springer Nature remains neutral with regard to jurisdictional claims in published maps and institutional affiliations.