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Influence of elastic–plastic base material properties on the fatigue and cyclic deformation behavior of brazed steel joints

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ABSTRACT

In this work, cyclic loading experiments were performed to investigate the influence of the elastic–plastic properties of the substrate material as well as of artificial brazing defects on the fatigue behavior of brazed steel joints. Brazing was performed with the steel X3CrNiMo 13-4 (AISI 316 C-NM) as a base material and with AuNi18 as a filler metal. After brazing, subsequent heat treatments were performed to influence the elastic–plastic properties of the substrate material. To investigate the influence of defects, defined defect geometries were introduced in the braze layer by electrical discharge machining (EDM). The results of the experiments show that the heat treatment has a significant influence on the fatigue lifetime. Furthermore it could be shown, that the fatigue behavior of brazed components is significantly influenced by the interaction of defects and elastic–plastic properties of the substrate material. To investigate the cyclic deformation, the materials strain response was investigated. Besides extensometer measurements, Digital Image Correlations (DIC) were used to measure the strain distribution during cyclic loading with a sufficient lateral resolution. Additional SEM investigations and FE-calculations were carried out to verify the experimental results and to investigate the complex mechanisms that can lead to fatigue failure of brazed components in detail. The results of this work underline the significant influence of the elastic–plastic properties of base material on the fatigue behavior and can be used for the appropriate design of brazed components.

1. Introduction

Today, advanced furnace brazing such as vacuum brazing or shielding gas brazing is often used as joining technology for seminal applications, as e.g. for components in energy production, in tool industry or for space applications. Compared to other joining technologies such as welding, brazing allows joining of a wide range of materials (e.g. dissimilar metals or ceramics to metals) at comparably low temperatures and fast processing times. Furthermore, brazing allows the realization of small and complex joint geometries and the processing of numerous brazings within one single step [1–4]. The above mentioned components are subjected to complex loading conditions in service, comprising mechanical, thermal or thermo-mechanical loads. As such, they can be classified as class A joints according to the American National Standard AWS C3.6M/C3.6:2008, which are subjected to special safety requirements [5].

Generally, brazing is performed by placing a filler metal between similar or dissimilar substrate materials and heating up the assembly above the melting point of the filler metal. The filler metal melts, wets the substrate surfaces and fills the joint gap. Cooling down of the assembly leads to solidification and the formation of a joint.

From a mechanical point of view, brazed joints represent complex, heterogeneous systems, consisting of the substrate material(s), the braze layer and a diffusion zone. The properties of brazed joints differ significantly from those of the individual joining partners. Uniaxial loading and the constrained deformation of the thin filler alloy layer can lead to a triaxial stress state which strongly influences the joint performance. Under quasi-static loading, this effect results in a decreased effective (von Mises) stress and an increased yield and tensile strengths of the brazed joint in comparison with the filler metal in its bulk form [6–11]. This constraining effect is more pronounced with increasing differences between the mechanical properties of the substrates and the filler alloy. During brazing, various defects such as incomplete gap filling or pores can form which strongly influence the strength of brazed components. Despite the fact that brazed components are widely used, procedures or guidelines for failure assessment of brazed joints are rather limited. In several recent studies it was demonstrated that the fitness-for-service approach, which was initially

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Nomenclature

Roman symbols

BSE	back scattered electrons (–)
DIC	digital image correlation
E	Young's modulus (MPa)
E_c	tangent modulus (MPa)
FE	finite element (method) (–)
F_{min}	minimum force (during cyclic loading) (N)
f_{test}	testing frequency (Hz)
HT	high-temperature (brazing process) (–)
HTM 1/2	heat treatment (procedure number 1 or 2) (–)
LM	light microscopy
n	hardening exponent
N_f	number of cycles to fracture (–)
R	load ratio (min. stress/max. stress; for stress controlled fatigue tests) (–)
SEM	scanning electron microscopy (–)
T	temperature (K)
T_m	melting temperature (K)
T-joint	specimen geometry used for the experiments (–)

Greek symbols

α	yield offset
ε	strain (%)
$\varepsilon_{a,plast}$	plastic strain amplitude (%)
ε_{ampl}	strain amplitude (%)
ε_{max}	maximum strain (%)
$\varepsilon_{pl,z}$	plastic strain in z-direction (%)
σ_{UTS}	ultimate tensile strength (MPa)
σ_Y	yield stress (MPa)
υ	Poisson's ratio

developed in the welding industry, can be used in structural assessment of brazed joints [12–14]. Leinenbach et al. considered the influence of the size and shape of brazing defects on the strength of braze joints under quasistatic tensile and bending loads using experimental and numerical methods, constructing FADs that allow estimating the maximum defect size in a braze joint subjected to a certain load or the maximum allowable load for a defined defect geometry and size [15–17].

To provide structural reliability for brazed components in service, their behavior under cyclic loading needs to be considered, too. However, only little information about the fatigue and cyclic deformation behavior of brazed joints is available in the literature. In the recent past, Leinenbach and co-workers investigated the fatigue behavior of the martensitic steel X3CrNiMo13-4 brazed with Au–18Ni or Ag–5Pd as filler materials [18–23]. It could be shown that under cyclic loading, brazed joints exhibit lower fatigue lifetimes when compared to their substrate material [18,19]. Furthermore, it was found that brazed round specimen are characterized by higher plastic strains at similar loading amplitudes, compared to the substrate material. This behavior was confirmed by FE-calculations, showing an inhomogeneous distribution of local stresses and strains in the proximity of the braze layer, leading to accelerated accumulation of fatigue damage and decreased lifetimes of brazed specimens [19]. In addition, a rather unusual fatigue crack growth behavior of brazed steel joints, i.e. extremely steep da/dN–ΔK curves and an unusually high threshold value in comparison with the ones of bulk materials was observed, which was related to a non-linear shielding mechanism which reduces the opening of a crack in the layer compared to a crack in bulk material under the same stress intensity [20]. The investigations have further shown that defects have a significant influence on the fatigue lifetime and a procedure was developed to estimate the lifetime of defect-free and defect-containing brazed joints on the basis of the stress intensity caused by a defect [21–23].

The fatigue of metallic materials is generally closely related to the formation of (local) irreversible strains in the bulk. In homogenous materials, the strains are relatively equally distributed over a macroscopic length scale and can therefore be averaged using integrating measurement techniques, e.g. with extensometers. However, plastic strains in brazed joints are usually localized in a small volume in or next to the brazing zone. The thickness of braze layers is usually in the range of 50–100 μm, so conventional strain measuring techniques cannot be applied reasonably. In a previous work, a first series of DIC measurements was performed by the present authors to analyze the strain development in brazed steel joints during cyclic loadings, [24,25]. The DIC technique is especially suitable for the analysis of heterogeneous strain fields and furthermore allows investigating the phases of crack initiation and propagation. With the DIC technique it was possible to show the complex local deformation behavior of brazed components and to achieve a more profound understanding of the mechanisms that lead to failure of brazed components.

In the present work, the fatigue performance and the cyclic deformation behavior of brazed martensitic stainless steel joints were characterized subjected to different heat treatments. The different heat treatments result in different mechanical properties of the substrate material, while the filler alloy properties remain unchanged. It could be shown that the deformation behavior and the defect tolerance of brazed joint is strongly influenced by the elastic–plastic substrate material properties. However, their influence on the fatigue behavior of defect-free and defect containing brazed specimens has not been investigated so far. For this, some results of our previous works were considered in this work, too. Besides extensometer measurements, high-speed camera measurements during the fatigue tests in combination with DIC were performed to characterize in-situ the strain evolution in the vicinity of the braze layer with a sufficient lateral resolution. The experimental tests were complemented by 2D and 3D FE calculations.

2. Materials and methods

2.1. Materials and specimen preparation

The fatigue tests in this work were performed with brazed specimens of the stainless steel X3CrNiMo 13-4 (AISI CA 6-NM). As shown in Table 1, the main alloying elements are Chromium, Nickel and Molybdenum. This material provides a high strength at a relatively large fracture strain and its mechanical properties can be varied significantly by different heat treatments. Foils of AuNi18 with a thickness of 100 μm were used as filler metal. The filler metal exhibits a good corrosion resistance, wettability and a melting point of 955 °C.

Table 1
Chemical composition of base material in wt.%.

Cr	Ni	Mo	Mn	Cu	Co	V	Fe
12.4	3.5	0.5	0.7	0.2	0.2	0.1	82.3