Evaluation of Brazed Joints Using Failure Assessment Diagram

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Abstract

Fitness-for service approach was used to perform structural analysis of the brazed joints consisting of several base metal / filler metal combinations. Failure Assessment Diagrams (FADs) based on tensile and shear stress ratios were constructed and experimentally validated. It was shown that such FADs can provide a conservative estimate of safe combinations of stresses in the brazed joints. Based on this approach, Margins of Safety (MS) of the brazed joints subjected to multi-axial loading conditions can be evaluated..

Introduction

It is hard to overestimate an importance of brazing in modern manufacturing processes. Sophisticated designs of structures and mechanisms used in airspace, aircraft, automotive, power and medical industries quite often expect various brazed joints to perform under complicated multi-axial loading conditions. In modern structures, it is expected and, in many industries required, to predict successful performance of any component by performing structural analysis resulting in positive MS.

Despite great advances in brazing technology and applications, evaluation of brazed joints remains to be one of the least developed fields of structural analysis. An effort to find any information on engineering practice of estimating or predicting load carrying capability of brazed joints subjected to combined stresses produces almost no results.

Several recent studies [1-3] demonstrated that fitness-for-service approach, originated in the welding industry [4-6], can also be used in structural assessment of the brazed joints. It was proposed that a stress ratio-based failure criterion (1) can be used to construct FAD.

$$\frac{\sigma}{\sigma_o} + \frac{\tau}{\tau_o} = 1 \qquad (1)$$

Here σ_o and τ_o are tensile and shear strength brazed joint (allowables), σ and τ are maximum tensile and shear stresses acting on the braze plane.

The purpose of this work is to summarize the experimental results obtained to-date and offer a simple engineering methodology to predict load carrying capability of structural brazed joints subjected to multi-axial loads.

Experimental Results

Experimental results used in this study were obtained from testing brazed joints consisted of several base metal/filler metal combinations, shown in Table 1

Table 1 Base and Filler Metal Combinations

Base Metal	Filler Metal	Test Temperature	Source/Year
Incoloy 800	AWS BNi-8	650°C	[7], 1983
Albemet 162	AWS BAlSi-4	RT	[1], 2009
304 Stainless Steel	AWS BAg8	RT	[2], 2011
304 Stainless Steel	Pure silver	RT	[2], 2011
Ti-6Al-4V	Al 1100	RT	[3], 2011

For each base metal / filler metal family of brazed joints, standard lap shear and butt brazed tensile specimens were tested to determine tensile σ_0 and shear τ_0 strengths of the respective brazed joints. In addition to standard braze test specimens, more complex test specimens designed to create combined tensile and shear stresses in the brazed joints, were fabricated and tested using identical braze processes and test temperatures. For convenience, all experimental results, expressed in terms of the stress ratios are plotted on the same graph shown in Fig.1

In order to deduce stress ratios from the results of Spingarn et al study [7], shear and tensile stresses at failure were divided, respectively by shear $\tau_0 = 80$ Mpa (11.6 ksi) and tensile $\sigma_0 = 160$ Mpa (23 ksi) allowables, calculated from the experimental results presented in [7] using the relationships between maximum principal stress and σ_0 [8].

Shear allowable τ_0 can be conservatively estimated as a half of σ_0 [9]. As one can see from the graph, a small uncertainty in values of σ_0 and τ_0 should not make significant affect on the location of the data points representing stress ratios relative to the FAD line. It is interesting to note that even though each base/filler metal combination can have different values of σ_0 and τ_0 one can compare the results on the same graph using stress ratios $R_\sigma = \sigma/\sigma_0$ and $R_\tau = \tau/\tau_0$, which is mathematically identical to plotting normalized data.
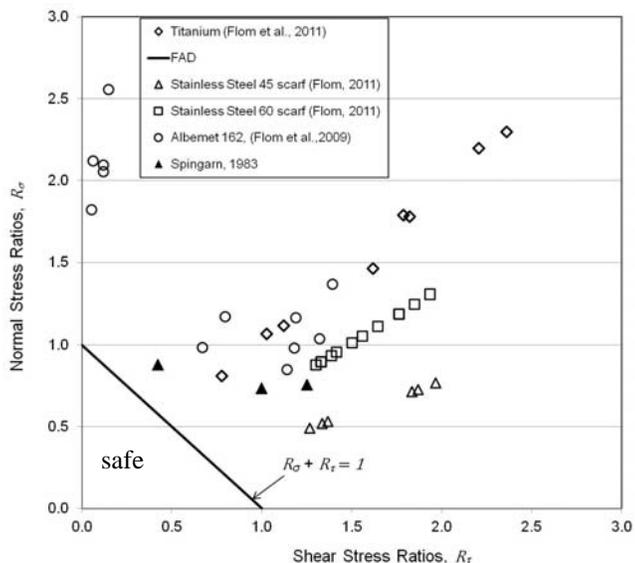
Fig.1 Combined results from the previous studies plotted as stress ratios. Note very conservative nature of the FAD line

Discussion

Experience shows that the most common failure theories (maximum stress theory, maximum shear theory and maximum distortion energy theory) used so successfully for design of homogeneous metallic structures are not suitable for the brazed joints subjected to the combined loading conditions. Even the safe operating loads could cause relatively high stress peaks at the edges of the brazed joints. According to the common failure theories, such high values of stresses should indicate the failure condition in a typical homogeneous metallic structure. The brazed joints, however, remain intact. Consequently, conventional yield and failure criteria are not reliable in predicting the failure in the brazed joints.
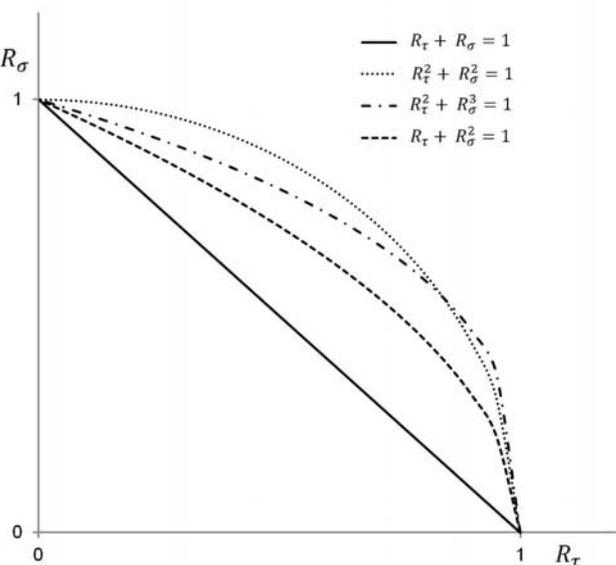

Fig. 2 Plots of several interaction equations. Note that straight line represents the most conservative case

As it was shown earlier [1], Coulomb-Mohr failure criterion [9] and/or interaction equations provide a more realistic means of predicting failures in the brazed joints. Expression (1) used for construction brazed joints FAD can be obtained directly from Coulomb-Mohr criterion or from the interaction curves [8] simplified to the most conservative case represented by the straight line, as shown in Fig.2 . It is important to be conservative when attempting to develop brazed joints failure criteria. Variability in brazing processes, uncertainties and scatter related to mechanical testing of the brazed joints, mechanical and metallurgical notches acting as stress concentrators, presence of flaws – all these factors have negative impact on performance of the brazed joints. Therefore, conservative approach in predicting failure of the brazed joints is well justified. For homogeneous metallic structures fabricated from well characterized alloys interactive curves separating safe and unsafe combination of stresses tend to be less conservative, as can be seen in Fig.2 . For example, Table 2 provides some of the well known interactive equations used quite successfully in the past for design of various aeronautical structures. It is interesting to note that for a combined bending and torsion loading case, the interactive equation in Table 2 is identical to equation (1). Normal and shear stresses acting on the braze plane can be obtained using Finite Element Analysis (FEA)

Table 2. Some Well-known Interaction Equations [8]

LOADING	INTERACTION EQUATIONS	MARGINS OF SAFETY (MS)
Normal and Bending Stresses	$R_\sigma + R_b = 1$	$\dfrac{1}{R_\sigma + R_b} - 1$
Normal and Shear Stresses	$R_\sigma^2 + R_\tau^2 = 1$	$\dfrac{1}{\sqrt{R_\sigma^2 + R_\tau^2}} - 1$
Bending, Torsion and Compressions	$R_b^2 + R_\tau^2 = (1 - R_c)^2$	$\dfrac{1}{R_c + \sqrt{R_\sigma^2 + R_\tau^2}} - 1$
Bending and Torsion	$R_b + R_\tau = 1$	$\dfrac{1}{R_b + R_\tau} - 1$

Essentially there are two ways of using FEA for structural analysis of the brazed joints. One approach is to use FEA of the entire structure as a whole. This approach is very common and used rather successfully in structural analysis of the complicated assemblies regardless of the nature of the joints, as long as they provide a continuous path for the load distribution within the structure. For this purpose, the so-called "global" model is developed to determine a coarse distribution of stresses and strains over the entire structure in a global coordinate system. In this case, brazed joint is represented by a line (or plane) with the same properties as the base metal. A distribution of stresses in the braze plane is determined and the maximum values of normal and shear stresses are used in expression (1). For this task, elastic solution is quite adequate. This approach was used in previous studies [1-3].

2

Another method is to use a detailed FEA model of the brazed joint and attempt to determine stresses acting within the brazed joint proper, consisting of the filler metal layer and the adjacent layer of the base metal. Knowledge of elastic modulus as well as the true stress-true strain relationship extending into the plastic range is required in order to perform detailed FEA of a majority of the brazed joints. Typically, there are small, much localized areas of plastic deformation (microplasticity) present within the brazed joints, primarily near the joint edges where stress peaking is observed. Such stress peaking can occur even in the brazed structure subjected only to moderate loads. Consequently, linear FEA are insufficient to generate a complete end-to-end deformation image of the brazed joint under the load. The main problem with this approach is that mechanical properties of the filler metal within the brazed joint are influenced by the extent of chemical interaction between the filler and base metals and by its microstructure. If no or very little metallurgical interaction occurs, the properties of the filler metal inside the brazed joint can be represented by the properties of the filler metal tested in the bulk form. If, however, a significant alloying between the liquid filler metal and the base metal occurs during brazing leading to substantial compositional changes and/or formation of the new phases, the properties of the filler metal within the brazed joint could no longer be represented by its bulk form.

Let's discuss how expression (1) can be used for evaluation of MS of the brazed joints. One of the most desirable qualities of brazed joint failure criteria is that it should be applicable to any brazed joint geometry. Consider expression (1) for each of the three basic joint geometries, such as single lap, butt and scarf as they are tested in tension. Lap shear test [10] provides a means of determining shear strength (allowable) of the brazed joint by calculating average shear stress at failure. Based on the engineering practice, it is assumed that normal stresses $\sigma = 0$. Consequently, expression (1) becomes:

$$\frac{0}{\sigma_o} + \frac{\tau}{\tau_o} = 1, \text{, and } \tau = \tau_0 \qquad (2)$$

Expression (2) indicates that lap shear joint is going to fail when the average shear stress reaches certain critical value (shear strength or allowable). In such case margin of safety can be estimated as:

$$MS = \frac{\tau_0}{\tau} - 1, \qquad (3)$$

Where τ is maximum shear stress expected to act on the brazed joint. In case of the butt brazed joint tested in uniaxial tension, it is assumed that only normal stress is present [10] and, consequently, expression (1) changes to:

$$\frac{\sigma}{\sigma_o} + \frac{0}{\tau_o} = 1, \text{ and } \sigma = \sigma_0 \qquad (4)$$

Expression (4) indicates that butt joint is going to fail when normal stress acting on braze plane reaches brazed joint tensile strength or tensile allowable σ_0. Margin of safety in this case is estimated as:

$$MS = \frac{\sigma_0}{\sigma} - 1, \qquad (5)$$

Where σ is maximum normal stress expected to act on the brazed joint. In case of a scarf joint (see Fig.3), both normal and shear stresses are present, i.e. the brazed joint is subjected to combined normal and shear stresses. In this case, expression (1) retains its form and margin of safety is estimated as:

$$MS = \frac{1}{R_\sigma + R_\tau} - 1, \qquad (6)$$

Where $R_\sigma = \frac{\sigma}{\sigma_0}$ and $R_\tau = \frac{\tau}{\tau_0}$. Graphically margins of safety (3), (5) and (6) are shown in Fig. 4
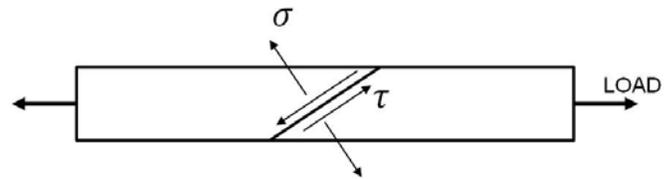

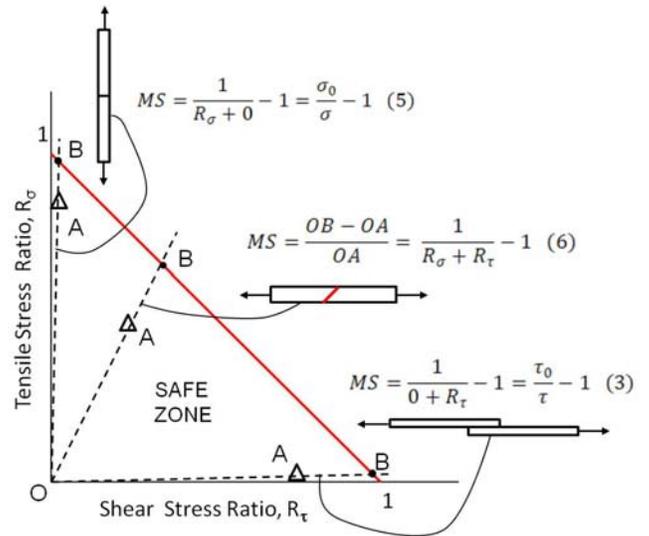Fig. 3 Normal and shear stresses acting on the braze plane in scarf joint subjected to uniaxial tension.

Fig. 4 Graphic representation of Margins of Safety (MS) for butt brazed, scarf and lap shear brazed joints.

Conclusions

Based on the studies of various base/filler metal combinations of the brazed joints it appears that the Coulomb-Mohr-derived failure criterion can be used for conservative estimate of Margins of Safety in brazed assemblies

Acknowledgements

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