Evaluation of Margins of Safety in Brazed Joints

Yury Flom, Len Wang, Mollie M Powell
NASA / Goddard Space Flight Center, Greenbelt, Maryland

Matthew A Soffa, Monica L. Rommel
ITT Space Systems Division, Rochester, New York.

Abstract

One of the essential steps in assuring reliable performance of high cost critical brazed structures is the assessment of the Margin of Safety (MS) of the brazed joints. In many cases the experimental determination of the failure loads by destructive testing of the brazed assembly is not practical and cost prohibitive. In such cases the evaluation of the MS is performed analytically by comparing the maximum design loads with the allowable ones and incorporating various safety or knock down factors imposed by the customer. Unfortunately, an industry standard methodology for the design and analysis of brazed joints has not been developed. This paper provides an example of an approach that was used to analyze an AlBeMet® 162 (38%Be-62%Al) structure brazed with the AWS BAlSi-4 (Al-12%Si) filler metal. A practical and conservative interaction equation combining shear and tensile allowables was developed and validated to evaluate an acceptable (safe) combination of tensile and shear stresses acting in the brazed joint. These allowables are obtained from testing of standard tensile and lap shear brazed specimens. The proposed equation enables the assessment of the load carrying capability of complex brazed joints subjected to multi-axial loading.

Introduction

Evaluation of strength margins in structural components is a normal practice used in the design of metallic and composite structures. Mechanical, welded or adhesively bonded joints in such structures are routinely assessed for their load carrying capabilities in accordance with widely accepted engineering analysis techniques and failure criteria (Ref.1-5). Brazed joints, however, seem to be an exception. Literature searches for analytical methods of the evaluation of the strength or Margin of Safety (MS) of complex brazed joints produced no satisfactory results. This is particularly true when the brazed joints are subjected to multi-axial loads.

Although this paper does not explore the reasons for a lack of books or guides on structural analysis of brazed joints, it would be beneficial to mention several factors commonly identified by designers as stumbling blocks precluding them from a comprehensive analysis of the brazed joints. These factors are:

o Lack of knowledge of the mechanical properties of the brazed joint filler metal interlayer;
o Uncertainty of how to use these properties, even if they, somehow, are made available;
o Inadequate attention to the analysis of the brazed joints from the structural professional community and academia as compared with other methods of assembly such as welding, adhesive bonding or fastening;
o Lack of techniques to account for defects commonly found in brazed joints like lack of fill or trapped salts;
o Non-standard joint configurations that have not been tested to validate analytical models.

It is quite clear that these factors offer challenging problems to metallurgical, materials and mechanical engineers in terms of understanding the interaction between the filler and the base metals, experimental techniques of measuring mechanical properties of the joints, as well as the appropriate interpretation of the results. The present paper deals with the issues that fall within the second factor mentioned above.

Many challenges exist in the analytical modeling of the braze joint. The foremost difficulty is that braze joints are normally very thin (less than a hundred of microns in thickness) compared to their lateral dimension. This disproportionally large aspect ratio not only makes the analytical calculation of the stress and strain incredibly difficult but also, most importantly, changes the fundamentals of the failure mechanism of a ductile material. The extraordinarily large aspect ratio constrains the braze joint in such a way that only a nearly pure shear loading condition, such as lap shear, can be handled using a standard yielding and failure approach, such as the Tresca (maximum shear) and Von Mises criteria. Under nearly pure shear loading, the filler metal will yield, undergo plastic deformation and reach failure in the normal failure process of most ductile metals and alloys.

However, when loading braze joints in tension or compression, a totally different failure mechanism is involved. Taking the standard butt brazed specimens described in the AWS C3.2 specification as an example, when the specimen is loaded in tension, the filler metal, which is the focus of the test, is no longer in the simple tensile loading condition. Large lateral tensile stress develops due to the lateral constraint. The lateral tensile stress can be as high as ~90% of the axial tensile stress, depending on the property differences between the

filler metal and the base metal. Under such a loading condition, the filler metal is actually under tri-axial tensile loading. The filler metal will not yield except at the edges. Often, the failure strength of the notched sample and smooth sample of such configuration are not much different, as will be shown by test results of the current study. When loading such a specimen in compression, the filler metal will basically be in hydrostatic compression. The filler metal will not undergo plastic deformation prior to failure. Apparently, under such conditions, the filler metal fails very differently compared to the homogenous tensile specimens or lap shear specimens. Even for a very ductile filler metal, it fails in a quasi-brittle manner.

When braze joints are under complicated loading conditions, this problem magnifies itself which makes the analytical analysis nearly impossible. Consequently, the first step in solving this problem is to find a failure criterion that combines the two major driving failure mechanisms and, at the same time, is suitable for practical use.

The purpose of this work is an attempt to develop a simple methodology enabling designers to estimate the safe operational range for the brazed joints under static multi-axial loads. In order to accomplish this task the following approach was implemented:

- o Establish brazed joint allowables by testing the standard test specimens described in the AWS C3.2 specification (Ref.6) under near pure shear and tensile loads. As explained above, the tensile test of braze joint measures the dilatational (volume change, see Ref. 7) tensile strength of the filler metal, not the simple tensile properties of the filler metal.
- o Develop an interactive equation to account for the combined action of distortional shear and dilatational tensile loads;
- o Verify the interactive equation by testing customized specimens subjected to multi-axial loads;

The brazed joints in this study were comprised of Brush Wellman AlBeMet® 162 (62% Be, 38%Al) metal matrix composite dip brazed with AWS BAlSi-4 (Al, 12%Si) filler metal. This system was selected because of its importance in the aerospace applications.

Procedure

Tensile Allowables
Tensile allowables were determined from the tensile tests of the standard butt brazed specimens described in the AWS C3.2 specification. In addition to the standard geometry, notched tensile specimens were also tested to determine the notch sensitivity of the AlBeMet® 162/ BAlSi-4 system. The results of the tests are summarized in Table 1. No significant difference in the failure loads was observed between the smooth and notched specimens. As mentioned above, this is not a surprise. Consequently, all values of failure load were pooled together to improve the statistical interpretation of the

results. A total of 40 specimens were tested. Fig. 1 depicts the geometrical features of both types of specimens.

Table 1 Tensile Test Results, Mpa (ksi)

Specimen	Min σ_{TUS}	Max σ_{TUS}	Avg σ_{TUS}	A-basis σ_{TUS}
smooth	104 (15.1)	255 (37)	185 (26.9)	86 (12.5)
notched	105 (15.2)	221 (32)	180 (26.1)	

The failure loads were divided by the initial cross sectional areas to obtain the ultimate tensile strength σ_{TUS}. A-basis is a statistical value of σ_{TUS} indicating that at least 99% of population is expected to be equal or exceed this value with 95% confidence (Ref.8). It was computed using the procedure described in Ref.9. Typical stress – strain curves from the tensile tests are shown in Fig. 2
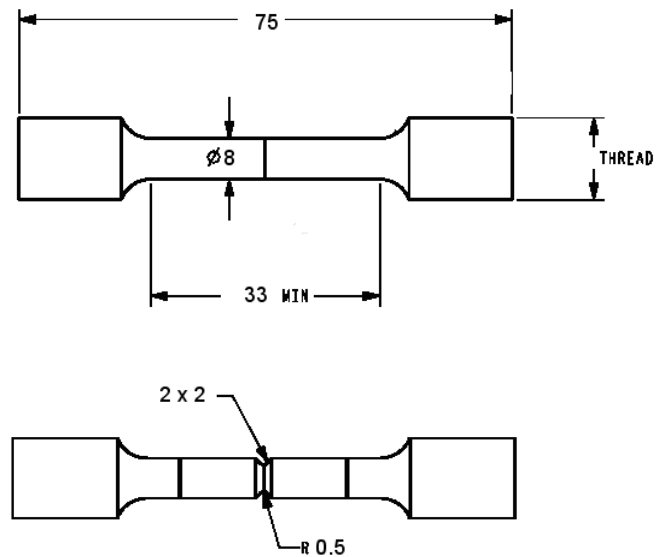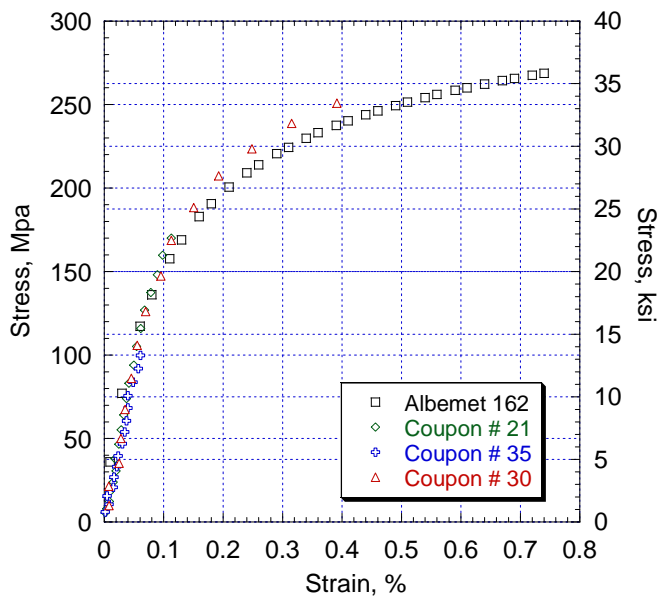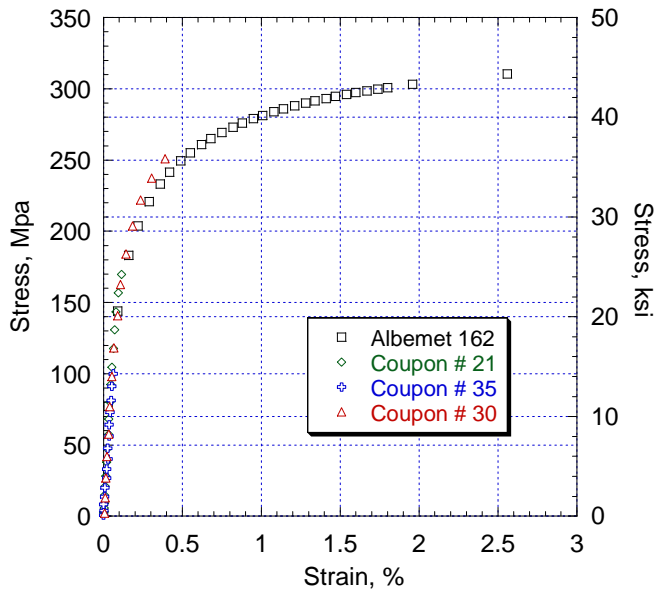

Fig.1 Smooth (top) and notched (bottom) butt brazed tensile specimens. All dimensions are in mm. More detailed information on specimen geometry is provided in Ref.6

Shear Allowables
Single lap shear test specimens per the AWS C3.2 standard were pull tested to determine the average shear strength of the brazed joints. The overlap length tested ranged from 1T to 3T, where T was the thickness of the base metal, as shown in Fig.3. Only the 1T specimens failed in the braze. All other specimens failed in the base metal away from the brazed joint. Consequently, only 1T test results were used for analysis. The ultimate shear strength τ_{sus} of each tested lap joint was determined by dividing the failure load by the total area of the overlap. Table 2 contains a summary of the lap shear test results. A total of 16 lap shear 1T specimens were tested. The historical data of testing pin shear specimens (a total of 46

specimens) brazed by the same vendor are also included in this table.

Fig.2 Examples of typical stress-strain curves from tensile tests

of butt brazed specimens (only 3 coupons are shown for clarity) compared with the base metal AlBeMet® 162. Top plot shows the strain range and the bottom one shows the

Specimen	Min τ	Max τ	Avg τ	A-basis τ
Lap shear, 1T	100 (14.5)	122 (17.7)	115 (16.7)	49 (7.1)
Pin shear	67 (9.7)	112 (16.2)	86 (12.4)	

initial portion of the test.

Table 2 Shear Test Results, Mpa (ksi)

Failure Criteria and Interactive Equation

A number of interactive equations or curves have been developed in the past to predict failure in structures subjected

(a)

(b)

Fig.3 Single lap shear (a) and pin shear (b) specimens configuration. Pin shear specimen geometry has been used for a long time as process control and witness samples for dip brazing (Ref. 10). Dimensions are in mm

to combined loads (Ref.1-3). These equations had been used to estimate the conditions of structural failure in homogeneous and ductile materials. Although most interaction equations were obtained empirically, they are based on the ductile behavior of metals and can be traced to the Tresca and Von Mises failure theories. Since the brazed joints do not behave as ductile homogeneous materials, with the exception of a "pure" shear condition, the conventional interaction equations do not apply to the highly restrained brazed joints subjected to multi-axial loading conditions. Consequently, highly constrained brazed joints should behave closer to the brittle materials.

It is instructive, therefore, to look at other failure criteria capable of predicting failures in brittle materials. One of them is Coulomb-Mohr fracture criterion (Ref. 11 and 12). In this criterion, fracture takes place in a given plane in a material when a critical combination of normal σ and shear τ stresses has occurred. In its simplest form, this stress combination assumes a linear relationship, as shown below:

$$\tau + \mu\sigma = c, \tag{1}$$

In this expression μ and C are material specific parameters. Christensen (Ref.12) modified the Coulomb-Mohr criterion and offered a more general form of failure condition by considering a combined effect of hydrostatic and Von Mises components of stress. His failure theory provides better correlation with the experimental results for homogeneous materials (Ref.11). However, because of its simplicity and ease of use for the brazed joints analysis, this study adopted the Coulomb-Mohr failure criterion.

If we let a normal stress be zero, as in the case of pure shear, the expression (1) takes the form of the Tresca (maximum shear) criterion, such as $\tau = C = \tau_{sus}$. It is easy to see that the parameter C is the ultimate shear strength of the material. With respect to the brazed joint, this is the maximum shear stress determined from the lap shear pull tests. Taking equation (1) and dividing it by τ_{sus} and re-arranging the terms, we obtain:

$$\frac{\tau}{\tau_{sus}} + \mu\frac{\sigma}{\tau_{sus}} = 1 \tag{2}$$

Recall that during tensile test of the butt brazed specimen, the conditions within very thin braze layer approach those of a tri-axial tensile stress state (or hydrostatic tension). Under such conditions, shear stress within brazed joint approaches 0. If we let $\tau = 0$, equation (2) becomes:
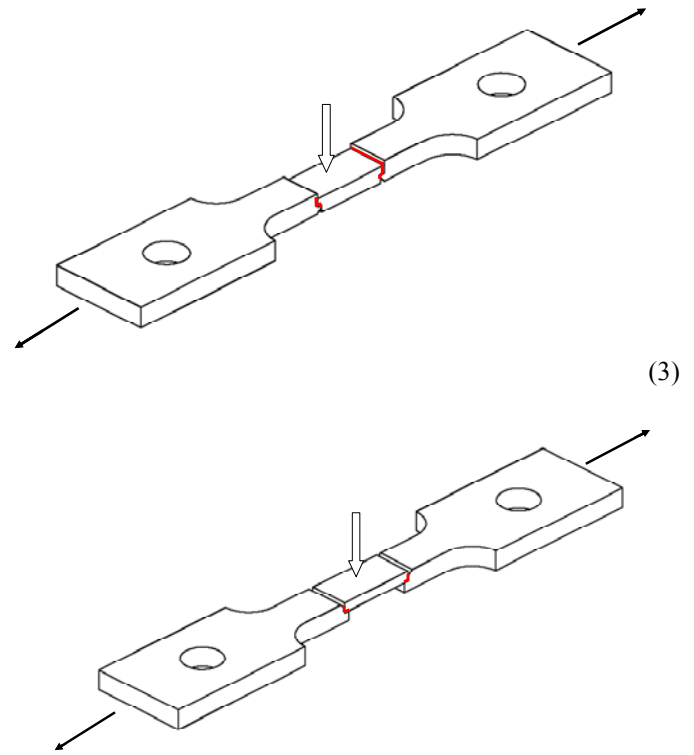
$$\mu\frac{\sigma}{\tau_{sus}} = 1 \quad or \quad \sigma = \frac{\tau_{sus}}{\mu}$$

The fracture condition of the butt brazed tensile specimens is achieved when the tensile stress pulling the joint apart equals the maximum dilatation stress that a brazed joint can withstand. To be consistent, we call it ultimate tensile stress σ_{TUS} of the brazed joint (not to be confused with σ_{TUS} of the filler metal tested in free form)

$$\sigma = \frac{\tau_{sus}}{\mu} = \sigma_{Tus} \quad or \quad \mu = \frac{\tau_{sus}}{\sigma_{Tus}}$$

From this we can see that, the material property μ, with respect to the brazed joints, is the ratio of ultimate shear stress to ultimate tensile stress of the brazed joint. Substituting μ with the ratio of the stresses into equation (2) leads to the following modified Coulomb-Mohr expression:

$$\frac{\sigma}{\sigma_{Tus}} + \frac{\tau}{\tau_{sus}} = 1 \quad or \quad R_\sigma + R_\tau = 1$$

(3)

Where R_σ and R_τ are the tensile and shear stress ratios, respectively.

J1 configuration (butt-lap-butt stair shaped joint)

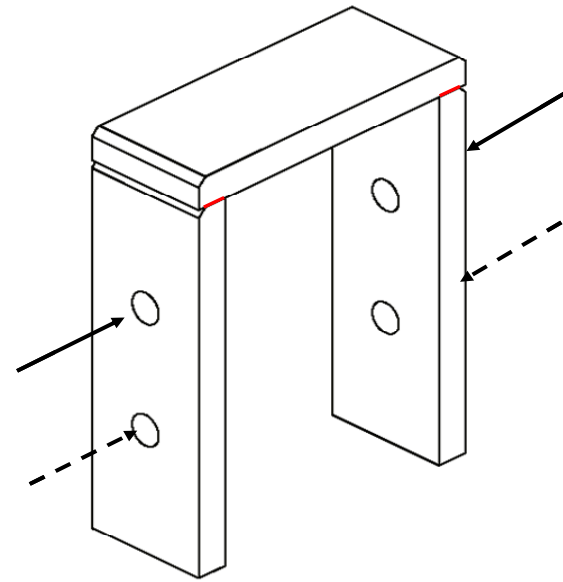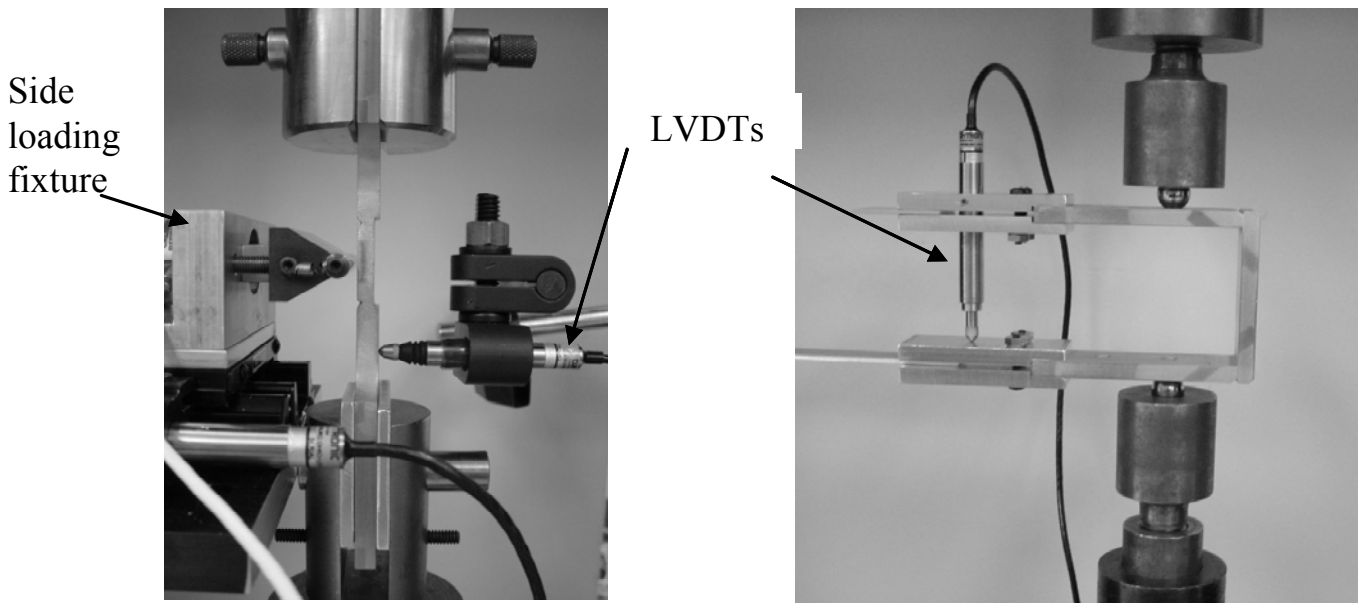J2 configuration (butt-lap L-shaped joint)

Pi configuration

Fig.4 J1, J2 and Pi configurations of the validation brazed test specimens. Base metal thickness was 6 mm (0.025 inch). The arrows represent various loading conditions. The specimens J1 and J2 were tested in uniaxial loading (solid arrows) and combined, tension + bending (solid + block arrows) conditions. The Pi specimens were tested in compression either along the black arrows or along the dotted arrows. The distance between the first set of holes and the top plate is 25 mm (1 inch), span or offset = 25 mm and the distance from the top plate to the second set of holes is 50 mm (2 inches), span = 50 mm

Fig. 5 Photographs of the validation specimens test setups for J1 and J2 (a) and

Pi specimen configurations. A total of 5 specimens of each type were tested. Linear Variable Displacement Transducers (LVDTs) recorded deflections of the specimens during the test

Validation

In order to test the validity of equation 3 in predicting fracture in brazed joints, several types of specimens were fabricated using the same brazing process and vendor that produced the standard test specimens. Fig.4 shows the configurations of the validation test specimens and the directions of the applied test loads.
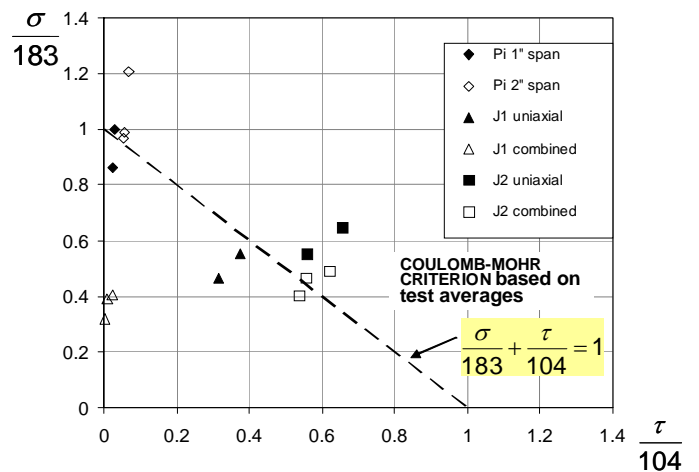
These specimens were tested under uni-axial and multi-axial loading conditions using specially designed and built loading fixtures. Fig.5 shows some of the test setups used to test the validation specimens. During each test, load versus displacement records were obtained using load cells and LVDT outputs. Using the maximum failure loads obtained experimentally, each specimen type was analyzed using hand calculations based on beam theory and the principles of stress superposition. From these analyses, the stress ratios R_σ and R_τ were calculated for each tested validation specimen at fracture loads using average and A-basis values for σ_{TUS} and τ_{SUS} (see Tables 1 and 2). Figures 6 and 7 show the calculated stress ratios compared with the modified Coulomb-Mohr failure criteria. As one can see all combinations of stress ratios that resulted in failure of all but 3 specimens lie outside the "safe" region below the A-basis Coulomb- Mohr failure locus.

Discussion

One of the main emphases of the current effort was to use a great deal of conservatism in analysis, testing and data interpretation. Therefore, A-basis statistical requirements were applied to the test data which resulted in significant knock down of the ultimate tensile and shear stresses used to define the lower bound of the failure region.

This was done to better align the analysis of the brazed joints with the standard practices of using A- or B – basis values in the design of aerospace structures. On the other hand, the Coulomb-Mohr failure locus based on the test average values for σ_{TUS} and τ_{SUS} (see Tables 1 and 2) is a better choice for predicting the actual stress ratios at failure obtained experimentally from testing the validation specimens, as shown in Fig.6.

Fig.6 Test results of validation specimens types J1, J2 and Pi tested to failure under uni-axial and combined loads. The three specimens (Δ) from J1 category tested under combined loads
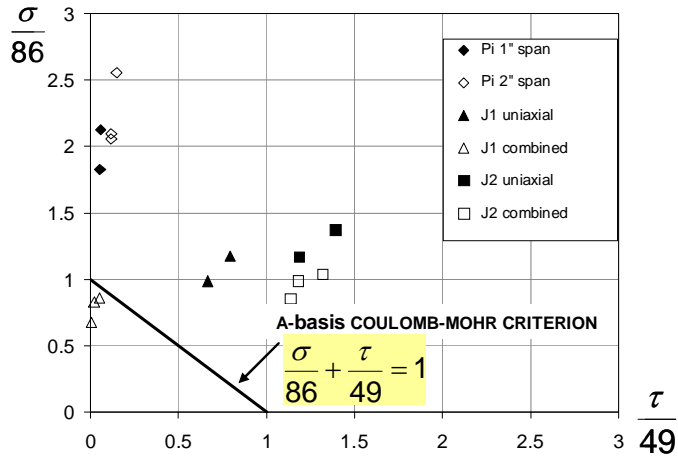

failed at much lower stresses than predicted by the Coulomb-Mohr failure criterion based on the test averages (see Tables 1 and 2). Examination of the fracture surfaces of these specimens revealed almost 80% lack of braze.

In addition to the expected test data scatter, there is another factor that needs to be taken into account when attempting to define the load carrying capability of the brazed joints. This factor is related to our ability to detect the internal discontinuities in the brazed joints. Notice the three data points ("J1 combined") located relatively far from the

predicted failure locus as well as lying inside the "safe" zone defined in Fig.7.

Fig. 7 Same test results as in Fig.6. Here, A-basis Coulomb-Mohr failure locus conservatively defines "safe" zone where where failures are not expected to occur. Again, the exception

are the three specimens (Δ) from J1 category showing the presence of severe lack of braze.

Examination of fracture surfaces of these validation specimens showed that in some cases up to 80% of the brazed joint areas were not brazed. Typically, most of the quality specifications allow lack of braze only up to 20% of the total area of the brazed joints. The quality of the rest of the validation specimens was not as bad, although the lack of braze was still considerably higher than the permissible 20%. However, based on the fact that all but 3 specimens failed outside the "safe" zone indicates that the conservatism exercised in this work was adequate to account for the presence of internal discontinuities well in excess of the 20% acceptable by most specifications.
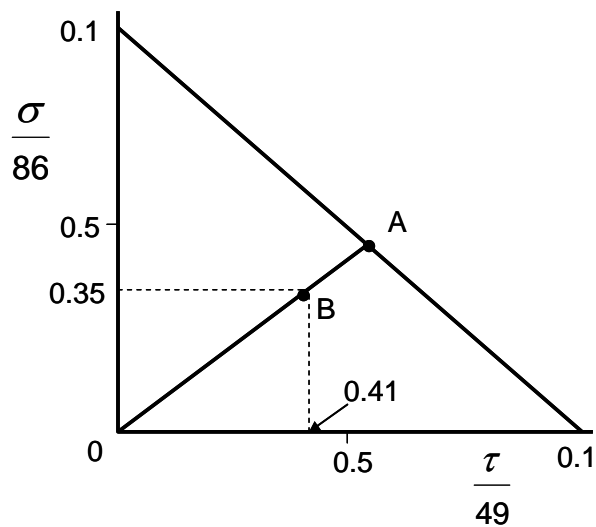

Fig.8 Point B represents an example of the brazed joint under safe loading condition, when σ = 15 Mpa and τ = 10 Mpa; Factor of Safety (MS) = 2; The Margin of Safety (MS) can be calculated graphically as MS = OA / OB - 1
Non-destructive examination of complex brazed assemblies is not trivial. Some discontinuities may remain undetected. In

order to account for undetected flaws it is reasonable to further reduce the expected load carrying capability of the brazed joints in critical brazed structures.

We can determine the Margin of Safety (MS) of the brazed joint following the approach described in Ref. 4. Ideally, if the sum of stress ratios in eq. (3) is less than 1, the brazed joint is safe. However, we must account for various uncertainties such as dimensional errors, heat treatment parameters, assembly stresses, braze joint discontinuities (as discussed above) during the manufacturing and brazing processes. These uncertainties have a negative impact on the strength of the brazed structure. Consequently, it is a common practice to introduce a certain Factor of Safety (FS) to downgrade the load carrying capability of the critical structure. With the inclusion of FS,
eq.(3) can be expressed as $(R_\sigma + R_\tau)$ x $FS = 1$. Thus, MS can be estimated as:

$$MS = \frac{1}{(R_\sigma + R_\tau) \times FS} - 1$$

For example if the brazed joint is under the combined action of 15 Mpa tensile and 10 Mpa shear stresses and using the A-basis ultimate tensile and shear stresses determined in this study (86 and 49 Mpa, respectively), and using FS=2, the MS would be:

$$MS = \frac{1}{\left(\dfrac{15}{86} + \dfrac{10}{49}\right) \cdot 2} - 1 = 32\%$$

Graphically, this is represented in Fig.8

Conclusions

The following conclusions can be drawn from this study:

1) The modified Coulomb – Mohr failure criterion can be used to predict failures in the brazed joints, especially when they are subjected to multi-axial loading conditions. The procedures developed in this study could be used to verify failure criterion in design and structural analysis of the critical brazed joints in other base / filler metal combinations.
2) The methodology of determining the allowables is based on testing standard brazed specimens which is relatively simple and inexpensive.
3) It is very important to be conservative in determining the ultimate properties of the brazed joints when testing standard specimens. A quantity of test specimens selected for testing should be sufficient to allow for a good statistical interpretation.
4) The quality of brazed joints in the standard and validation specimens should be representative of the quality of production assemblies. An appropriate FS

should be used to account for the uncertainties of the brazing process.

5) One of the main advantages of the proposed methodology is that it does not require a specific knowledge of the properties of the filler metal inside the brazed joint. The allowables are determined by testing standard tensile and lap shear specimens and used to construct the modified Coulomb-Mohr fracture line and evaluate MS, see equation (4) and Fig.8

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