Failure Assessment of Stainless Steel and Titanium Brazed Joints

Yury Flom
NASA Goddard Space Flight Center
Yury.a.flom@nasa.gov

Abstract

Following successful application of Coulomb-Mohr and interaction equations for evaluation of safety margins in Albemet 162 brazed joints, two additional base metal/filler metal systems were investigated. Specimens consisting of stainless steel brazed with silver-base filler metal and titanium brazed with 1100 Al alloy were tested to failure under combined action of tensile, shear, bending and torsion loads. Finite Element Analysis (FEA), hand calculations and digital image comparison (DIC) techniques were used to estimate failure stresses and construct Failure Assessment Diagrams (FAD). This study confirms that interaction equation $R_\sigma + R_\tau = 1$, where R_σ and R_τ are normal and shear stress ratios, can be used as conservative lower bound estimate of the failure criterion in stainless steel and titanium brazed joints.

Introduction

Prediction of failure in brazed joints subjected to complex loading conditions continues to challenge designers and structural analysts attempting to estimate margins of safety in brazed structures. Despite the fact that brazed components and structures are extensively used in the aerospace industry, literature is lacking engineering procedures or guidelines for failure assessment of brazed joints.

Earlier work [1] demonstrated that interaction equation

$$R_\sigma + R_\tau = 1 \qquad\qquad (1)$$

could be used for failure assessment of Albemet 162 joints brazed with AWS BAlSi-4 (88%Al, 12%Si) filler metal. In this equation R_σ and R_τ are normal and shear stress ratios as defined below:

$$R_\sigma = \frac{\sigma}{\sigma_0} \ \ and \ \ R_\tau = \frac{\tau}{\tau_0},$$

where σ_o and τ_o are tensile and shear strength brazed joint allowables, and σ and τ are maximum tensile and shear stresses acting within the brazed joints. In the current effort, different base / filler metal combinations were tested to verify the applicability of equation (1) to other brazed systems. The base metals and respective brazing filler metals used in this study are listed in Table 1.

Table 1 Base / filler metal combinations used in this study

Base Metals	Filler Metals	
CRES 304 SS	AWS BAg-8 (78%Ag, 28%Cu)	AWS BAg-0 (Pure silver)
Ti-6Al-4V	Aluminum Alloy 1100	

Experimental Procedure

Stainless steel and titanium test specimens are shown in Fig. 1 and Fig.2. All specimens were brazed in vacuum furnace. Filler metal in foil form was preplaced in the braze joints prior to brazing and was held there by gravity. All stainless steel specimens were nickel plated to facilitate wetting.
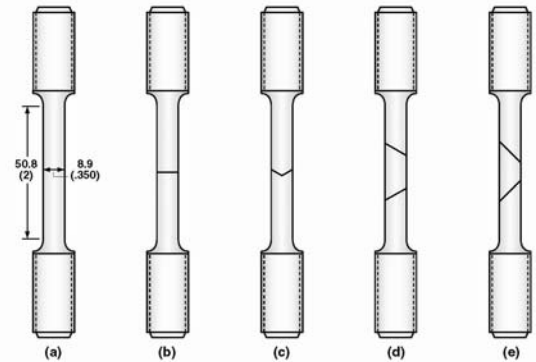

Fig.1 Geometry of the test specimens used in this study. Base metal blanks (a) were tested to establish the property baseline. Butt brazed (b), V60 (c) and double scarf D60˚(d) and D45˚(e) were tested to determine the failure loads used to calculate normal and shear stresses at failure acting on the braze layer

The double scarf geometry reduces the tendency of specimen to rotate during tensile test. Also, since the double scarf test specimen has two geometrically identical brazed joints and the failure occurs in only one joint, each tested specimen has one brazed joint still intact. This allows for a metallographic examination of the brazed joint that experienced the condition of imminent failure. The V-type specimen geometry [2] eliminates rotation, provides fully axisymmetric loading conditions while subjecting the brazed joint to a combined tension and shear load. Scarf angles in brazed joints were either 45° or 60°. More details description of the test specimens and their fabrication can be found in ref. [3]
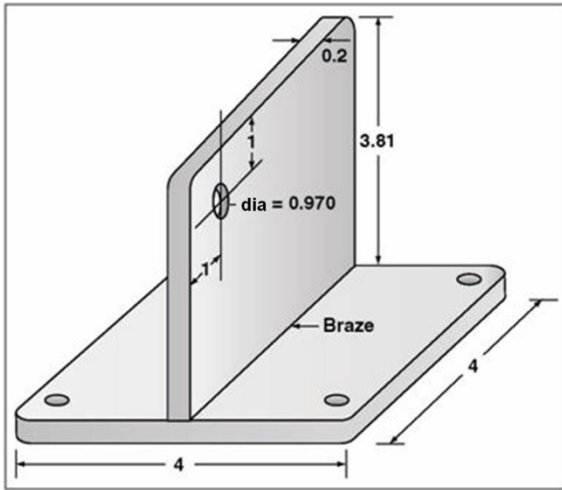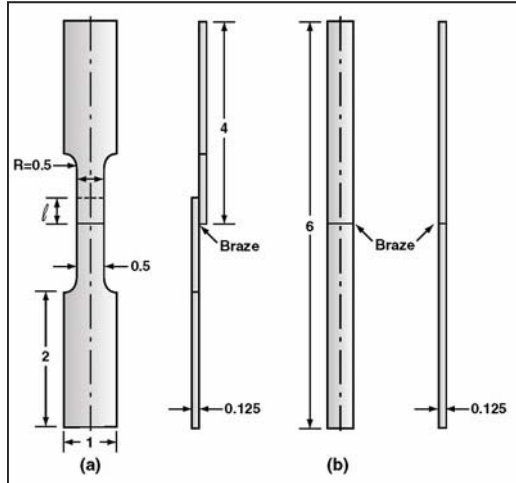
Fig.2 Lap shear (a) and butt tensile (b) specimens used in this effort to derive tensile and shear allowables. T-specimens (bottom) shown on the right was used for testing brazed joints under various loading configurations. Dimensions are in inches

All titanium test specimens were fabricated from the Ti-6Al-4V alloy. Tensile and lap shear test specimens were used to determine tensile and shear allowables. T-specimens were designed and fabricated to test the brazed joints under the combined action of shear and normal stresses. Detailed description of specimen fabrication and brazing is provided in ref. [4].

All specimens, including the blank ones, were tested on Instron 4115 test frame using a crosshead speed of 0.05 in/min. A 1" gage length extensometer was used to record the elongation of the stainless steel test specimens. In case of the double scarf specimens, the extensometer was recording the elongation across only one joint. Prior to tensile testing, the stainless steel blanks, used for measuring properties of the base metal, were exposed to the same brazing cycle time/temperature conditions as the brazed specimens.

In order to test T-specimens under combined tensile and shear loads, special 30° and 45° wedge fixtures were used to mount

the specimens (see Fig. 3). By interchanging the different wedges and by varying the angle of rotation of the T-specimen, a total of 6 different loading configurations were established for this study. The T-specimen deformation was measured using an Aramis™ digital image correlation (DIC) system. DIC measures strain by tracking the positions of identifiable features on the object's surface. DIC tracking is often aided by application of a stochastic speckle pattern to the surface of the specimen which provides the locally unique, trackable features on the surface. For this study, the flat surfaces of the T-specimens were painted with a white background and a black speckle pattern, as shown in Fig.3
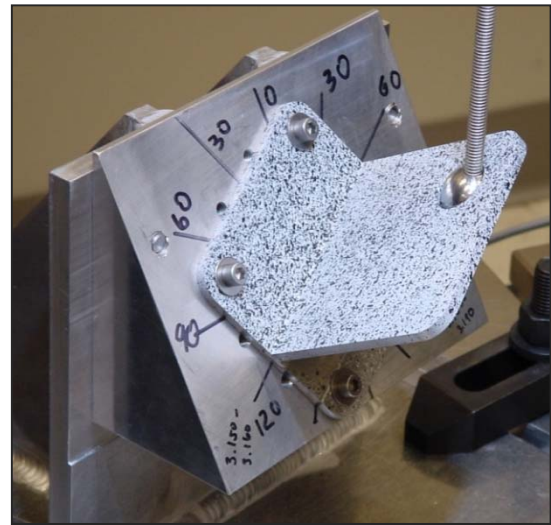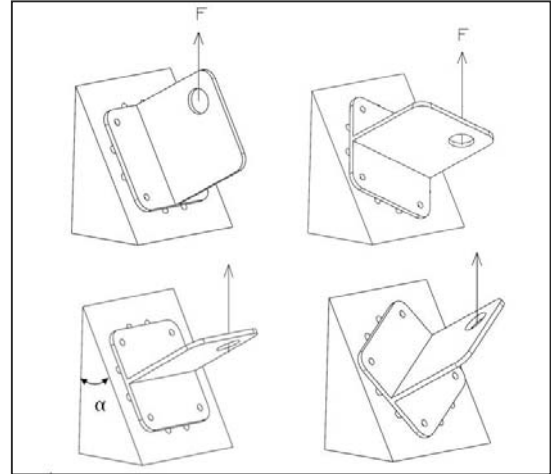

Fig.3. Different loading configurations of the brazed T-specimens are shown on the top. Wedge angle α was either 30° or 45°. Rotation of the T-specimen on the face of the wedge provided desired combined loading conditions. The bottom photograph shows one of the speckled T-specimen loaded into the test fixture. More details describing DIC process and T-specimen testing are provided in ref. [4].

Results and Discussion

Stainless Steel Specimens

The results of testing brazed specimens are compared with the tensile tests of the base metal blanks and are plotted in the form of engineering stress –strain curves as shown in Fig.4.

STRESS - STRAIN CURVES OF BAg8 BRAZED SPECIMENS AND 304SS BASE METAL AFTER BAg8 CYCLE

STRESS - STRAIN CURVES OF Ag BRAZED SPECIMENS AND 304SS BASE METAL AFTER Ag CYCLE
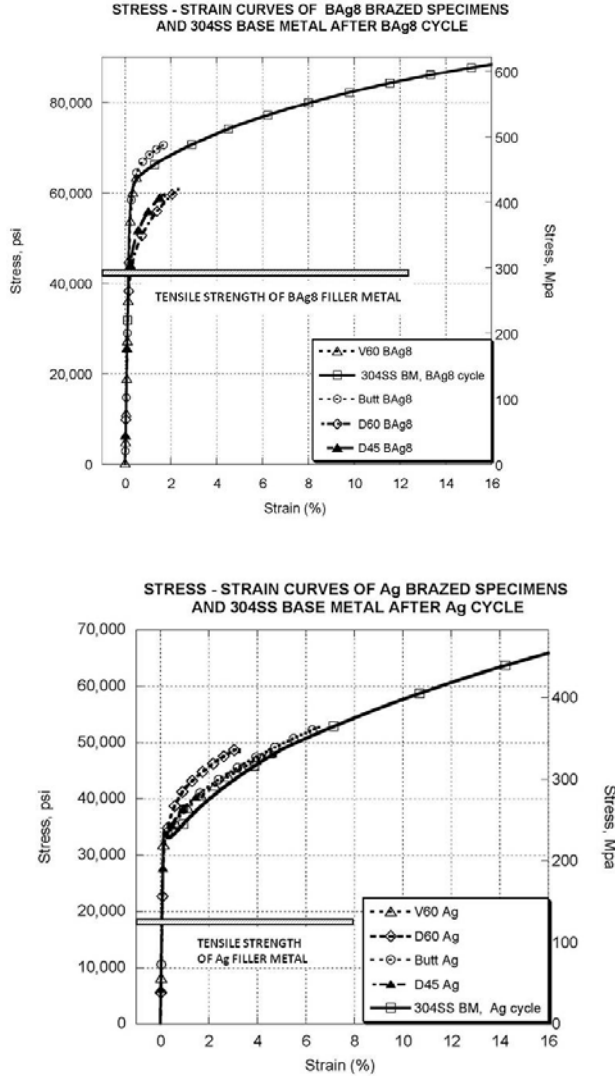
Fig. 4. Engineering stress-strain plots grouped according to the AWS BAg8 (top) and Ag (bottom) filler metals. All specimens demonstrated higher strength than their respective filler metals

On these plots tensile stress was determined by dividing the load over the initial cross sectional area of the test specimens. The test results confirm a well established fact that the strength of the brazed joints exceeds the strength of the filler metal itself, tested in the bulk form [5]. Ag-brazed joints essentially follow the deformation behavior of the 304SS base metal. It appears that D60 Ag scarf joints required higher stresses to sustain their plastic deformation compared to the rest of the joints including the base metal. BAg8 – brazed specimens also follow the base metal stress strain curve. In this case, however, the scarf joints yielded earlier than butt- and V-brazed joints as well as the base metal itself. It appears

that behavior of the scarf-brazed joints was not consistent in terms of their yield onset. Yielding could occur either below or above their respective base metals. This observation is most likely due to an experimental artifact caused by a complex interaction between the slip along the braze interfaces and extensometer readout. Brazed joint tensile strength allowable σ_o was determined using test results of butt Ag specimens, which ranged from 46 to 53 ksi (316 to 363 Mpa). Tensile strength of the butt joints brazed with BAg8 filler metal was approximately 50% higher than their Ag-brazed counterparts. Since we are interested in determining the lower bound failure criteria, the logical choice would be to use Ag-brazed butt specimen showing the lowest strength. Based on simple statistical analysis, σ_o was determined to be 38.4 ksi (265 Mpa). More details on test results are provided in ref. [3]. Since the shear strength of stainless steel lap joints brazed with silver-based filler metals is a well established quantity [6-8] it was more cost effective to omit fabrication and testing of the lap shear specimens. Instead, it was decided to accept $\tau_o = 15$ ksi (103.5 mpa) as the value of shear strength allowable listed in [8].

Tensile and shear stress ratios $R_\sigma = \sigma/\sigma_o$ and $R_\tau = \tau/\tau_o$ are plotted in Fig.5. All Ag-brazed joints are denoted by solid symbols and all BAg8-brazed joints are shown with open symbols. A line connecting points with coordinates (1, 0) and (0, 1) represents interaction equation equation (1) or $R_\sigma + R_\tau = 1$, where R is tensile or shear stress ratios. Values of σ and τ were calculated as average normal tensile and shear stresses acting on the braze plane, as described in [3].
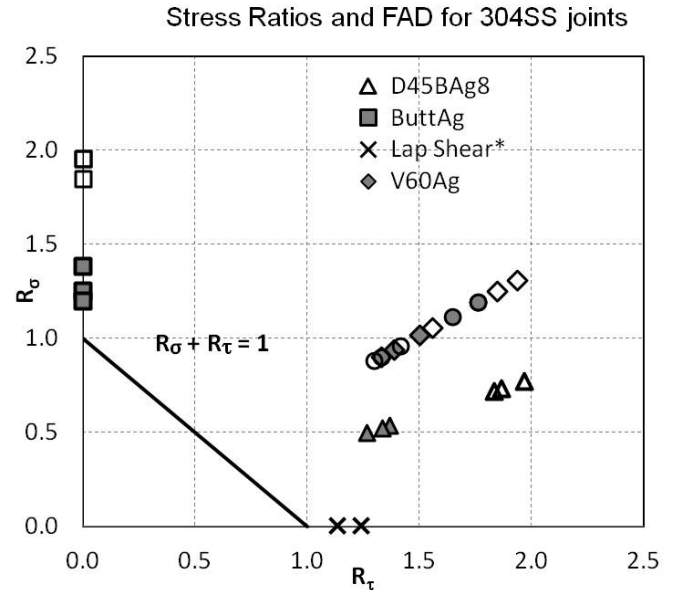

Stress Ratios and FAD for 304SS joints

Fig.5 Plot of the stress ratios at failure for all tested specimens. Lap shear test results from the previous investigations [6,7] are marked with "x" and denoted with asterisk in the legend. As one can see all experimental results are located noticeably far away from the lower bound FAD. Consequently, the region inside the FAD line can be considered a "safe" zone.

It is quite clear that FAD line is very conservative and quite adequate to be used as lower bound FAD even for 304SS

brazed with pure silver. All BAg8-brazed joints tested higher than the Ag-brazed ones and, therefore, are located further away from the FAD line.

Titanium Specimens

Tensile Ultimate Strength (TUS) of tested butt brazed specimens varied between 22 and 29 ksi (153 and 198 MPA). Following similar statistical analysis used for stainless steel specimens, σ_o was determined to be 16 ksi (110 Mpa). Shear strength was measured on single lap shear specimens having different overlap lengths, as per AWS C3.2 [9] and determined to be 8 ksi (55 Mpa), as described in [4]. In case of titanium specimens, it was decided to adopt a more conservative approach and use maximum principal and maximum shear stresses acting at any point within the braze plane. These stresses were calculated using FEA and hand calculations, as described in more details in reference [4]. A combined plot representing the FEA and hand calculation results are shown in Fig. 6. As one can see there is a good agreement between FEA and hand calculated stress values and/or stress ratios. Stress ratios R_σ and R_τ were calculated as:

$$ R_\sigma = \frac{\sigma_1}{\sigma_0} \ \ and \ \ R_\tau = \frac{\tau_{max}}{\tau_0}, $$

where σ_o and τ_o are 16 ksi (110 MPa) and 8 ksi (55 MPa) respectively. σ_1 is the first principal and τ_{max} is maximum shear stresses acting in the brazed joint.
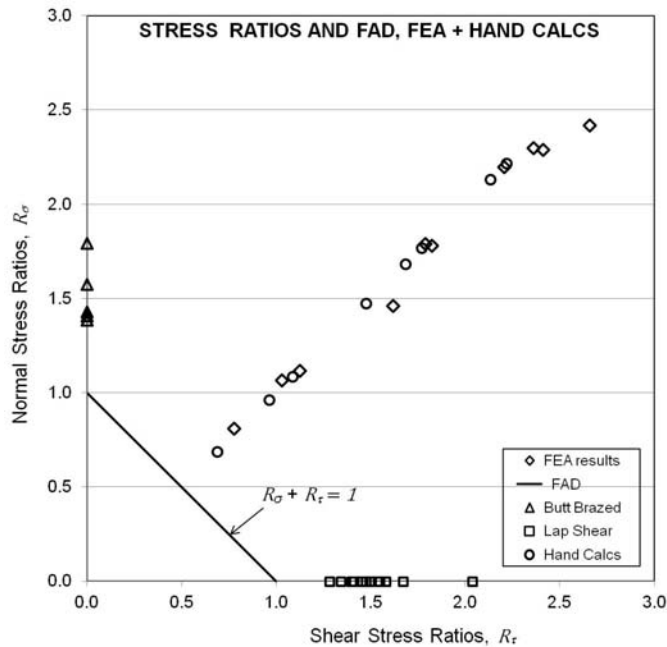

Fig.6 Stress ratios at failure evaluated using FEA and hand calculations. Both methods resulted in very similar stress values. Each symbol represents a combination of stress ratios estimated for a different T-specimen failed under specific loading conditions.

Conclusions

1. The Failure Assessment Diagram (FAD) based on eq.(1) can provide a very conservative estimate of safe combination of shear and tensile stresses in brazed joints subjected to static loading conditions.
2. Such conservatism is justified by a large scatter in mechanical properties of the brazed joints, even when determined by testing the standard test specimens
3. A degree of conservatism of FAD can be controlled by the level of conservatism used to estimate brazed joint allowables. For example, A-basis allowables will result in the most conservative FAD
4. The applicability of FEA analysis to determine tensile and shear stresses in brazed joints was validated using DIC.

Acknowledgements

References

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