FLAW TOLERANCE IN LAP SHEAR BRAZED JOINTS – PART 2

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ABSTRACT

This paper presents results of the second part of an on-going effort to gain better understanding of defect tolerance in braze joints. In the first part of this three-part series, we mechanically tested and modeled the strength of the lap joints as a function of the overlap distance. A failure criterion was established based on the zone damage theory, which predicts the dependence of the lap joint shear strength on the overlap distance, based on the critical size of a finite damage zone or an overloaded region in the joint. In this second part of the study, we experimentally verified the applicability of the damage zone criterion on prediction of the shear strength of the lap joint and introduced controlled flaws into the lap joints. The purpose of the study was to evaluate the lap joint strength as a function of flaw size and its location through mechanical testing and non-linear finite element analysis (FEA) employing damage zone criterion for definition of failure. The results obtained from the second part of the investigation confirmed that the failure of the ductile lap shear brazed joints occurs when the damage zone reaches approximately 10% of the overlap width. The same failure criterion was applicable to the lap joints containing flaws.

KEYWORDS

Braze Joint, Lap Shear, Flaw, Damage Zone, Failure Criterion, FEA

INTRODUCTION

At the present time, the influence of various flaws on the load carrying capability of the brazed joints is not well understood. Also inadequate is our methodology of assessing strength of the actual brazed joints containing flaws. Although several industrial and government brazing quality standards, such as American Welding Society (AWS) C3.3, C3.4, C3.5, C3.6, C3.8 and MIL-B-007883C, do stipulate maximum acceptable flaw size and its location within the joint, they are not very applicable in situations where one needs to determine load carrying capacity of the long structural joints containing flaws.

Over the years, it has been well established experimentally that the shear strength of the brazed lap joints is a function, keeping everything else constant, of the joint overlap (Refs.1-8). In general, the relationship between the shear strength and overlap is expressed graphically as shown in Fig. 1. It is not clear, however, if the lap joints containing flaws would exhibit similar

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Goddard Space Flight Center, Code 541, Greenbelt , MD 20771, USA.
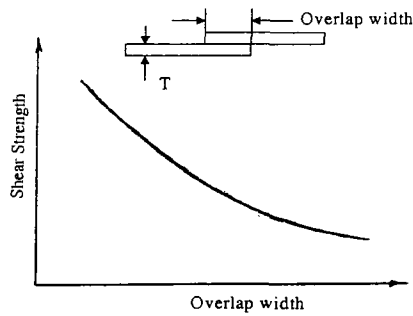
Fig.1 General behavior of ductile lap shear brazed joints. T is the thickness of the base metal.

behavior. In other words, does the lap joint containing a defect have the same strength as the defect-free joint whose overlap area is reduced by the size of the flaw? In order to answer this question and to develop an engineering methodology of assessing load carrying capability of the structural joints with the flaws, one needs to understand what causes the lap joint to fail. Is it a case of simple overload when the failure occurs as soon as some stress within the lap joints exceeds a certain critical value? Or could it be a more complicated situation requiring a stress overload over a certain area of the joint, pointing to the existence of a critical size damage zone?

In the first part (Ref. 9) of this three part investigation (Part 1 hereafter), the authors showed that the experimental results of testing brazed lap shear specimens correlated quite well with the analytical results obtained by elasto-plastic FEA employing damage zone failure criterion. The size of the damage zone was determined to be approximately 10% of the joint area. The results of Part 1 are summarized below:

- At small overlaps (equal to or less than 0.5T, where T is the thickness of the base metal) stress distribution within the joint is uniform
- Joint strength is not sensitive to gap sizes at least in the range of 0.001- 0.008 in (0.025 - 0.2 mm)
- Failure occurs in the filler metal for overlaps as wide as 5T
- Von Mises* stress of the 0.5T joint can be used as a critical value to define failure.
- It appears that the joint fails if von Mises stress exceeds the critical value over 10% of the overlap width. Hence, the damage zone can be used as failure criterion.
- The 10% damage zone rule checks well against stainless steel/silver filler metal braze joints

In the current study we wanted to verify the results obtained in Part 1 and to see if the damage zone criterion can be used to determine the strength of the lap joints containing flaws.

EXPERIMENTAL AND FEA PROCEDURES

The test specimens were machined using electrolytic nickel-plated 2.3 mm (0.090in) thick 347 stainless steel sheet and commercially pure silver filler metal. The plating thickness was approximately 0.0005 inches (0.013mm) Brazing was performed in a vacuum furnace. The fabrication of the test specimens was identical to that in part one. The only difference was in the test specimen width, as shown in Fig.2. In this study we used 25.4 mm (1 in) wide specimens as opposed to 12.77 mm (0.5 in) width pieces employed in part one. This change was made to see if the test specimen width would affect the correlation between the damage zone-based analysis

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* von Mises stress is one of yield criteria that defines the initiation of the plastic flow under complicated loading conditions. It is widely used in elasto-plastic finite element analysis.

and the experimental results. Also, from the practical considerations, introduction of controlled sized flaws was easier to do in the wider specimens. A total of 8 flaw-free lap shear test specimens were fabricated with the overlap width ranging from 0.5T to 5T. The purpose of these test specimens was to verify the results of Part 1 of the investigation. Ten additional test

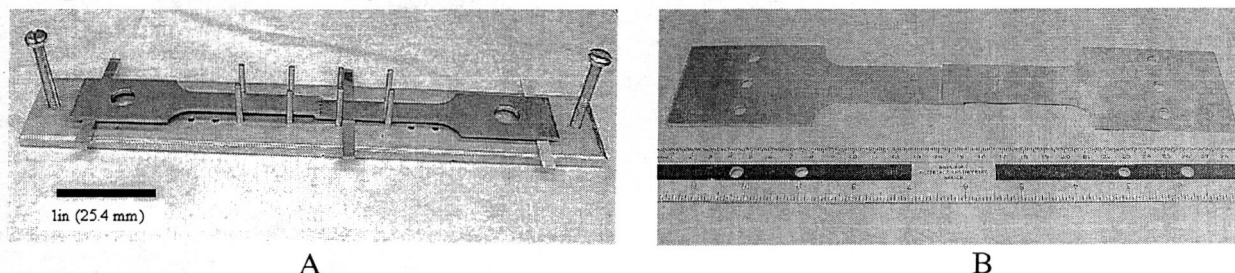Fig.2 Typical brazing fixture used in fabrication of the Part 1 0.5 in (12.7 mm) wide test specimens (A) and 1 in (25.4 mm) wide specimens (B) in the current work, Part 2.

specimens were fabricated with the constant overlap of 5T containing controlled flaws introduced into the joint area with the help of the stop-off paint (see Fig.3). All test specimens were loaded in shear and pulled to failure.
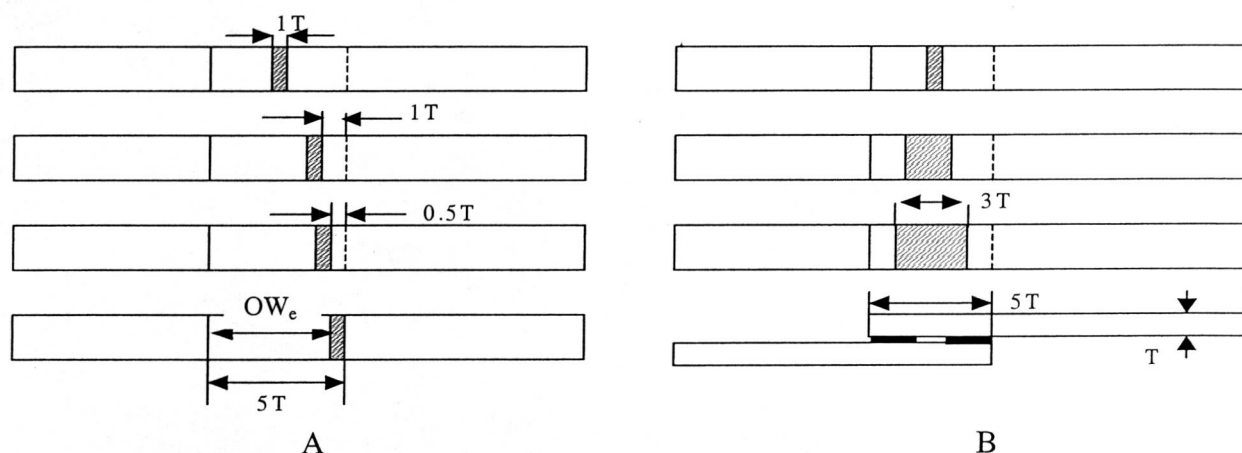

Fig.3. Moving 1T flaws (A, equivalent overlap width $OW_e = 5T - 1T = 4T$) and expanding flaws (B) introduced in the brazed joints. All flaws were transverse and extended all the way through the joint length, as shown on the side view. Total overlap width was maintained at 5T. All expanding flaws were located in the middle of the joints. For simplicity all specimens are shown schematically as rectangles.

Finite Element Analysis (FEA)

The finite element analysis was performed using COSMOS/M software. A four-node elasto-plastic plane strain element was used throughout the analysis. In order to closely simulate the material behavior, true stress-strain properties of the materials (347 stainless steel and silver) were obtained in Part 1 of this investigation. A perfect interface bond was assumed as a result of merging every node at the interface. The loading process was accomplished by applying a uniform displacement at one end of the FEA model to simulate the tensile test. Normally, the loading process consists of one hundred or more incremental iteration steps. Tensile load was

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obtained by integrating the longitudinal stress of the elements on the loading end at each desirable step. Elemental von Mises stress was used to represent the stress level inside the filler

metal, which is an average of von Mises stresses of nodes inside each element. The elemental von Mises stress was found to be uniform inside the filler metal for FEA models with very short overlap distance (0.5T or less), as shown in Fig.4. Therefore, the ultimate von Mises strength of the filler metal was obtained by comparing the results of FEA model and mechanical test of 0.5T overlap specimens.
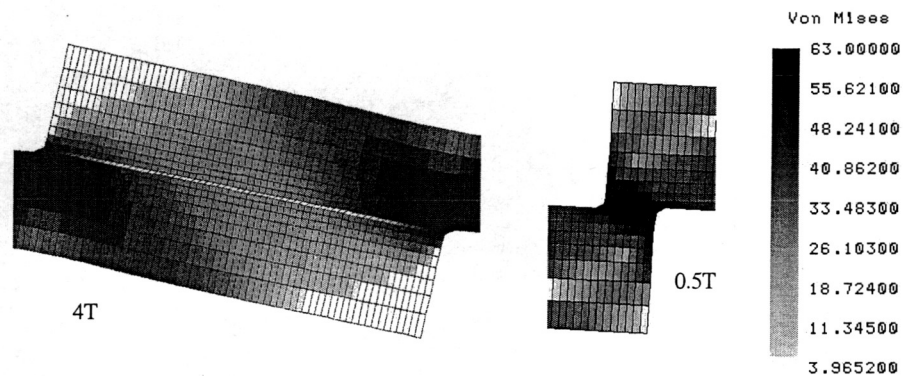

Fig.4 Distribution of Von Mises stress (Ksi) in 0.5T and 4T overlap joint at failuré load.

The loading of the FEA computer model was stopped as soon as the simulated load reached the value of the failure load determined experimentally on 0.5T overlap test specimens. The ultimate von Mises strength of the filler metal obtained this way turned out to be 63 ksi (434 Mpa).

RESULTS AND DISCUSSION

Shear Tests

All test specimens failed in the braze joint, i.e. fracture path was exclusively within the filler
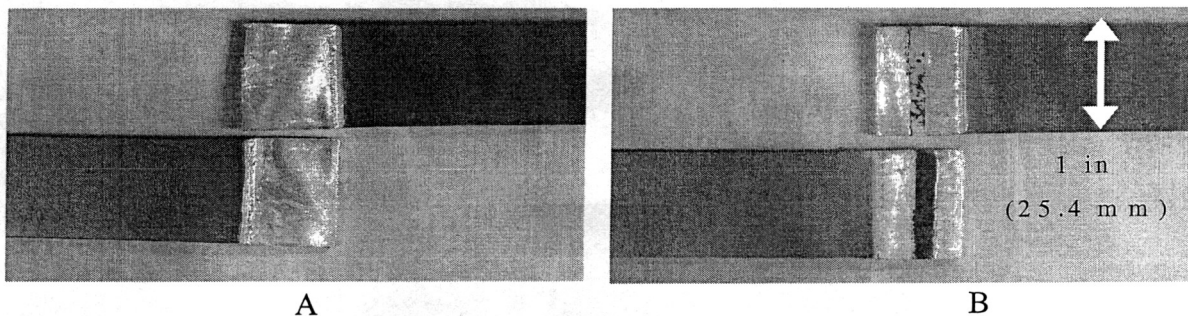

A   B

Fig. 5. All tested specimens containing no flaws (A) as well as the ones with the controlled flaws (B) fractured through the filler metal. Stop-off paint was used to introduce flaws in the overlap prior to brazing. Filler metal strip was pre-placed between the faying surfaces.

metal (see Fig.5) The test results are summarized in figures 6, 7 and 8. Actual overlap widths measured after brazing were somewhat different from the nominal overlaps of 1,2,3,4 and 5T intended for these test specimens, since the brazing fixture used in this study allowed for a free
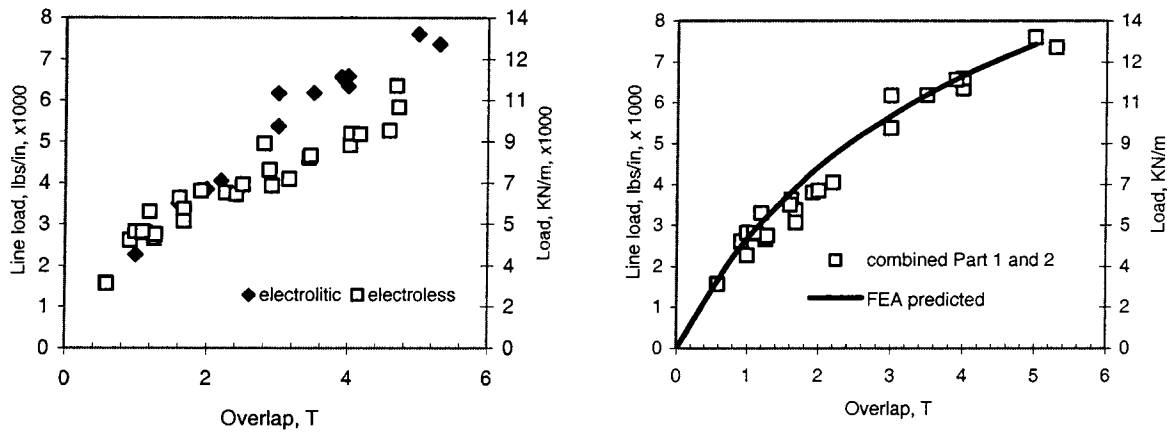
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Fig. 6 Failure load (expressed as line load) as a function of the overlap displaying the combined results from Part 1 and Part 2. In (A) it is evident that for the overlaps exceeding 2T electroless Ni plated specimens deviated from the trend and showed lower strength than the electrolitically plated ones. In (B) all electroless specimens with overlaps larger than 2 T were removed to show the data with the similar trend. An excellent agreement between the combined data and the analytical "master" curve obtained using FEA analysis based on the 10% damage zone.

movement of the blanks in the longitudinal direction during brazing, as shown in Fig.2. Comparing the results of the shear test performed on the 1 inch (25.4 mm) wide flaw-free specimens in this study with the result from Part 1, it appears that the electrolytic plated Ni specimen tend to break at the higher loads, especially in the lap joints with the overlap widths exceeding 2T. If the results of both Part 1 and the current study are plotted on the same graph, this tendency is particularly evident, see Fig. 5(a,b). Since the brazed joints in the current investigation were twice as long as the ones used in Part 1, the values of the failure loads were divided by the length of the brazed joint. Therefore, the plots in Fig.5 show load values per unit length of the test specimens or the "line load" as sometimes referred to in the industry. The same results can be displayed in terms of the ultimate shear strength as a function of the overlap widths for all types of specimens tested in Part 1 and the current work (see Fig. 7)
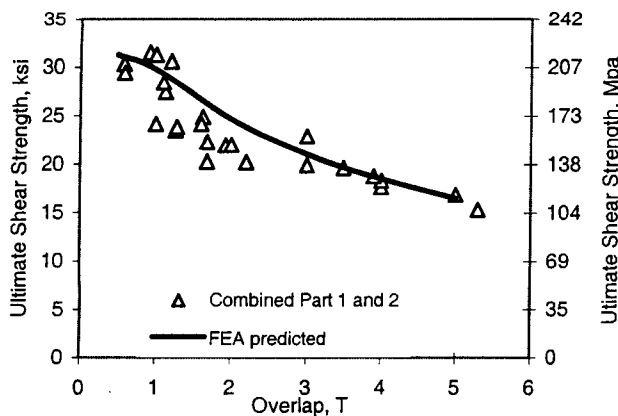

Fig.7 Combined results of Part 1 and Part 2 plotted in terms of the Ultimate Shear Strength of the brazed joints as a function of the overlap width.

The line load nomenclature was also used to plot the test results for the specimens containing flaws (see Fig. 8). The load at failure was plotted as a function of the remaining overlap. The remaining overlap is the length of the overlap excluding flaw, as shown in Fig.3. In one case, the 1T long transverse through flaw was moved incrementally from the middle of the 5T overlap to the edge of the braze joint. Another set of specimens consisted of the joints contained 1T, 2T and 3T -wide transverse through flaws located in the middle of the 5T overlap. The failure line loads for both cases are compared

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with the analytical values predicted by FEA based on the 10% damage zone failure criterion.

Again, good agreement exists between the experimental results and the FEA predicted values. The test results for the specimens with the controlled flaws are plotted in Fig.7 along with FEA
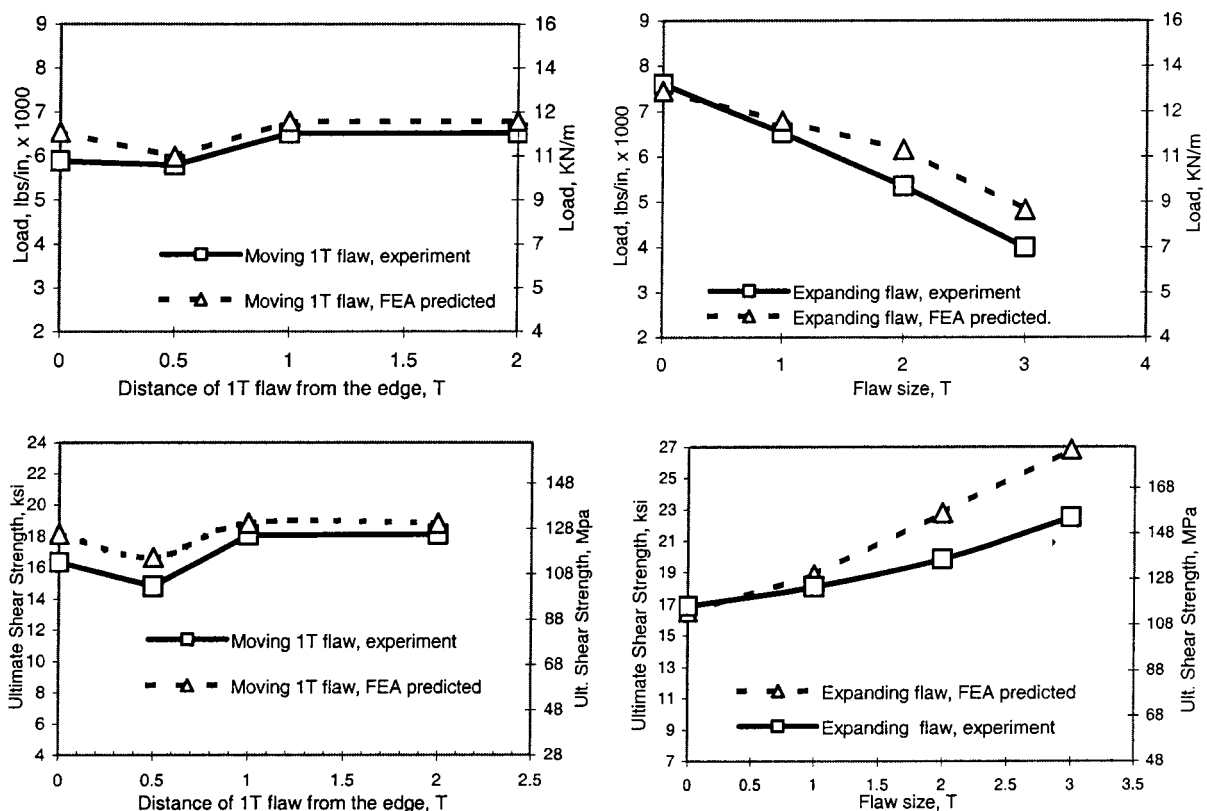

Fig.8.Failure load (top) and shear strength (bottom) as a function of the flaw position (left) and flaw size (right). These data are compared with the theoretical (solid line) and experimental (dashed line) values obtained for the joints containing no flaws and having the overlap areas equivalent to the bond areas in the joints containing flaws.

predicted values of the failure loads and ultimate shear strengths. In one case, the 1T flaw was incrementally moved from the center of the joint all the way to the edge, as shown in Fig.3a. Another case consisted of specimens with the flaws located in the center of the joint, but the flaw size was incrementally increased (see Fig. 3b). These results corellate quite well with the strength values for the flaw-free joints having overlap widths equivalent to the remaining overlap width joints containing flaws. In other words, $OW_e = 5T - $ Flaw Width, where OW_e is the equivalent overlap width and 5T is the total overlap width maintained constant for all the specimens containing flaws.

DISCUSSION

Comparison of the experimental and analytical results shows very good agreement between the measured and predicted strength of the lap shear joints with or without flaws. The predicted values were obtained using FEA assuming the 10% damage zone failure criterion. As in Part1, the von Mises stress distribution within the normalized overlap distance was plotted for the

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specimens with various overlaps at their respective failure loads, as shown in Fig.9. Again, as in Part 1, all the curves in Fig.9 crossed the ultimate von Mises stress line of about 63 Ksi (434 Mpa) at the same point, located approximately 5% of the overlap width away from each end of the joint. Based on this observation, the size of the damage zone was determined to be 10% of the overlap width. The damage zone failure criterion is not a new concept. In fact, the zone-based failure criteria are used quite extensively in treatment of adhesively bonded structural joints (Ref.10). For example, the failure of the adhesive joints is said to occur when the maximum tensile or shear stress exceeds certain critical value over a finite zone. The results of our study provide clear evidence that the damage zone failure criterion can be successfully used for the strength analysis of the ductile lap shear braze joints. Since the braze joint under load experiences a combined action of shear and peel, and undergoes elasto-plastic deformation, we elected to use von *Mises stress over a finite zone as the most* convenient criterion of failure. We applied this concept to the experimental results reported by other researchers that brazed 304 stainless steel with the AWS
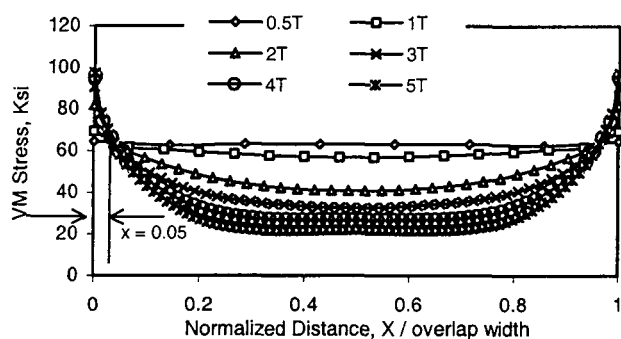

Fig.9 Distribution of von Mises stress within normalized overlap at failure load. According to this graph, the specimens fail when the VM stress exceeds its critical value over the zone of about 5% from each end.
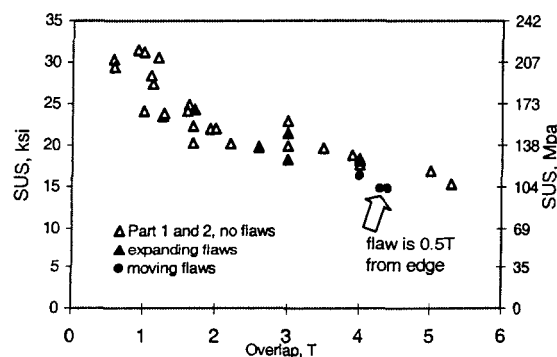
BAg13 filler metal (Ref.2).

Fig.10 Good agreement between the data by Bredzs and Miller (Ref.2) for lap shear specimens brazed at two different temperatures and predicted SUS using a 10% damage zone.
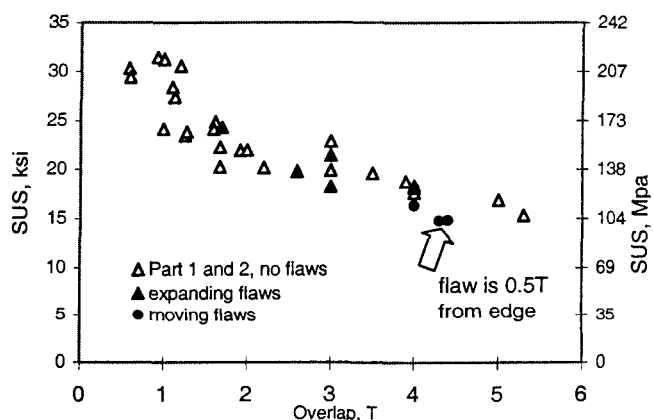

Fig.11 Strength of the joints containing flaws (filled symbols) compares quite well with the joints without flaws (open symbols) possessing an equivalent bond area.

Fig. 10 shows a very nice correlation between the classic data and our 10% damage zone failure model. Applying the 10% damage zone criterion to the joints with the controlled flaws also demonstrates its reasonable applicability to the analysis of a braze joint with defects. Fig. 8 shows fairly good correlation between the experimental and the FEA predicted values. An interesting observation was made while testing and analyzing the specimens containing an 1T wide flaw moving from the middle of the overlap to the edge of the joint. Both the experimental

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and the finite element analysis indicate that the lap joint shear strength drops as the flaw gets within 0.5T from the joint edge (see Fig. 8 and 11). It is not clear why this happens. Perhaps the fact that the flaw is approaching the damage zone, which, in our case, is 10% of the total overlap (i.e. 5T x 0.1 = 0.5T) may be responsible for this drop. Further review of the results presented in Fig.11 indicate that the strength of the lap joints containing the controlled flaws can be estimated as the strength of the flaw-free joints reduced by the area of the defect. For example, the strength of the 5T lap joint containing a 1T wide center flaw seems to be no less than the strength of the 4T joint containing no flaws! Therefore, at least for the family of austenitic stainless steels brazed with the ductile silver or silver-copper based filler metals, the strength of the lap shear joints containing flaws can be viewed, for the most part, as simply a bond area reduction issue. A case when the flaw location is approaching the damage zone may require a separate treatment. It is worth mentioning that our FEA is based on a ductile overload type failure of the braze joint. The influence of fracture mechanics is not considered in our model. This fact may be important when the large flaws are present in the bond area of the braze joint. Perhaps the fracture mechanics considerations could be responsible for the slight over-estimation of strength by the FEA in the joints containing progressively expanding flaws, as can be seen in the lower right graph in Fig.8. Finally, it should be pointed out that the specimens with the short overlaps showed more experimental scatter than those with the wide overlaps. As the overlap width becomes smaller, the relative error of measuring the actual overlap width increases, causing an increase of the shear stress scatter, since the joint area is a multiple of the overlap width and the joint length. This difficulty was mentioned previously (Ref.11) and perhaps can be blamed for the large scatter of the test data reported in the literature for specimens with the short overlaps.

CONCLUSIONS

The results of this work verified that the damage zone can be successfully used as the failure criterion for deformation of ductile lap shear braze joints. The behavior of the joints containing flaws is also consistent with the damage zone concept, although in the case of large flaws, their strength is somewhat reduced possibly due to fracture mechanics considerations. Internal discontinuity reduces the strength of the ductile lap shear braze joint by the amount proportional to its area (accept for flaws located very close to the joint edge). More work is required to assess a potential benefit of using the damage zone failure criterion in the quality control of manufacturing of the structural brazements and engineering practices of testing shear strength of the braze joints. Plans for the third part of the study include validation of the damage zone failure model on full scale brazed structures. Also, an attempt will be made to simplify an existing methodology for measuring shear strength of the braze joints.

ACKNOWLEGEMENT

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