A Comparison of Lap Shear and Pin-Collar Specimens for Evaluating A286 Stainless Steel Brazes

There is good shear strength agreement between the two geometries for ductile filler metal, but not so with brittle-acting filler metal

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ABSTRACT. Shear specimens are used to evaluate the quality of brazed joints, even though using these data for design is difficult. In this study, the standard AWS (American Welding Society) lap shear specimen is compared to the pin-collar specimen proposed by IIW (International Institute of Welding). Brazed joints of nickel-plated A286 stainless steel were prepared using filler metals BAu-4 and BNi-2. Other variables examined include: braze joint clearance, specimen overlap, and post-braze heat treatment. For the ductile brazes evaluated in this study, the shear strengths measured using different specimen geometries show good agreement for comparable overlaps. Furthermore, these strengths are consistent with torsion results from these braze systems. For brittle brazes, the shear strengths measured using the different specimens show poor agreement. This difference in the sensitivity of measured shear strength to specimen geometry can be explained if failure of ductile brazes is controlled by plastic deformation, *i.e.*, shear stresses, while failure of brittle brazes is controlled by fracture toughness, *i.e.*, normal stresses. For both the lap shear and pin-collar geometries, regimes of constant or near constant shear strength are found at small specimen overlaps. Some concerns regarding conventional AWS lap shear testing are discussed.

Background

For more than 30 years, brazing professionals have debated the "best" specimen for evaluating braze joints. Often, specimen designs are selected based on convenience, availability of material, or similarity to some actual component. A problem arises because when unusual specimen geometries or test conditions are used, it is difficult to transfer that data to any other circumstances. In 1976, Peaslee (Ref. 1) reviewed several of the specimen designs discussed in the literature and urged that a single design be standardized. He recommended that, in the absence of a better choice, the single lap shear geometry be used to measure braze shear strength.

There are many advantages to using a lap shear specimen. These advantages include: the existence of an American Welding Society specification (Ref. 2) describing the fabrication and testing of lap shear specimens; over 50 years of literature data on a variety of brazements based on lap shear testing; and minimal cost and skill required for the preparation and testing of these specimens, relative to other designs. Lap shear specimens provide designers with a direct measurement of the overlap required to induce base metal failure during lap shear-like loading.

Conversely, there are disadvantages to using a lap shear specimen. Probably the greatest drawback to this specimen design arises from the difficulty in interpreting the physical meaning of the apparent shear strength at failure (failure load divided by shear area). Numerous investigators (Refs. 2–4) have observed that the apparent lap shear strength decreases as the specimen overlap increases. During mechanical testing, the braze plane rotates as much as 30 deg, relative to the stress axis, which loads the braze with a combination of shear and peel (normal) stresses. It is not well understood whether the apparent strength decrease with overlap arises from (1) the bending (rotation) of the specimen (and the implied complex stress state), (2) the stress concentrations which generally exist at any sharp corner, or (3) some combination of factors.

Since it is difficult to avoid stress concentrations at joints, most of the "improved" specimen designs are aimed at eliminating or minimizing specimen bending. For example, Datta (Ref. 5) uses a single lap shear specimen geometry but restrains out-of-plane rotation with external fixturing. This concept solves the geometric problem introduced by rotation, but complicates any analysis of braze-plane stress state, since localized compressive transverse stresses from the restraining fixture must be added to the tensile lap shear stress. The complex stress state that arises is not necessarily undesirable, since the effect of stress state on braze failure is not clear. Other specimens designed to minimize macroscopic bending are the double lap shear (tuning-fork) specimen, the symmetric (stepped) lap shear specimen (Ref. 6), and the pin-collar specimen (Ref. 7). In each case, although the net bending moment on the whole specimen may be small or

KEY WORDS

Braze Shear Specimen
Lap Shear Specimen
Pin Collar Specimen
Brazed Joint Quality
AWS Lap Shear Test
Specimen Design
Lap Shear Strength
A286 Stainless Steel
BAu-4 BNi-2 Filler
AWS IIW Braze Tests

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Table 1—Compositions (wt-%)

	Fe	Ni	Cr	Mo	Ti	Au	B	Si
Base metal – A286 SS	57.0	25.0	14.0	1.5	2.2	–	0.006	0.3
Nickel – electroplated	–	100	–	–	–	–	–	–
Braze filler metal – BAu-4	–	18.0	–	–	–	82.0	–	–
Braze filler metal – BNi-2	3.0	82.0	7.0	–	–	–	3.0	4.5

zero, some off-axis loading does exist at the braze plane. The influence of specimen design on apparent strength of solders has been investigated by MacKay and Thwaites (Ref. 8) and Thwaites and Duckett (Ref. 9). They found that single lap shear, double lap shear and pin-collar geometries yield similar shear strengths for Cu soldered with Pb-Sn. Again, it should be remembered that even if specimen bending were eliminated, the effect of braze-plane rotation on apparent shear strength has not been established. One of the goals of the present study is to clarify the relative importance of specimen bending versus edge stress concentration. Of the two commonly used zero-net bending moment geometries – double lap shear and pin-collar – the pin-collar specimen is found to be the easiest to fabricate reproducibly, and the axisymmetric shape will make any follow-up analysis more straightforward. For these reasons, the pin-collar design was selected for detailed study in this program.
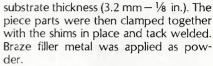
The attention given to the problem of interpreting apparent shear strength detracts from a close examination of the reasons for using a braze specimen in the first place. These reasons include: optimizing fabrication procedures; monitoring production quality; generating design information; and comparing different filler metals. To a large extent, the appropriateness of a specific specimen design may depend on the success with which the specimen meets these other criteria. This point will be expanded upon at the end of this report.

Experimental Procedure

In this study, A286 stainless steel was brazed using two commercial braze filler metals, BAu-4 and BNi-2. Both fillers have been used for jet engines and other critical applications. The A286 stainless steel was selected for this experiment for two reasons. First, A286 is used extensively by industry, so the brazing data may be of value to the design community. Second, A286 can be precipitation-hardened (raising the base metal yield strength without changing the braze microstructure). The influence of base metal strength on the apparent braze shear strength was one factor examined.

For all specimens, the A286 base metal was nickel plated to promote filler metal wetting and flow. Typical compositions for the materials selected for this study are given in Table 1.

The test specimens were fabricated by following published specifications. Lap shear coupons were fabricated to AWS C3.2-82 (Ref. 2). Braze joint clearance was controlled by inserting stainless steel shims at the width edges of the coupons. Since BNi-2 filler metal dissolves nickel plating, the final braze thickness for the BNi-2 specimens was the sum of the shim and twice the thickness of the nickel plating. The final braze thickness for the BAu-4 specimens was slightly greater than the shim, due to limited nickel dissolution. Coupons were prepared by adjusting the overlap manually to span the range 1 mm ($\frac{1}{3}$ t) to 6 mm (2t) (0.04 to 0.24 in.), where t is the lap shear

substrate thickness (3.2 mm – $\frac{1}{8}$ in.). The piece parts were then clamped together with the shims in place and tack welded. Braze filler metal was applied as powder.

The BNi-2 lap shear specimens were made in two iterations. During the first iteration, the nickel plating was too thick and not uniform in thickness. As a consequence, the final braze joint clearances ranged from 125 to 175 microns and all of the specimens had a eutectic (multiphased) microstructure, as discussed in the next section. During the second iteration, the nickel thicknesses were controlled, and the desired range in microstructures was achieved. Data from the first iteration are referred to as "previous data."

Pin-collar coupons were fabricated to ISO T/C 44/SC3 234E (Ref. 7), with a few minor modifications. The dimensions of the coupon piece parts are shown in Fig. 1. Concerns regarding the specific dimensions selected for the pin-collar specimen have been raised by others, and some of these concerns are addressed in the Appendix. Braze joint clearance was preset by careful machining of the female piece part, and the final overlap (h) was varied during a post-braze machining operation. The two piece parts were slip fit together, a procedure which minimized angular misalignment of the parts. As with the lap shear specimens, filler metal was applied as powder.

All of the brazing was done in vacuum and without flux. Specimens prepared using the BAu-4 filler were soaked at 900°C (1650°F) for 15 min and then brazed at 1015°C (1860°F) for 15 min. Specimens prepared using the BNi-2 filler were soaked at 930°C (1710°F) for 20 min, brazed at 1065°C (1950°F) for 15 min, and then given an immediate diffusion treatment at 1025°C (1875°F) for 2 h. Cooling rates were about 100°C per minute. Factors such as surface finish (Ref. 10) or plating bath composition were controlled, as well as practicable. Nonetheless, each set of specimens was manufactured at different times, and thus the results of this study automatically incorporate typical variations in braze fabrication, that is, nickel plating bath and thickness, assembly consistency and furnace cycle.

One-half of the coupons of both specimen geometries were precipitation-hardened at 720°C (1325°F) for 16 h in vacuum. Since the aging temperature is well below the brazing temperature, no microstructural changes should accompany the aging treatment. After all heat treatments were complete, specimens were machined to final shape. For the pin-collar design, the braze fillet was machined off and a reference plane perpendicular to the pin axis was established. A predetermined overlap length was
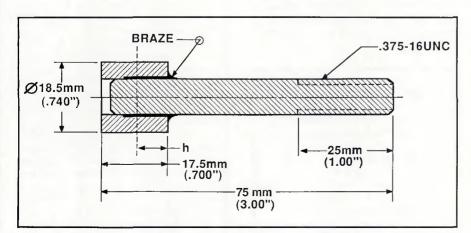

Fig. 1—As-brazed pin-collar specimen design. After brazing, the fillet is removed and the end machined to a predetermined overlap (h)

obtained with a parting cutter, again using the axis of the pin to maintain perpendicularity.

The lap shear specimens were mechanically tested by pin loading per the AWS specification. For the pin-collar specimens, a special test fixture was built using spherical washers to support the top and bottom surfaces of the collar. The top washer set was finger-tightened against the unloaded end of the specimen to restrain bulging, while the bottom washer set was used to minimize off-axis loading.

The overall test program is summarized in Table 2. Features varied include specimen geometry, filler metal composition and properties, and fabrication practice. Examining this many features complicates the study. Nonetheless, it is likely that these features are interactive, and only by understanding how each feature relates to all of the others can the predictions of this study be confidently extended to other material combinations.
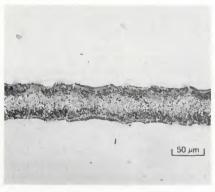
Braze Microstructures

Typical A286/BAu-4 microstructures are shown in Fig. 2. The joint clearances, although larger than anticipated, range from 50 to 160 microns and span the range generally encountered in practice. The observed microstructures are consistent with the Au-Ni phase diagram (Ref.
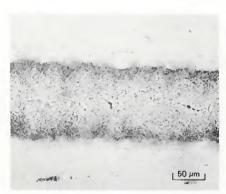
Table 2—Test Program

Feature Examined	Variable/Range	
Specimen geometry	Lap shear	AWS
	Pin-collar	IIW
Specimen overlap	1–6 mm	⅓ t–2t for lap shear
Filler metal composition	BAu-4	gold-nickel, always ductile
	BNi-2	nickel-silicon-boron, ductility depends on joint clearance
Braze joint clearance (target)	25–125 microns	BAu-4 filler metal
	50–150 microns	BNi-2 filler metal
Filler metal ductility	Ductile	BAu-4 all joint clearances, BNi-2 single-phase only
	Brittle	BNi-2 multiphased (large joint clearances)
Base metal yield strength	As-brazed	Y.S. = 276 MPa (40 ksi)
	Aged	Y.S. = 724 MPa (105 ksi)

11). At the braze temperature, the brazing filler metal will dissolve nickel from the plating, and the liquid composition will lie on the nickel-rich side of the solidus minimum. As a consequence, on cooling, the initial grains to solidify adjacent to the plating and base metal will be enriched in nickel, while the remaining liquid at the centerline will be rich in gold. At temperatures slightly below the solidus, the seam will have a single phase (solid solution) microstructure. After phase separation, due to a miscibility gap at approximately 790°C (1450°F), the region adjacent to the plating (with the higher nickel con-

centration) will contain more of the dark-etching, nickel-rich phase than will the center. This description is consistent with the metallography shown in Fig. 2. It is clear from examining this figure that the detailed grain structure, i.e., the specific amounts of gold- and nickel-rich phase, varies as a function of joint clearance. However, in the absence of other information, one cannot predict whether these subtle changes in microstructure will influence shear strength or any other property.

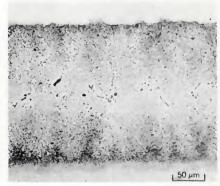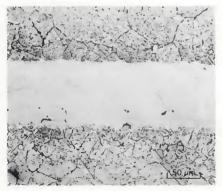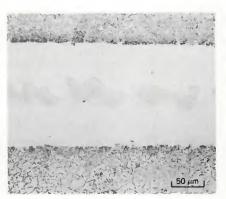The braze joint clearances for the BNi-2 specimens range from 80 to 180 mi-

Fig. 2 — Typical microstructures of BAu-4 brazements, after aging, as a function of braze joint clearance. Base metal, nickel plating and two-phase filler metal can be seen
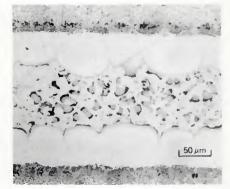

Fig. 3 — Typical microstructures of BNi-2 brazements as a function of braze joint clearance. Filler metal microstructure is not affected by aging. Nickel plating has dissolved into filler metal. Borides and silicides form in base metal adjacent to filler metal and along grain boundaries
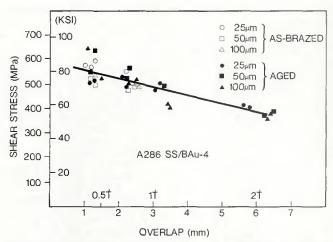
Fig. 4 — Effect of overlap on the apparent shear strength for BAu-4 tested using lap shear geometry. Neither aging nor joint clearance (target) have a large influence on measured strength
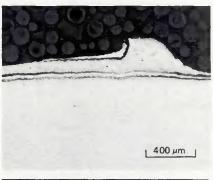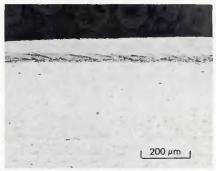

Fig. 5 — Measured specimen rotation at failure for BAu-4 lap shear specimens

crons, inducing microstructures from single-phase solid solution nickel at the narrowest joint clearances to continuous centerline eutectic (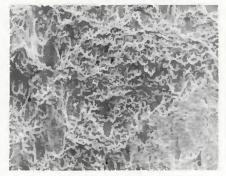hard) phase at the widest. Intermediate joint clearances contain less of this brittle phase. In some cases, only isolated patches are present at the centerline. All of these microstructures are illustrated in Fig. 3.

The interaction between braze filler metal and base metal differs for gold-versus nickel-based compositions. Gold-nickel systems are fairly benign for stainless steels, causing limited grain boundary dissolution. In contrast, nickel-silicon-boron systems allow large amounts of silicon and boron to diffuse into the base metal, generally forming grain boundary borides and a variety of silicides. These particles are brittle, and this near-seam region may show increased susceptibility to crack growth or corrosion.

Results for BAu-4 Filler Metal

Lap Shear

Although each specimen was inspected and measured for overlap, there was still considerable scatter in the lap shear braze data for BAu-4 filler metal. Individual data points are shown in Fig. 4, a graph of apparent shear strength at failure versus braze overlap. Not included in this plot are failure strengths for unaged specimens having large overlaps (1t and 2t) which fail in the base metal rather than through the filler metal. From these data several conclusions can be drawn:

1. The apparent lap shear strength depends on overlap, which is consistent with published literature, and decreases about 28% as the overlap increases from 0.5t to 2t.

2. The apparent lap shear strength does not depend on base metal yield strength. The strengths for as-brazed and aged specimens are essentially identical for overlaps allowing joint failure.

3. The apparent lap shear strength does not depend on braze joint clearance over the range examined.

For this braze system, braze-plane

rotation during testing has no apparent effect on lap shear strength. The rotation of the braze plane was measured after fracture, and is plotted versus overlap in Fig. 5. The difference in the amount of bending between aged and as-brazed specimens is clear and not surprising. Lugscheider (Ref. 12) predicted that this difference in braze-plane rotation should induce a 15–20% drop in as-brazed (large rotation) strength. Although there is considerable data scatter, particularly at small overlaps, no rotation-induced strength drop is seen in Fig. 4.

The lap shear specimens fail in ductile shear. A typical metallographic cross-section and SEM fractograph are shown in Fig. 6. Although the majority of the fracture occurs in the BAu-4 filler metal, in some cases failure actually initiates in the nickel plating (cohesive failure of the nickel). This observation suggests that nickel plating variables, such as plating thickness, bath composition or deposition rate, may influence braze strength. Failure propagates in a straight path through the BAu-4 filler metal, with considerable plastic deformation apparent in the filler metal. The fractograph reveals elongated dimples, indicating shear deformation.

Pin-Collar

Drawing conclusions from the failure strengths of the pin-collar tests is not straightforward, since not all of the specimens failed in the braze plane. The aged brazes all failed in one of two ways. At small overlaps, failure occurred through the centerline of the filler metal; at large overlaps failure occurred in the threads of the pin in a region remote from the braze. None of these large overlap data are included on any of the figures. In contrast, all of the as-brazed pin-collar specimens, small and large overlaps, fail in tension in the base metal adjacent to the braze. These failure paths are illustrat-

Fig. 6 — Metallographic cross-sections and SEM fractograph for BAu-4 lap shear failure

ed in Fig. 7. The large deflection in the as-brazed specimen arises because excessive joint clearance was permitted between the spherical washer and the outside diameter of the pin during mechanical testing. A closer fit of these parts, as recommended in the specification (Ref. 7), will minimize bending and possibly force brazing filler metal failure. Simple analyses of the stress on the deflected braze plane indicate actual shear stresses about 15% below those assumed when dividing load by cross-sectional area.
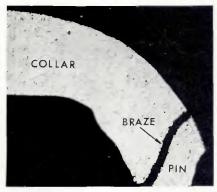
For the above reasons, only pin-collar data from aged specimens are shown in Fig. 8, a graph of pin-collar braze shear strength versus overlap. From this plot, the following conclusions can be drawn:

1. For this geometry, the shear strength is weakly dependent on overlap, decreasing about 50% as the overlap increases from 1 to 6 mm (extrapolated).

2. The shear strength does not depend on braze joint clearance over the range examined, which agrees with the lap shear results.

Much like lap shear tests, braze failures for the pin-collar specimens are ductile. Failure occurs down the centerline of the filler metal. For these specimens, the nickel plating was thin, compared to the lap shear specimens, and no failures initiating in the plating were observed. A typical metallographic cross-section is shown in Fig. 9. The fracture surfaces are heavily smeared during testing, and thus a fractograph is not very informative.
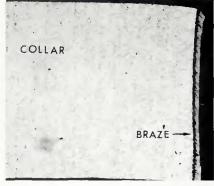
The apparent strengths of the aged

Fig. 7 — Influence of post-braze aging on failure location for BAu-4 pin-collar geometry. As-brazed specimens failed in pin material adjacent to braze at loads higher than their aged counterparts

specimens (braze failure) and unaged specimens (base metal failure) are compared in Fig. 10. The strengths of unaged specimens are comparable to, or slightly greater than, their aged counterparts, which is consistent with the idea of shear stress reduction through braze plane rotation. For unaged specimens, the base metal failure is generally tensile and depends strongly on plastic straining of the collar. This observation suggests that failure results from the discontinuity in plastic deformation between the pin and collar. Under these circumstances, reducing the joint clearance between the spherical washer and specimen diameter may not change the fracture path.

Results for BNi-2 Filler Metal

Joint clearance effects on shear strength can often be attributed to microstructural variations, rather than a geo-

metric effect of clearance. In the section on BNi-2 filler metal, it is convenient to separate the behavior of single-phase braze microstructures from that of multi-phase braze microstructures.

Single-Phase BNi-2

Lap Shear. In many ways, the behavior of single-phase BNi-2 parallels that of BAu-4. The data from lap shear specimens are shown in Fig. 11. The following conclusions can be drawn:

1. The apparent lap shear strength depends on overlap. However, whereas the shear strength of BAu-4 declines by 28% as the overlap changes from $\frac{1}{2}t$ to $2t$, the shear strength of single-phase BNi-2 drops 50%. Further, as the plot indicates, most of the decline in shear strength occurs between overlaps of 3 to 6 mm (0.12 to 0.24 in.). This point will be elaborated upon in the discussion sec-
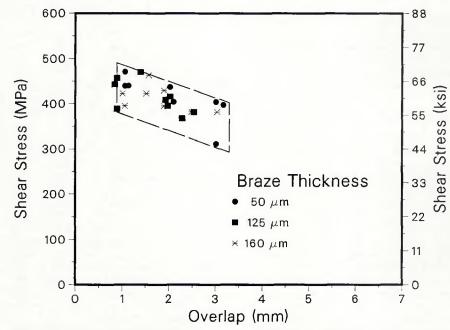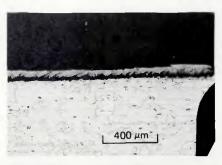

Fig. 8 — Effect of overlap on the shear strength of BAu-4 brazements, using the pin-collar geometry. Only data from aged specimens is shown, since as-brazed specimens failed outside the filler metal. No influence of joint clearance is found
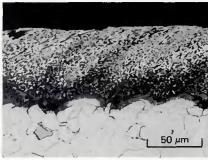

Fig. 9 — Metallographic cross-section for BAu-4 pin-collar failure. Fracture surface is heavily smeared
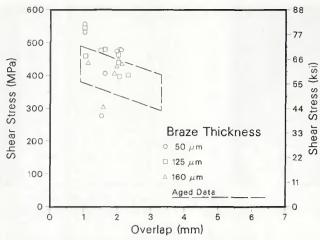
Fig. 10—Comparison of shear strength for as-brazed BAu-4 pin-collar specimens (which do not fail in braze) with aged data from Fig. 8, where failure does occur in joint

Fig. 11—Effect of overlap on the shear strength of single-phase BNi-2 brazements using lap shear geometry. A region of constant shear strength extends up to 3 mm or 1t overlap

tion.

2. The apparent lap shear strength does not depend on base metal yield strength; the shear strength of as-brazed and aged specimens is identical.

The influence of braze joint clearance could not be evaluated for this microstructure.

Single-phase nickel fractures in a ductile fashion, often initiating at the filler/base metal interface and propagating through the single-phase filler metal. The
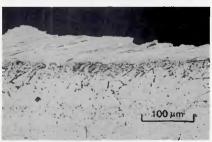

Fig. 12—Metallographic cross-sections and SEM fractograph for single-phase BNi-2 lap shear failure

fracture and fracture path are illustrated in Fig. 12. The single-phase nickel filler deforms considerably prior to fracture. The fractograph reveals a typical ductile shear failure.

Pin-Collar Specimens. All of the pin-collar specimens with single-phase BNi-2 filler metal failed, either through the braze or in the pin threads remote from the braze (in which case the data are not plotted). The data obtained are shown in Fig. 13.

Conclusions from these data are:

1. The shear strength is independent of overlap over the range permitting braze failures.

2. The shear strength is independent of base metal yield strength.

Single-phase nickel fracture morphologies in pin-collar specimens appear ductile. The crack propagates almost exclusively along the filler/base metal interface through a region heavily loaded with silicide and boride particles. Nonetheless, the fracture surface, although heavily smeared, appears ductile. This fracture path is shown in Fig. 14.

Multiphase BNi-2

The behavior of the multiphased BNi-2 contrasts sharply with that for BAu-4 and single-phase BNi-2.

Lap Shear. Lap shear data from specimens with large braze joint clearances (and a hard eutectic phase at the braze centerline) are presented in Figs. 15 and 16. Figure 15 shows the data from the first lot of specimens where the nickel plating thickness was not well controlled. These data are identified on subsequent graphs as "previous data." Figure 16 shows the data from a second, smaller lot of specimens where the nickel plating was thinner and more uniform. From these graphs, the most important conclusions are:

1. The lap shear strength depends

strongly on overlap for both aged and as-brazed specimens. The apparent shear strength drops almost 50% from 0.5t to 2t.

2. Unlike previous types of specimens, the apparent lap shear strength does depend on base metal yield strength, where aged specimens are stronger than unaged specimens. Interestingly, for lap shear specimens the apparent shear strengths of the aged multiphased BNi-2 filler metal are close to those of the single-phase BNi-2 (compare Figs. 11 and 15).

3. The accumulated data from both Figs. 15 and 16 are not adequate to demonstrate an effect of braze thickness on shear strength for multiphased BNi-2 microstructure, even though the limited data on Fig. 16 suggest that thin joint clearances may be stronger than wide joint clearances.

The failure path for multiphase BNi-2 runs down the center of the filler metal and the fracture is brittle. A typical fracture path is shown in Fig. 17. The centerline hard phase is extremely brittle, as indicated by the multiple fractures in the figure. It appears that, where possible, fracture propagates along the interface between the single-phase and multiphase microstructures. This observation may explain why small amounts of eutectic phase are almost as deleterious as large amounts.

Pin-Collar Specimens. The failure strengths of the wide joint clearance BNi-2 pin-collar specimens are plotted in Fig. 18. For this geometry, the single-phase nickel shear strengths are much higher than those multiphased microstructures (compare Figs. 13 and 18). Moreover, the multiphase nickel again breaks up into two groupings, leading to the following conclusions:

1. The shear strength shows very little influence of overlap over the range tested (1 to 6 mm).
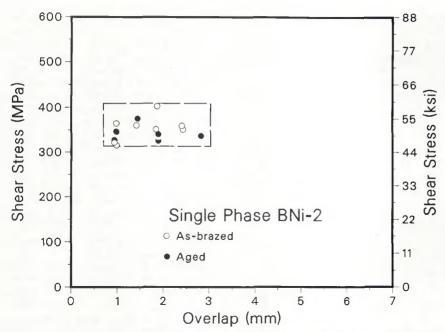
Fig. 13 — Effect of overlap on shear strength of single-phase BNi-2 brazements using pin-collar geometry. At 6 mm overlap specimens broke in region remote from braze

Fig. 14 — Metallographic cross-sections of single-phase BNi-2 pin-collar failures

2. The shear strength depends on base metal yield strength and, as seen with lap shear specimens, the aged specimens appear stronger than the as-brazed specimens.

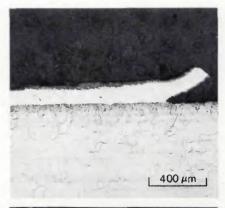3. The thickness of the brittle layer has, at most, a small influence on the shear strength.

The failure path for these specimens is almost identical to that for the lap shear specimens, as shown in Fig. 17.

Discussion

The absolute values of the shear strengths measured in this study are in reasonable agreement with published data. For example, for BAu-4, Eng (Ref. 13) reports a lap shear strength (at 1.5t overlap) of 441 MPa (64 ksi), as compared to 435 MPa (63 ksi), measured in this study. Other literature data based on lap shear testing of this filler metal span the range 414–531 MPa (60–77 ksi). Waldron, et al. (Ref. 14), report pin-collar strengths for BAu-4, using Fe-12Cr-2Mo-2.5Ni alloy as the base metal, of about 350 MPa (51 ksi), for joint clearances comparable to those tested here, at an overlap of 6 mm. Ignoring the overlap dependence suggested in Fig. 8, for reasons to be discussed in the next section, the strength data in this report agree well with those of Waldron.

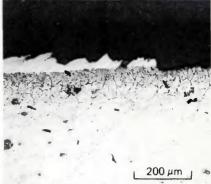The literature data for narrow clearance BNi-2 filler metal are spread over a wide range. This spread in shear strength is consistent with the observations that the strength of Ni-Si-B filler metals increases with increasing time at braze temperature, even for single-phase microstructures (Ref. 15). Evidently, subtle changes in the single-phase microstructure, perhaps involving specific base metal interactions, can influence the shear strength of BNi-2. Thus, Eng (Ref. 13) reports strengths as high as 372 MPa (54 ksi), Pattanaik (Ref. 16) reports values

Fig. 15 — Effect of overlap on shear strength of multiphased BNi-2, using lap shear geometry. These data were obtained during the first iteration of specimen fabrication, and are referred to in other plots as "previous data." The strength difference between as-brazed and aged specimens is clear
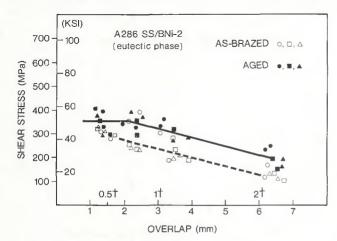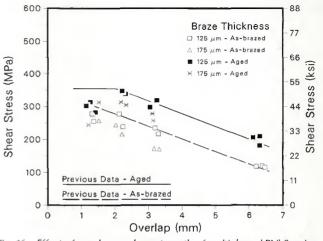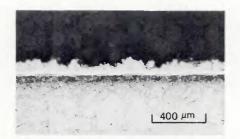

Fig. 16 — Effect of overlap on shear strength of multiphased BNi-2, using lap shear geometry. These data were obtained during second iteration of specimen fabrication, where nickel thickness was more uniform. Same trends as previous figure
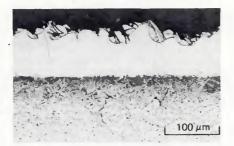
Fig. 17 — Metallographic cross-sections and SEM fractograph of multiphase BNi-2 lap shear failure. Note brittle fracture surface

as low as 179 MPa (26 ksi), and the data from this study fall very close to the values reported by Eng.

The data from the two specimen geometries are compared in Figs. 19-21. The reader is cautioned that a variety of factors relating to fabrication practice could not be controlled. Nonetheless, for BAu-4 and single-phase BNi-2, the shear strengths and trends measured by two

techniques are in good agreement. Consistent with the solder results of MacKay and Thwaites (Ref. 8), the pin-collar strengths are 10–20% lower than those for lap shear. These data are combined with torsion results obtained in our laboratory (Ref. 17) and presented in Tables 3 and 4. The agreement among geometries is discussed further.

For multi-phase BNi-2, the measured shear strengths, and especially the trends, as shown in Fig. 21, are in poor agreement. This lack of agreement is not clarified by including torsion data (Ref. 17) — Table 5. The torsion data for BNi-2 involve relatively few specimens and, therefore, are much less reliable than those for BAu-4.

Specimen Overlap

At the present time, at least within the metals literature, there are no analytical explanations for the dependence of shear strength on overlap. Indeed, in the simplest view, one expects that the load-carrying capability of a shear joint will increase linearly with overlap, i.e., constant shear strength, until a maximum is approached when the load will be carried entirely by the ends of the joint (analogous to joining two sheets using ten rivets in series). (At the critical load the outer two rivets fail, followed by next outermost, etc.) At these large overlaps, additional overlap length (or additional rivets in series) does not contribute to the joint load capacity. At these large overlaps, the apparent shear strength will decrease geometrically. In real materials, the stresses are redistributed either elastically or plastically along the length of the joint. Thus, the load capacity of the joint continues to increase with increasing overlap. At some very large overlap (probably in excess of 10t), a maximum load will be approached, but invariably at these large overlaps, base metal failure

will precede braze failure. This simplified situation is illustrated schematically in Fig. 22. In this figure, the two key variables are the maximum overlap, for which the load carrying capability of the joint increases linearly (labeled Lc), and the slope of the "hardening" curve. At the present time, the quantity Lc and the slope cannot be predicted analytically; however, a limited data survey suggests that, for the lap shear geometry, Lc is about 1t and the hardening slope is about 20–30% of the constant shear strength slope. Notice that the presence or absence of hardening has little effect on the shape of the large overlap region (in the shear stress curve), which generally decreases as 1/overlap, in reasonable agreement with most literature.

The shear stress-overlap data reported here are fairly consistent with the simple picture discussed for Fig. 22. For single-phase BNi-2, the load-carrying capability of the joint increases linearly with overlap, resulting in a constant shear strength over the range from 0.3 to 1t and a geometrically decreasing strength with larger overlaps. These trends hold for both the lap shear and the pin-collar geometries, albeit restricting ourselves to the limited range of overlaps for which the failure occurs in the filler metal. For multiphase BNi-2, the region of constant shear strength extends from 0.3 to 2t overlap for the pin-collar geometry, and although no such "flat" behavior is seen in the lap shear data, it is probable that both of these observations regarding multiphase BNi-2 are fortuitous, for reasons to be discussed later. Finally, for the BAu-4 filler metal, the shear strength versus overlap curve appears to monotonically decrease, although rather slowly compared to the geometric decreases observed by others. It is possible that constant strength regimes exist for BAu-4, using both geometries when the overlap is smaller than 0.6t; however, the scatter
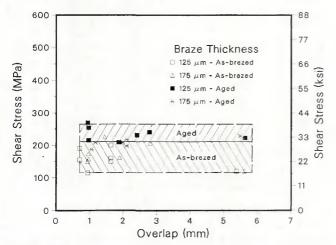

Fig. 18 — Effect of overlap on shear strength of multiphase BNi-2 using pin-collar geometry
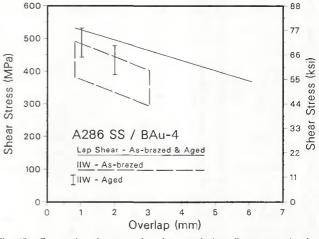

Fig. 19 — Comparison between lap shear and pin-collar geometries for measuring the shear strength of BAu-4 brazements. Trends and absolute values are in reasonable agreement

Table 3—Shear Strength Measurements—BAu-4		
	As-Brazed MPa (ksi)	Aged MPa (ksi)
Lap shear (at 1-mm overlap)	550 (80)	570 (83)
Pin-collar (at 1-mm overlap)	500 (72)	450 (65)
Thin-wall torsion	450 (65)	450 (65)
Solid-bar torsion	530 (77)	500 (73)
Average	508 (73.6)	493 (71.4)
Std. deviation	44 (6.3)	56 (8.2)

Table 4—Shear Strength Measurements—BNi-2, Single-Phase		
	As-Brazed MPa (ksi)	Aged MPa (ksi)
Lap shear (at 1-mm overlap)	390 (57)	390 (57)
Pin-collar (at 1-mm overlap)	360 (52)	345 (50)
Thin-wall torsion	400 (58)	420 (60)
Solid-bar torsion	430 (62)	—
Average	395 (57.3)	384 (55.7)
Std. deviation	28 (4.1)	35 (5.1)

Table 5—Shear Strength Measurements—BNi-2, Multiphase		
	As-Brazed MPa (ksi)	Aged MPa (ksi)
Lap shear (at 1-mm overlap)	290 (42)	340 (49)
Pin-collar (at 1-mm overlap)	150 (22)	230 (33)
Thin-wall torsion	340 (49)	300 (43)
Solid-bar torsion	380 (55)	—
Average	290 (42)	290 (42)
Std. deviation	100 (14)	56 (8.1)

is too large to support that conclusion.

The influence of overlap, on the apparent lap shear strength, observed in this study differs from that described by many others. However, the data reported by Lehrer and Schwartzbart (Ref. 18), using a symmetric lap shear geometry, seem to fit the model presented here. Specifically, at small overlaps (smaller than 1t), a region of almost constant shear strength was observed in their study, as well as in this one, where others find a strength which monotonically decreases. Since our lap shear data seems consistent with the clearly flat pin-collar data, some three possible sources of error in measuring apparent lap shear strength will be mentioned (recognizing the danger of discussing data reported by others). These sources of error are: (1) braze fillet effects, (2) defects and (3) small numbers of samples.

First, and probably most importantly, one must always account for the influence of the braze fillet when calculating the actual shear area. A fillet having a radius of 0.4 mm (1/64 in.) will increase the shear area by about 0.2 mm × 2 × width, or 0.12t for a typical lap shear specimen. Thus, for a base metal overlap of 0.5t, the actual shear area is 0.62t (× width) or 25% larger than calculated, and

the apparent shear strength will be 25% larger than an unfilleted specimen. At overlaps of 2t, the error due to fillet is only 6%, and this effect is lost in normal braze scatter.

For nickel filler metals, there is a tendency to assume that, because the fillet material is brittle, the fillet will crack during lap shear testing and not contribute to the overall strength of the joint. In this study, it was observed that: (1) specimens having small overlaps do not rotate very much, thus minimizing peel on the fillet, and (2) the inherent strength of multiphased BNi-2 is close to that of single-phase BNi-2, at least for lap shear testing. Nonetheless, the flatness of the lap shear strength-overlap curve for single-phase BNi-2 may be due to eliminating the fillet influence via fillet cracking, as discussed above.

For ductile filler metals, such as gold-nickel, most researchers would agree that the strength of braze filler metal in the fillet is comparable to the strength of the braze filler metal in the joint (ignoring alloying), and therefore, fillet strengthening should be predictable. It is interesting to note that the data scatter for lap shear tests is largest at small overlaps (see, for example, Fig. 4). For the specimens used in the bulk of this report, the lap shear

fillet radii were held to 0.4 mm (0.016 in.) (one fillet at each end of the specimen), and the pin-collar fillet radii were held to 0.2 mm (0.008 in.) (one end only — the other end was machined off to vary the overlap distance). For the BAu-4 specimens, the slight slope to the shear strength-overlap curve may be due to the presence of a fillet.

To test this hypothesis, a small number of untested BAu-4 lap shear specimens were located and carefully machined to remove virtually all braze fillet. Shadow-graphic measurements indicate a residual fillet of no more than 0.05 mm (0.002 in.).

The results from testing these limited data are plotted in Fig. 23. At large overlaps, 1t and 2t, the shear strengths of unfilleted specimens are identical to those prepared to the AWS specification. However, at small overlaps, about 1/3t, the apparent shear strength drops considerably when the fillet is removed. The explanation for the low values found in this test is not clear, but the scatter is consistent with the data in Fig. 4: 500–600 MPa range for filleted specimens versus 400–500 MPa range for unfilleted specimens. It seems reasonable to suggest that the lap shear strength may be constant over the range 1/3 to 1t, when fillet effects are
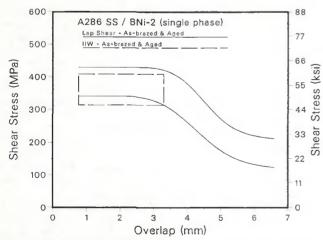

Fig. 20 — Comparison between lap shear and pin-collar geometries for measuring the shear strength of single-phase BNi-2 brazements. Agreement is excellent
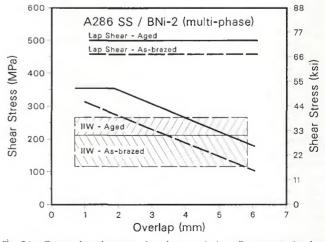

Fig. 21 — Comparison between lap shear and pin-collar geometries for measuring the shear strength of multiphase BNi-2 brazements. Trends and absolute values among the geometries differ substantially
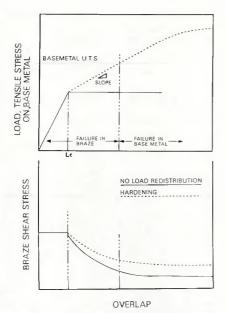
Fig. 22 — Schematic illustration of simple explanation for the effect of braze overlap on the load carrying and apparent shear strength of a brazed joint in the absence of specimen rotation. The tensile stress on the base metal is proportional to the load

properly accounted for. Further, the estimated constant shear strength of 450 MPa agrees well with other data in Table 3. Fillet influence on pin-collar strengths could not be tested experimentally because no specimens were available. It is difficult to envision a mechanism by which the shear strengths measured in torsion should be smaller than those measured in lap shear. For most geometries, stress concentrations lower the apparent strength.

The AWS specification calls out a fillet radius of 0.4 mm (1⁄64 in.) for lap shear specimens. This tight radius generally requires a secondary machining or grinding operation, and it is the author's experience that this requirement is occasionally ignored by researchers. As the fillet radius increases, the slope of the shear strength versus overlap curve increases rapidly. For generating design data, the AWS requirement appears too loose. Two alternate requirements might be: (1) a plunge-type undercut to eliminate the fillet entirely, or (2) a fixed overlap of 1t and a defined radius, which, for the materials in this study, seem to balance fillet effects with the unloading associated with excessive overlap. The version of the IIW specification used in this study did not specify a fillet radius, although later versions might. Clearly, it is important for future researchers to measure and report actual fillet sizes whenever short overlap lap shear data are presented.

A second source of errors in interpreting literature data is a willingness to ascribe lower than expected strength values to defects observed on the braze plane. For the filler metals studied here, the filler metal fracture toughness (critical plane strain fracture toughness) (Ref. 17) is sufficiently high that defects must be larger than 2 mm (0.080 in.) before defect-dominated fracture occurs. For defects smaller than 2 mm, the presence of a defect simply decreases the actual load bearing area, which for typical brazements leads to only a small increase in the actual shear strength.

Finally, a third source of literature error arises from the limited numbers of specimens tested. In this study, large numbers of specimens were carefully fabricated using high-quality industrial facilities. Specimens were individually handled, machined and measured. Nonetheless, the data scatter, as shown in several figures, is substantial. It seems clear that using small numbers of specimens and discarding "defective" data can easily lead to erroneous conclusions.

Base Metal Yield Strength

It has been reported that the strength of brazes tested in tension can increase as the strength of the base metal increases (Ref. 19). This strengthening is believed to arise from the variation in Poisson's ratio on opposite sides of the interface. The difference in Poisson's ratio induces triaxial constraint on the braze and lowers the effective stress. The large value of Poisson's ratio for the braze is required because of the volume change which accompanies plastic tensile deformation. Shear deformation does not require any volume change, and as a consequence, no discontinuity in Poisson's ratio exists across the base metal/braze interface. Therefore, no constraint is imposed on the braze by the base metal, and thus, the shear strength of a braze should be independent of base metal strength. In studies using solid bars butt joint brazed together and tested in torsion (Ref. 17), constant shear strength was measured for A286/BAu-4 brazements when the base metal yield strength was varied from 275 MPa (40 ksi) to 760 MPa (110 ksi) in several steps.

Braze Joint Clearance

Unfortunately, it is very difficult to separate the effects of braze joint clearance on strength from the effects of braze joint clearance on microstructure, which may then influence strength. In the absence of any microstructural effects, i.e., for insoluable materials such as steel brazed with pure silver, the seam shear strength should be independent of joint clearance, by reasoning similar to that for the absence of a base metal yield strength effect. Regardless of intuition, there does exist data for the steel-silver system showing that as the braze joint clearance increases in thickness the tor-

sional shear strength decreases (Ref. 20). Sasabe and Okane (Refs. 21, 22) have modeled this observation in terms of dislocation pile-ups (similar to the Hall-Petch model for grain size-yield strength effects). The complication which arises for these materials is that the absence of chemical interaction between silver and iron seems to limit grain nucleation, and as a result, the braze seam often contains only two or three very large grains. During shear testing, the deformation behavior of the joint is highly dependent on the specific crystalline orientation of those few grains. Thus, it is not clear whether the conclusions based on these model systems will extend to other material combinations, such as BAu-4, used here, for which the grain size is much smaller than the braze joint clearance. Similarly, it is not clear that models for yielding phenomena are appropriate for describing fracture. For the BAu-4 brazes tested in this study, no evidence of a joint clearance dependence was found.

The data taken for this study tend to fall into two groups. The first group consists of filler metals BAu-4 and single-phase BNi-2. These brazed joints, having filler metals that fail in a ductile fashion, i.e., by microvoid coalescence, have the following features in common:

1. The measured shear strength of the brazed joint is independent of base metal yield strength. The shear strengths in this study were the same, regardless of whether the specimens were tested in the as-brazed condition (A286 yield strength around 276 MPa/40 ksi) or tested in the aged condition (A286 yield strength near 724 MPa/105 ksi). The yield strengths of BAu-4 and BNi-2 specimens differ slightly due to the difference in brazing temperature and its effect on precipitate dissolution and renucleation.

2. The measured shear strengths of the brazed joints are independent of specimen geometry. As indicated in Tables 3 and 4, the shear strength obtained using the lap shear specimen is essentially the same as that measured using the IIW pin-collar design, particularly if fillet effects are accounted for. Both of these values agree well with the torsional shear strength.

3. Over the narrow range of braze joint clearances examined, the measured shear strength does not depend on braze thickness. For this study, the joint clearance only ranged from 50 to 150 microns. This conclusion would probably not be true for brazements where the final composition in the seam depends strongly on joint clearance.

In contrast, the second grouping of data consists of the brittle-behaving filler metals, which in this study are typified by the thick BNi-2 brazes. The characteristics of this group are:

1. The measured shear strength

depends on base metal yield strength. This dependence is clearly illustrated in Figs. 15 and 18.

2. The measured shear strength depends on specimen geometry. Table 5 and Fig. 21 show the wild variation in apparent strengths one measures, depending on base metal strength and geometry.

3. Joint thickness may or may not influence measured shear strength. In this study, the lap shear strength was only slightly affected by joint clearance, while the pin-collar strength decreased dramatically as the joint microstructure changed. Interestingly, in both cases the strength of joints with only a small amount of eutectic phase was very close to those joints with a large amount. Both thick and thicker joints fail in a brittle fashion and at similar strengths.

These observations can be explained if failure of the ductile specimens, i.e., all BAu-4 and single-phase BNi-2, occurs via plastic deformation and ductile overload, a process controlled by the shear stress in the filler metal. The shear stress in the filler metal is closely related to the applied shear stress; however, shear stress concentrations do exist. Since both the lap shear and pin-collar geometries are nominally pure shear stress states, the measured strengths are very similar. Presumably, strength measurements made using other nominally pure shear specimen geometries should yield similar results.

For this class of ductile filler metals, the effect of specimen rotation on measured strength appears overemphasized. Plastic deformation of the filler metal redistributes the shear and tensile stresses throughout the joint, creating a fairly uniform stress state along the length of the joint. For example, in this study it was observed that: (1) during lap shear testing, no effect on apparent lap shear strength was found, even though very large differences in rotation occur when aged and as-brazed specimens are compared; and (2) similar shear strengths were obtained for two specimen geometries, one maximizing rotation (lap shear) and one minimizing rotation (pin-collar). The absence of a rotation effect is only expected for ductile behaving filler metals.

The failure of the brittle specimens occurs by a different fracture mechanism. The presence of a base metal yield strength effect suggests that failure results from the discontinuity between the plastic deformation in the base metal and the elastic behavior of the filler. This discontinuity creates tensile stresses across the base metal-filler metal interface. Therefore, the failure of the brittle specimens is hypothesized to occur by crack growth, following the rules of fracture toughness. Since these failures are almost certainly due to Mode I or crack
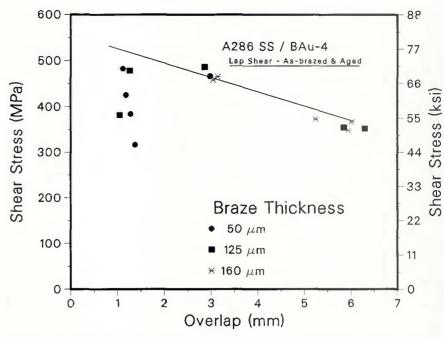

Fig. 23—Effect of removing braze fillet from BAu-4 lap shear specimens. Line is taken from Fig. 4, based on specimens made to AWS specification. Decrease in apparent shear strength at small overlaps is shown

opening forces, the normal stress across the braze interface should control the load at fracture. The normal stress distribution for the lap shear and pin-collar geometries must differ considerably, and, as a consequence, the apparent shear strengths differ considerably. Furthermore, the stress concentrations generally encountered for normal stresses are much higher than for shear stresses, which tends to exaggerate the strength differences. One can speculate that plastic deformation of the pin-collar geometry requires through-thickness yielding of the collar, which explains the flat shear strength-overlap curves — Fig. 18. For lap shear geometries, the plastic deformation may be a mixture of through-thickness yielding of the base metal perpendicular to the braze plane (leading to constant rotation to failure, which can be similar to constant load to failure), combined with yielding parallel to the braze plane. This deformation pattern would cause the shear strength-overlap curve to decrease monotonically — Figs. 15, 16.
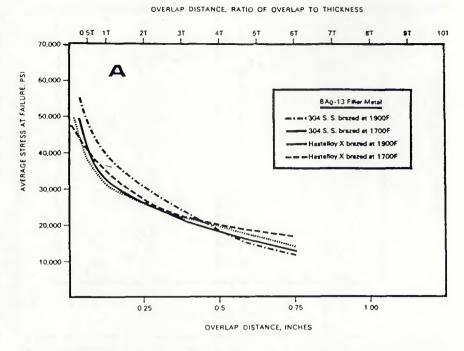
On the basis of the above discussion, it follows that the shear strength measured on brittle filler metals has no physical significance or design value. Assessments like "even though the filler metal is brittle, the lap shear strength is much higher than my design requires" are dangerous, because toughness (which is a function of normal stress and flaw size), and not strength, may determine the load-carrying capability of the joint. Fracture toughness testing is currently under way to try to define the limits of strength-controlled designs.

Interpretation of Braze Coupon Data

Braze coupons are used during process development to select materials and procedures, and during production to monitor product quality. In light of the observations of this study, it seems appropriate to review the capabilities and limitations of specimen testing.

For ductile filler metals, it was found that coupon testing generally checks filler metal wetting and may monitor filler metal microstructure, but not always. For example, the lap shear strengths of BNi-2 brazes over a wide range of microstructures are almost the same. Other fabrication variables such as joint clearance, braze temperature, post-braze heat treatment or porosity may not be revealed by measuring shear strength, except insofar as these factors influence the underlying filler metal microstructure. Strength comparisons between different filler metals are valid for reasonable coupon geometries, as long as both filler metals behave in a ductile fashion. A common mistake made during development is to compare a ductile with a brittle filler metal; occasionally, this comparison turns out to be specimen geometry dependent and one filler metal appears stronger when one specimen design is used, but weaker when a different design is selected. For this reason, it is important to examine the deformation behavior of the filler metal before drawing conclusions.

Clearly, one must use considerable caution when trying to extract design data from coupon tests. Filler metal properties such as shear strength can be
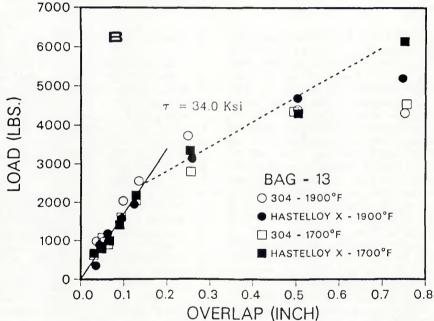
OVERLAP DISTANCE, RATIO OF OVERLAP TO THICKNESS

Fig. 24 — Data from Bredzs and Miller (Ref. 4) for BAg-13 filler metal. A — Data plotted per AWS specification reproduced from original paper. B — Data plotted as load versus overlap; shear strength obtained from slope of the initial portion of plot (load/(overlap × width)). Original units are maintained

For brittle filler metals, the number denoted "shear strength," as measured by any of the coupons discussed here, has absolutely no value as an engineering measurement. For brittle materials, the load-carrying capacity is determined by fracture toughness features and is strongly influenced by normal stress distribution. The wild variation in apparent shear strengths as shown in Table 5 for wide joint clearance BNi-2 illustrates the ineffectiveness of trying to use strength numbers to design with brittle filler metals.

Finally, it should be pointed out that the deformation behavior of the filler metal can only be gauged by microscopic examination, such as metallography or scanning electron microscopy. Engineers are sometimes misled by the shape of the coupon stress-strain curve. Evidence of macroscopic plastic deformation is invariably due to base metal yielding or coupon rotation; narrow joint displacements generally cannot be easily measured.

Summary

In view of the many features and interactions examined in this study, it is worthwhile to capsulize the observations using Table 2 (test program) as a reference.

Specimen geometry. For ductile-behaving filler metals, specimen geometry does not influence measured shear strength, as long as overlaps remain small (typically less than 1t for lap shear or 3 mm (0.12 in.) for pin-collar). For brittle-behaving filler metals, the measured shear strength depends strongly on specimen geometry at all overlaps.

Specimen overlap. Shear strength decreases with increasing overlap. At small overlaps, a region of constant shear strength can be observed if care is given to specimen fabrication. The critical values for determining acceptably small overlaps depend on specimen geometry and filler mechanical behavior. General guidance must await a larger database.

Filler metal composition. Filler metal composition can influence the sensitivity of shear strength measurements to variations in joint clearance, residual fillet and overlap.

Braze joint clearance. For BAu-4 filler metal, joint clearance had no effect on measured shear strength. However, other filler metals having significant base metal/filler metal alloying may show a microstructure-based joint clearance effect. Filler metals whose ductility depends on joint clearance may display a substantial clearance effect, although again, these variations are primarily due to changes in microstructure.

Filler metal ductility. Microscopic ductility of the filler metal dictates the dependence of shear strength on specimen

estimated from pin-collar specimens or carefully machined and measured lap shear coupons. Based on this study, another way to extract a useful shear strength from AWS-type testing is to prepare the load-overlap plot per Fig. 22 and select the shear strength from the initial slope. This procedure is illustrated in Fig. 24 for data taken from Bredzs and Miller (Ref. 4). When the data is plotted per the AWS technique, as in Fig. 24A, it is evidently quite difficult to select a meaningful design strength. However,

when the same data is plotted as load versus overlap, as in Fig. 24B, the scatter is averaged out and a realistic shear strength can be determined. When one has gone to the trouble of preparing multiple samples at different overlaps, it is probably worthwhile conducting the load-overlap analysis. However, the actual load-carrying capacity of any specific brazed joint must also account for the length of overlap, the severity of stress concentrations, and the presence of superimposed normal stresses.
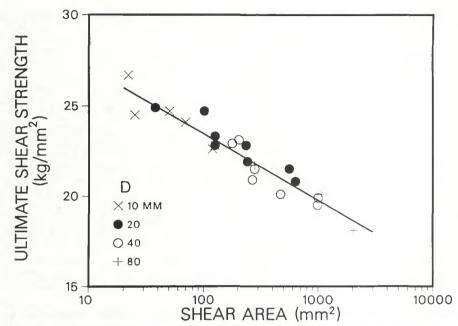
Fig. 25 — Replotted data of Shawki and El-Sabbagh (Ref. 23). Compressive shear strengths from different geometries converge when strength is plotted against shear area. Original units are maintained

geometry. As long as the filler metal behaves in a ductile fashion, a wide variety of specimen geometries can be used to measure braze shear strength.

Base metal yield strength. For ductile filler metals, base metal yield strength does not influence braze shear strength, for all geometries examined. For brittle filler metals, failure may be driven by fracture mechanics concerns, where strain is important. Therefore, the shear strength (a physically useless quantity under these circumstances) of brittle brazed joints will increase as the yield strength of the base metal increases.

Conclusions

1. For the ductile brazes examined in this study, BAu-4 and single-phase BNi-2, the shear strengths measured using different specimen geometries, AWS single lap shear and IIW pin-collar, agree well for comparable overlaps. For these brazes, shear strength is not strongly influenced by braze joint clearance, base metal yield strength or specimen geometry.

2. For the brittle brazes examined in this study, multiphase BNi-2, the shear strengths measured using the different specimen geometries are in poor agreement. For these brazes, shear strength can be influenced by base metal yield strength and specimen geometry.

3. These differences in sensitivity to geometry and base metal strength can be explained if failure of ductile brazes is controlled by plastic deformation, while the failure of brittle brazes is controlled by fracture toughness.

4. Some of the difficulties encountered when using short overlap lap shear specimens are due to the residual fillet and limited data. The scatter problems can be improved by using the initial slope of the load-overlap curve to estimate shear strength.

Appendix

Note on the influence of specimen dimensions on the shear strength measured using the pin-collar specimen:

The only data found showing the effect of specimen diameter and overlap on the shear strength of pin-collar specimens was reported by Shawki and El-Sabbagh (Ref. 23). Two conclusions were drawn from their experiments: (1) the shear strengths of pin-collar brazed joints tested in compression are 50% higher than those tested in tension; and (2) the absolute magnitude of the specimen diameter influences the compressive shear strength even when diameter is normalized by overlap. This second conclusion was examined experimentally for a few specimens in tensile shear, and no effect of absolute diameter was observed. Nonetheless, any data suggesting that specimen dimensions can influence measured shear strength should be examined carefully.

The difference between tensile and compressive testing of pin-collar specimens is that compressive testing causes a volumetric expansion of the pin, which induces compressive stresses normal to the braze interface. This compression results in frictional stresses during testing, which must be added to the applied shear stress. One expects that the radial expansion will occur primarily near the junction of the pin and collar, as illustrated in Ref. 6. Therefore, this frictional contribution should diminish as the overlap length (and shear area) increases. To verify this hypothesis, the data of Shawki was re-analyzed by plotting shear strength against braze area. The replotted data, shown in Fig. 25, converge to a single, monotonically decreasing curve for all diameters tested. This area dependence strongly supports the view that the compressive shear strengths at failure are controlled by friction. At constant overlap, Fig. 25 predicts that the compressive shear strength will decline as the diameter increases. This decrease is consistent with the idea that, as the diameter increases, the axial stress, and hence the axial and radial strains, will fall off proportionally, which reduces the frictional contribution. Using this simple analysis, it is not surprising that the sheer strengths measured in compression are significantly larger than those measured in tension. Moreover, there is no reason to believe that the absolute magnitude of the diameter will have any effect on the tensile shear strength, since frictional forces should be absent during tensile testing. The tensile data of Shawki suggest that the ratio of the braze diameter to the outside diameter for pin-collar specimens has, at most, a small effect. On the basis of this reanalysis, for the current study, pin-collar specimen dimensions were selected for convenience in fabrication and testing.

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Stress Rupture Behavior of Postweld Heat Treated 2¼ Cr-1Mo Steel Weld Metal
By C. D. Lundin, S. C. Kelley, R. Menon and B. J. Kruse

WRC Bulletin 315 complements Bulletin 277, issued in May 1982. Together, these bulletins address the creep properties of 2¼Cr-1Mo steel weld metal deposited with several different welding processes. They contain data obtained from the literature as well as from the many tests conducted on this program. The experimental data, in both reports, are for weld metal of several different carbon contents, postweld heat treated at either of two commonly used postweld heat treating temperatures.

Publication of this report was sponsored by the Subcommittee on Weld Metals and Welding Procedures of the Pressure Vessel Research Committee of the Welding Research Council. The price of WRC Bulletin 315 is $18.00 per copy, plus $5.00 for postage and handling. Orders should be sent with payment to the Welding Research Council, Ste. 1301, 345 E. 47th St., New York, NY 10017.

WRC Bulletin 316
July 1986

Two additional Technical Position Documents that Supplement WRC Bulletin 300, December 1984, have been published under the direction of the Technical Committee on Piping Systems of the Welding Research Council.

Technical Position on Piping System Installation Tolerances
By E. B. Branch, N. Kalyanam, D. F. Landers, E. O. Swain and D. A. Van Duyne

This document, prepared by the Task Group on Industry Practice, provides tolerances on the as-built geometry of light water reactor piping and pipe support locations that are considered acceptable for reconciliation with as-designed geometry.

Technical Position on Damping Values for Insulated Pipe—Summary Report
By J. L. Bitner, S. N. Hou, W. J. Kagay and J. A. O'Brien

This document, prepared by the Task Group on Damping Values, is an extension of the "Technical Position on Damping Values for Piping—Interim Summary Report," appearing in WRC Bulletin 300.

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