NASA TECHNICAL NOTE

NASA TN D-5917

c. 1

NASA TN D-5917

MAGNETIC FORCE UPSET WELDING OF DISSIMILAR THICKNESS STAINLESS-STEEL T-JOINTS

by Kenneth H. Holko

Lewis Research Center
Cleveland, Ohio 44135

NATIONAL AERONAUTICS AND SPACE ADMINISTRATION • WASHINGTON, D. C. • JULY 1970

1. Report No. NASA TN D-5917	2. Government Accession No.	3. Recipient's Catalog No.
4. Title and Subtitle MAGNETIC FORCE UPSET WELDING OF DISSIMILAR THICKNESS STAINLESS-STEEL T-JOINTS		5. Report Date July 1970
		6. Performing Organization Code
7. Author(s) Kenneth H. Holko		8. Performing Organization Report No. E-5624
9. Performing Organization Name and Address Lewis Research Center National Aeronautics and Space Administration Cleveland, Ohio 44135		10. Work Unit No. 129-03
		11. Contract or Grant No.
12. Sponsoring Agency Name and Address National Aeronautics and Space Administration Washington, D.C. 20546		13. Type of Report and Period Covered Technical Note
		14. Sponsoring Agency Code

15. Supplementary Notes

16. Abstract

Sheet-to-plate T-joints were resistance welded using the magnetic force upset welding (MFUW) process. Both AISI Type 304 and Armco 17-7PH T-joints were evaluated. The best results were obtained with sheet beveled at the joint interface and the more ductile Type 304 plate. An unwelded area under the weld fillet caused a stress concentration that lowered the strength of 17-7PH weldments. Removal of the weld fillet or the use of more ductile Type 304 plate greatly improved weld strength. Welds in 17-7PH were as strong as the plate after removal of the weld fillet. MFUW was successful because of short heating times and magnetic force delay relative to weld current capability.

17. Key Words *(Suggested by Author(s))* Magnetic force upset welding T-joints	18. Distribution Statement Unclassified - unlimited

19. Security Classif. (of this report)	20. Security Classif. (of this page)	21. No. of Pages	22. Price*
Unclassified	Unclassified	30	$3.00

*For sale by the Clearinghouse for Federal Scientific and Technical Information
Springfield, Virginia 22151

MAGNETIC FORCE UPSET WELDING OF DISSIMILAR THICKNESS STAINLESS STEEL T-JOINTS

by Kenneth H. Holko

Lewis Research Center

SUMMARY

Sheet-to-plate T-joints were resistance welded using the magnetic force upset welding (MFUW) process. Sheet thickness was 1/16 inch (1.59 mm) and plate thickness was 23/32 inch (18.22 mm). Both AISI Type 304 and Armco 17-7PH stainless steels were evaluated. In some cases, the sheet was beveled at the joint to concentrate current and force. Sheet stickout S from the electrode tooling was upset into a fillet during welding. The decrease in sheet length ΔL was used as a measure of upset at the joint. A stress concentration (unwelded area) was present under the fillet; this area was similar to a cold shut (plastic and liquid material forced into close contact with solid material without welding). The weldments were tensile tested either in full-size T-joints or in small sheet specimens machined from the T-joints.

Full strength welds were achieved with both materials. However, Type 304 plate was preferred over 17-7PH plate because of the low ductility of 17-7PH plate. The welds were stronger than the plate for both beveled and unbeveled 17-7PH joints. But the joint usefulness was limited because the 17-7PH plate was weaker and less ductile than the 17-7PH sheet.

Higher joint strengths (~40 percent) were achieved for the 17-7PH joints when the stress concentration was removed. This comparison was true for the two types of full-size tensile specimens. Fracture propagated through the weld heat affected zone (HAZ) in the 17-7PH plate at low strengths if the stress concentration was present to initiate early failure. However, by using more ductile Type 304 plate, higher strengths were achieved even with the stress concentration present.

The best welds were made with beveled sheet. A small bevel angle and small initial contact thickness are preferred. Weld strength may be controlled by indirectly controlling the amount of decrease in sheet length.

Unbeveled joints were a combination of solid-state and fusion welding, whereas beveled joints were principally fusion welded. Unbeveled joint strength was controlled by careful selection of sheet stickout and by a decrease in sheet length.

MFUW was successful in this study because heating was concentrated at the interface between two dissimilar section thicknesses. Short heating times and delay of magnetic force relative to weld current made this possible.

INTRODUCTION

Many aerospace components require T-joints between dissimilar thickness materials (e.g., compressor and turbine blades joined to rotors and disks). However, most of the conventional welding processes are not readily applicable to making a T-joint between sections of greatly different thickness. Usually, the thinner sheet section is heated more rapidly than the thicker plate section. Since heating is not concentrated at the T-joint junction (interface), a poor quality (low strength) weld results.

Resistance welding lends itself to the sheet-to-plate T-joint problem since maximum heat is developed at the interface, where resistance is high. However, in the conventional mode of several cycles (0.05 sec) or more of current, there is sufficient time for unequal heat dissipation to occur away from the interface. And insufficient interfacial heating results in a weak weld (refs. 1 and 2).

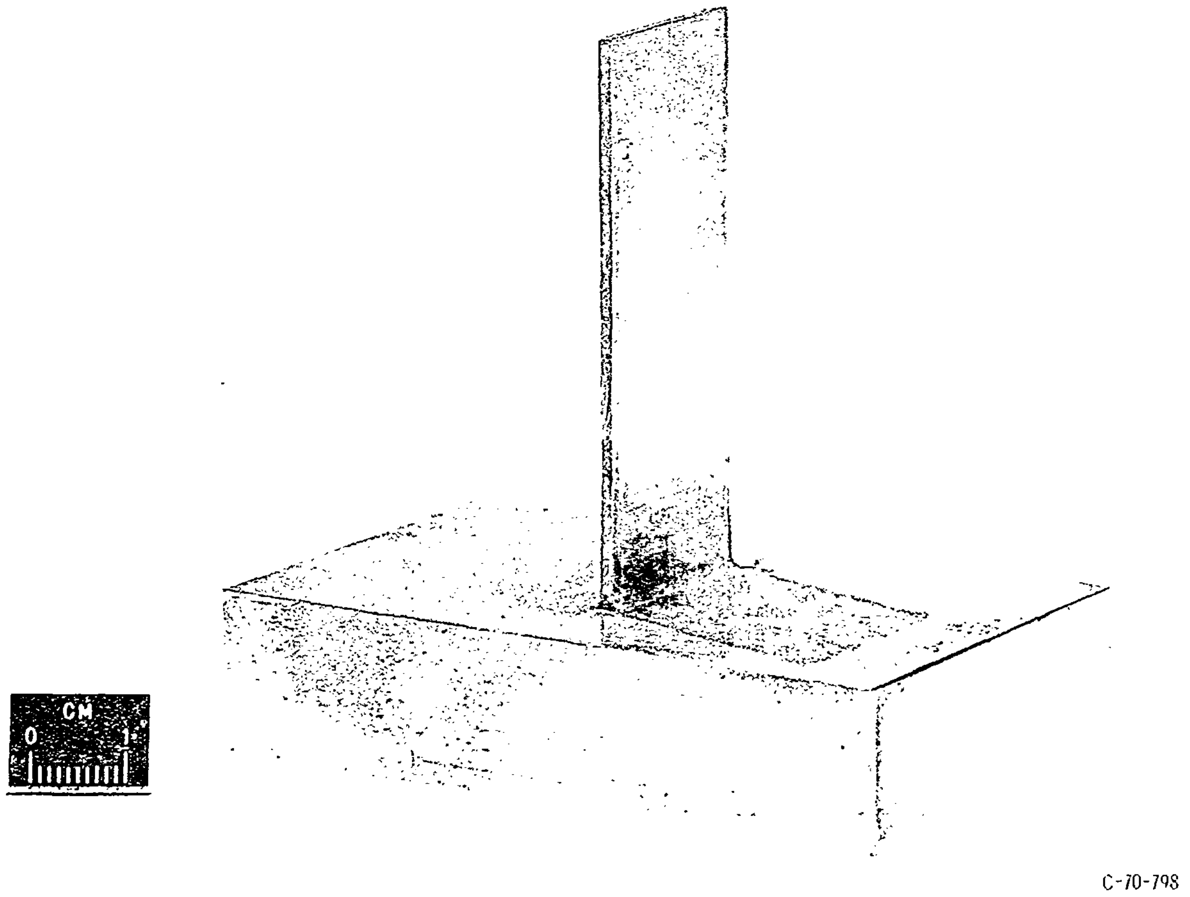


Figure 1. - Typical welded T-joint.

Magnetic force upset welding (MFUW) differs from conventional resistance welding in that a forging weld force is applied by a 120-hertz electromagnet. The force wave can be electronically timed in relation to the welding current. After a few milliseconds of interfacial heating, the force wave may be applied. MFUW controls can be set for short weld current times (<8 msec) and high peak currents. Short times at high current densities cause rapid interfacial heating, to minimize the effect of the unequal heat dissipation. Materials with different thermal conductivities may be joined by this method (ref. 3). MFUW may be used to make solid-state welds in a great variety of materials (ref. 4).

The purpose of this study was to evaluate the potential of MFUW for joining stainless steel sheet and plate in a T-joint configuration with the sheet as the leg of the T (as illustrated in fig. 1). Sheet thicknesses were 1/16 inch (1.59 mm) and plate thicknesses were 23/32 inch (18.2 mm). AISI Type 304 and 17-7PH[1] stainless steels were welded. 17-7PH was selected for its high strength and Type 304 for its good weldability and high ductility. Welding parameters evaluated included timing and magnitude of force and current, stickout of the sheet from the electrode tooling, and the amount of upset at the joint. Variations in tooling and joint configuration were also studied. Weld integrity was determined by metallographic sections and tensile tests.

MATERIALS AND PROCEDURE

Materials and Heat Treatment

Sheet specimens 1/16 inch by 15/16 inch by $2\frac{17}{32}$ inches (1.59 mm by 23.8 mm by 64.3 mm) of 17-7PH and Type 304 stainless steel were welded to plate specimens 23/32 inch by 2 inches by $3\frac{1}{4}$ inches (18.2 mm by 50.8 mm by 82.6 mm) of the same materials.

The nominal chemical compositions of the two materials are as follows:

Alloy	Nominal composition, wt.%						
	C	Mn	Si	Cr	Ni	Al	Fe
17-7PH	0.07	0.70	0.40	17.0	7.0	1.15	Bal
Type 304	.06	1.50	.50	19.0	10.0	----	Bal

[1]Tradename of Armco Steel Corp. and tentative AISI type.

Most of the welds were 17-7PH sheet to 17-7PH plate, although other combinations of the two materials were tried. All contacting surfaces on both types of specimens were machined to a 16 rms (40.7×10^{-6} cm rms) or better finish.

All the 17-7PH material was welded in the solution annealed condition and the Type 304 was in the mill-annealed condition. All the 17-7PH to 17-7PH welds and some 17-7PH to Type 304 welds were heat treated to the TH1100 condition (1400° F (760° C)/ $1\frac{1}{2}$ hr/air cool + 1100° F (593° C)/$1\frac{1}{2}$ hr/air cool). Tensile properties for the 17-7PH sheet and plate (short transverse) in the TH1100 condition are shown in table I. Also shown are tensile strengths for annealed 17-7PH sheet and Type 304 sheet. Note the low strength and ductility of the 17-7PH plate in the short transverse direction as compared to those of 17-7PH sheet in the rolling direction.

Welding Procedure

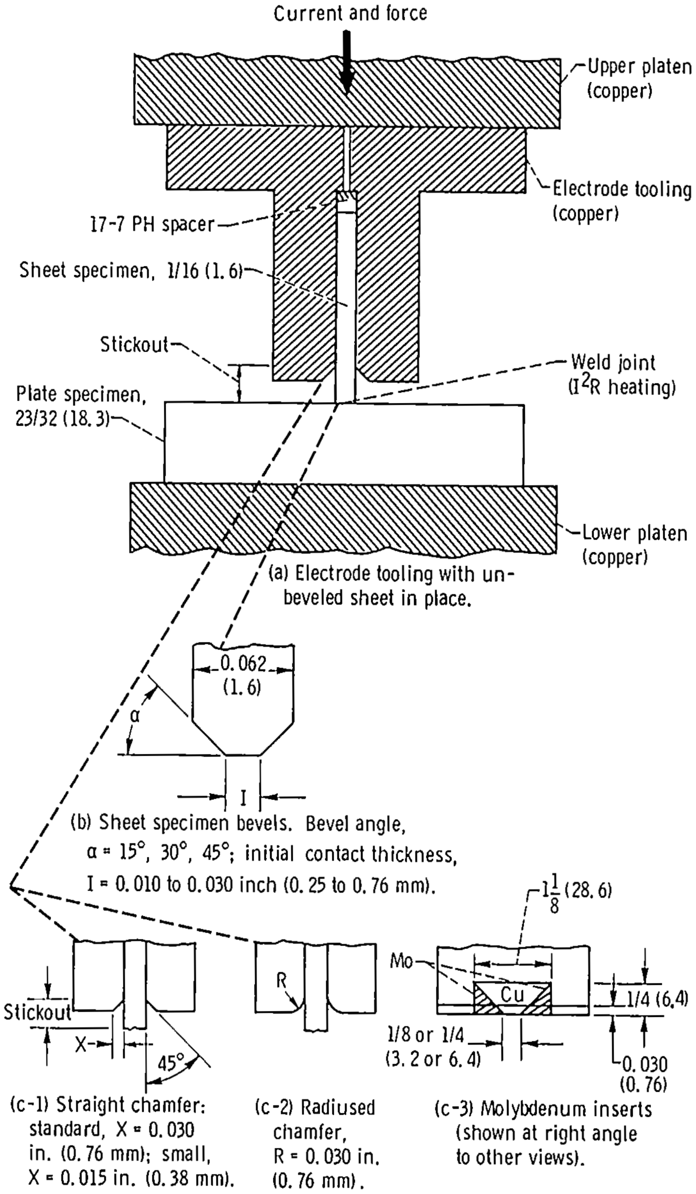
Joint configuration. - The electrode tooling and joint configurations are illustrated in figure 2. Two types of sheet specimens were used. The unbeveled sheet is shown in place in the tooling in figure 2(a). Beveled sheets were also used (fig. 2(b)) with various initial contact thicknesses and angles of bevel. This type was used to concentrate current and eliminate undesirable effects to be described later.

Force and current are applied as shown in figure 2(a). Welding occurs as I^2R (where I denotes current and R denotes resistance) resistance heating takes place at the interface between the sheet and plate. Fillets are formed at the sheet-plate interface as the sheet is upset.

Electrode tooling configuration. - The tooling used to hold the sheet specimen and introduce current and force is shown in figure 2. The tooling material is RWMA Class II copper. A typical sheet specimen is shown in place. The stickout of the sheet from the tooling is shown (figs. 2(a) and (c)) and will be discussed in a later section.

The most frequently used tooling had a 45° chamfer with a 0.030-inch (0.76-mm) leg (see X dimension in fig. 2(c)). This chamfer is used to form the fillet at the junction of the thin and thick members. Variations of this chamfer are shown in figure 2(c) and include a smaller chamfer, a radiused chamfer, and the use of a Mo insert for part of the chamfer.

Magnetic force upset welding (MFUW). - MFUW differs from conventional resistance welding in that the forge force is applied by a 120-hertz electromagnet (see fig. 3). The advantage is that the force half-waves can be timed in duration and phase shifted in relation to the current half-waves. The heating may be more effectively developed and concentrated at the interface in this manner. By delaying the initiation of the force half-wave until after the initiation of the current half-wave, the current can flow through an



(c) Various tooling configurations.

Figure 2. - Joint configurations and electrode tooling variations for magnetic force upset welding (MFUW) sheet-to-plate T-joints.

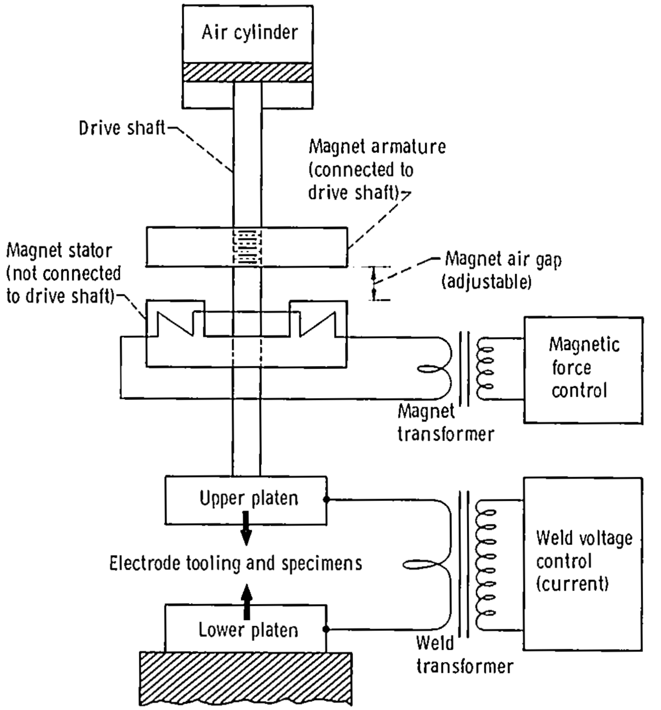


Figure 3. - Simplified diagram of magnetic force upset welding (MFUW) equipment. The methods of applying pneumatic force, magnetic force, and weld current are shown.

interface that is under low pressure, and thus, has high resistance. Thus, the R in the I^2R term may be maximized during current flow, thus maximizing the resistance heating at the interface (refs. 5 and 6). This is essential if unequal sections are to be welded.

MFUW is used with high welding current densities (typically 1.5×10^6 A/in.^{2} (0.233×10^6 A/cm^2)) and short current times (<16 msec). This convention follows from the use of MFUW for solid-state welding, where melting is avoided (ref. 4). The short times and high current densities may also be used to counteract the heat balance problem (ref. 2). The rate of heat input to the interface may be adjusted to be much greater than the rate of heat dissipation away from the interface. This makes the dissimilar heat dissipation rates of the two sections less influential in determining the location of maximum heating. The current and force capabilities for the MFUW machine used in this study are shown in table II.

MFUW force - current relations. - For most of the work reported herein, less than one full cycle of 60-hertz current and less than two full cycles of 120-hertz magnet force were used. This consisted of a small preheat half-cycle and a larger welding half-cycle, as shown in figure 4. The preheat half-cycle provides both macro- and microalinement between members, incipient welding, and an increase in interfacial temperature. The welding half-cycle provides the bulk of heating and upset necessary in the formation of the weld. A few welds were made with less than two and three cycles of current and less than four and six cycles of force.

Wave initiation, duration, and magnitude are dependent upon conventional ignitron

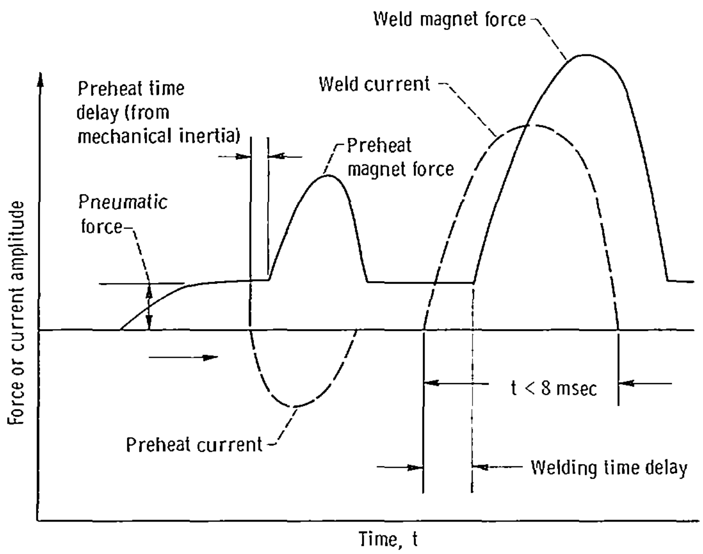


Figure 4. - Typical current and force waves used in magnetic force upset welding (MFUW) for less than one cycle of 60-hertz current and two cycles of 120-hertz force.

"heat" settings. In the case of the magnetic force wave, however, magnet gap may also be adjusted to vary the force magnitude at one ignitron setting. By adjusting the ignitron setting and magnet gap, then, the time relation between force initiation and current initiation may be varied while force magnitude is held relatively constant.

There is an inherent time delay of the force wave of about 0.5 millisecond, due to the mechanical inertia of the welding head (or movable platen). This is the time required to transmit the force from the magnet to the workpieces. Thus, there will actually be a slight force delay when the force and current ignitron settings are the same.

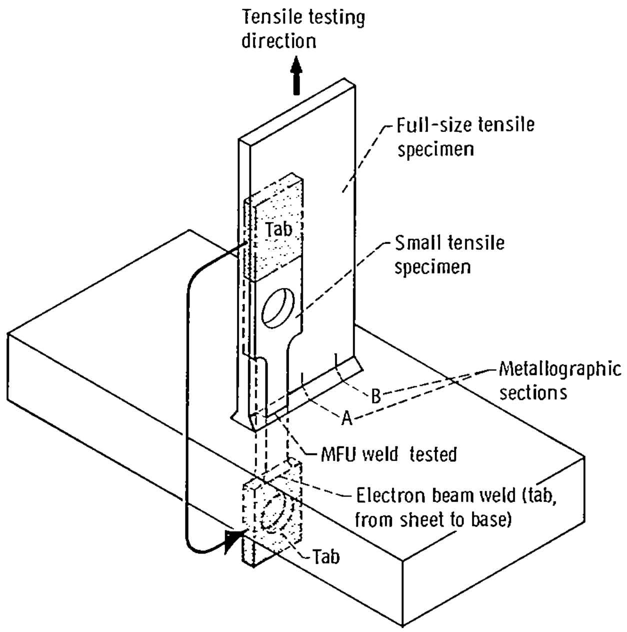
To delay the force wave even more behind the current wave, the ignitron setting is decreased (e.g., 50 percent to 40 percent "heat" setting) while keeping the current setting constant. A constant force magnitude is retained by decreasing the magnet gap, which effectively increases peak force back to the original value. This is necessary since a decrease in ignitron setting also decreases peak force.

Peak welding current was measured with a Duffers' Current Analyzer. Wave-shapes of primary and secondary current, magnetic force, and primary and secondary voltage were recorded on an ultraviolet light sensitive recording instrument (Visicorder).

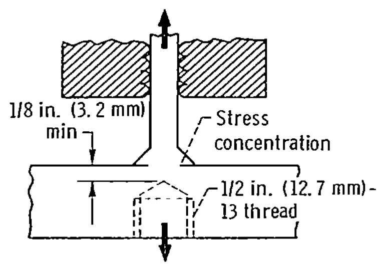
Weld Evaluation

Tensile tests. - The welded T-joints were sectioned in various ways to provide several types of tensile and metallographic specimens. Three types of tensile specimens were used. The sheet-type specimen (termed "small tensile specimen"), shown in figure 5(a), was machined from the sheet and planes parallel to the sheet surfaces through the plate. A tab from the unaffected sheet material was welded onto the plate side of the small specimen to provide increased length for testing purposes. The gage section was 1/2 inch (12.7 mm) long with a 0.188-inch by 0.060-inch (4.77-mm by 1.53-mm) cross section. Tensile testing was done in air at room temperature with a strain rate of 0.1 inch per inch per minute. Only specimens of 17-7PH plate heat treated to TH1100 were tested in this configuration.

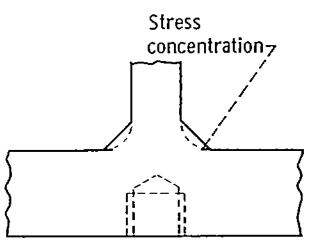
The other two types of tensile specimens were designed to test the entire T-joint (termed "full-size tensile specimens"). One had a stress concentration present at the sheet-plate interface under the weld fillet (fig. 5(b)). The other had the weld fillet hand-filed to remove the stress concentration (fig. 5(c)). Both types of specimens were tested with conventional serrated tensile grips and a threaded pull rod that fit in the tapped hole in the plates, as shown in figure 5(b). An accurate weld area could not be measured for the full-size tensile specimens. So the T-joints were compared by taking the failure loads, dividing by the sheet cross-sectional areas, and expressing the resultant sheet stresses at weld failure as percentages of the sheet ultimate tensile strength (UTS). It



(a) Location of small tensile specimen and metallographic sections.



(b) Full-size tensile testing with serrated grips and tapped hole.

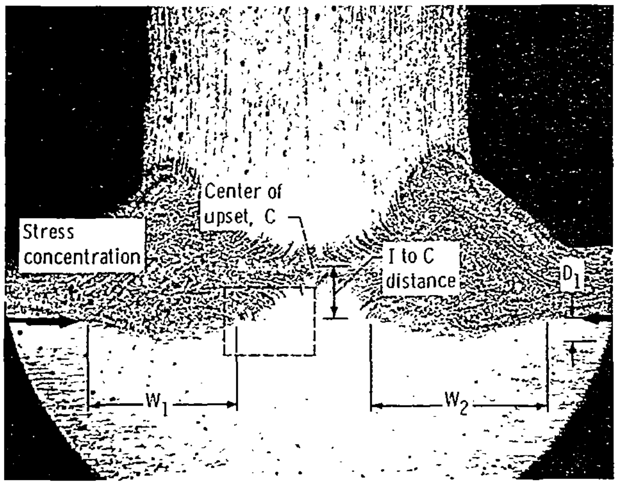


(c) Full-size tensile specimen with weld fillet filed to remove stress concentration.

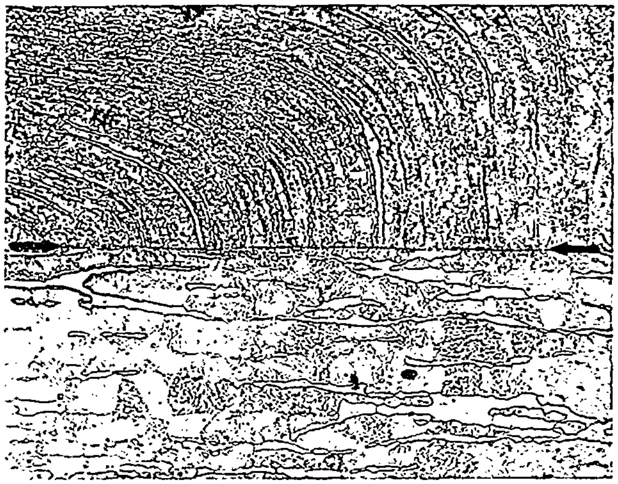
Figure 5. - Location and types of tensile and metallographic specimens machined from T-joint.

should be pointed out that the sheet UTS for the particular sheet material used in each T-joint was used to calculate this percentage (i.e., Type 304, 17-7PH, and 17-7PH in the TH1100).

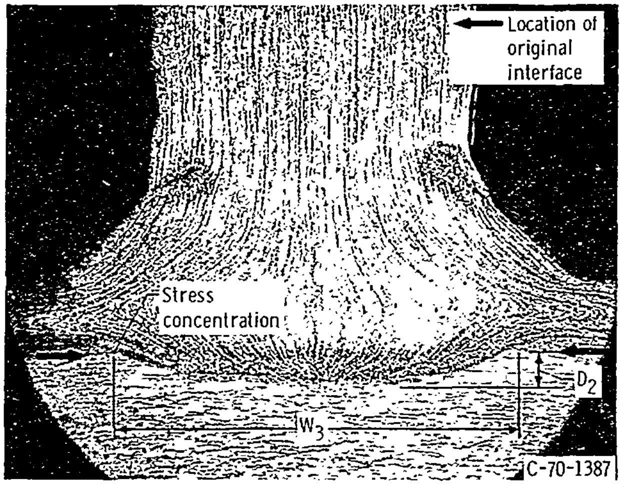
Metallographic evaluation. - Metallographic specimens were machined from some of the specimens at two sections transverse to the weld joint at the center and edge, as indicated by A and B in figure 5(a). They were mounted, polished, and etched with oxalic acid. An average metallographic area A_m was measured for each specimen (see fig. 6). From many observations, the A_m was found to approximate the fusion weld area on a plane through the original interface. The large arrows shown in figure 6 point to the



(a) Center section. Etched; X36.



(b) Enlargement of block in (a). Etched; X250.



(c) Edge section. Etched; X36.

Figure 6. - Typical magnetic force upset sheet-to-plate weld in 17-7PH (weld made with < 1 cycle of 60-Hz current) and unbeveled joint configuration (specimen I8-25). Section locations shown in figure 2. Etchant, oxalic acid. Parameters used to indicate amount of interfacial heating are shown: Average metallographic area, $A_m = ((W_1 + W_2 + W_3)/2)L$.

Average depth of maximum penetration, $D_m = \frac{D_1 + D_2}{2}$.

original interface of the T-joint. Area A_m was obtained by averaging the straight-line weld width (along the original interface) and multiplying it by the length of the weld. (A_m is actually a relative, rather than absolute, weld area. Therefore, area units are not used.) The average depth of maximum penetration D_m of the fusion weld below the original interface was obtained by averaging the maximum penetrations for the two sections. Also, an interface-to-center-of-upset (I/C) distance was measured for the unbeveled joints (fig. 6(a)). These three dependent variables are indicators of the extent of interfacial heating. They are used to determine the effects of variations in weld settings.

Welding parameters. - The decrease in length ΔL of the sheet was measured for each welded specimen and used as a measure of the upset. Essentially, all the upset takes place in the material sticking out of the tooling since it is heated and not fully constrained.

Stickout S is measured from the last point of contact with the tooling to the end of the sheet, as shown in figure 2, for a 0.030-inch (0.76-mm)/45° chamfer. However, in order to compare variations of this chamfer (fig. 2(c)), an "effective" stickout was used. For the 0.015-inch (0.38-mm)/45° chamfer, 0.0078 inch (0.20 mm), or 1/128 inch, was added to the measured stickout. And for the 0.030-inch (0.76-mm) radiused tooling, 0.0039 inch (0.10 mm) was subtracted. These corrections follow from heat balance considerations.

Delay D is defined as the time delay of the initiation of the force wave after the beginning of the welding current wave. It was estimated from the Visicorder traces.

RESULTS AND DISCUSSION

Over 150 welds were made in this study to evaluate the effects of welding variables on joint properties. The best combinations of welding parameters found, based on tensile strengths and metallographic observations, are shown in table III. Only parameters for short-time welds made with less than one cycle of 60-hertz current, and less than two cycles of 120-hertz magnet force are shown. Longer time welds were tried, but were judged to be unsatisfactory.

Selected specimens were tensile tested and metallographically examined. The tensile test results are shown in table IV for unbeveled joints and in table V for beveled joints. Variations in welding parameters are responsible for the scatter in the data shown.

Mechanical Properties

Unbeveled joints. - The tensile results are shown in table IV for unbeveled joints. The best weld settings of those used are shown in table III. For the 17-7PH/17-7PH (TH1100) joints tested full size (stress concentration present), the best weld strength obtained was 63 percent of the sheet UTS (i.e., when the weld failed, the sheet was stressed to 63 percent UTS). Sheet stress has been used since the weld area could not be accurately measured. All the welds were irregularly shaped combinations of fusion and solid-state welds.

For the full-size specimens, the stress concentration present at the junction of the sheet and plate under the weld fillet (see fig. 6) caused failure at low tensile strengths. Fracture, initiated at the stress concentration, easily propagated through the 17-7PH plate which has low ductility in the short transverse direction (see table I). Type 304 sheet has only about half the strength of 17-7PH sheet (in the TH1100 condition). Although tensile data are not available for Type 304 plate in the short transverse direction, it is generally accepted that the Type 304 plate is both weaker and more ductile than 17-7PH plate in the short transverse direction. However, joints with Type 304 plates were as strong as those with 17-7PH plates (specimens C9-1 and I8-12, table IV). The reason for this is thought to be the higher ductility of Type 304 plate in the short transverse direction and the resistance to crack propagation from the stress concentration it offers. Further evidence of the beneficial effect of the Type 304 ductility is given by the 100 percent UTS values for the Type 304/Type 304 joints in table IV. When the stress concentration was removed by machining the small tensile specimen in 17-7PH/17-7PH joints, base metal strength was attained.

For the small-size tensile specimens of 17-7PH, ultimate tensile strengths over 140 ksi (964 MN/m^2) with yield strengths of 134 ksi (920 MN/m^2) and 4 to 6 percent elongation were achieved (see specimens I8-21, I8-24, and I8-25 in table IV). These weld strengths are good when compared to the lower average plate strength of 144 ksi (990 MN/m^2) shown in table I. Weld ductility is also higher than the plate average. The higher sheet strength of 17-7PH could not be attained, probably because weld strength was limited by the relatively weak plate.

Beveled joints. - Tensile tests on full-size specimens produced from beveled joints indicated that removal of the stress concentration under the fillet resulted in higher joint strengths. For example, as high as 86 percent sheet UTS was reached for 17-7PH/17-7PH beveled joints tensile tested full size with the stress concentration removed (specimens J9-5 and J9-6 in table V). This is an increase of about 25 percentage points over beveled joints tested with the stress concentration present (specimens J9-3 and J9-4). Welding parameters used are shown in table III. By using the ductile Type 304 plate, slightly higher strength welds (88 percent sheet UTS) were obtained even with the stress concentration present (specimens J9-7 and J9-8). Again, the advantage of the more ductile Type 304 plate is seen. If the stress concentration is not removed, the beveled 17-7PH/17-7PH joints are no stronger than the unbeveled joints, as can be seen by comparing table IV (specimens C9-1 and C9-3) and table V (specimens J9-3 and J9-4).

Tests on the small tensile specimens indicated ultimate tensile strengths as high as 160 ksi (1100 MN/m^2) with yield strengths over 143 ksi (985 MN/m^2) were achieved with the beveled 17-7PH/17-7PH joints (table V). However, actual weld strengths were higher than this in some cases since failure occurred in the plate. The relatively poor plate properties then limit the theoretical joint strength (i.e., the strength of the 17-7PH sheet).

Although high strengths were achieved with multiple-cycle beveled joints (table V(b)), they are not recommended. The marginal solid-state welds formed had poor resistance to crack propagation, as shown by the low strength of the full-size tensile specimens (table V(a)).

Metallography

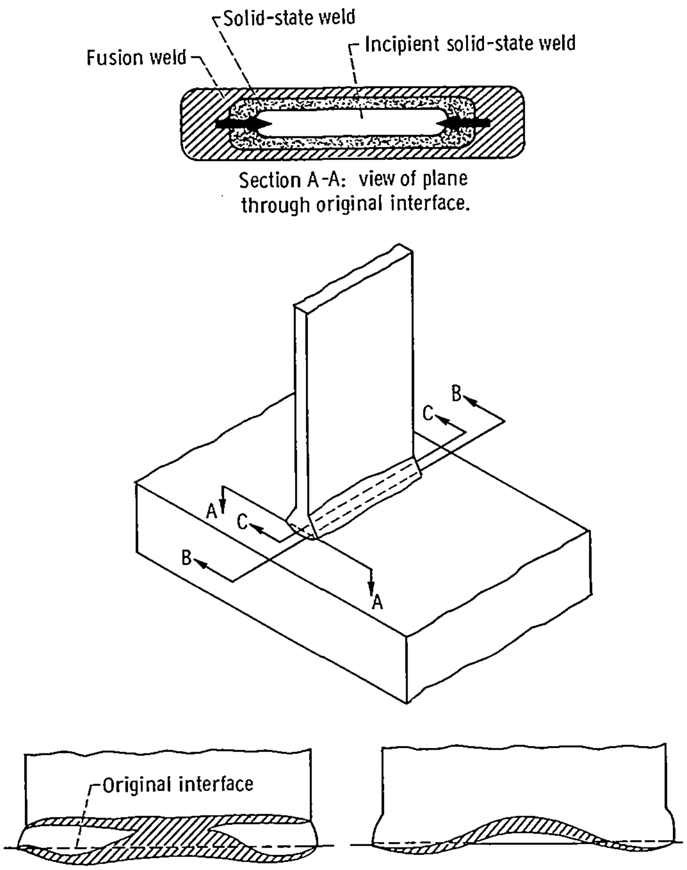
Unbeveled joints. - The unbeveled sheet-to-plate T-joint consisted of both solid-state and fusion welds (principally grain boundary melting) for the settings shown in table III. Transverse metallographic sections from the center and edge of a 17-7PH joint are shown in figure 6. The large arrows indicate the location of the original interface. As can be seen in the center section (figs. 6(a) and (b)), fusion welding occurred at the outside and incipient solid-state welding in the center. In the edge section (fig. 6(c)), only fusion welding occurred.

The fillets formed at the base of the sheet section (fig. 6) are the result of the chamfer in the electrode tooling. However, notice that the sheet and plate are not completely welded under the fillets and stress concentrations are present. Hot sheet material at the outside has come into contact with the cold plate surface, and the resultant stress concentration is similar to a "cold shut" sometimes found in castings and forgings.

In both sections shown in figure 6, localized heating has occurred just above the fillet, actually at the last point of contact between the sheet and tooling, before upset. The reason for this is that most of the current enters the sheet from the tooling at this point. Hardly any current enters the 17-7PH sheet along the rest of its length because of its high resistance as compared to the copper tooling.

The reason for the "dumbbell-shaped" appearance of heated material in the center section (fig. 6(a)) is the occurrence of the "skin effect." This effect is normally associated with higher frequency current as commonly used in induction heating. However, the occurrence of this effect at 60 hertz has been described (ref. 7). The rapid rise of current I with respect to time t (dI/dt) used in this program also favors the skin effect. Briefly, the skin effect is the tendency for current passing through a conductor to concentrate in a tubular element near the surface. The current density is then highest just below the surface and decreases towards the center of the conductor. The higher current density results in melting near the outside surface. The lower density results in various degrees of solid-state welding at the center (fig. 6(b)). The skin effect is not normally seen in conventional resistance welding because multiple cycles of current are used. In this study, welds made with three cycles of current did not have the skin effect.

The shape of the heated material in the weld joint is shown schematically by the three sections in figure 7. The section drawings have been constructed from many actual



Section B-B: Just inside sheet specimen surface (heated material crosshatched).

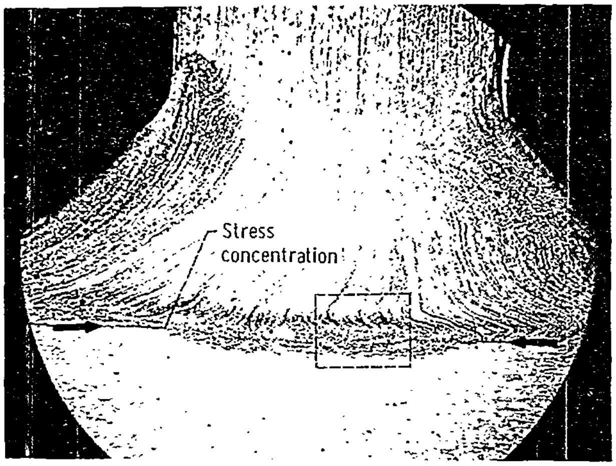
Section C-C: Middle of sheet specimen thickness.

Figure 7. - Various sections through unbeveled welded joint showing geometry of heated material.

metallographic sections, and the reasons for their shapes will be discussed in the next section.

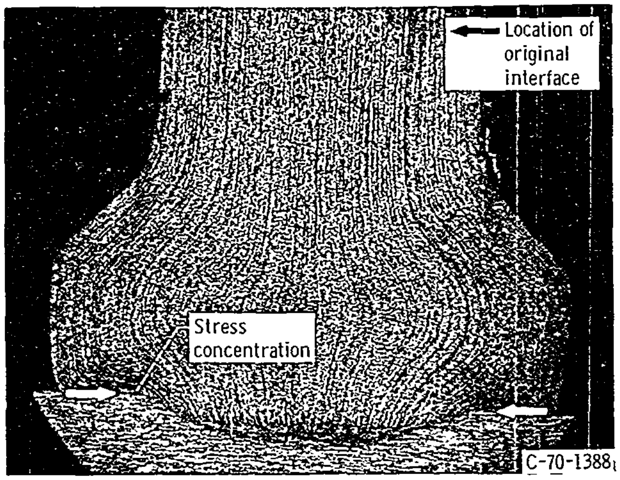
Beveled joints. - With the proper weld settings (table III), a fusion weld was obtained for the entire sheet width in the beveled joint. The skin effect was avoided since the bevel constricted the current. This caused a high current density across the initial contact thickness. However, if the initial contact thickness was too large, the skin effect still occurred. Typical transverse center and edge sections with fusion welding are shown in figure 8. Figure 8(b) shows the typical grain boundary melting that occurred. The weld is similar for both sections, but the penetration is greater at the edge. (Large arrows in fig. 8 indicate original interface location.) The reason for this is the "edge effect" as described in the appendix.

Very little welding is present under the fillets in either section shown in figure 8. This situation can be improved by decreasing the bevel angle, which increases the weld



(a) Center section Etched; X36.

(b) Enlargement of block in (a). Etched; X250.



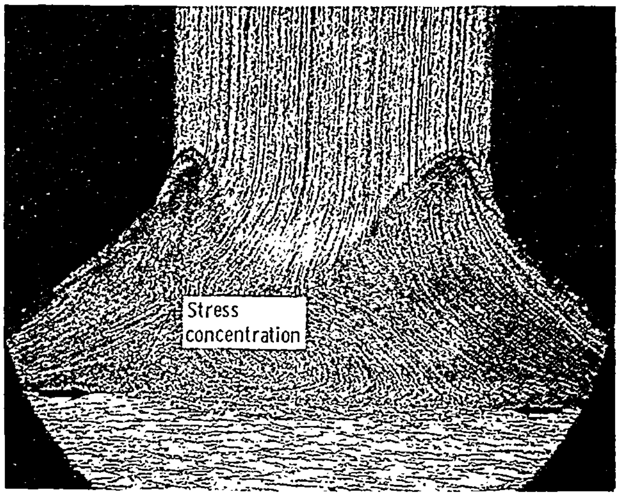
(c) Edge section. Etched; X36.

Figure 8. - Typical magnetic force upset sheet-to-plate weld in 17-7PH (made with less than 1 cycle of 60-Hz current) and beveled (0.020 in. (0.51 mm) /45°) joint configuration (specimen H8-12). Etchant, oxalic acid.

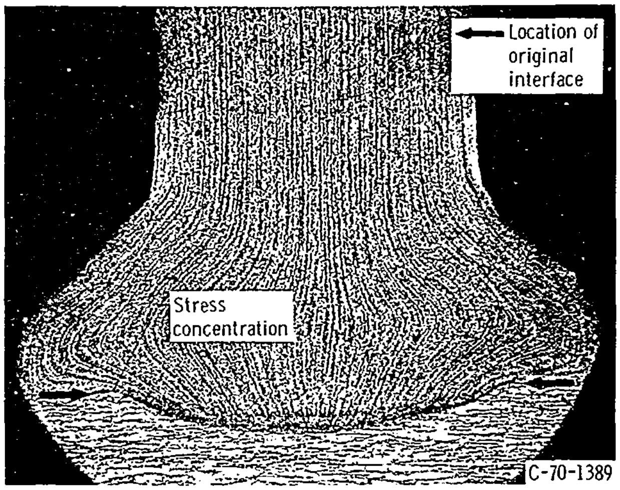
width, as shown in figure 9. The sheet in figure 8 had a 45° bevel and the one in figure 9 a 15° angle. In effect, more sheet material can come into contact with the plate during upsetting if the angle of bevel is small. Localized heating at the last point of contact is only present in the center section.

Influence of Welding Variables on Joint Properties

Extensive analysis was made to determine the effects of the welding variables on the strengths of the joints. The results of this analysis (summarized in figs. 10 to 15) indicate the relative importance of each welding variable studied in this program. For



(a) Center section. Etched; X36.



(b) Edge section. Etched; X36.

Figure 9. - Typical magnetic force upset sheet-to-plate weld (made with less than 1 cycle of 60-Hz current) and beveled (0.015 in. (0.38 mm)/15°) joint configuration (specimen C9-17). Etchant, oxalic acid.

unbeveled joints stickout S, decrease in sheet length ΔL, the ratio $\Delta L/S$, and delay D were all important in obtaining highest strengths. For beveled joints, only ΔL and D were important.

Slight variations occur in the weld parameters (of the type shown in table III) that are considered constant for each point plotted in figures 10 to 15. But, from observation of many specimens, it is felt that these variations do not significantly influence the relation between the parameters shown in each figure.

Stickout. - Figure 10 indicates the effect of stickout on the strength of unbeveled joints tested in both the full- and small-size tensile configurations. A stickout range of about 12/128 to 14/128 inch (2.4 to 2.7 mm) yielded the highest sheet stresses at failure

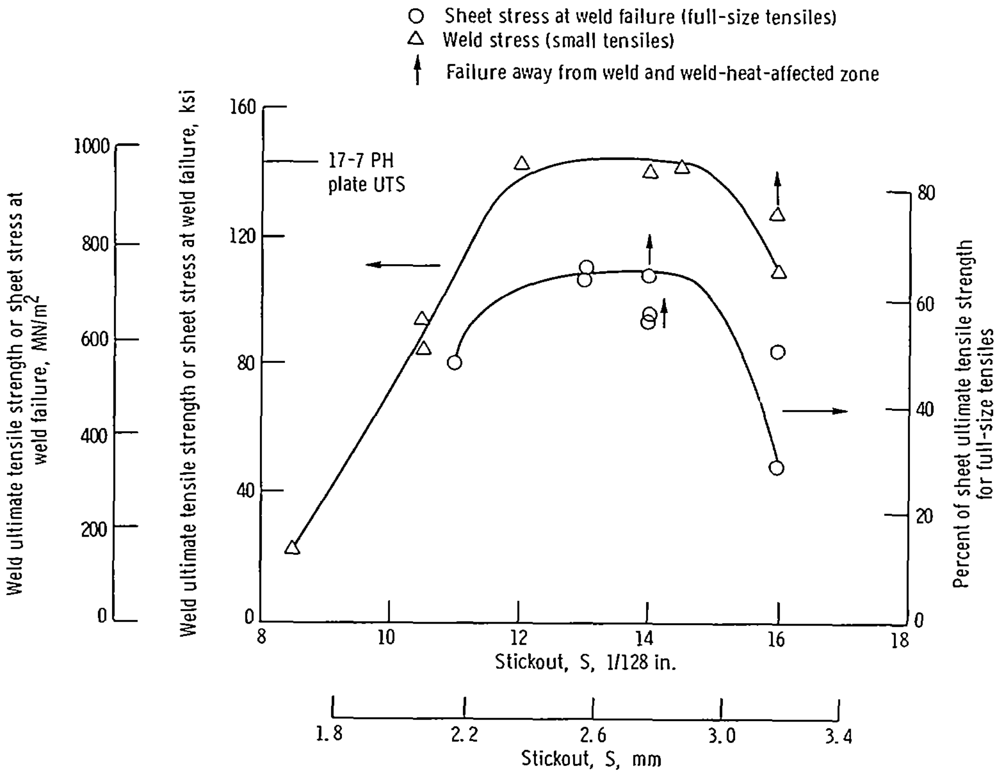


Figure 10. - Effect of stickout on joint strength of unbeveled 17-7 PH/Type 304 and 17-7 PH/17-7 PH T-joints.

for unbeveled joints. This range provided the best heat balance at the sheet-plate interface. Larger stickouts resulted in (1) too much sheet heating away from the interface and (2) the center of upset moving well away from the interface (see fig. 6(a)). Small stickouts did not allow sufficient heat to be developed at the interface because the closeness of the copper tooling dissipated the heat too rapidly. In either case, little fusion welding and a weak incipient solid-state weld resulted. Removal of the stress concentration, by machining the small tensile specimen, resulted in about a 35-ksi (241-MN/m^2) strength increase (compare the two curves in fig. 10).

For the unbeveled joints, decreases in sheet length ΔL vary directly with stickout, as shown in figure 11, if welding current, force, and delay are held constant. Since more sheet sticks out from the tooling, a greater material volume is heated, softened, and upset. This follows since the bulk of the sheet sticking out as well as the portion near the interface, is resistance heated.

Beveled joint strength was not as dependent upon stickout as that of unbeveled joints. The reason is that heating is concentrated at the interface by the sheet bevel. The bevel constricts the current, causing a high density, and the interface is locally heated.

The 13/128- to 14/128-inch (2.6- to 2.7-mm) stickout range is recommended for

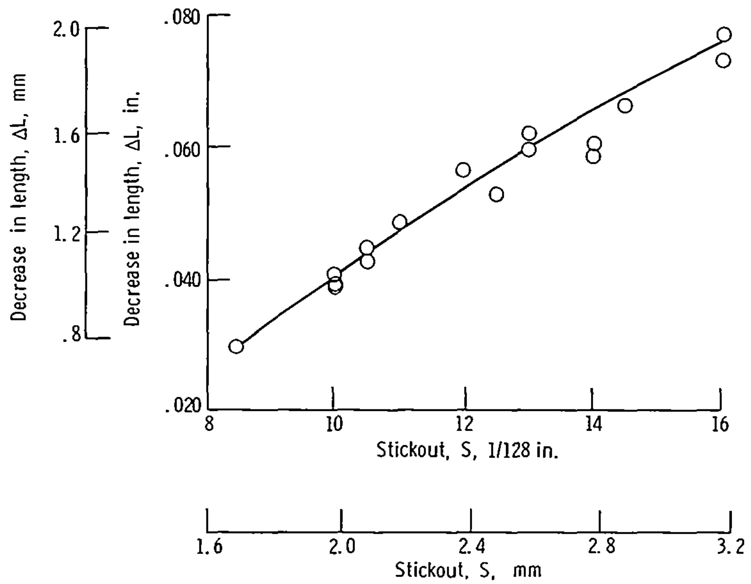


Figure 11. - Effect of sheet stickout from electrode tooling on decrease in sheet length. Unbeveled sheet-to-plate T-joints in 17-7 PH.

both unbeveled and beveled joints in table III because successful welds were made at these settings.

Decrease in sheet length. - As upsetting occurs, the center of upset in the sheet moves towards the interface. This causes increased interfacial heating and more fusion and solid-state welding. For unbeveled joints, correlation of interfacial heating and strength with ΔL was only found when stickout remained constant. Variations in stickout changed the heat balance enough to override the effect of ΔL. So, by itself, ΔL is not a reliable indication of interfacial heating for unbeveled joints.

For unbeveled joints and the stickouts recommended in table III, at least 0.060-inch (1.5-mm) ΔL was required for the highest 17-7PH/17-7PH joint strengths. The 17-7PH sheet/Type 304 plate joints required at least 0.063-inch (1.6-mm) ΔL and the Type 304/ Type 304 joints required 0.057 inch (1.4 mm) (not shown in table III).

For the beveled joints, interfacial heating varied directly with ΔL, as shown in figure 12. Both weld strength (small tensile) and interfacial heating (the product $A_m \times D_m$) increased, which indicates increasing interfacial heating. The product $A_m \times D_m$ and the tensile strength are directly related but are not shown here. Variations in stickout did not interfere with the relation because of the beveled joint's insensitivity to stickout. A good relation between ΔL and sheet stress for the full-size specimen was not found because of the variable influence of stress concentration (figs. 8 and 9).

Extremely small stickouts (12/128 in. (2.4 mm) or less) required at least 0.052 inch (1.3 mm) ΔL to avoid a "ring weld" due to the skin effect. For larger stickouts

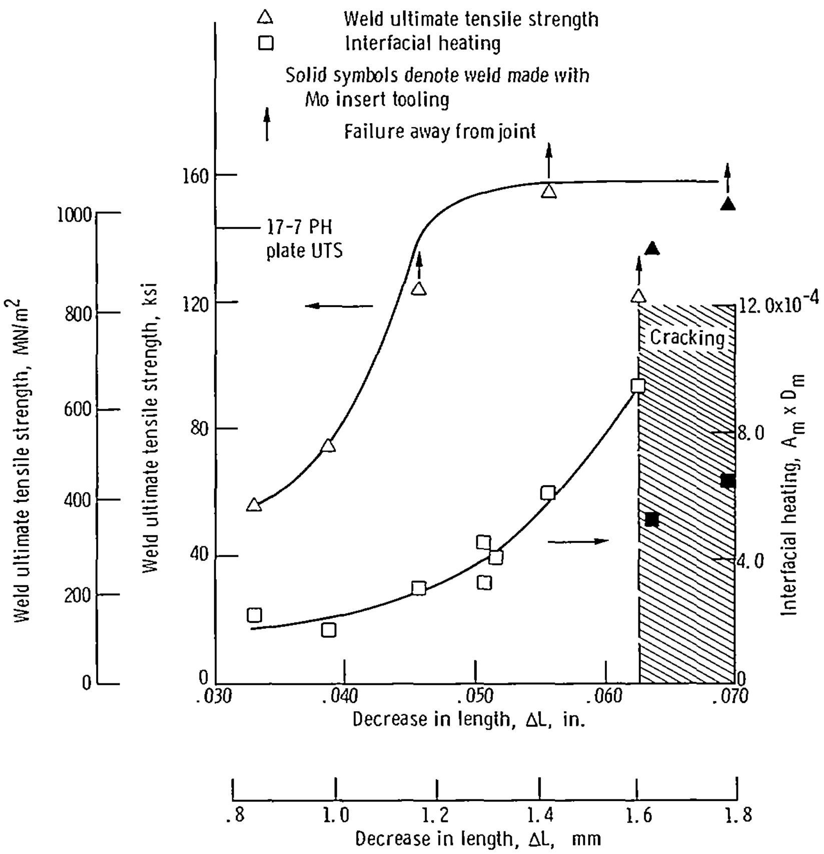


Figure 12. - Effect of decrease in sheet length on weld ultimate tensile strength and interfacial heating in beveled 17-7PH joints.

((14/128 in. (2.8 mm) and up), ΔL should be between 0.046 and 0.063 inch (1.2 and 1.6 mm) to reach maximum strength and avoid cracking. Less severe bevels (0.015 in. (0.38 mm)/15^{o}) can tolerate more upset than those shown in figure 12 (0.015 in. (0.38 mm)/45^{o}) without cracking. This is because a greater volume of sheet material is available to compensate for expulsion during upsetting.

The joints made with the Mo insert tooling cracked at lower values of $A_m \times D_m$ than the joints made with solid Cu tooling (see fig. 12). More heat is built up in the sheet near the interface because of the lower heat conductivity of the Mo.

Upset to stickout ratio. - Both ΔL and S determine the amount of heating at the interface for unbeveled joints. For larger values of S, more ΔL is required to bring the center of upset (fig. 6(a)) to the interface. So when S varies, it is the ratio of ΔL to S that determines how much interfacial heating occurs. (ΔL is measured after the weld is made but can be indirectly controlled by selection of weld settings.)

Actually, S is slightly more important in the ratio $\Delta L/S$. So a relation of $\Delta L/S^{1.2}$ was empirically derived for these data. In figure 13, as the ratio $\Delta L/S^{1.2}$ increases,

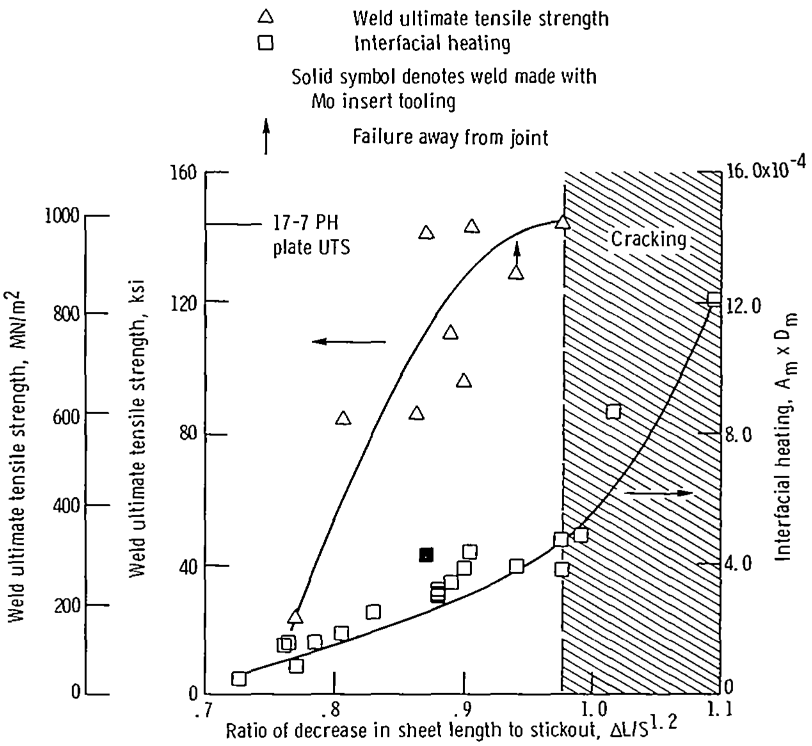


Figure 13. - Effect of ratio of decrease in sheet length to stickout on weld ultimate tensile strength and interfacial heating. Specimens machined from unbeveled sheet-to-plate T-joints of 17-7 PH/Type 304 and 17-7 PH/17-7 PH.

tensile strength and the product $A_m \times D_m$ also increase. These dependent variables are both indications of interfacial heating. And too much heating ($\Delta L/S^{1.2} \geq 0.975$) results in cracking. Too little heating ($\Delta L/S^{1.2} < 0.9$) results in a weak weld.

The interface-to-center-of-upset (I/C) distance (fig. 6(a)) is an indication of the amount of interfacial heating. As the center of upset moves closer to the interface, more heating and welding occur. For small values of I/C, high weld strengths resulted. The empirical ratio $\Delta L/S^{1.5}$ determines the location of the center of upset. As previously described, when this ratio increased, so did the interfacial heating. Thus, the center of upset moved closer to the interface, as shown in figure 14. Again, too much heating resulted in cracking.

Since the sheet bevel overrides (within reasonable limits) the influence of S, the ratio $\Delta L/S$ does not correlate with interfacial heating for beveled joints.

Delay. - Interfacial heating increases as the delay of the force half-wave behind the current half-wave increases (see fig. 4). This effect is shown in figure 15 in terms of fusion-weld fracture area and sheet stress at failure for various unbeveled joints. The fracture area is the approximate area of melted material pulled out of the plate in full-size specimen fracture (see fig. 7). For example, increased delay shifted the fracture from the plate to the sheet in a series of Type 304/Type 304 joints as the fusion-weld

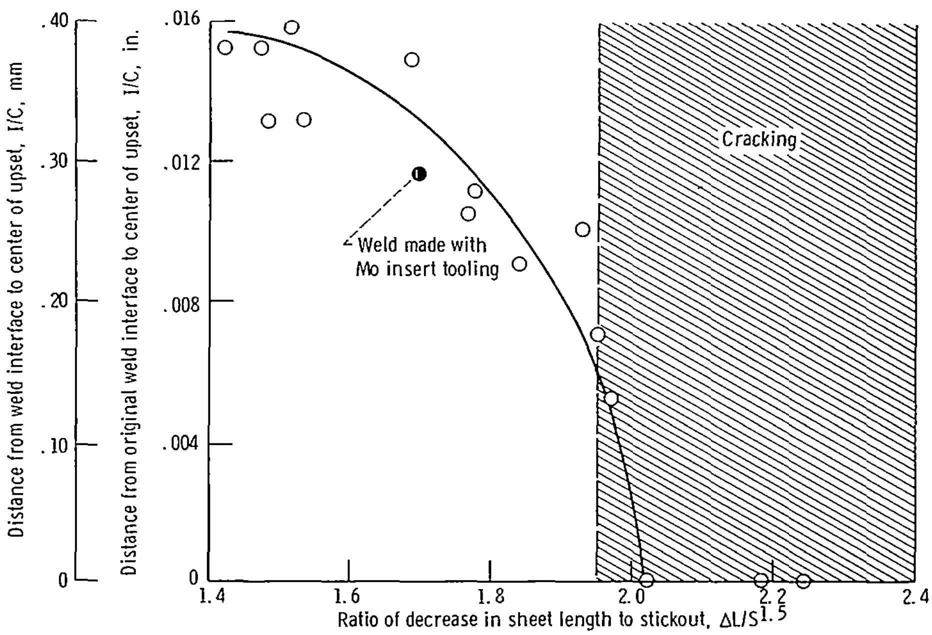


Figure 14. - Effect of ratio of decrease in sheet length to stickout on distance from weld interface to center of sheet upset. Unbeveled sheet-to-plate T-joints in 17-7 PH/Type 304 and 17-7 PH/17-7 PH.

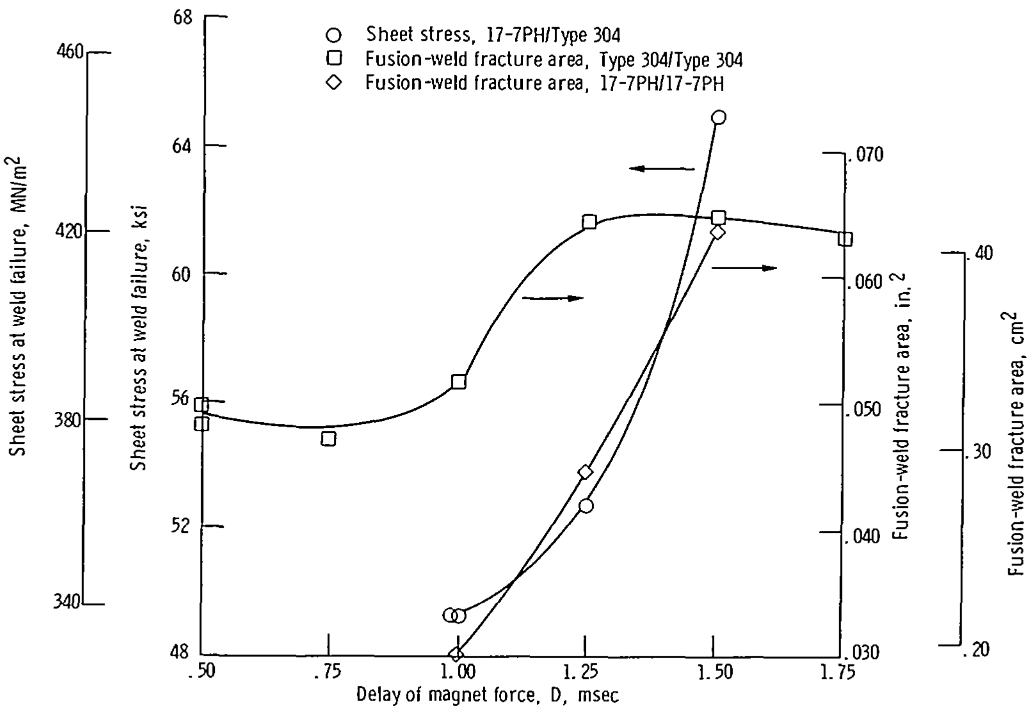


Figure 15. - Effect of delay of magnet force initiation (relative to weld current) on sheet stress at weld failure and fusion-weld fracture area. Unbeveled sheet-to-plate full-size T-joints.

area increased. Relative strengths for these joints are shown in table IV (J9-9 to J9-15). Percent sheet UTS at weld failure for 17-7PH/Type 304 joints increased from 38 to 50 percent for a delay increase of 1.0 to 1.5 millisecond. These strengths are low because a low preheat current half-cycle was used and the weld interface was not adequately heated.

When the force half-wave preceded the current half-wave (negative delay), little interfacial heating occurred. For example, one weld with a negative delay of 1.0 millisecond had an exceptionally low $A_m \times D_m$ for its $\Delta L/S^{1.2}$ ratio.

Only 1.0-millisecond delay was used to obtain a full-section fusion weld for the beveled joints. This was due to the current and force concentrating effect of the bevel.

CONCLUDING REMARKS

This program was limited in scope since many of the possible variables were held constant so that the few described could be studied. I believe that some of the other variables should also be studied. Among these, the effect of smoother and rougher faying surface finishes on joint properties should be determined.

The value of using a weld current reading as an indication of weld quality should be examined. It is my opinion that weld current readings have been overemphasized in resistance welding technology and can be very misleading. In this study, for example, it was possible to have relatively high weld current readings and no interfacial heating or welding. Weld voltage and resistance readings are much more valuable.

Because of the highly localized heating capability offered by MFUW, the process may be applicable to materials considered unweldable. Materials with low ductility and those adversely affected by heating from conventional welding processes may now be more weldable. Among these may be cast superalloys and fiber-reinforced composites.

SUMMARY OF RESULTS

Sheet-to-plate T-joints in AISI Type 304 and 17-7PH stainless steels were resistance welded by using the magnetic force upset welding (MFUW) process. The results are summarized as follows:

1. Full-strength welds were achieved in dissimilar thickness T-joints with both Type 304 and 17-7PH sheet and plate.

2. A stress concentration existed at the sheet-plate interface under the weld fillet due to the presence of an unwelded area. Removal of the weld fillet (and elimination of the stress concentration) resulted in about a 40 percent strength increase in full-size

17-7PH/17-7PH T-joints. Almost all failures in these T-joints occurred through the weld heat-affected zone on the plate side of the weldment. The greater ductility of the Type 304 plate compared to that of the 17-7PH plate lessened the effect of the stress concentration under the fillet.

3. Because of the possible existence of a stress concentration in this type of T-joint, ductility is a more important criterion than strength in selecting the plate material. Type 304 is preferred over 17-7PH as the plate material because of the low ductility of 17-7PH plate in the short transverse direction.

4. From metallurgical observations, the best welds were achieved with beveled joint configurations. A small sheet bevel angle and initial contact thickness (0.015 in. (0.38 mm)/15°) are preferred. Beveled joints were principally fusion welded; whereas, unbeveled joints were a combination of fusion and solid-state welding.

5. For unbeveled joints, stickout S, decrease in sheet length ΔL, the ratio $\Delta L/S$, and delay of force relative to current D were all important in obtaining highest strengths. For beveled joints only ΔL and D were important.

6. MFUW was a successful welding process in this study because heating was concentrated at the interface between the two dissimilar section thicknesses. This was accomplished by delaying the initiation of the magnetic force wave and by using short weld-current times set by unique MFUW controls.

Lewis Research Center,
National Aeronautics and Space Administration,
Cleveland, Ohio, May 5, 1970,
129-03.

APPENDIX - EDGE EFFECT

Figures 6 and 7 show that there is more fusion welding in the edge section than at the center. This is termed the "edge effect." As resistance heating occurs at the sheet-plate interface, the "fusion-weld front" moves toward the center principally from the short edges, as shown by the arrows in figure 7. Increases in delay (force relative to current) increase the amount of fusion-weld-front movement. There are three interrelated reasons for the edge effect.

The first factor is mechanical. Pressure is not distributed uniformly across the sheet thickness or width at the original interface (ref. 8). Rather, it is highest at all four edges of the cold interface and decreases parabolically as the center is approached. This causes contact resistance near the edges to be lower. And this favors more current flow and a higher current density near the edges.

Secondly, heating occurs in the form of a thin outer ring at the sheet-plate interface because of the skin effect. However, as the material temperature rises, so does its electrical resistance. Current is forced inward, from both long and short edges, toward the cooler, lower-resistance material. Portions of the interface near the short edges receive increased current from both long and short edges. The current density is necessarily higher near the short edges. This causes the fusion-weld front to move inward faster from the short edges.

Thirdly, as the material near the edges is softened by resistance heating, it no longer is able to support the load. The pressure on the remaining material increases with a corresponding drop in contact resistance. This allows more current through the remaining center portion of the interface. Thus, resistance heating increases, and the fusion-weld front moves inward.

Thus, increased current density and more heating occur near the edges, just ahead of the moving fusion-weld front. So, all three of the factors described, together, cause the inward movement of fusion welding shown in figure 7.

Delay of the magnetic force initiation allows more inward movement of the fusion-weld front. In fact, too much delay results in excessive heating, expulsion and cracking. Too little delay does not allow enough heat to be developed, resulting in very little fusion and only a marginal solid-state weld. For the unbeveled joints, a delay of 1.5 milliseconds provided optimum amounts of fusion and solid-state welding. Complete fusion welding in unbeveled joints was accompanied by shrinkage cracking.

As magnetic force is applied, pressure increases sharply on the non-fusion-welded area of the interface. Contact resistance drops; and even though high current is available, little resistance heating takes place because of the low contact resistance. Solid-state welding occurs because upsetting brings hot sheet material into close contact with the plate along the interface.

Less delay (1.0 msec) was used with the molybdenum-insert tooling when the unbeveled sheet was welded. The purpose of the molybdenum was to counteract the edge effect and force more current into the center of the joint. The molybdenum inserts were shaped to form a more resistive path along the edge than the center. More heating took place toward the center, and less delay was required. However, there was a tendency to overheat the sheet at the last point of contact with the molybdenum because of its low heat conductivity.

REFERENCES

1. Del Vicchio, E. J., ed.: Resistance Welding Manual. Vol. 1. Third ed., Resistance Welder Manufacturers' Assoc., 1956, Chs. 1 and 5.
2. Phillips, Arthur L., ed.: Welding Handbook. Sect. 2. Fifth ed., American Welding Soc., 1963, ch. 30.
3. Park, F. R.: Magnetic Force Welding. Product Eng., vol. 29, no. 39, Sept. 15, 1958, p. 4.
4. Boolen, R. F.: Magnetic Force Welding Applications at Battelle Northwest. Rep. BNWL-422. Battelle-Northwest, May 1967.
5. Schueler, Arthur W.: Magnetic Force Butt Welding for Nuclear Cladding. Welding J., vol. 47, no. 8, Aug. 1968, pp. 638-643.
6. Funk, E. J.: Recent Developments in Magnetic-Force Welding. Welding J., vol. 36, no. 6, June 1957, pp. 576-582.
7. Stevenson, William D., Jr.: Elements of Power System Analysis. McGraw-Hill Book Co., Inc., 1962.
8. Timoshenko, Stephen P.; and Goodier, J. N.: Theory of Elasticity. Second ed., McGraw-Hill Book Co., Inc., 1951.
9. Anon.: Properties of Some Metals and Alloys. The International Nickel Co., Inc.

TABLE I. - ROOM-TEMPERATURE BASE METAL TENSILE PROPERTIES[a] OF 17-7PH AND AISI TYPE 304 STAINLESS STEELS

Material	Condition	Ultimate tensile strength		0.2-Percent yield strength		Elongation in 1/2 in. (1.27 cm), percent	Fracture
		ksi	MN/m^2	ksi	MN/m^2		
17-7PH Plate (tested in short transverse to rolling direction)	TH1100 (precipitation hardened)	144	990	---	----	2	Brittle
17-7PH Sheet (tested parallel to rolling direction)	TH1100	177	1220	149	1025	17	Ductile
17-7PH Sheet (ref. 9)[b]	Solution annealed	130	895	40	275	30	Ductile
Type 304 sheet (tested parallel to rolling direction)	Mill annealed	94	645	---	----	--	Ductile

[a]Averaged values of three or more tests.
[b]Data is for a 2-in. (5.1-cm) gage length.

TABLE II. - MAGNETIC FORCE UPSET WELDING MACHINE CAPABILITIES

[Current and force waves independently controlled by phase shift heat controls.]

Welding current:
200 kA at short circuit
Single-phase, 60 Hz, 440-V, 400-kVA transformer
Force:
Magnet force, 6.5 kips (27.9 N) peak
Pneumatic force, 3.7 kips (16.5 N) maximum
Single-phase, 60-Hz, 440-V, 100-kVA transformer producing 120-Hz force wave

TABLE III. - OPTIMUM WELD PARAMETERS FOR SHEET-TO-PLATE T-JOINTS IN

17-7PH AND AISI TYPE 304 STAINLESS STEELS

[Less than one cycle of 60-Hz current.]

Parameter	Unbeveled	Beveled	
Material (sheet/plate)	17-7PH/17-7PH	17-7PH/17-7PH	17-7PH/Type 304
Bevel, in. (mm)/deg	--------------------------	0.015 (0.38)/15	
Tooling chamfer, in. (mm)/deg	0.015 (0.38)/45 or 0.030 (0.76)/45	0.030 (0.76)/45	
Stickout, S, in. (mm)	13/128 to 14/128 (2.6 to 2.8)	13/128 to 14/128 (2.6 to 2.8)	
Current (peak),[a] kA	45.5/60	34/50	35/51
Magnetic force (peak),[a] kips (kN)	3.45/3.7 (15.3/16.4)	1.5/4.0 (6.65/17.8)	1.5/3.8 (6.65/16.9)
Delay,[a] D, msec	0.5/1.5	1.5/1.0	
Current duration,[a] msec	4.7/6.0	4.6/5.7	4.6/5.9
Force duration,[a] msec	5.7/5.9	4.9/6.2	4.9/6.1
Decrease in length, ΔL, in. (mm)	0.060 to 0.067 (1.5 to 1.7)	0.062 to 0.063 (1.57 to 1.6)	
Ratio of decrease in length to stickout, $\Delta L/S^{1.2}$	0.92 to 0.96	------------------------------------	

[a]Preheat/weld, see fig. 4.

TABLE IV. - TENSILE TEST RESULTS FOR UNBEVELED T-JOINTS IN 17-7PH AND AISI TYPE 304 STAINLESS STEELS

(a) Full-size tensile specimens

Speci-men	Tooling			Material		Heat treatment[a]	Percent of sheet ultimate tensile strength at failure[b]	Fracture mode
	Material	Chamfer		Sheet	Plate			
		in.	mm					
B9-1	Copper	0.030	0.76	17-7PH	17-7PH	TH1100	33.6	Solid-state weld
B9-2							46.0	and plate heat-
C9-1							63.0	affected zone
C9-3							53.8	Mostly solid-state weld
E8-9		.015	.38		Type 304	As welded	83.4	Through sheet at fillet
E8-10		.015	.38				37.8	
E8-12		.015	.38				37.8	Mostly solid-
E8-16		.030	.76				40.5	state weld
E8-17							50.0	
E8-18							73.3	
E8-19							83.8	Tensile hole in
E8-20							75.0	plate initiated
E8-21							41.5	Through sheet
J9-9				Type 304			90.1	Solid-state weld
J9-10							92.0	and plate heat-
J9-11							85.7	affected zone
J9-12							100.0	
J9-13								
J9-14								Through sheet
J9-15								
I8-12	Mo inserts[c]			17-7PH		TH1100	63.0	Mostly solid-state weld

(b) Small tensile specimens in 17-7PH, heat treated to TH1100

Specimen	Tooling			Ultimate tensile strength		0.2-Percent yield strength		Elongation in 1/2 in. (1.27 cm), percent	Fracture mode
	Material	Chamfer		ksi	MN/m^2	ksi	MN/m^2		
		in.	mm						
I8-24	Copper	0.015	0.38	144	992	134	926	4	Two-thirds solid-state weld, one-third heat affected zone
I8-25				143	985	135	930	6	
I8-26				111	765	---	---	2	Mostly solid-state weld
I8-27				67	464	---	---		
I8-28				85	586	---	---		
I8-30				129	890	124	857		Through plate
L8-4		[d].030	[d].76	96	663	---	---		Mostly solid-state weld
L8-5				86	595	---	---		
L8-6				23	157	---	---	0 to 1	All solid-state weld
L8-11[e]				83	572	---	---	1	
I8-21	Mo inserts[f]	.030	.76	142	975	135	926	4	Mostly plate heat-affected zone

[a]All materials were welded in annealed condition.

[b]Based on an average sheet UTS of 177 ksi (1220 MN/m^2) for 17-7PH sheet in the TH1100, 130 ksi (895 MN/m^2) for 17-7PH sheet annealed, and 94 ksi (645 MN/m^2) for Type 304 sheet.

[c]1/8-in. (3.18-mm) Mo taper (see fig. 2(c)).

[d]Radius.

[e]Weld made with less than three, rather than less than one cycle of 60-Hz current; and less than six, rather than less than two cycles of 120-Hz magnet force.

[f]1/4-in. (6.36-mm) Mo taper (see fig. 2(c)).

TABLE V. - TENSILE TEST RESULTS FOR BEVELED T-JOINTS IN 17-7PH AND AISI TYPE 304 STAINLESS STEELS

(a) Full-size tensile specimens; tooling material, copper; chamfer, 0.030 in. (0.76 mm)

Specimen	Material		Sheet bevel			Heat treatment[a]	Percent of sheet ultimate tensile strength at failure[b]	Fracture mode
	Sheet	Plate	Initial contact thickness		Angle, deg			
			in.	mm				
J9-3	17-7PH	17-7PH	0.015	0.38	15	TH1100	57.6	Mostly plate heat-affected zone
J9-4							63.9	
J9-5							[c]85.6	
J9-6							[c]84.2	
J9-7		Type 304			45		88.4	
J9-8		Type 304					87.0	
C9-6[d]		17-7PH	.020	.51			21.2	All solid-state weld
C9-7[d]			.020	.51			19.0	
C9-10			.025	.64	30		51.7	Half solid-state weld, half heat-affected zone
C9-11			.030	.76	30		44.6	
C9-12			.020	.51	15		43.3	
C9-14			.020	.51	45		62.2	
D9-1			.010	.25	45		42.1	
D9-2[e]			Knife edge		45		24.6	Through cracked fusion weld
J9-1	Type 304	Type 304	0.015	0.38	15	As welded	58.0	Solid-state and plate heat-affected zone
J9-2	Type 304	Type 304	.015	.38	15	As welded	99.4	Mostly plate heat-affected zone

(b) Small tensile specimens in 17-7PH, heat treated to TH100

Specimen	Tooling			Sheet bevel			Ultimate tensile strength		0.2-Percent yield strength		Elongation in 1/2 in. (1.27 cm), percent	Fracture mode
	Material	Chamfer		Initial contact thickness		Angle, deg	ksi	MN/m^2	ksi	MN/m^2		
		in.	mm	in.	mm							
L8-1	Copper	[g]0.030	[g]0.76	0.015	0.38	45	124	855	---	----	1	Through plate
L8-2		[g].030	[g].76	.015	.38	45	122	840	---	----	0	
C9-8		.030	.76	.015	.38	30	56	383	---	----	2	Mostly solid-state weld
C9-9				.025	.64	30	75	517	---	----	1	
C9-17				.015	.38	15	155	1069	145	995	0	Through plate
C9-5				.015	.38	45	61	421	---	----	0	Mostly solid-state weld
C9-15[d]				.020	.51		161	1105	143	985	0	Through plate
C9-16[d]				.020	.51		153	1052	146	1006	2	
I8-22	Mo inserts[f]			.032	.81		152	1048	118	812	6	
I8-23	Mo inserts[f]			.023	.58		137	940	126	870	4	Half plate heat-affected zone, half plate

[a]All materials welded in annealed condition.
[b]See footnote (b), table IV.
[c]Stress concentration removed, see fig. 5(c).
[d]See footnote (e), table IV.
[e]Weld made with less than two cycles of current and four cycles of magnet force.
[f]1/4-in. (6.36-mm) Mo taper (see fig. 2(c)).
[g]Radius.