

Practical Method for Diffusion Welding of Steel Plate in Air

Sound welds can be produced in thick steel plates using deadweight loading and an autogenous (self-generated) surface cleaning principle

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ABSTRACT. This work was designed to determine whether a simple and easily applied diffusion welding operation could be developed for thick steel plate. The novel feature of this welding method is that diffusion welds are made in air with deadweight loading. Another objective of this work was to examine the use of an autogenous (self-generated) surface-cleaning principle (termed "auto-vac cleaning") to reduce the effects of surface oxides that normally hinder diffusion welding.

A series of nine butt joints were diffusion welded in thick sections (3.8 to 5.1 cm, 1½ to 2 in.) of AISI 1020 steel plate. Diffusion welds were attempted at three welding temperatures (1200, 1090 and 980C) using a deadweight pressure of 3.45×10^4 N/m² (5 psi) and a 2-hour hold-time at temperature. Auto-vac cleaning operations prior to welding were also studied for the same three temperatures. Evaluation of weld quality was based on metallographic examination and room temperature tensile and bend tests.

Results indicate that sound welds were produced at the two higher temperatures when the joints were previously fusion seal welded completely around the periphery. Also, auto-vac cleaning at 1200C for 2½ hours prior to diffusion welding was highly beneficial, particularly when subsequent welding was accomplished at 1090C.

This program is considered to be successful because sound diffusion welds were

made in thick steel plate using simple procedures that can be readily applied in many industrial uses. Thus, the results of this study are believed to have considerable potential in both aerospace and other industrial applications.

Introduction

In this report, a simple and easily applied method of diffusion welding steel plate in air is described. The feasibility of applying this welding method was clearly established for AISI 1020 steel. The main purpose of this study was to devise a practical method of diffusion welding steel plate; that is, a procedure that does not require a vacuum furnace or hot press. Another purpose was to gain information on the diffusion welding of a metal (steel) having an oxide that is unstable at elevated temperatures. Thus, information developed for the diffusion welding of steel is directly applicable to other metals that can absorb their oxides during the diffusion welding cycle. The results of this study are believed to have considerable potential in basic industrial as well as aerospace applications.

Kinzel¹ conducted early solid state welding studies on the pressure welding of AISI 1020 steel and other materials. Kinzel's technique involved pressure welding at temperatures between 800

and 1230C but the pressures were sufficient to produce measurable decreases in length. Therefore, these were solid state deformation welds. Welds made at 1230C were reported to be indistinguishable from the parent metal with good tensile, bend and impact properties. In the study reported herein, similar quality welds were produced at pressures low enough to prevent macrodeformation. (This solid-state welding operation with no macrodeformation is termed diffusion welding².)

This program was of limited scope. For the initial portion, two solid-state butt welds were made in 1.3-cm (0.5-in.) diameter type 304 stainless steel bar. Subsequently, nine butt welds were made in AISI 1020 steel plate, 3.8 to 5.1 cm (1½ to 2 in.) thick, using a diffusion welding process. Welding temperatures evaluated included 1200, 1090 and 980C. Time at temperature was 2 hr and the applied pressure was only 3.45×10^4 N/m² (5 psi).

An integral part of the diffusion welding operation was the use of an autogenous (self-generated) faying surface cleaning principle. This cleaning principle has been described by Medovar³ and Nikiforov⁴. Medovar points out that for a steel assembly seal welded at the periphery of the faying surfaces and heated to 1200C for ½ hr, surface cleaning takes place auto-

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genetically, After an initial pressure increase according to Charles' law, a vacuum is formed within the sealed gap. Nikiforov visualizes that the oxygen within such a closed space is used up and further diffusion of metal ions to the surface enriches the surface with metal atoms. This was summed up as a peculiar process of dissolving oxides, which is possible in principle for any metal. Because of the fact that cleaning takes place autogenetically and a vacuum is theoretically produced in the gap, we have termed this process auto-vac cleaning.

Evaluation of weld quality was made on the basis of metallographic examination and room-temperature tensile and bend tests. All AISI 1020 steel weldments were exposed to a double normalizing heat treatment prior to mechanical testing.

Type 304 Stainless Steel Bar

To investigate the effectiveness of the auto-vac cleaning principle, two 1.3-cm diam by 3.8-cm ($1/2$ -in. diam by $1\frac{1}{2}$ -in.) AISI type 304 stainless steel bars were prepared for butt welding to produce a 7.6-cm (3-in.) long weldment. As shown in the outline in Fig. 1, the faying surfaces were ground (40.7×10^{-6} cm rms (16 rms)) and degreased in acetone just prior to seal welding at the joint periphery. The seal is the first step in preparing the assembly for auto-vac cleaning. The assembly after gas tungsten-arc (GTA) seal welding in helium is shown in Fig. 2. The machined flange served to minimize restraint on the weld bead and to minimize the heat input required for seal welding.

Electron-beam seal welding was also investigated but showed no advantage over GTA based on metallographic examination of solid-state welded joints. In addition, seal welds were made by the shielded-metal-arc (SMA) welding process; Longer heating times were required to produce the auto-vac cleaning effect for the SMA seal-welded assemblies. Thus, it was decided to use GTA seal welding.

Auto-vac cleaning was applied to one of the GTA-sealed assemblies by heating to 1200C for 1 hr in argon. (An air-atmosphere furnace would have been equally satisfactory.) The second sealed assembly was not auto-vac cleaned (see Fig. 1). Both assemblies were subsequently solid-state welded in an induction heated vacuum hot press as follows:

Fig. 2—Type 304 stainless steel assembly seal welded at periphery of faying surfaces. Sketch illustrates joint design for seal weld. Dimensions are in mm (in.)

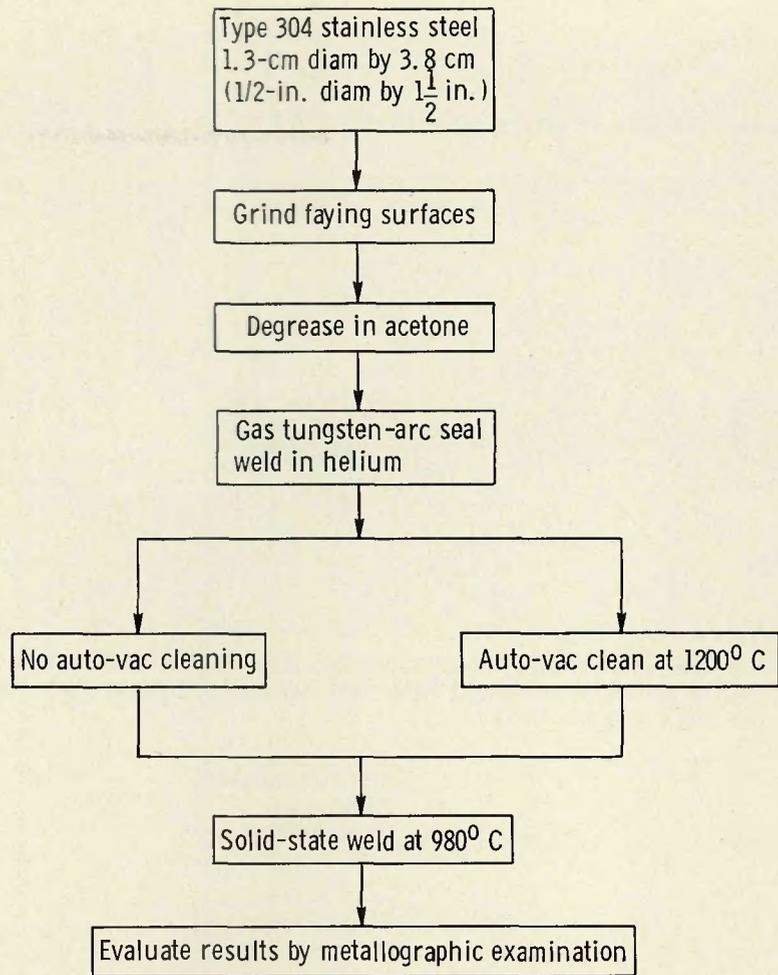
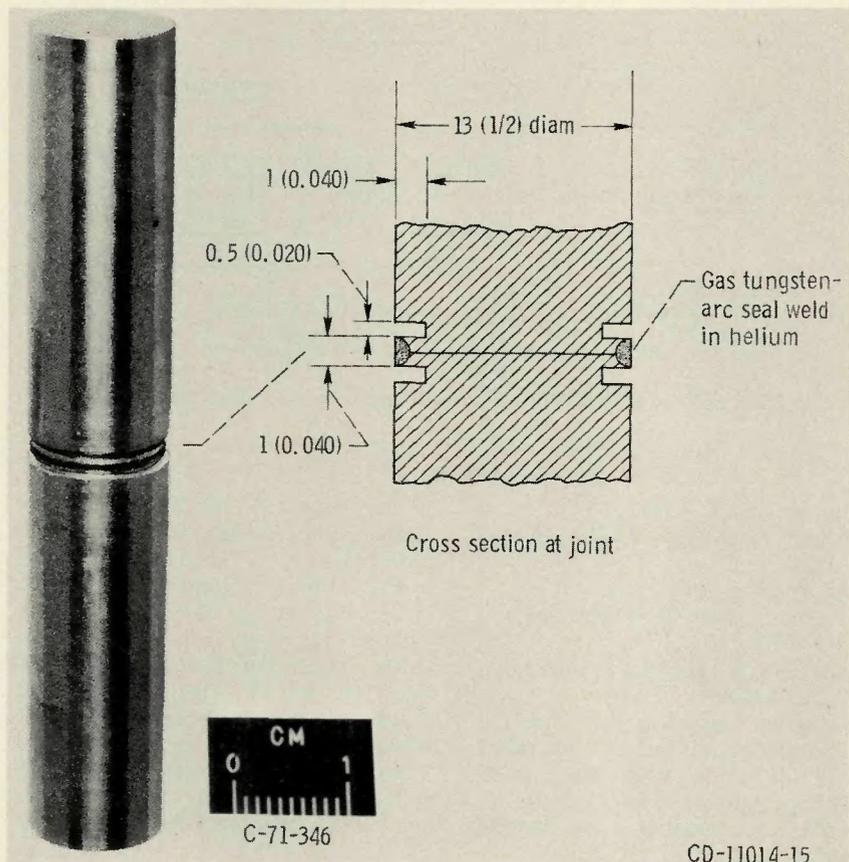


Fig. 1—Outline of auto-vac cleaning study using Type 304 stainless steel bar



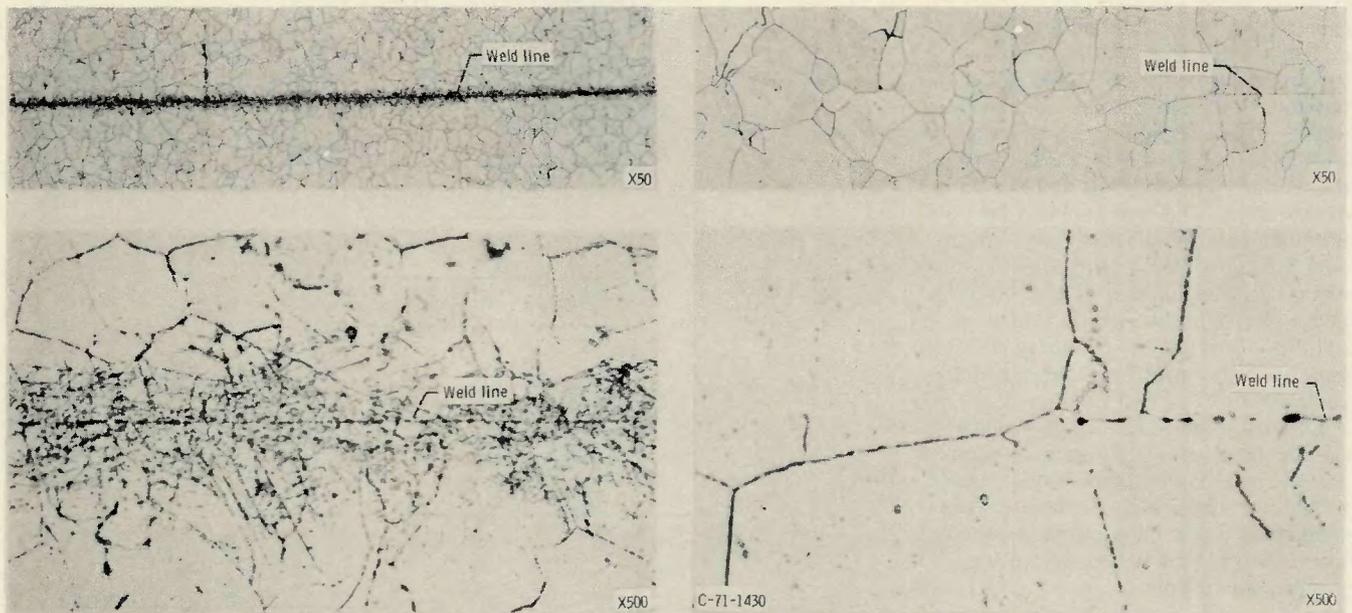


Fig. 3—Solid-state welds in AISI Type 304 stainless steel illustrating the effect of preweld auto-vac cleaning: left, no auto-vac cleaning prior to solid-state welding at 980C; right, auto-vac cleaned at 1200C for 1 hour prior to solid-state welding at 980C. Etchant, 10% oxalic acid, electrolytic

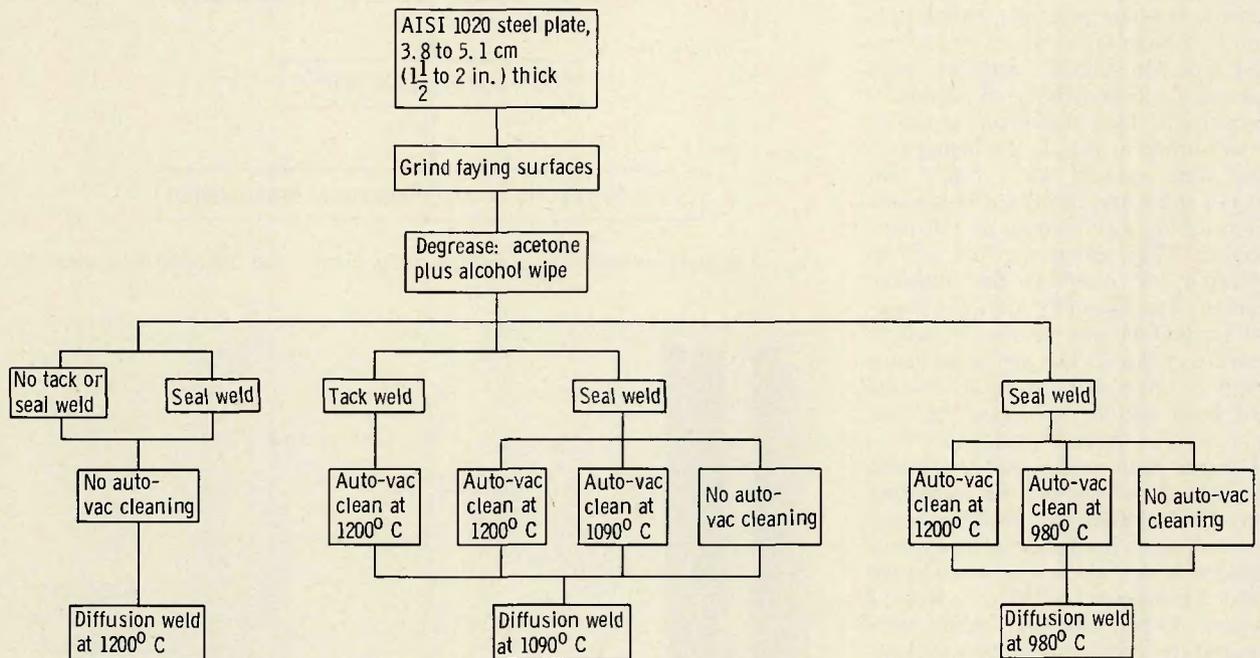


Fig. 4—Program outline of diffusion welding study on heavy steel plate

Temperature, °C—980
 Pressure, N/m² (ksi)— 1.88×10^7
 (2.73)
 Time at temperature, min.—5
 Atmosphere, N/m² (torr) vacuum—
 2.7×10^{-3} (2×10^{-5})
 Upset, mm (in.) decrease in length—
 0.2 (0.008)

It should be noted here that since the joint periphery was sealed, the solid-state welds could have been made equally well in air. The vacuum hot press was used because it was readily available.

The beneficial effect of auto-vac cleaning prior to solid-state welding of type 304 stainless steel is clearly shown in Fig. 3. With no auto-vac cleaning, a large amount of foreign material, believed to be principally chromium oxide, is concentrated near the weld line (Fig. 3a). However, the weldment that was auto-vac cleaned shows little evidence of oxide at the weld line and extensive grain growth across the original interface (Fig. 3b). These results clearly demonstrate that auto-vac cleaning at 1200C for 1 hr removes

foreign material from the faying surfaces of type 304 stainless steel. Auto-vac cleaning thus makes it possible to subsequently produce high quality welds in type 304 stainless steel at 980C. In these solid-state welding runs, however, a macrodeformation decrease in length of (0.2 mm (0.008 in.)) was produced. But it was felt that if the auto-vac cleaning principle could be utilized in conjunction with a diffusion welding operation (no macrodeformation), many more applications would be found in industry. Thus, it was decided to at-

tempt to diffusion weld AISI 1020 steel in air with deadweight loading.

Experimental Procedures

An outline of the welding program on AISI 1020 steel plate is shown in Fig. 4. Nine butt joints were fabricated in 3.8 to 5.1 cm (1½ to 2-in.) material using a diffusion welding process. Seal welds at the joint periphery were made prior to diffusion welding in most cases. And auto-vac cleaning effects were studied at three temperatures. Diffusion welds were subsequently produced at the same three temperatures as shown in Fig. 4.

Weld Specimen Preparation

The dimensions of the weldments and the weld joint relation to the plate rolling direction are shown in Fig. 5. In preparation for diffusion welding (see Fig. 4), the faying surfaces were ground to about a 40.7×10^{-6} centimeter rms (16 rms) finish. Just prior to assembly for diffusion welding, a protective oil was removed by wiping with acetone and then alcohol. In assembling the butt joint, C-clamps were used to position the faying surfaces. Tack welds were then applied. This was followed by seal welding along the flanges of the faying surfaces, as shown in Fig. 6. For both tack and seal welding, the SMA welding process was used with 3.2-mm (¼-in.) diam AWS-E7018 covered electrodes. The SMA welding process was used for seal welding for convenience. No other seal-welding methods were considered.

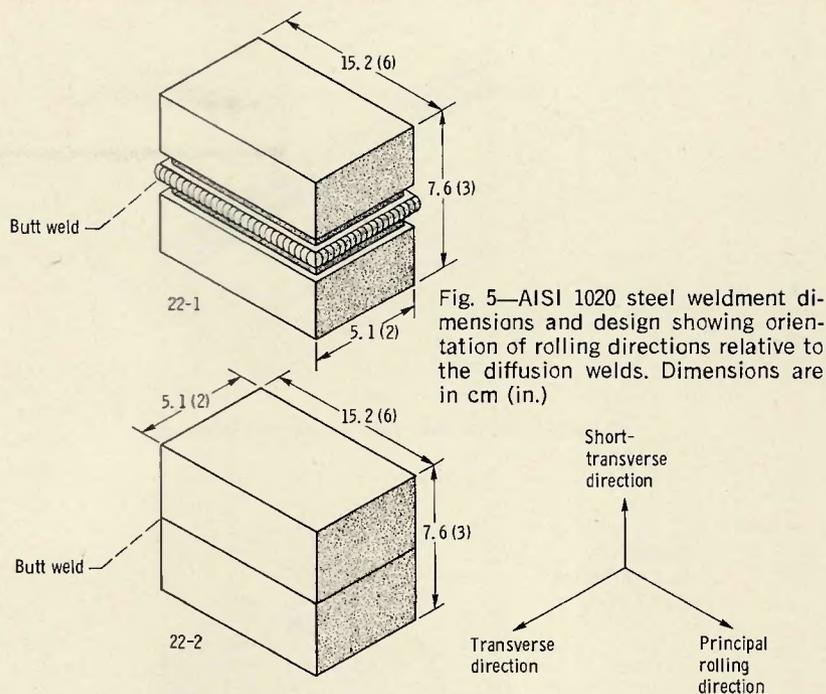
Auto-Vac Surface Cleaning

The seal-welded assembly shown in Fig. 6 now was ready for auto-vac cleaning of the faying surfaces. Auto-vac cleaning was accomplished by placing the seal-welded assembly in an air atmosphere, resistance heated furnace. During the auto-vac cycle, the assembly was positioned flat as shown in Fig. 7. Three different auto-vac, time-temperature cycles were tried:

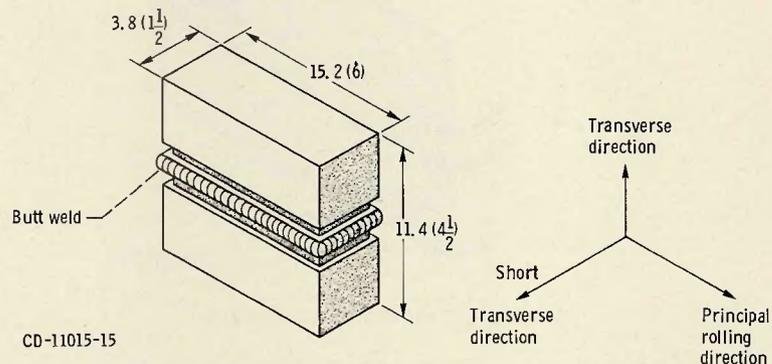
Cycle	Temperature, °C	Time, hr
1	1200	2½
2	1090	2
3	980	2

The assemblies were furnace cooled in all three cases. In addition, an

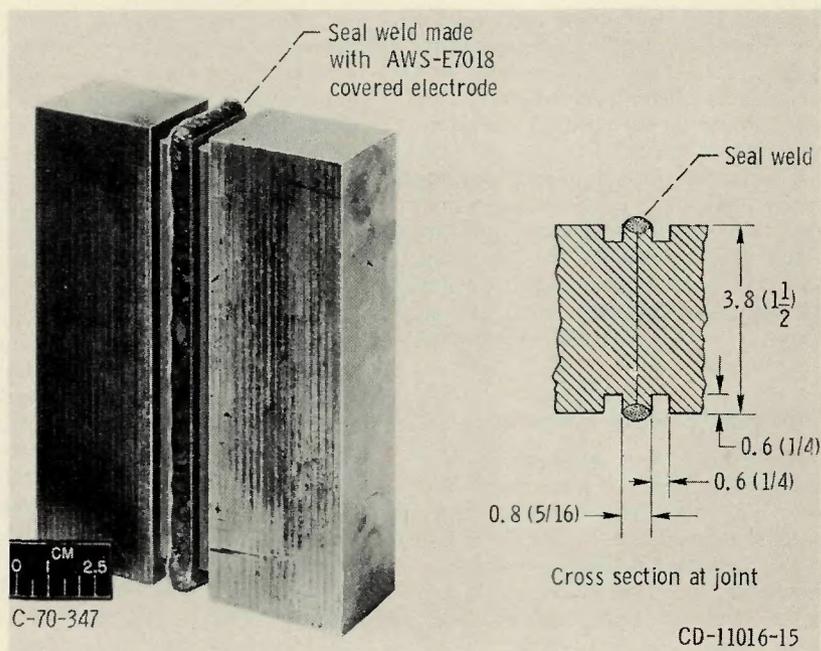
Fig. 6—Weld assembly in AISI 1020 steel with seal weld at periphery of faying surfaces. Cross-section sketch gives design of flange area at joint. Dimensions are in cm (in.)

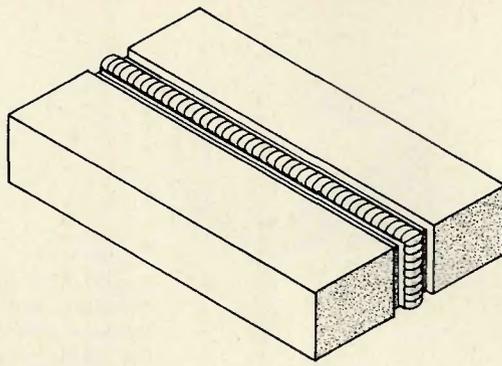


(a) 1200° C weldments (numbers 22-1 and 22-2).

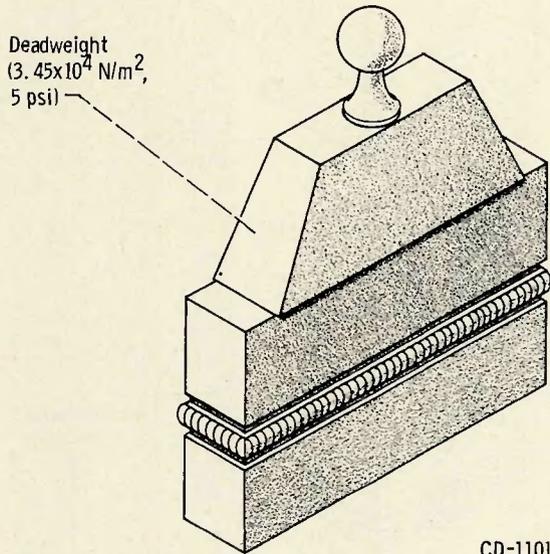


(b) 1090° C and 980° C weldments (numbers 20-1, 20-2, 20-3, 20-4, 18-1, 18-2, and 18-3).





(a) Flat position for auto-vac cleaning heat treatment.



(b) Vertical position for diffusion welding.

Fig. 7—Positions of seal-welded assemblies during auto-vac cleaning heat treatment and during diffusion welding operation

assembly that was only tack welded (not sealed) was auto-vac cleaned using cycle 1 (see Fig. 4). This run was designed to determine whether tack welds would be sufficient for the auto-vac cleaning cycle.

If according to auto-vac cleaning theory a vacuum is developed within the sealed gap, atmospheric pressure would be applied to the assembly. And thus, a component of force would act normal to the weld joint. The influence of this force was not studied independently.

Diffusion Welding Program

All welding runs were made in a resistance heated, air atmosphere furnace. Butt joints were diffusion welded at three temperatures: 1200, 1090 and 980C. Deadweight loading placed as shown in Fig. 7 produced only $3.45 \times 10^4 \text{ N/m}^2$ (5 psi) pressure at the weld joints. The deadweight of the upper weld specimen contributed about

$3.4 \times 10^3 \text{ N/m}^2$ (0.5 psi) additional pressure. Furthermore, atmospheric pressure due to auto-vac cleaning could produce up to $102 \times 10^3 \text{ N/m}^2$ (14.7 psi) at the joint. For all welding runs, the time at temperature was 2 hours.

No preweld auto-vac cleaning was applied for the two welding runs that were made at 1200C. One run was made using seal-welded flanges to determine if auto-vac cleaning and diffusion welding could simultaneously be accomplished at this high temperature. For the other 1200C welding run, one block (without a flange or seal welding) was simply placed on top of another and loaded with deadweights (see program outline in Fig. 4). The latter run, therefore, was made to determine whether any fusion welding at the joint periphery is necessary in order to subsequently produce a sound and strong diffusion weld.

Auto-vac cleaning procedures were used for three of four 1090C welding

runs and for two of three 980C welding runs (see Fig. 4).

Evaluation Procedure

Cross sections were taken at mid-length from each weldment. Photomicrographs were obtained in the as-welded and double normalized conditions.

Also, tensile and bend test specimens were machined from each of the weldments. But prior to machining the test specimens, all weldments were double normalized as follows:

- Step 1: 900C for 1 hour, air cool
- Step 2: 900C for 1 hour, air cool

The weldments were double normalized to minimize structural differences in the AISI 1020 steel materials that were exposed to various time-temperature auto-vac and diffusion welding cycles.

As shown in Fig. 8, bend specimens 1 cm by 2.5 cm by 11.4 cm ($\frac{3}{8}$ in. by 1 in. by $4\frac{1}{2}$ in.) were prepared from two of the weldments. For the other weldments, bend specimens 1 cm by 1.3 cm by 11.4 cm ($\frac{3}{8}$ in. by $\frac{1}{2}$ in. by $4\frac{1}{2}$ in.) were used (Fig. 8). Guided bends were made with a 19-mm ($\frac{3}{4}$ -in.) radius punch following the ASTM E190-64 specification. Transverse tensile specimens were obtained with the weld at the middle of the reduced section (Fig. 8). Tensile specimens were 1.3-cm ($\frac{1}{2}$ -in.) diam at the threaded ends and 7.6-cm (3-in.) long. Diameter at the reduced section was 6.35 mm ($\frac{1}{4}$ in.) with a 25.4-mm (1-in.) gage length. The tensile tests were conducted at a crosshead speed of 1.3 mm (0.05 in.) per minute.

Results

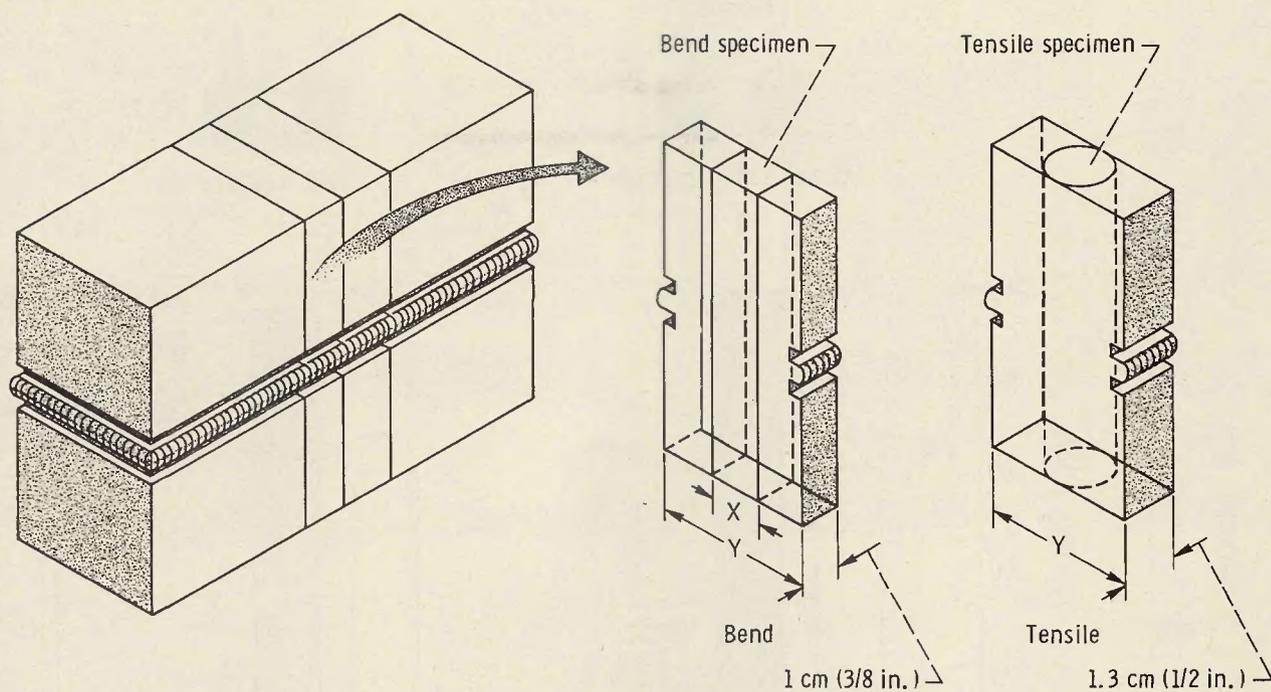
Results are discussed in groups based on diffusion welding temperature: 1200, 1090 and 980C. For all the diffusion weldments, weld quality was lower near the edges. These regions exhibited less grain growth across the weld line and more extensive oxides.

Diffusion Welds Made at 1200C

For these two diffusion welding runs, preweld auto-vac cleaning was not applied. Therefore, the objective was to obtain both auto-vac cleaning and subsequent diffusion welding during the time-temperature cycle.

Microstructure. The microstructure of sealed weldment 22-1 near midthickness is shown in Fig. 9a. Grain growth across the weld line is complete. Only a few isolated oxide particles are evident at the weld line.

Weldment 22-2, which was not seal welded prior to diffusion welding, exhibits a band of small oxide particles in the vicinity of the weld (Fig. 9b).



Weldment	Dimensions, cm (in.)	
	X	Y
22-1, 22-2	2.5 (1)	5.1 (2)
20-1, 20-2, 20-3, 20-4, 18-1, 18-2, 18-3	1.3 (1/2)	3.8 (1 1/2)

Fig. 8—Location of test samples for bend and tensile tests

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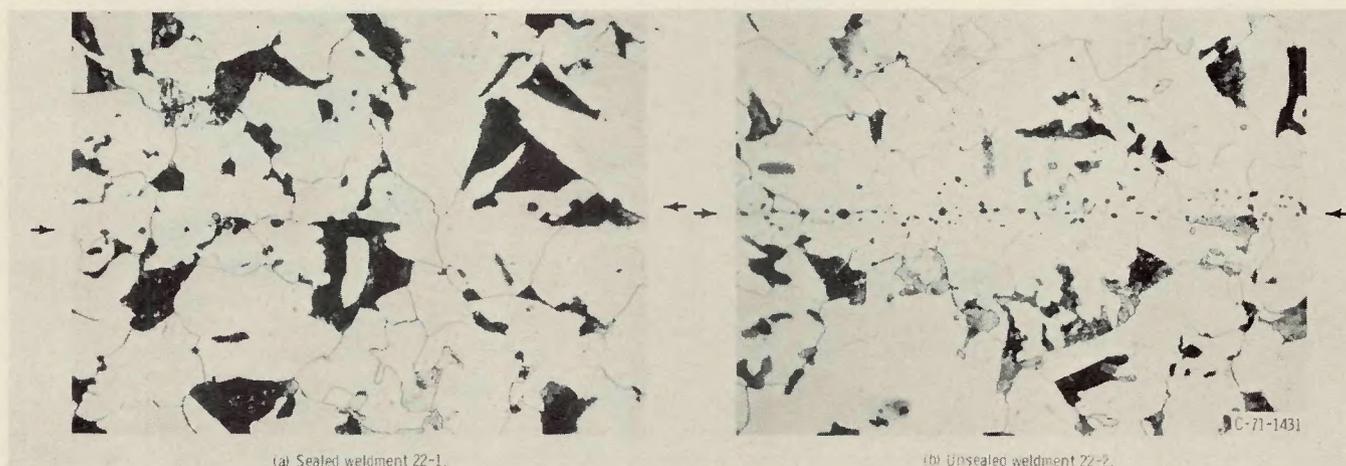


Fig. 9—Diffusion welds in AISI 1020 steel made at 1200C with no preweld auto-vac treatment: left, sealed weldment 22-1; right, unsealed weldment 22-2. After welding the weldments were double normalized at 900C. Etchant, 4% nital; X500

Absence of a seal weld thus has resulted in a lower quality weld than weldment 22-1. Longer time at 1200C would tend to remove the oxide particles. This effect, however, was not investigated.

Tensile tests. Duplicate room temperature tensile tests (Table 1 and Fig. 10) clearly showed the beneficial effect of seal welding at the periphery of the

faying surfaces. Fracture took place in the parent material for weldment 22-1 which was seal welded. And the elongation was about 21%. Tensile specimens from weldment 22-2 failed at the weld with only 8.5% elongation.

Bend tests. Bend test results (Table 1) exhibited a more dramatic difference than the tensile results. As shown in Fig. 11, sealed weldment 22-1 passed a

180 deg bend, while unsealed weldment 22-2 broke at 10 deg. The parent metal fissures shown in weldment 22-1 in Fig. 11 resulted from the fact that the long side of the bend specimen was parallel to the short-transverse direction of the plate (Figs. 5 and 8).

Diffusion Welds Made at 1090C

Four diffusion welding runs were



Parent metal fracture



Weld fracture

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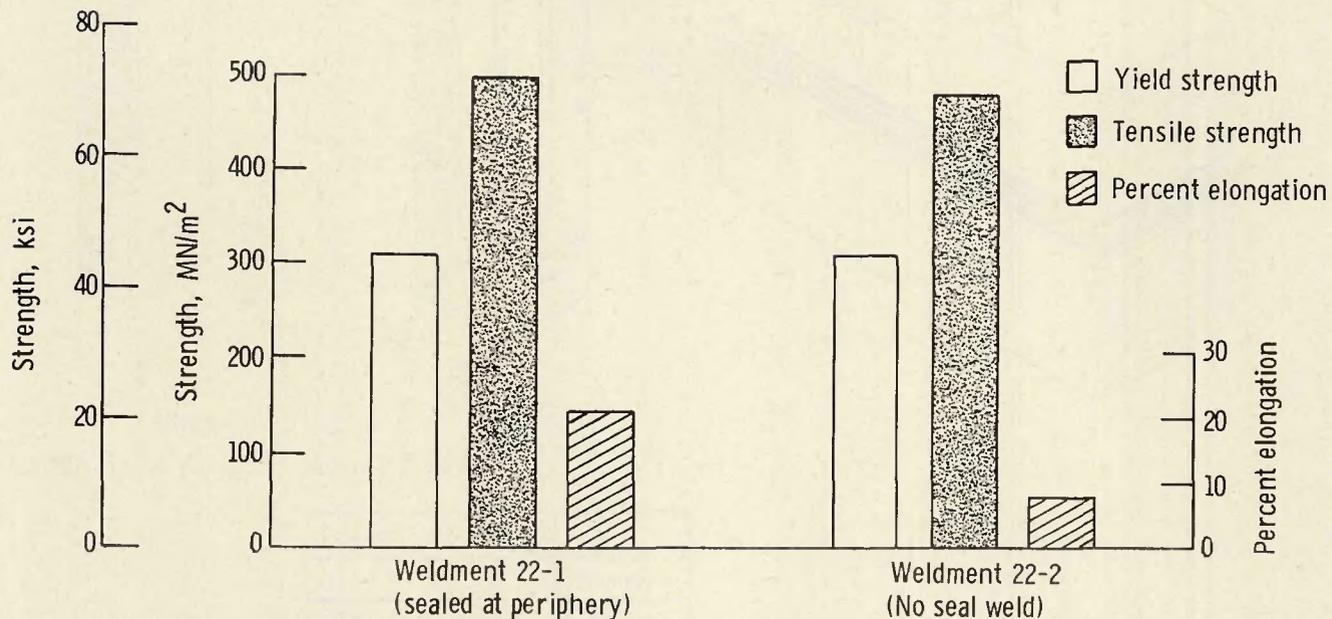
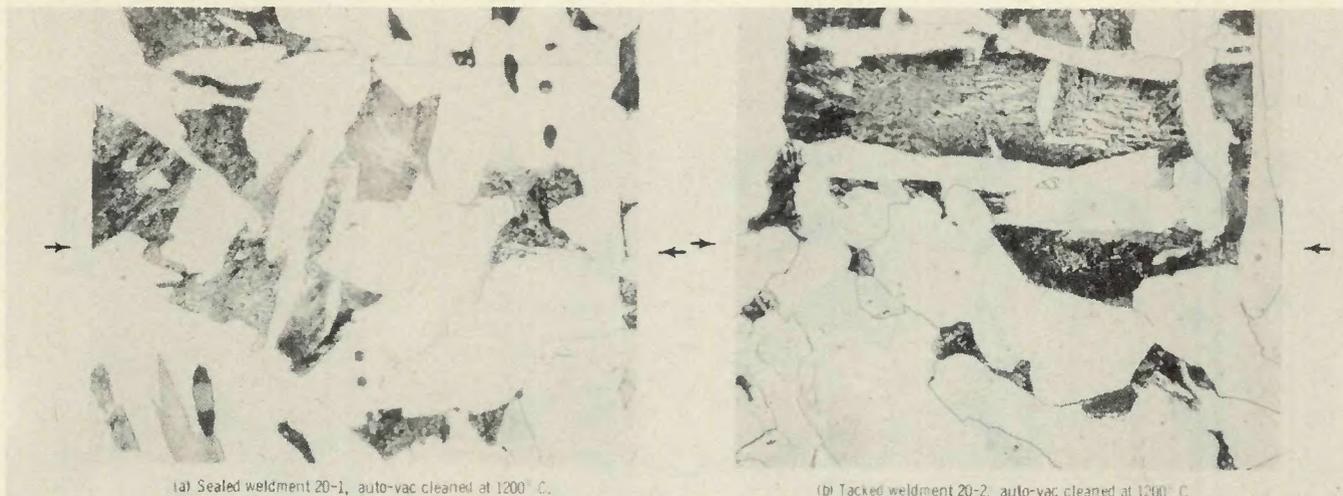


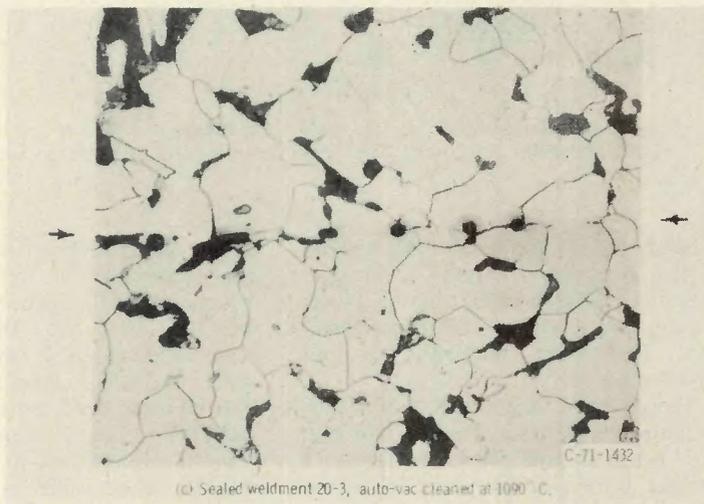
Fig. 10—Room-temperature tensile properties of diffusion welds in AISI 1020 steel made at 1200C and subsequently double normalized at 900C. Average of duplicate tests for each condition



(a) Sealed weldment 20-1, auto-vac cleaned at 1200° C.

(b) Tacked weldment 20-2, auto-vac cleaned at 1300° C.

Fig. 12—Diffusion welds in AISI 1020 steel at 1090C and 3.45×10^4 N/m² (5 psi) for 2 hours after various preweld auto-vac heat treatment. These welds were double normalized at 900C after welding. Etchant, 4% nital; X500



(c) Sealed weldment 20-3, auto-vac cleaned at 1090° C.

C-71-1432

made at 1090C. For these runs (Fig. 4) effects of several auto-vac cleaning procedures were studied. And in one case there was no auto-vac cleaning applied prior to diffusion welding (weldment 20-4).

Microstructure. Auto-vac cleaning at 1200C proved to be extremely effective. Sealed weldment 20-1, which is shown in Fig. 12a, exhibits complete grain growth across the weld line. In addition, there is practically no evidence of oxide particles at the weld line. Thus, the weld line is virtually not detectable. Weldment 20-2, which was tack welded rather than completely sealed welded, was of similar metallographic quality (Fig. 12b) under the tack welds. In regions between tack welds, however, diffusion welding was incomplete.

Sealed weldment 20-3 which was auto-vac cleaned at 1090C showed grain growth across the weld line, but numerous oxides (Fig. 12c) were present. The 1090C auto-vac cleaning is obviously much less effective than the 1200C auto-vac cleaning.

Sealed weldment 20-4, which was not auto-vac cleaned prior to diffusion welding, was similar in microstructural appearance to weldment 20-3 (Fig. 12c). But the oxides were larger and more continuous in weldment 20-4.

Tensile tests. Results of duplicate transverse tensile tests of these diffusion welds are shown in Table 1 and Fig. 13. These data show that sealed weldment 20-1, which failed in the parent metal, had the best tensile strength and ductility. This advantage is probably the result of auto-vac cleaning at 1200C. Weldment 20-2 gave variable results (parent and weld fracture) showing that tack welding (rather than seal welding) contributes to a variable weld quality.

Square-edge fracture at the weld was characteristic of sealed weldment 20-3 which was auto-vac cleaned at 1090C. Sealed weldment 20-4, which was not auto-vac cleaned prior to diffusion welding, had lower strength and ductility but a similar fracture to weldment 20-3. Weldments 20-1 and 20-2 had lower yield strengths than weldments 20-3 and 20-4 because the former two had larger grains (Figs. 12a and b) than the latter two (Fig. 12c) due to the 1200C auto-vac cleaning cycle.

Bend tests. The guided bend test specimens are shown in Fig. 14. Of the four diffusion weldments, only sealed weldment 20-1 gave a sound 180 deg bend. This result clearly shows that the 1200C auto-vac cleaning followed by 1090C diffusion welding produced a sound weld.

Weldment 20-2 was bent 60 deg before fracture occurred at the weld. Although this weldment was auto-vac cleaned at 1200C, the assembly was tack welded rather than seal welded. This

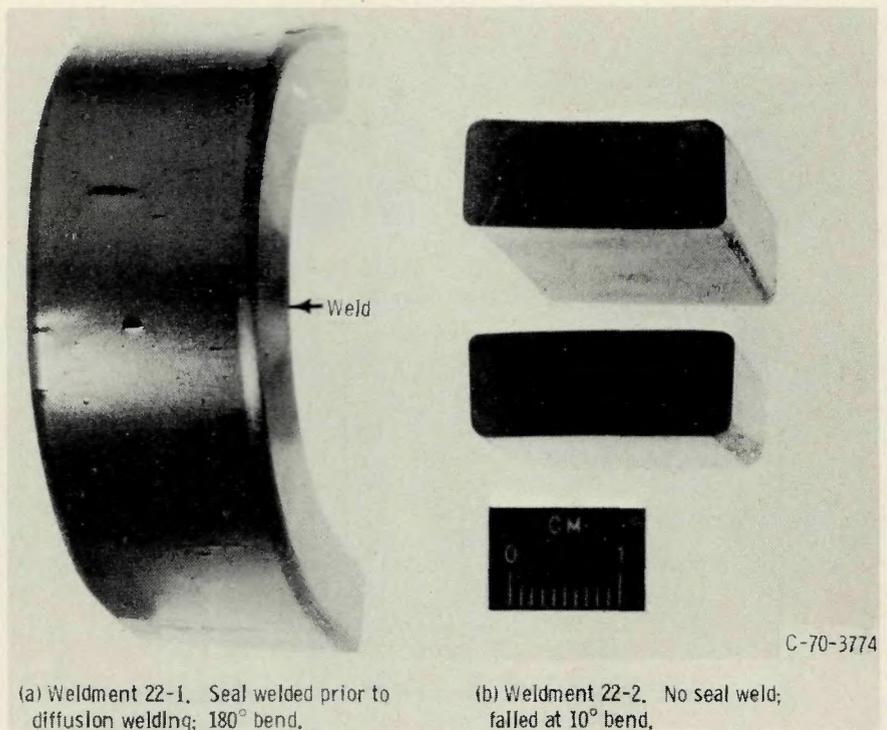


Fig. 11—Bend tests of diffusion welds in AISI 1020 steel made at 1200C and 3.45×10^4 N/m² (5 psi) for 2 hours and double normalized at 900C after welding. Parent metal fissures are present in weldment 22-1 because the bend axis was normal to the short-transverse direction in the plate

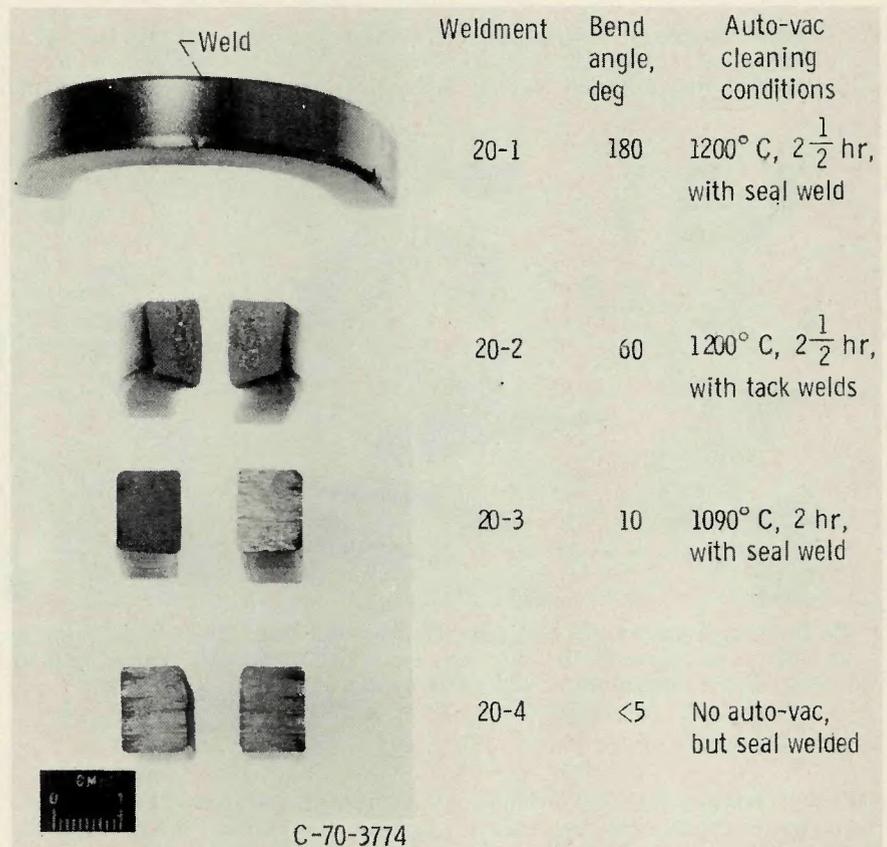


Fig. 14—Effect of auto-vac cleaning prior to diffusion welding AISI 1020 steel on bend properties. Diffusion weld parameters: temperature, 1090C; pressure, 3.45×10^4 N/m² (5 psi); time, 2 hours. All weldments were double normalized at 900C after diffusion welding

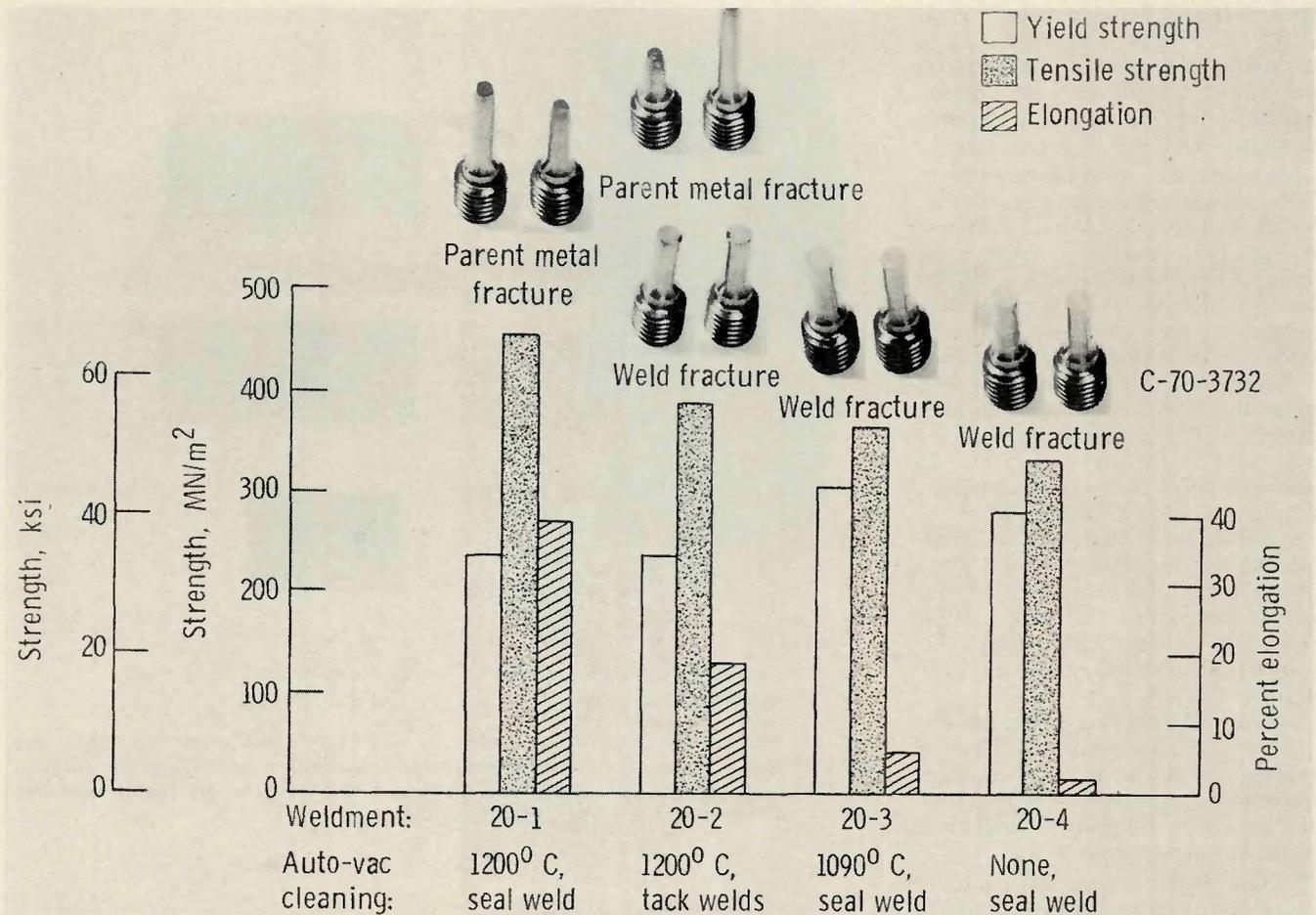


Fig. 13—Effect of auto-vac cleaning prior to diffusion welding AISI 1020 steel on room-temperature tensile properties. Welding parameters: temperature, 1090°C; pressure, 3.45×10^4 N/m² (5 psi) deadweight; time, 2 hours. All weldments were double normalized at 900°C after diffusion welding. Average of duplicate tests for each condition

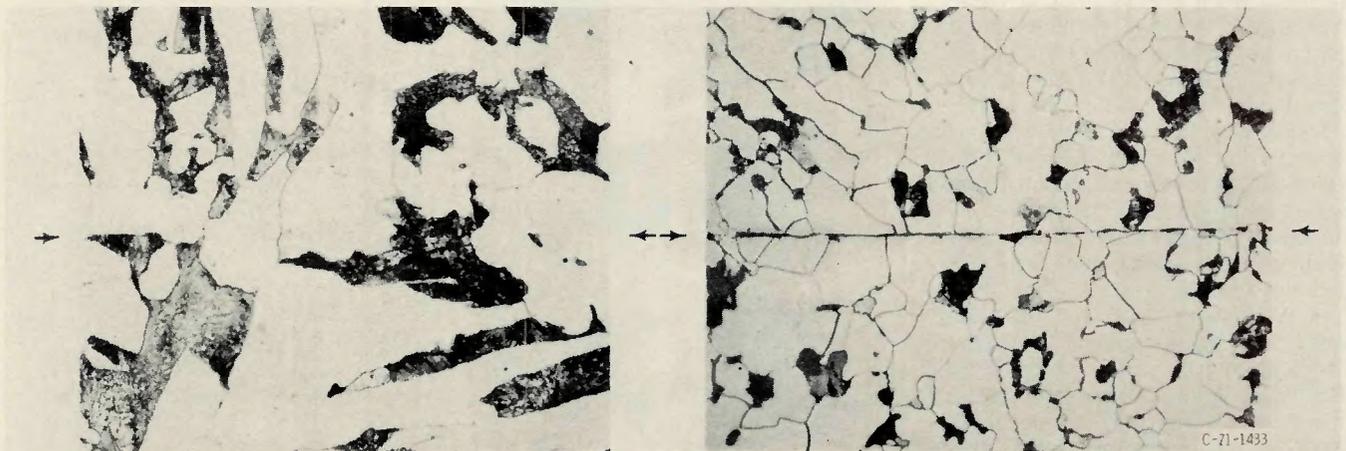


Fig. 15—Diffusion welds in AISI 1020 steel made at 980°C and 3.45×10^4 N/m² (5 psi) for 2 hours, after preweld auto-vac heat treatments: left, sealed weldment 18-1, auto-vac cleaned at 1200°C; right, sealed weldment 18-2, auto-vac cleaned at 980°C. All weldments were double normalized at 900°C after welding. Etchant, 4% nital; X500

bend result indicates that seal welding is necessary to achieve a 180 deg bend.

Auto-vac cleaning at 1090°C prior to diffusion welding was of no great benefit as measured by the bend test of sealed weldment 20-3. Fracture took place at the weld at 10 deg of bending. Weld

fracture occurred at less than 5 deg of bending for sealed weldment 20-4, which was not auto-vac cleaned prior to diffusion welding. Thus, there appears to be only a small benefit from the 1090°C auto-vac cleaning (i.e., 10 deg bends as compared to 5 deg bends). Hold times

at 1090°C for longer than 2 hr for auto-vac cleaning would tend to produce cleaner surfaces. But this was not investigated. The side bend test is seen to be a more severe test of these diffusion welds than metallography or tensile tests.

Table 1—Mechanical Properties of Diffusion Welds in AISI 1020 Steel Plate

Weldment	Auto-vac cleaning temperature °C	Diffusion welding temperature ^a °C	Tensile tests ^a							
			Yield strength		Tensile strength		Elongation %	Reduction in area %	Fracture location	Guided bend ^b degrees
MN/m ²	ksi	MN/m ²	ksi	%	%					
22-1 ^c	None	1200	310	44.9	495	71.8	20	30	Parent metal	180
			304	44.1	503	72.9	22	33	Parent metal	
22-2 ^c	None ^e	1200	304	44.1	474	68.6	8	11	Weld joint	Fracture at weld at 10
			307	44.5	484	70.0	9	11	Weld joint	
			227	32.9	454	65.7	36	61	Parent metal	
20-1 ^d	1200	1090	238	34.5	455	65.9	42	63	Parent metal	180
			227	32.9	456	66.1	32	62	Parent metal	
20-2 ^d	1200 ^f	1090	233	33.7	317	45.9	5	6	Weld joint	Fracture at weld at 60
			306	44.3	378	54.7	7	9	Weld joint	
20-3 ^d	1090	1090	300	43.5	355	51.5	4	6	Weld joint	Fracture at weld at 10
			298	43.3	368	53.3	6	8	Weld joint	
20-4 ^d	None	1090	269	39.0	1	4	Weld joint	Fracture at weld at 5		
			231	33.5	454	65.7	35		56	Parent metal
18-1 ^d	1200	980	233	33.7	442	64.1	32	56	Parent metal	Fracture at weld at 45
18-2 ^d	980	980	Specimens fell apart							
18-3 ^d	None	980								

^a Welding pressure, 3.45×10^4 N/m² (5 psi); welding time, 2 hr.

^b Bend angle.

^c Tensile specimen axis and long side of bend specimens were parallel to short transverse direction in parent metal plate (Figs. 5 and 8).

^d Tensile specimen axis and long side of bend specimens were parallel to transverse direction in parent metal plate (Figs. 5 and 8).

^e No tack or seal weld at joint periphery.

^f Tack weld only, not sealed completely at joint periphery.

^g All weldments were double normalized at 900C prior to testing.

Diffusion Welds Made at 980C

As indicated in Table 1, two sealed assemblies (18-1 and 18-2) were diffusion welded at 980C after auto-vac cleaning. And one diffusion weld was made (sealed assembly 18-3) which was not auto-vac cleaned prior to welding (Fig. 4).

Microstructures. As has already been shown, 1200C auto-vac cleaning effectively removes surface oxides. This is again evident in the structure of sealed weldments 18-1, shown in Fig. 15a, where oxides are essentially absent. Grain growth across the weld line has virtually eliminated all evidence of the weld. In other areas of this same weldment (not shown) a few small oxide particles were present at the weld line.

For the weldment cleaned at lower temperatures (Fig. 15b), a line of oxides at the weld with very limited grain growth across the weld line is typical. Auto-vac cleaning at 980C is clearly not effective. Sealed weldment 18-3, which was not preweld auto-vac cleaned, was similar in appearance to 18-2.

Tensile tests. In duplicate tensile tests of weldment 18-1, failure took place in the parent metal (see Table 1). Thus, on this basis, the weld appears to be as strong as the parent metal. Tensile testing of weldments 18-2 and 18-3 was not done because the blanks fell apart at the weld joint in machining.

Bend tests. A poor result was obtained in the bend specimen from weldment 18-1. As shown in Table 1, this specimen failed at the weld at a 45 deg bend angle. This bend failure was surprising because the weld had ap-

peared to be sound in metallographic examination and it exhibited good transverse tensile strength. The poor bend test result indicates that the 980C weld temperature is not sufficiently high to eliminate a line of weakness at the weld line. Thus, although the preweld auto-vac cleaning at 1200C removed the oxides, a diffusion welding temperature greater than 980C appears to be necessary during the 2-hr hold time at 3.45×10^4 N/m² (5 psi). Higher pressure or longer hold time might also produce a stronger weld.

Bend tests were not made for weldments 18-2 and 18-3 because the blanks broke at the weld line during machining.

Discussion

Seal welding at the joint periphery was shown to be necessary to produce a sound, strong diffusion weld in air. For sealed assemblies diffusion welded at 1200C, preweld auto-vac cleaning was not necessary because both cleaning and diffusion welding take place during the 2-hr weld time at this temperature. Diffusion welding was made possible by the fact that the oxides were dissolved in the parent metal and trapped gases were absorbed by the parent metal (the auto-vac cleaning effect). Ludemann⁹ has pointed out that some FeO also may be reduced by carbon during diffusion welding. In the 1090C diffusion welding studies, it was demonstrated that a high quality weldment similar to 22-1 could be produced providing a 1200C auto-vac cleaning cycle was applied prior to diffusion welding.

We have seen that a seal-welded assembly not auto-vac cleaned in advance

(weldment 22-1) could be diffusion welded successfully at 1200C. However, sealed weldment 20-4, which was diffusion welded at 1090C without preweld auto-vac cleaning, failed the bend test at less than 5 deg. Thus, it is evident that temperature plays a major role in auto-vac cleaning and diffusion welding.

Concluding Remarks

Solid-state welding is not new. Kinzel¹ chose this subject for the American Welding Society's Adams Lecture in 1944. Kazakov⁶ has published a book on the diffusion welding of ferrous, nonferrous and nonmetallic materials; and Gerken and Owczarski⁷ have published an excellent review of diffusion welding. Medovar⁸ used an auto-vac surface cleaning procedure prior to the application of solid-state deformation welding processes that involved rolling, pressing or extrusion.

What is new and is described in this report is a practical method for diffusion welding steel in air with deadweight loading. No welding machine or hot press is required. Because of the limited nature of our study, many technical questions are not fully answered. The following points, however, should be made:

1. A practical, easily applied method is now available for diffusion welding AISI 1020 steel.

2. This concept, with modifications, is applicable to many other materials that have been solid-state welded in vacuum hot presses up to this time.

3. This diffusion welding procedure may have economic advantages as a

complement to or in place of submerged arc, electroslog, and other fusion welding methods for joining large steel components such as pressure vessels. Where applicable, there is no thickness or cross-sectional limitation to the joint to be diffusion welded.

4. For technical reasons (e.g., weld properties equivalent to the parent material, lack of residual stress, and microstructure identical to the parent material), this diffusion welding method may be chosen over fusion welding processes for critical applications.

5. Technical problems, such as surface decarburization and unwelded areas near the edges, can be overcome by tailoring weld preparation, procedure, and parameters to the specific requirements involved.

6. From the work reported herein, we feel that it may be possible to auto-vac clean and/or diffusion weld without seal welding first. For instance, a glass or ceramic material may be applied at the joint periphery to exclude the atmosphere. Or, the heating cycle described herein could be performed in a protective atmosphere such as CO₂ (for steel), or argon (for reactive or refractory metals). In this manner, oxygen is prevented from entering at the edges of the joint.

7. Although the entire weldment was heated in a furnace for this study, the principles discussed herein could also be applied using local heating at the joint. Strip heating elements, induction heating, ultrasonic heating or other

suitable methods could be employed.

Summary of Results

Diffusion welding of 3.8 to 5.1 cm (1½ to 2 in.) thick AISI 1020 steel plate in air was accomplished with deadweight loading. This welding method was made possible by using an autogenous (self-generated) faying surface cleaning principle, designated "auto-vac" cleaning. The extent of this study was limited, consisting of only nine welding runs in AISI 1020 steel and two runs in type 304 stainless steel to study auto-vac cleaning. Butt joints were prepared using ground and degreased surfaces. Evaluation of weld quality was based on metallographic examination and room temperature tensile and bend tests. Results were as follows:

1. Excellent diffusion welds were produced in air with no macrodeformation of the AISI 1020 steel base metal. Diffusion promoted grain growth across the weld line and virtually eliminated the original interface. The welds were as strong as the base metal as judged by transverse tensile tests and bend tests.

2. To achieve these high quality diffusion welds, it was necessary to seal weld at the periphery of the joint. This permitted auto-vac cleaning of the faying (mating) surfaces prior to or during diffusion welding.

3. The best diffusion welds in AISI 1020 steel were obtained by using either set of the following welding parameters:

- (a) No auto-vac cleaning; diffusion welding at 1200C for 2 hr at 3.45×10^4 N/m² (5 psi)
- (b) Auto-vac cleaning at 1200C for 2½ hr; diffusion welding at 1090C for 2 hr at 3.45×10^4 N/m² (5 psi).

4. Auto-vac cleaning of the faying surfaces was accomplished by heating AISI 1020 steel to 1200C for 2½ hr. Type 304 stainless steel was auto-vac cleaned in 1 hr at 1200C.

5. Bend tests in AISI 1020 steel weldments were a more severe test of weld quality than metallographic examination or transverse tensile tests.

References

1. Kinzel, A. B., "Adams Lecture—Solid-Phase Welding," *Welding Journal*, Vol. 23, No. 12, 1944, pp. 1124-1144.
2. Anon., "Terms and Definitions," AWS A3, 0-69, American Welding Society, 1969.
3. Medovar, B. L., et al., "New Methods of Producing Intermediate Pieces for Welding Dissimilar Steels," *Automatic Welding*, Vol. 20, No. 10, 1967, pp. 55-59.
4. Nikiforov, G. D., et al., "The Mechanism of Joint Formation in Welding and Brazing," *Welding Prod.*, Vol. 14, No. 12, 1967, pp. 6-12.
5. Ludemann, W. D., "A Fundamental Study of the Pressure Welding of Dissimilar Metals Through Oxide Layers," Ph.D. Thesis, Rep. UCRL-50744, Univ. California, Oct. 1969.
6. Kazakov, N. F., "Diffusion Welding in a Vacuum," Rep. FTD-MT-24-419-68, Foreign Technology Div., Air Force Systems Command, Aug. 13, 1969. (Available from DDC as AD-698097.)
7. Gerken, J. M., and Owczarki, W. A., "A Review of Diffusion Welding," Bulletin No. 109, Welding Research Council, Oct. 1965.

"Mig Welding with Pulsed Power"

By A. Lesnewich

This report, prepared for the Interpretive Reports Committee of the Welding Research Council, presents a concise summary of the present state-of-the-art of pulsed-arc MIG welding. The effect of pulsed current on MIG welding is so significant that some authorities accord the technique the status of a new welding process, calling it pulsed spray to differentiate it from other forms of pulsed power. Actual changes associated with this method involve a new concept in power supply design and, to a minor degree, some adaptations in the way the welding equipment is used.

Included in the report is an explanation of why pulsed power was developed for welding and how the pulsed spray technique works. The effect of variables such as pulse frequency, pulse amplitude and pulse width are described in detail. Also covered are the fundamentals of the power supply and the adaptability of the process for welding steel, aluminum, magnesium and copper.

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