Resistance NOR-Ti-BOND Joining of Titanium Shapes

Joint strength equal to that of the base metal is obtained with a new process which utilizes resistance heating to form a Ti-Cu eutectic at Cu-plated titanium joint interfaces where subsequent diffusion treatment then reduces the Cu content

BY K. C. WU

ABSTRACT. The principle of a new resistance bonding process is to use resistance heating to form a titanium-copper eutectic at the copperplated titanium joint interface at a relatively low temperature (1625° F). Subsequent diffusion treatment reduces the copper content in the fillet from approximately 70 to below 6% in 4 hr at 1700° F. In the diffusion treated condition, the mechanical properties essentially equal those of the base metal. The minimum quantity of copper for the new resistance bonding process was determined.

To optimize the bonding parameters, the effect of bonding parameters and specimen geometry was studied. I-beams, integrally stiffened skin panels and tapered I-beams were fabricated. The microstructure, copper content, and microhardness in the joints were studied or determined. Room temperature fatigue tests were conducted on I-beams, T-shapes, and channels.

Results indicated that the joint strength of shapes joined with the new process was as good as that of the base metal. It was also shown that a 0.125 in. radius for the fillets was necessary to maintain good fatigue strength. The results obtained from this program indicated that the new resistance bonding process is an economical and metallurgically sound joining process for titanium structural shapes.

Introduction

Titanium structures are increasingly used in modern aircraft because of their strength-to-weight ratio at ambient and at elevated temperatures. At present, the fabrication techniques for titanium structures are extrusion plus machining, machining, or diffusion bonding. The minimum thickness of a titanium extrusion is claimed to be 0.07 in.; when a high thickness ratio is required in a structural shape, the mininum thickness is about 0.09 in. The width of titanium integrally stiffened skin section is limited to 22 in. due to the size of extrusion equipment available. Extrusion plus machining may achieve dimensional objectives, but the cost is high. Not only is material wasted and elaborate machines employed for machining, but, in addition, severe difficulties due to residual stresses and warpage are experienced.

The solid-state diffusion bonding process can fabricate complicated shapes. However, the fabrication of precision tooling, removal of metal inserts, and the requirement of heavy equipment providing high pressure makes this process for production of structural shapes expensive.

A titanium-copper system for diffusion bonding has been developed at Northrop[1, 2] to fabricate titanium structural shapes at low cost. The basic theory of this process* is to produce a Ti-Cu eutectic composition at the joint interface at the relatively low temperature of 1635° F (890° C), thus forming a joint. The formation of Ti-Cu liquid phase in the joint allows a low bonding force to be used, which reduces distortion and eliminates any need for heavy equipment. The joint is then diffusion treated to reduce the copper content below 6%, giving good mechanical properties.

In this program, a resistance seam welding machine was used to supply the heat required for bonding. Instead of using an external heat source, an a-c current passes through the joint and the I^2R heating in the faying surface raises the joint temperature above 1625° F where the electrolytically-plated copper reacts with titanium to form a Ti-Cu eutectic. Solidification of the joint occurs upon cooling. Subsequent diffusion treating at 1700° F for 4 hr disperses the copper content from 70 to below 6% in the fillet and produces a strong, tough joint. With appropriate tooling, this resistance bonding technique can be used to fabricate titanium shapes with minimum material waste and low labor cost.

This paper describes the results obtained from the program using resistance bonding techniques.

Materials and Procedures

Materials

Duplex-annealed Ti-8A1-1Mo-1V sheets and mill-annealed Ti-6A1-4V sheets were used. The thicknesses varied with different shapes. Table 2 lists the information on the materials used in this program.

Electrolytic Plating

For I-beam and simple stiffened skin specimens, copper was electroplated on the facesheet only. The width of copper strips was about 0.125 in. wider than the thickness of vertical members. Before plating, the

* NOR-Ti-BOND process.

Table 1—Instrumentation Used to Measure Parameters

Instrument	Type	Purpose
Electrode force gauge	Cantilever-dial gauge	Measure electrode force
Current meter	Duffers secondary current meter	Welding current, RMS
Current recorder	Light oscillograph. Multichannel	Welding current
Tachometer		Wheel speed

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area to be plated was mechanically cleaned. After abrasion, the plating surface was cleaned with alcohol and wiped dry with oil-free paper.

Copper sulphate solution was used for the electrolyte. The quantity of copper should be kept near the minimum giving a good bond to minimize the length of the diffusion treatment required to get maximum copper concentration below 7% in the fillet. Plating current and time corresponding to required copper content quantity were calculated from Faraday's law:

$$Q = 0.000033\, I^{\prime}\, t$$

where Q = copper density in mg/in.^{2}; I = plating current in amperes; t = time in seconds.

Copper quantity was measured with an instrument based on beta ray backscattering principles.

Tooling

In this process, tooling is used to position the components, maintain dimensional control, to limit the amount of upset and distortion, to introduce inert gas for protecting the joint from oxidation, and, in some cases, to carry the bonding current through the joint. Various tooling designs have been developed throughout this program.

A copper alloy, such as RWMA Class 1, is preferred for fixture material when current-carrying capability is required. Pure copper is too soft for handling.

Diffusion treating was either conducted in an evacuated and sealed envelope made of 0.003 in. thick stainless steel, or specimens were diffusion treated in a vacuum furnace.

Equipment

Instrumentation. Instruments used to record or measure various parameters are listed in Table 1.

Resistance Bonding Equipment. The major part of the work was conducted on a 150 kva single-phase, a-c, seam-spot welding machine. The maximum electrode force for seam welding is 2000 lb. Wheel speed is adjustable from 18 ipm to 120 imp for a 10 in. wheel. Class 1 welding wheels were used.

Determination of Binding Parameters

The basic bonding parameters for the resistance bonding of titanium are the same as those used for seam welding of titanium, except that a lower bonding current is required. In addition to these parameters, the dimensions of the tooling and material play a very important role in dictating the bonding current, electrode force, bonding speed, and amount of distortion.

The thickness of the web is the determining factor for determining the electrode force. Other conditions being the same, an increase of electrode force will increase the amount of upset in the web near the joint. If a high electrode force is necessary, a smaller clearance between the copper tooling and flange has to be used to compensate for the increased amount of upset that would result. Low electrode force may cause wheel sticking to the facesheet due to the increase in contact resistance. An electrode force that gives a minimum upset and uniform bonding without wheel sticking should be selected.

The on-off time and wheel speed is closely related for obtaining a good bond. Long on-time increases the chance of overheating, distortion, and upset. Long off-time causes nonuniformity of bonding. For a given on-off time and bonding current, increase of wheel speed decreases heat in the joint and may cause discontinuity of the bond.

Electrode materials are divided into many classes based on their thermal and electrical conductivities. A different electrode material alters the temperature gradient in the facesheet. Therefore, by using appropriate electrode materials, it is possible to compensate, or partly compensate, for differences in the thermal conditions such as width or thickness of the flange or facesheet or two joints made simultaneously. For example, Class I wheel (Cu-Cd alloy) has a higher thermal conductivity than Class II wheel (Cu-Cr alloy). When facesheets

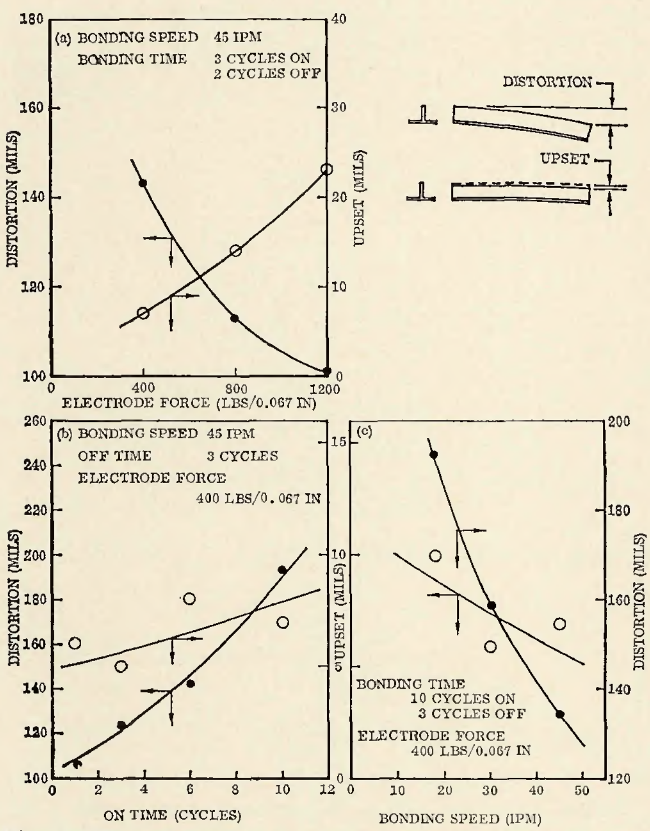

Fig. 1—Effect of bonding parameters on distortion and upset

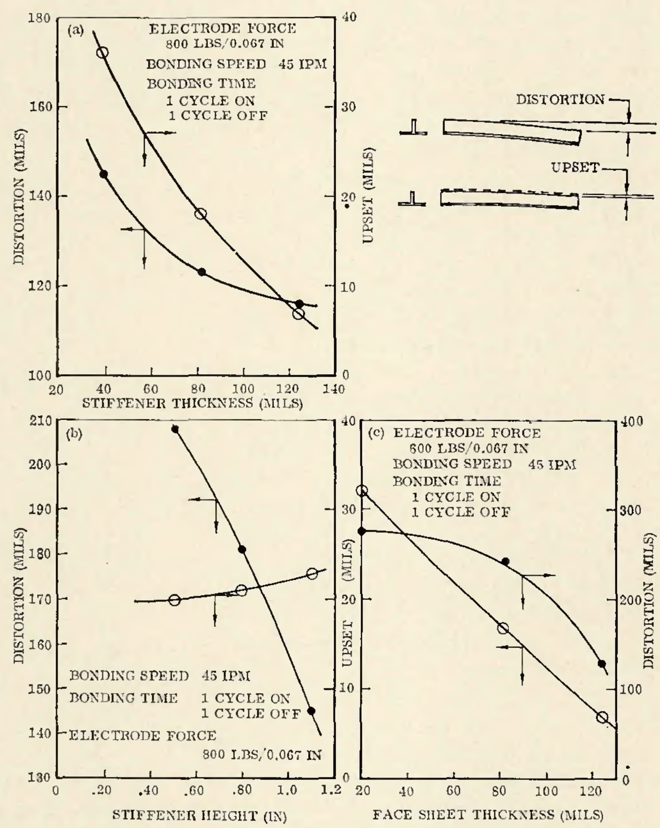

Fig. 2—Effect of geometry on distortion and upset

of different thicknesses are used, Class I wheel should be used on the thinner flange or sheet, and Class II wheel should be used on the thicker flange or sheet. In such a way, the heat in the joint can be equalized.

An electrode wheel with a contoured surface can compensate for misalignment of the wheels. It should be noted that the contour of the wheel surface affects heat conduction noticeably. Therefore, different contours on the two wheels can influence the heat balance on the top and bottom joints to a certain degree. Therefore, sometimes flat surface wheels were used.

The most influential bonding parameter is obviously the bonding current. For a given on-off time, electrode force and bonding speed, an optimum bonding current should be such that the width of a zone adjacent to the joint in which the copper dissolved in the titanium was approximately 0.040 inch. With a bonding current less than this amount, the bond quality may not be consistent. If the bonding current is too high, surface burning, excessive deformation, and electrode marking may occur.

Effect of Bonding Parameters on Distortion and Upset

Effect of Electrode Force. Bonding parameters that will affect the amount of distortion and upset are bonding time (on-time), electrode force, and bonding speed. Distortion is the amount of deviation of one end from its original position, while the other end remains fixed; and upset is the amount of reduction in web height. To determine these effects, a group of single stiffener panels (Fig. 1) were bonded with these parameters varied one at a time, while other parameters were held the same. The upset increases with the increasing electrode force, from 0.114 to 0.146 in., while the bonding speed and bonding on- and off-times were held constant.

In this test, the current was varied to maintain the same amount of heat generated in the joint, since electrode force influences both current and contact resistance and current and contact resistance affect heat. The constant heat is judged by the same width of the copper plate dissolve in the facesheet adjacent to the stiffener. Figure la shows that the increase of electrode force decreases distortion and increases upset.

At the first glance, it seems to be illogical that high electrode force reduces distortion. However, the amount of upset which takes place in the stiffener contributes only slightly to the distortion. Distortion is mainly affected by the plastic deformation in the facesheet. For each thickness, the deeper the plastic zone, the more the distortion in the facesheet. When the electrode force is increased, so is the temperature gradient in the facesheet. Thus, the amount of penetration of this plastically deformed zone is decreased. Therefore, the increase of electrode force reduces the amount of distortion.

Upon further increase of electrode force, the amount of distortion should level off. To maintain a constant pressure under the stiffeners, electrode force varies with the width of the stiffener. For clarity, the electrode force is expressed by pounds per 0.067 in. width of the stiffener.

Effect of On-Time. On-time is the length of time, in number of cycles, 60 cycles/sec, during which the bonding current is flowing, and off-time is the length of time during which the bonding current is turned off. The increase of on-time prolongs the heating time and increases temperature. Heat is conducted away from the joint in three directions, through the stiffeners and two sides of the facesheet. The increase of heat by increasing on-time increases the width of the plastic deformation zone in the stiffener as well as in the facesheet; thus, both upset and distortion are increased—Fig. 1b.

Effect of Bonding Speed. On the contrary, a higher bonding speed reduces both the distortion and upset—Fig. 1c. In order to dissolve the same width of copper along the joint, bonding current had to be increased with bonding speed. At the faster speed, the temperature gradient is steeper and so is the plastically deformed zone. Therefore, both distortion and upset are reduced.

Effect of Geometry on Distortion and Upset. The same type of specimen was used to determine the effect of geometry on distortion and upset. Changes were made in the width and height of the stiffeners and the thickness of the facesheets.

Effect of Stiffener Thickness. Figure 2a shows the effect of stiffener thickness on distortion and upset. Both the distortion and upset decreased with the increasing of stiffener thickness. It is obvious that the increase of stiffener thickness proportionally increases the rigidity of the panel. Although the bonding current was increased for thicker stiffeners to maintain the same heat effect along the joint, the increase of rigidity is apparently more than compensating for the effect of current increase. Thus, the distortion was lowered. When the width of the stiffener increases, the mass that conducts heat from the joint is also increased. This causes smaller plastically deformed zones in the stiffener and reduces upset.

Effect of Stiffener Height. The rigidity of a rectangle increases with the cube of its height. It is to be expected that an increase of the height of a stiffener reduces the distortion as shown in Fig. 2b. Doubling the height of the stiffener reduced distortion almost 30%.

The influence of stiffener height on the upset is very small. There is no contribution from the stiffener height to the upset. Increase of the stiffener

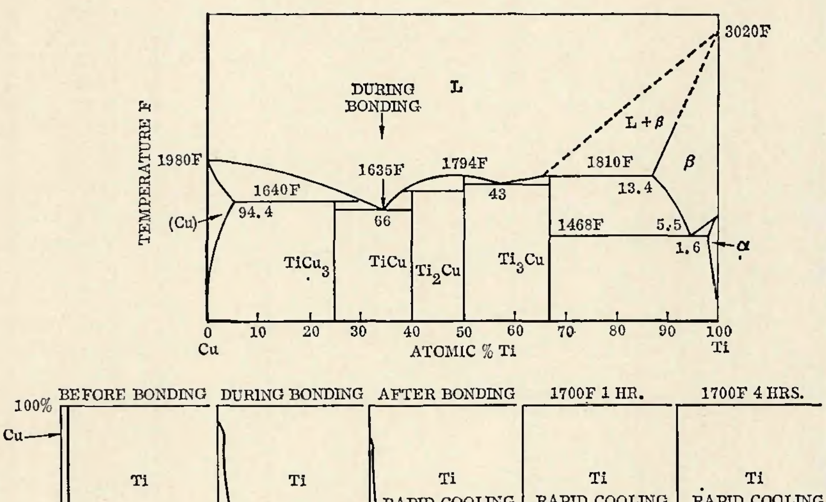

Fig. 3—Ti-Cu equilibrium phase diagram and copper content in the joint at various stages

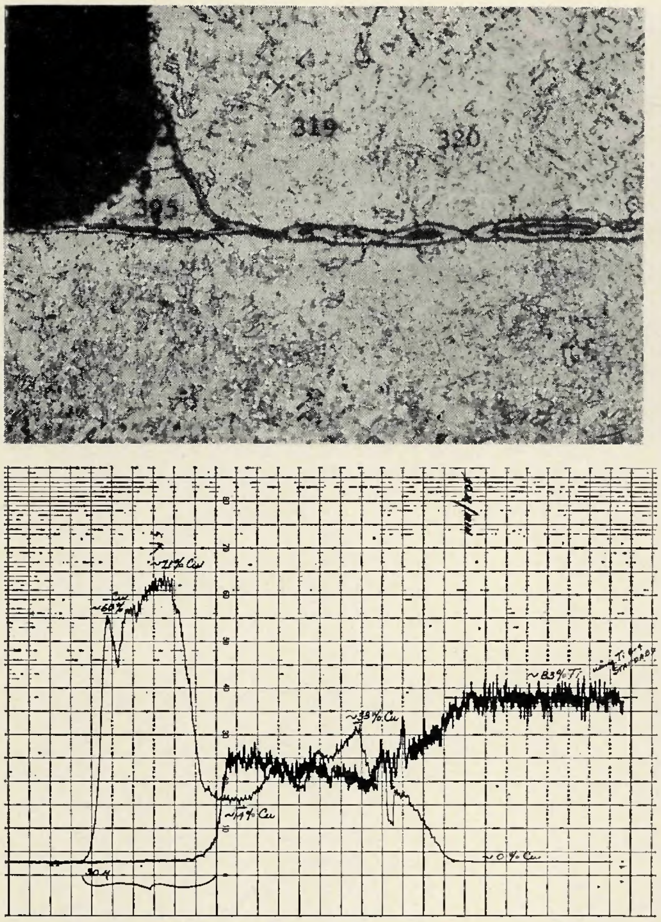

Fig. 4—Microstructure and electron microprobe traces in the fillet of an I-beam as-bonded. For microstructure: numbers are hardness readings in KHN; Kroll's etch; X250 (reduced 5% on reproduction)

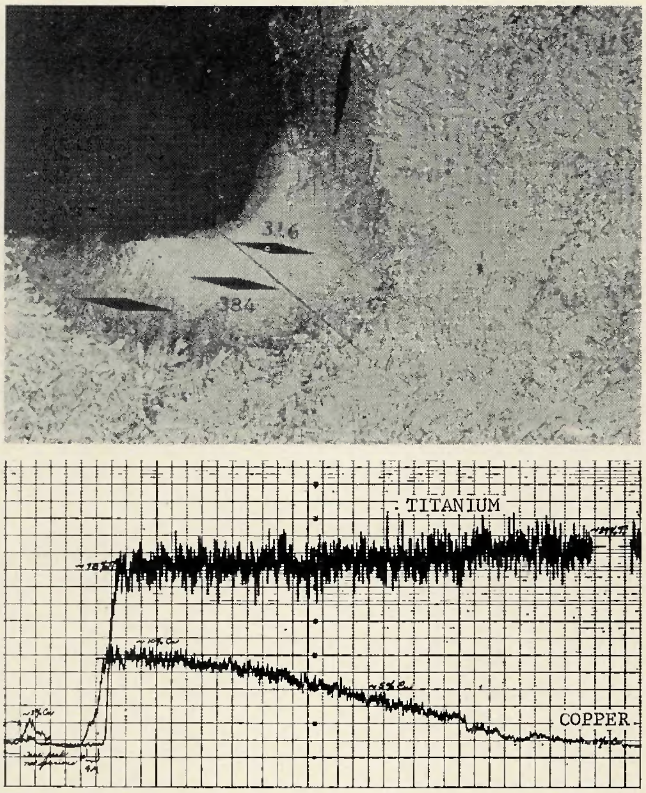

Fig. 5—Microstructure and electron microprobe trace in the fillet of an I-beam, diffusion treated at 1700° F for 1 hr, air cool. For microstructure: numbers are hardness readings in KHN; Kroll's etch; X250 (reduced 22% on reproduction)

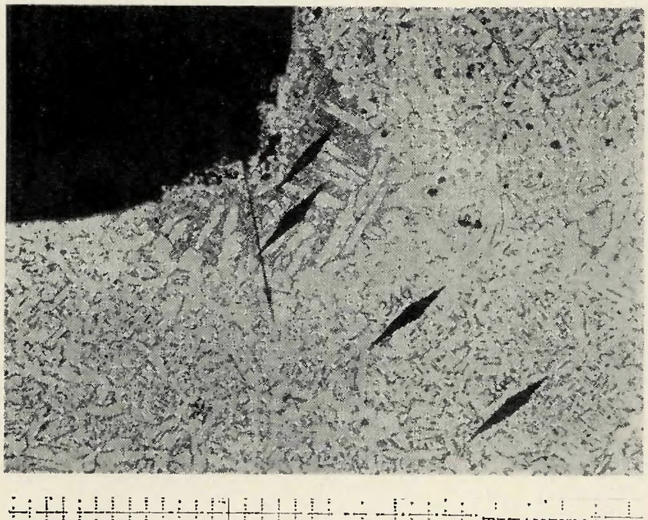

Fig. 6—Microstructure and electron microprobe traces in the fillet of an I-beam, diffusion treated at 1700° F for 1 hr, furnace cool. For microstructure: numbers are hardness readings in KHN; Kroll's etch; X250 (reduced 22% on reproduction)

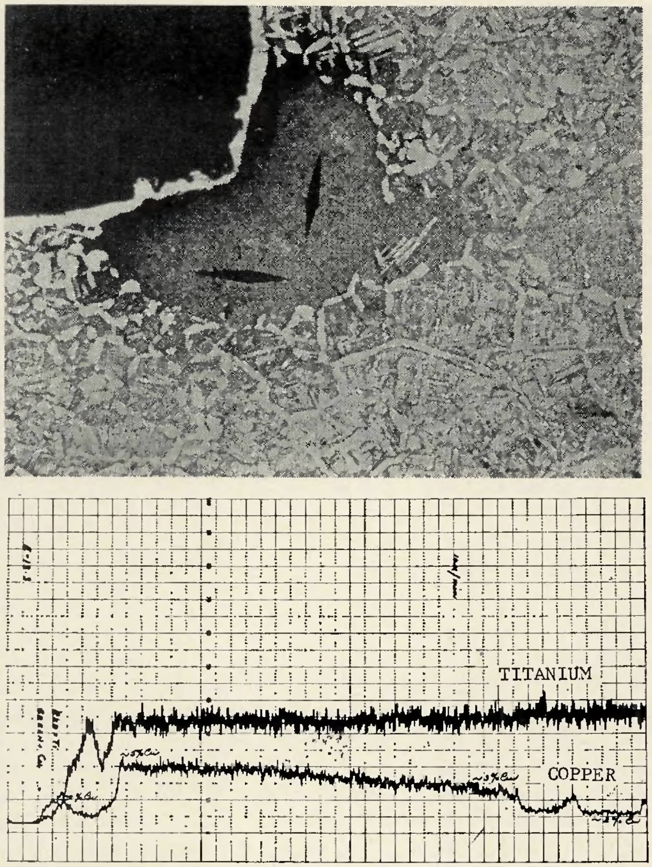

Fig. 7—Microstructure and electron microprobe trace in the fillet of an I-beam, diffusion heated at 1700° F for 4 hr, air cool. For microstructure: numbers are hardness readings in KHN; Kroll's etch; X250 (reduced 22% on reproduction)

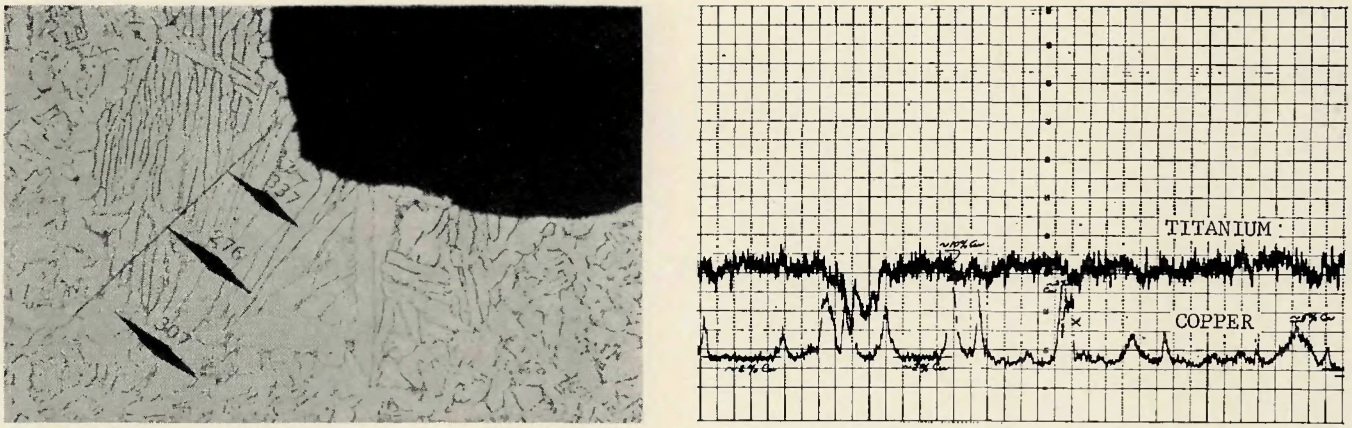

Fig. 8—Microstructure and electron microprobe traces in the fillet of an I-beam, diffusion treated at 1700° F for 4 hr, furnace cool. For microstructure: numbers are hardness readings in KHN; Kroll's etch; ×250 (reduced 21% on reproduction)

from 0.5 to 1.10 in. only shows an increase of less than 2% of upset.

Effect of Facesheet Thickness. The effect of facesheet thickness on distortion is shown in Fig. 2c. The increase of sheet thickness increases the rate of heat transfer. To maintain the same heat effect in the joint, the bonding current has to be adjusted accordingly. Thus, for thicker facesheets, higher current was used. Apparently, the increase of heat transfer, plus temperature gradient and rigidity in the thicker facesheet, reduces the plastically deformed zone in the joint. Therefore, the distortion and upset are reduced by an increase of facesheet thickness.

In I-beams and integrally stiffened skin panels, upset is still measureable, but distortion is not, because of the symmetrical geometry. However, the restrained distortion actually is "transformed" into residual stress. Therefore, the results obtained from the bonding of T-joints are applicable to most structural shapes.

Based on the information obtained from this phase of work, a guideline for choosing bonding parameters which will produce low distortion or residual stresses was established:

1. Electrode force should be so chosen that distortion is the least and upset is tolerable.

2. On-time should be as short as possible. One-cycle-on and one-cycle-off were used for 32 ipm bonding speed for all structural shapes during the rest of this program.

3. Bonding speed should be as fast as practical. At the present stage, a bonding speed of 32 ipm is the fastest and yet controllable speed for present setup.

4. Under the above conditions, a bonding current should be selected so that a 0.040 to 0.060 in. wide copper plate along the joint will dissolve in the titanium sheet.

Microstructural Studies in the NOR-Ti-BOND Joints

To illustrate the metallurgical reactions during and after bonding and after diffusion treatment, an equilibrium phase diagram and several schematic copper concentration diagrams are shown in Fig. 3. Since during resistance bonding the reaction is far from equilibrium, the equilibrium phase diagram is used only for reference.

Before bonding, copper is electrolytically plated on the surface of titanium (for simplicity disregard its alloying elements) corresponding to the end phase in the phase diagram and the copper concentration is 100% (before bonding). When the faying surfaces are heated up by the bonding current, titanium and copper reacts immediately to form Ti-Cu eutectic. The actual temperature of the eutectic liquid may exceed 1635° F due to rapid heating rate.

Since there is only a thin film of copper and the supply of copper is limited, the maximum copper content in the liquid phase is about the eutectic composition, 70%. Diffusion of copper into titanium at this instant is very rapid. The copper content in the liquid varies in a wide range, from eutectic to the liquidus line in the $L + \beta$ region.

Because of the fast cooling rate, the gradient of copper concentration in the titanium is rather steep. After cooling, it contains eutectic structure about 70% of Cu and compounds in a narrow surface region and β plus α and/or α'—see schematic diagrams. The possibility of α' formation is dependent upon cooling rate. At 1700° F for 1 hr, diffusion treatment will reduce the maximum copper content from 70 to 10%. The microstructure after rapid cooling from diffusion treating temperature will contain β, α, and/or α'. When the diffusion treatment time at 1700° F increases to 4 hr, the copper concentration will reduce 5% or less with transformed α phase only.

The above mentioned metallurgical reaction takes place in the faying surface. The distance of the diffusion path in the fillet is longer, requiring a longer time and/or higher temperature for the copper to disperse. To determine the diffusion parameters for tees, specimens were diffusion treated at various temperatures and times, and the microstructures in the fillet of these specimens were studied by techniques including microhardness measurement and electron microprobe analysis.

Figures 4–8 illustrate the microstructure in the fillet, along with electron microprobe traces and hardness measurements for as-bonded, 1700° F for 1 hr furnace cool, 1700° F 1 hr air cool, 1700° F 4 hr furnace cool, and 1700° F 4 hr air cool.

In the as-bonded condition, the solidified Ti-Cu eutectic occupies the major portion of the fillet. The maximum copper content in this region is 71%. In the interface, dark Ti_2Cu is surrounded by retained β. Diffusion treatment of 1700° F up to 1 hr did disperse copper in the joint to 10% and lower—Figs. 5 and 6. The long diffusion path in the fillet requires higher temperature to reduce the copper content to a desired level.

When the diffusion time increases from 1 to 4 hr, the overall maximum copper content in the fillet decreases from 10 to 5%—Figs. 7 and 8. This indicates that 4 hr at 1700° F is the minimum time required to regain ductility of the fillet.

To determine the effect of cooling rate on the microstructure in the fillet, two cooling rates, furnace cool approximately 1700 to 1300° F in 3 hr and air cool, were used in addition to two diffusion treating times, 1 and 4

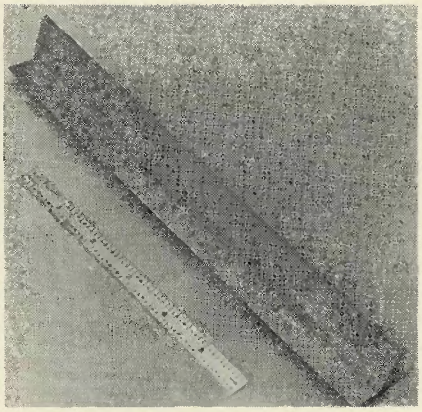

Fig. 9—Resistance bonded T-shape

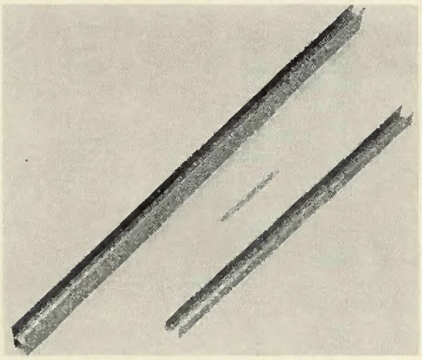

Fig. 10—Resistance bonded I-beam and finished edge member

hr. The specimen shown in Fig. 6 was diffusion treated at 1700° F for 1 hr and furnace cooled. As compared to Fig. 5 that was air cooled, it is obvious that slower cooling rates allow β to transform to large alpha platelets on cooling. When cooling rate is high, β transforms to fine acicular alpha and/or martensite. In the high (10%) Cu concentration area, possibly high temperature β is retained.

The shape of the electron-microprobe traces shown in Fig. 5 and 6 are quite different due to different microstructures. During air cool, β was retained in the high Cu concentration area, and acicular alpha formed in the low Cu concentration area—Fig. 5. The copper content is

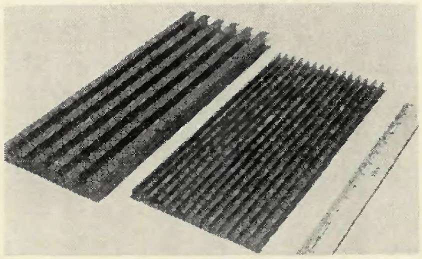

Fig. 11—Resistance bonded integrally stiffened skin panels

maximum at the edge of the fillet, about 10%, and continuously decreases to zero in the base metal. The hardness in the fillet is relatively high, except in the retained β area.

The specimens shown in Fig. 6 contain alpha grains and Ti_2Cu compound. As alpha grew into the fillet on slow cooling, copper was rejected into the area between alpha grains and forms Ti_2Cu. The copper content in the alpha grain is about 2 to 3%—that is, the solid solubility of Cu in Ti, and corresponding to the valleys of the trace. The peaks represent the average copper content under the electron beam in the area containing compound and fine alpha particles.

The fast cooling rate experienced by the specimen shown in Fig. 7 increases the nucleation rate of alpha. Thus, fine alpha needles are observed. Because of the low copper content, β is not retained as in the specimens shown in Fig. 5. The fineness of alpha needles and the finite size of electron beams gives the copper concentration trace a smooth appearance, gently decreasing from its maximum of 5 to 0% in the titanium-base metal.

Figure 8 shows the microstructure and copper content in the fillet in a furnace cooled specimen after 4 hr of diffusion. This cooling rate allows alpha grain to grow completely to fill the fillet. Hardness is lower than that in any other of the four conditions. The copper content varies with location as in Fig. 6. Again, copper was rejected from the alpha grain during

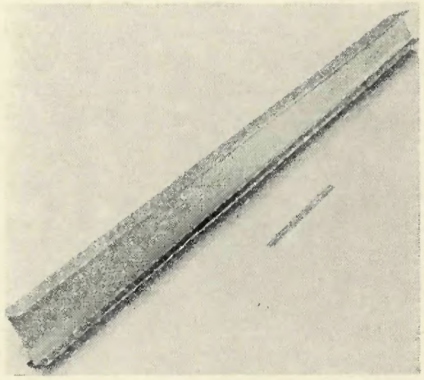

Fig. 12—Resistance bonded tapered I-beam

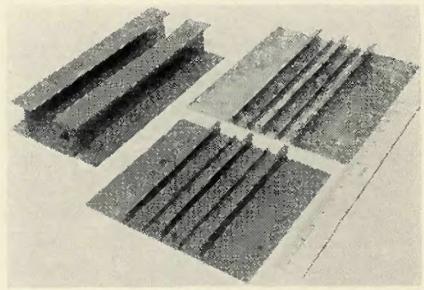

Fig. 13—Other structural shapes fabricated with new resistance bonding process

growth on cooling. The copper concentration is about 10% maximum between grains and is 2% in the alpha grains.

The results obtained from this study indicate that:

1. A diffusion treatment at 1700° F for 4 hr is the minimum requirement to disperse the copper content below 5% in the fillet.

2. The cooling rate should be less than 1350° F/hr to obtain large alpha grains and regain toughness in the fillet.

Bonding of Structural Shapes

Ti-6Al-4V T-shapes containing an 0.125 in. thick by 1.0 in. wide web and 0.016 in. thick by 1.5 in. wide facesheet for a length of 12 in. were fabricated. This design was being con-

Table 2—Materials Used in This Program

	Heat no.	Thickness, in.	Chemical composition, % C	Fe	N	Al	V	H	O	Yield strength, ksi	Ultimate tensile strength, ksi	Elongation, %
Ti-6Al-4V	G-3370	0.102	.023	.09	.009	5.9	4.0	.007	.12	L. 132.3	142.0	14.0
										T. 141.6	145.3	12.5
	G-1359	0.150	.022	.06	.009	5.8	4.0	.008	.13	L. 125.0	136.7	17.5
										T. 131.8	142.8	15.0
	G-6226	0.063	.025	.09	.012	6.1	4.0	.006	.11	L. 134.3	142.9	15.0
										T. 135.3	142.0	11.0
	300886	0.040	.04	.12	.010	5.4	4.4	.0065	.150	134.2	144.8	10.0
	G-5566	0.090	.023	.08	.010	6.0	4.1	.003	.11	135.3	141.7	13.5
	G-4902	0.080	.069	.04	.031	6.31	3.84	.010	.12	158.0	163.0	11.5
Ti-8Al-1Mo-1V	D-5657	.062	.026	.11	.011	7.9	1.0	1.0	.004	L. 134.0	148.1	14.0
										T. 132.1	145.4	13.0

sidered in conjunction with a boron composite to form floor beams for the SST. Appropriate tooling and procedures were required to produce straight and flat Tees. The fabricated T-shape is shown in Fig. 9.

Figure 10 shows the resistance bonded I-beam from which a C-shaped edge member is made by machining off flanges on one side. The edge member is used for bonding of honeycomb panels.

Integrally stiffened skin panels having 1 in. and 0.5 in. spacing are shown in Fig. 11. By use of appropriate tooling, the cap and face-sheet were resistance bonded simultaneously. Edgewise compression tests indicated that the panel strenght reached its theoretical value.

A tapered I-beam having a 0.20 in./ft is shown in Fig. 12. The taper is on the top-side only and does not present problems during bonding.

Other structural shapes fabricated are shown in Fig. 13. With appropriate tooling design, the size of structural shapes can be varied within a wide range. This indicates the versatility of the new resistance bonding process for fabricating structural shapes.

Mechanical Properties of Various Structural Shapes

Tensile Properties. The certified tensile properties of titanium sheets are listed in Table 2.

To determine the effect of fillet radius on the tensile strength of the T-shapes and to compare the tensile properties of the bonded and extruded Tees, Ti-6A1-4V extrusions and joined with the new process tees with and without machined fillet radius of 0.125 in. were fabricated. A $^3/_8$ in. thick Ti-6A1-4V plate was purchased from TMCA and used for making webs. The extrusions were supplied by H. M. Harper Company. The tensile properties of the $^3/_8$-inch plate and extrusions are listed in Table 3. The resistance bonded tees were machined from I-beams. Those without fillet radius were bonded with 0.080 in. thick web, and those with 0.125 in. thick radius fillet were bonded with $^3/_8$ in. thick web and then machined to 0.080 in. thick.

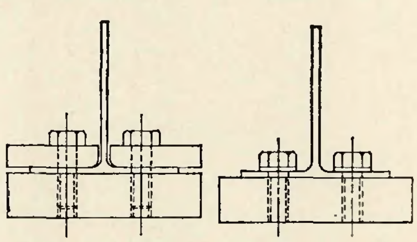

Fig. 14—T-shaped tensile and fatigue test specimens—with fixtures restrained (left) and unrestrained (right)

Table 3—Tensile Properties of Ti-6Al-4V Plate and Extrusion (Average of 2)

Material	Elongation in 1 in., %	Yield strength (0.2%), ksi	Ultimate tensile strength, ksi	Specimen location
$^3/_8$ inch plate	15.0	113.6	137.8	Parallel to the rolling direction.
Extrusion	15.5	130.6	151.0	In the base, transverse to extrusion.
Extrusion	13.0[a]	117.4	154.6	In the vertical member, transverse to extrusion.

[a] Measured with strain gage

Table 4—Tensile Strength of Bonded and Extruded Tees

Material	Fillet radius, in.	Loading type	Ultimate tensile strength, ksi	Failure location
Bonded	No	Restrained	103 (Avg of 3)	Near joint
Extruded	0.125	Restrained	154 (Avg of 2)	Vertical number
Bonded	0.125	Restrained	140 (Avg of 2)	Vertical number
Bonded	No	Not Restrained	64 (Avg of 3)	Near joint

The extruded and machined Tees and bonded tees were tested in two modes. One is in restrained manner, Fig. 14 (left), and the other is more flexible, as shown in Fig. 14 (right). The tensile strengths of tees are shown in Table 4.

The results indicate:

1. The failure location can be changed from the joint to the base metal by using a fillet radius of 0.125 in.

2. When failure occurred in the base metal, naturally the strength of tees was the strength of the base metal.

3. In the unrestrained loading condition, strength is further reduced due to the increase of loading moment at the fillet.

4. When a fillet radius is lacking, the stress concentration at the joint lowered the strength, although failure occurred in the base metal first.

Fatigue Testing. Tees machined

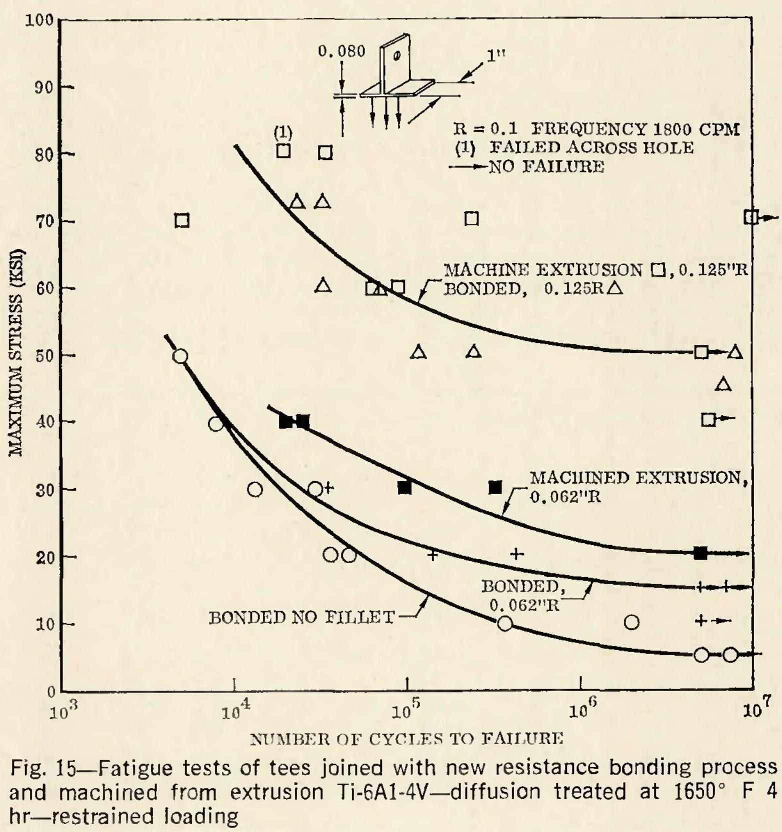

Fig. 15—Fatigue tests of tees joined with new resistance bonding process and machined from extrusion Ti-6A1-4V—diffusion treated at 1650° F 4 hr—restrained loading

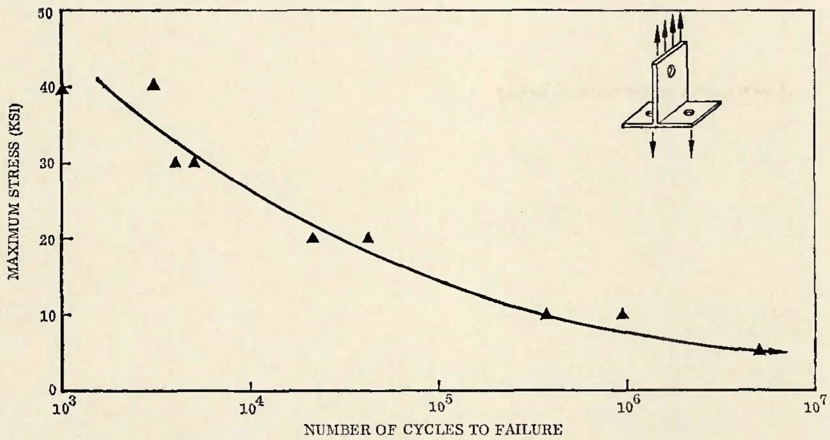

Fig. 16—Fatigue tests of tees joined with new resistance bonding process—no fillet radius, unrestrained loading with R = 0.1—Ti-6A1-4V diffusion treated at 1700° F 4 hr—1800 cpm frequency

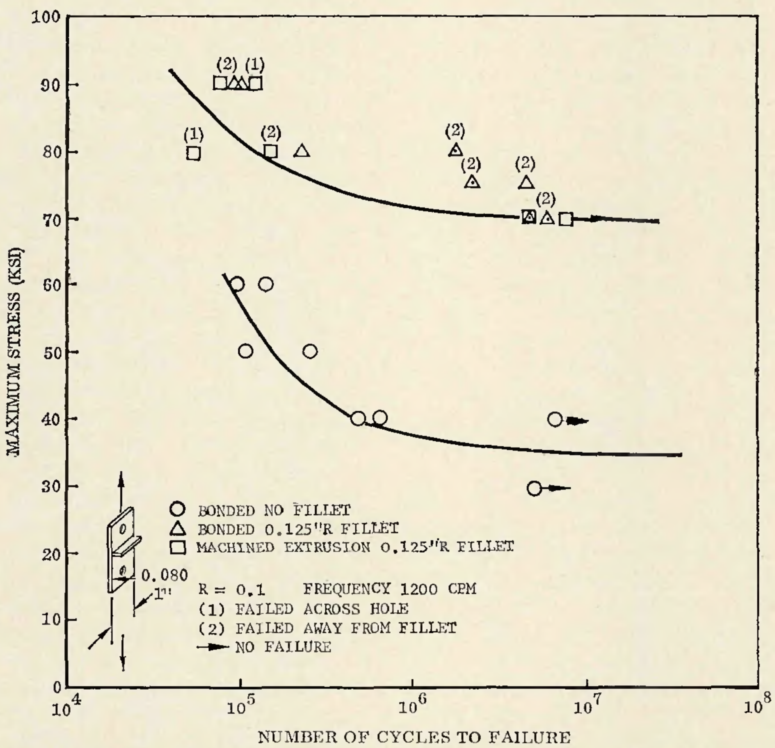

Fig. 17—Fatigue tests of stiffened plate joined with new resistance bonding process and machined from extrusion Ti-6A1-4V—diffusion treated at 1650° F 4 hr

from extrusions and joined with the new process tees with two sizes of fillet radius were tested in fatigue by the clamping method shown at the left of Fig. 14. The results shown in Fig. 15 indicated that:

1. A fillet radius of 0.125 in. or less will give low fatigue strength in either extruded or bonded tees.

2. Resistance bonded tees having 0.125 in. fillet radius are as strong as extruded tees having the same geometry.

3. Considerable scattering of the fatigue strength of the extruded tees was observed. It could probably be attributed to the nonhomogeneous microstructure.

When the clamping method changed from the left one of Fig. 14 to the right one, the loading condition was changed from near tension to tension plus bending. Because of the notch effect at the joint, the addition of bending stress does not appreciably affect the endurance limit of the specimens prepared with the new resistance bonding process—Fig. 17. However, at higher stress levels, the more severe loading condition did reduce its fatigue life to about $^1/_4$-th of that of the less severe loading condition.

The third type of fatigue test specimen is the single stiffener plate, as shown in Fig. 16. Specimens without fillet radius have only one-half the endurance limit of the specimens with a 0.125 in. fillet radius. For the specimens having a 0.125 in. fillet radius, the specimens prepared with the new process give a slightly higher fatigue strength than the extruded specimens. The loading severity of this type of specimen is less than that of tees.

Conclusions

From the work conducted during the past three years, the following conclusions can be drawn:

1. The resistance NOR-Ti-BOND process can be used to fabricate economical and metallurgically sound titanium structural shapes.

2. Resistance bonded joint strength is equal to that of Ti-6A1-4V base metal.

3. In order to maintain good fatigue strength, a fillet radius of 1t, about 0.125 in., is required at tee joints.

Acknowledgement

This paper presents the results obtained from the program entitled "Resistance NOR-Ti-BOND Joining of Titanium Structures" which was conducted in the Materials Research Department under the direction of Dr. R. E. Lowrie. Experiments were performed by J. W. Lewis. Assistance in fatigue testing and electron microprobe was contributed by D. C. Atmur and R. E. Herfert, respectively. Consultations from R. R. Wells and A. H. Freedman and advice from Dr. E. B. Mikus and D. M. Badger are gratefully appreciated.

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2. Krinke, T. A., and Wells, R. R., "Thin-Film Diffusion Brazing of Titanium Alloys," Northrop Corporation, Report MRG-66-01, Part I and Part II, July 1966.

Memo to Authors . . . The deadline for mailing the 500 word abstracts of papers which you want to present at the AWS 53rd Annual Meeting is September 15. See pages 401 and 402 of the June issue of the Welding Journal.