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METAL INERT-GAS WELDING OF TIN BRONZE CASTINGS

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PHYSICAL METALLURGY DIVISION

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METAL INERT-GAS WELDING OF TIN BRONZE CASTINGS

by

M.J. Nolan* and K. Winterton**

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ABSTRACT

Considerable experimental work has been done to determine a suitable welding method for the repair of tin bronze castings. Preliminary investigations with the metal-arc, carbon-arc, tungsten inert-gas and metal inert-gas processes indicated that best welds were produced with metal inert-gas welding. With other processes, there was a greater tendency for generally poor mechanical properties associated with cracking and porosity.

Metallurgical investigations indicate that weld porosity may derive from hydrogen in the sand-cast base metal. Steam-reaction porosity is inhibited by a higher degree of deoxidation in the weld metal.

Some of the cracking problems are associated with the brittle tin-rich delta constituent, which is precipitated in increased amounts in the weld metal and in the heat-affected zone. Lead, often blamed for cracking troubles, does not appear to be harmful in small amounts.

An experimental procedure has been developed for metal inert-gas welding using a modified bronze composition of filler wire with enhanced silicon and phosphorus content, which will produce joints with good mechanical properties, comparable with those of the base material, and substantially free of welding defects.

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Direction des mines

Rapport de recherches R 92

SOUDAGE À L'ARC AVEC FIL ÉLECTRODE EN ATMOSPHÈRE INERTE DE PIÈCES DE BRONZE COULÉES

par

M.J. Nolan* et K. Winterton**

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RÉSUMÉ

Dans le cas de la réparation des pièces de bronze coulées, on a déjà fait beaucoup de travail expérimental afin de déterminer une méthode convenable de soudage. Les recherches préliminaires ont porté principalement sur les procédés à l'arc avec électrodes métalliques enrobées, avec électrodes de carbone, avec électrodes de tungstène en atmosphère inerte, et avec électrodes métalliques en atmosphère inerte. Ce dernier procédé a donné les meilleurs résultats; des proprieétés mécaniques inférieures, ainsi que la présence de fissuration et de soufflures, semblaient être la caractéristique des autres procédés.

A en juger par les résultats obtenus au cours de certaines recherches métallurgiques, les soufflures dans le cordon de soudure seraient imputables à l'hydrogène provenant du métal de base qui se trouve à l'état brut de coulée en sable. Une désoxydation plus poussée du métal fondu empêcherait la formation de ces soufflures par la vapeur d'eau.

Le problème de la fissuration s'associe partiellement à la présence de la phase delta riche en étain, précipitée en quantité plus considérable dans le cordon de soudure et dans la zone de transformation. Le plomb en petites quantités ne semble pas apporter d'effets nuisibles, même si la fissuration lui a souvent été attribuée.

Dans le cas de soudage à l'arc en atmosphère inerte, le développement d'une technique expérimentale a conduit à l'emploi d'un fil électrode de bronze, enrichi de silicium et de phosphore; grâce à cette technique, les joints posséderont de bonnes qualités mécaniques comparables à celles du métal de base et seront relativement libres de défauts de soudage.

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CONTENTS

TABLES

FIGURES

INTRODUCTION

The desirability of a procedure for the repair of tin bronze castings was indicated when various companies, engaged in the production of pump and valve casings for a naval project, found that the casting of these complicated forms resulted in many defects. Typically, the greater number of defects occurred in areas where thick and thin sections joined, such as flanges, reinforcing ribs, etc. Such locations do not lend themselves to repair by flow welding, and the thickness of the material discourages the use of any but an arc process for welding.

A survey of literature concerning repair of tin bronze castings indicated that, although these materials were not considered highly weldable, satisfactory repairs had been obtained on several occasions by means of carbon-arc or metallic-arc welding, using commercially available phosphor bronze electrodes or filler rods(1,2). However, when attempts were made to adapt these procedures to the repair of the castings concerned, considerable difficulty was encountered. As a result, it was decided that some work should be done to determine those factors that affect the welding of tin bronze and to decide what modifications would make the recommended procedures suitable for the repair of existing castings.

The results of this program, which included the use of the metal-arc, carbon-arc, tungsten inert-gas and metal inert-gas processes and some minor work with silver brazing, indicated that the metal inert-gas process produced welds of superior quality. It also showed, at that time, the necessity for a more thorough understanding of the many variables which affect the welding of tin bronzes.

This paper includes some of the test data obtained in the exploratory project and a more detailed presentation of the steps taken to obtain a better understanding of the problem. These experiments culminated in the development of a filler material containing phosphorus and silicon, which results in welds of good density and satisfactory mechanical properties.

PRELIMINARY WORK

Preliminary work consisted of a study of the effect of different arc-welding processes on bronze slabs cast in the 1A and 2A compositions of ASTM Specification B143, with and without additional lead (see Table 1). Two thicknesses were used, 5/16 in. and 3/4 in. Various weld preparations were tried which, in

TABLE 1

Summary of Preliminary Work

	5/16-in. Plates				3/4 in. Plates			
Melt Number	229	230	227	232	226	230	225	232
ASTM Classification	1A	1A + Pb	2A	2A + Pb	1A	1A + Pb	2A	2A + Pb
Chemical Composition Elements, %								
Cu	86.74	87.56	90.10	87.02	85.77	87.56	87.80	87.02
Zn	2.52	2.54	4.06	4.33	3.38	2.54	4.23	4.33
Pb	N.d.	0.47	0.62	2.69	0.05	0.47	1.35	2.69
Sn	10.78	9.58	4.95	5.74	10.33	9.58	6.10	5.74
P	0.02	0.013	0.02	0.02	0.05	0.013	0.05	0.02
UTS, psi								
As-Cast	38,600	38,000	45,000	42,100	17,400*	31,000	17,000	24,900
Welded	33,800	34,400	38,400	30,000	33,350	16,700	14,300	-
Brazed	37,300	29,000	42,300	36,700	-	29,800	-	-
% El. in 2 in.								
As-Cast	13.0	13.0	39.0	37.0	8.5	19.0	18.0	12.5
Welded	-	-	-	-	10.7	4.2	8.5	-
Brazed	-	7.5	23.7	21.0	-	13.0	-	-

*Defect in test pieces.

general, conformed to accepted joint geometry for materials of these thicknesses when welded from one side. Four arc processes were investigated: (1) Metal-arc welding using phosphor bronze and aluminum bronze electrodes; (2) carbon-arc welding with phosphor bronze and silicon bronze filler rods; (3) tungsten inert-gas welding with the above mentioned filler rods; and (4) metal inert-gas welding with phosphor bronze and silicon bronze wires. Welds were made with and without preheat and peening. They were examined by radiography and, if no serious cracking was evident, were machined to provide 0.505 in. test bars, with the weld in the centre of the gauge, and sections for macroscopical and microscopical examination.

Several assemblies were also made in the 5/16 in. thick plate, using AWS/ASTM grade B Ag-1 silver brazing alloy (45.0% silver, 15.5% copper, 16.5% zinc, 18% cadmium).

It was found that metal-arc welding with phosphor bronze electrodes resulted in porous welds with many flux inclusions and some small cracks in the weld metal. Welds made with aluminum bronze electrodes, although free from porosity and cracking, were characterized by lack of fusion between weld and parent metal. Both of these metal-arc procedures required considerable skill on the part of the operator.

Tungsten inert-gas welding resulted in reduced porosity but longitudinal cracking occurred in multi-pass welds.

At this stage of the work, metal inert-gas equipment was not available and best results were obtained with the carbon-arc process using silicon bronze filler rod and a solution of borax-based flux in alcohol. These welds were considerably less porous than those made with the metal-arc process and, when made with preheat and peening, showed no evidence of cracking in the weld or parent metal. Chemical compositions and mechanical properties of the base metal and the results of tensile tests on bars machined from cross-sections of the welds are shown in Table 1. This table also includes data on tests made with silver-brazed joints.

Because of the exploratory nature of this phase of the project, the information in Table 1 is incomplete. It is included in this report to convey a general idea of the test data obtained. The primary value of this preliminary work was the understanding it provided of the difficulties associated with the welding of tin bronze castings. As a result, the project was reassessed and the scope was narrowed to the application of metal inert-gas welding, equipment for which had, by that time, been obtained. The process was chosen because it showed great promise and could be used without the complicating factors associated with the use of fluxes. Another major consideration was the fact that the use of automatic equipment reduced the influence of the human element.

One of the most disconcerting problems in the welding of tin bronzes was the variation in the mechanical properties of the parent metal. Not only did these values vary with different slabs poured from the same heat, but there was considerable variation in properties of test pieces taken adjacent to one another in the same slab; for example, the average ultimate tensile strength of three 0.505 in. tensile test specimens taken from a four-inch section of slab (Section B, Figure 2) was 41,800 psi, the highest value being 49,500 psi and the lowest, 38,900 psi (ASTM-B-143 1A composition, unchilled). Figure 1(3) shows the mechanical properties of test pieces taken with relation to the cold end of a slab (ASTM-B-143 2A composition).

It will be apparent from Figure 1 that another factor affecting the mechanical properties of the parent metal was the thermal gradient to which it was subjected in the mould. This shows that slabs cast with a single wedge-shaped cast iron chill possess higher mechanical properties than those cast without a chill. Subsequent experience confirmed these findings with regard to ultimate tensile strength. However, ductility as measured by elongation was so erratic that no conclusions were possible.

It will be noted in Table 1 that the ultimate tensile strength of thin castings is considerably greater than that of the thicker castings. This is characteristic of the tin bronzes, the greater strength of the thin sections being attributed to more rapid cooling in the mould.

Since the mechanical properties of the parent metal could be expected to have an influence on the strength of a welded joint, it was necessary to include in the investigation both chilled and unchilled castings. It was assumed that the chilled metal would correspond to the sound metal found in the thinner sections of commercial castings and the unchilled metal would be characteristic of the thicker sections.

An analysis of the difficulties associated with the welding of tin bronze castings indicated that the first requisite for success was to weld on sound metal. A satisfactory repair procedure, therefore, would require the removal of all spongy areas before welding commenced. When welds were deposited on sound metal, cracking in the weld and parent metal and extensive porosity in the weld metal became major problems. The second stage of the project was designed to find methods for the correction of these welding defects, using automatic metal inert-gas welding.

MATERIAL AND EQUIPMENT

Bronze slabs, 12 in. by 16 in. by 1-in.-thick, were poured from induction-melted 250-lb heats(3). Six slabs were obtained from each heat, three of which were poured into unchilled sand moulds and three in sand moulds chilled by a single wedge-

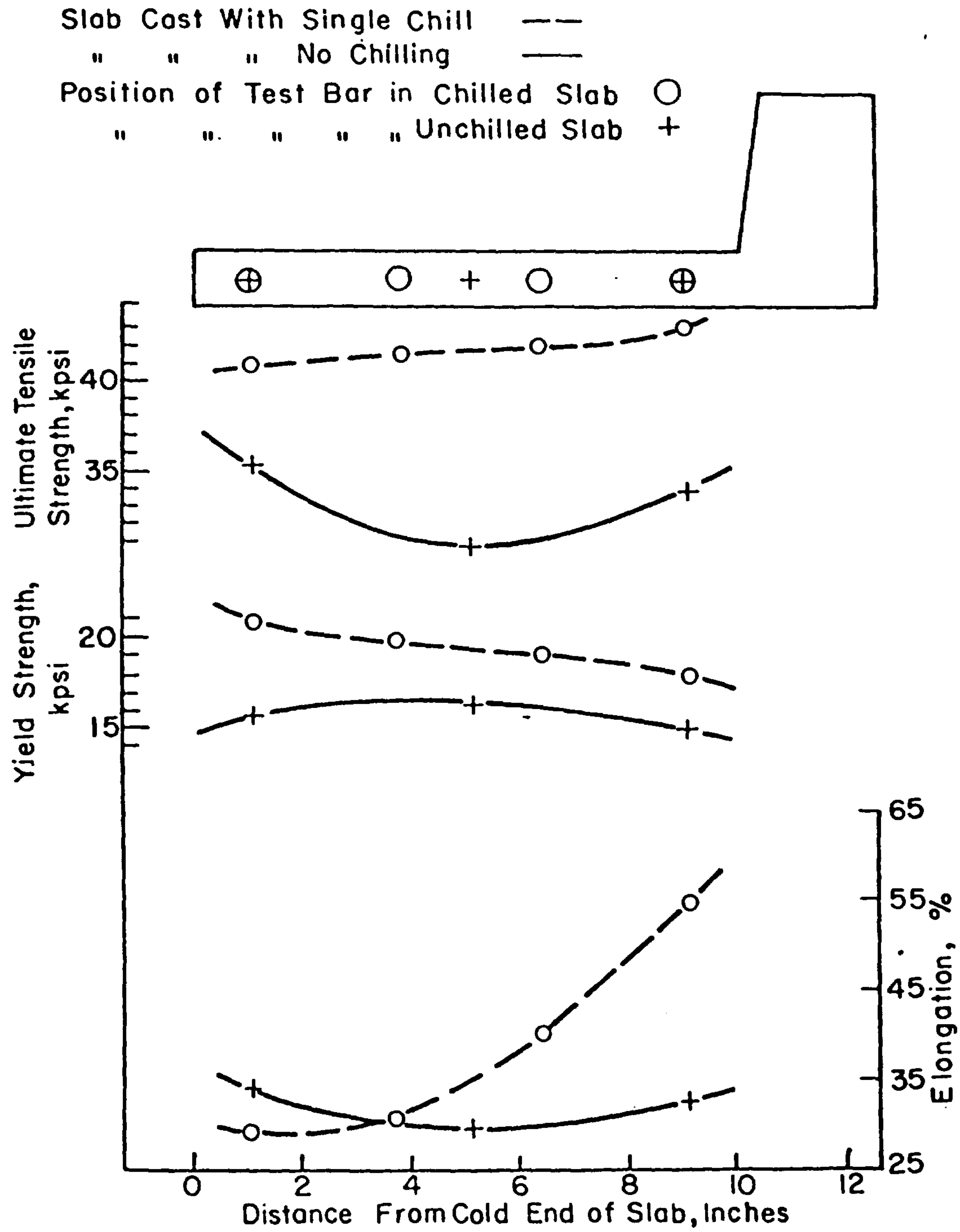

Figure 1. Variation in Mechanical Properties in Cast Slab.

shaped cast-iron chill. Risering was from one end and the riser was cut off flush with the top of the plate, the portion remaining on the plate being used for run-on and run-off blocks (see D and E in Figure 2). Chemical compositions of the various heats are reported in Table 2.

All plates were X-rayed to determine soundness, and sectioned as shown in Figure 2.

Commercially available 1/16-in.-diameter silicon bronze and phosphor bronze filler wires were used to deposit welds. Nominal compositions of these are included in the list of filler metal compositions (Table 3).

Cold wire additions were made, using rods of various alloys of copper with such elements as aluminum, titanium, uranium, phosphorus, and silicon. The chemical composition of the silicon bronze cold wire was the same as that used for welding.

Various shielding gases were tried, including argon and nitrogen and combinations of the two. It was found that argon shielding was most effective.

Part of the equipment used to deposit test welds is shown in Figures 3 and 4. It consists of a Vickers rectified d-c power source, with a constant potential attachment, and an Aircomatic AMH-B head, mounted on a Berkley side-beam carriage, with suitable controls to vary the speed of travel, the wire feed, and the gas flow.

Cold wire additions were made by inserting a wire into the guide tube attached to the welding head (see Figure 3) so that the end of this wire was located in the weld groove just ahead of the current-carrying filler wire. The other end was anchored in a small holding device. Changes in the amount of cold wire material were accomplished by using different diameters. In practice, two sizes were used, 1/16 in. and 3/32 in.

PROCEDURE

The machined sections, A and C, Figure 2, were tightly butted in a heavy steel jig to form the weld groove.

The jig base was formed from 2¼-in.-thick mild steel plate with a grooved ¼ in. by 2 in. copper backing bar inserted. Clamps of 1-in. steel plate were drawn down by nuts on four 1-in.-diameter studs welded to the base and located as shown in Figure 4. Sufficient restraint was developed by this means to prevent rotational distortion.

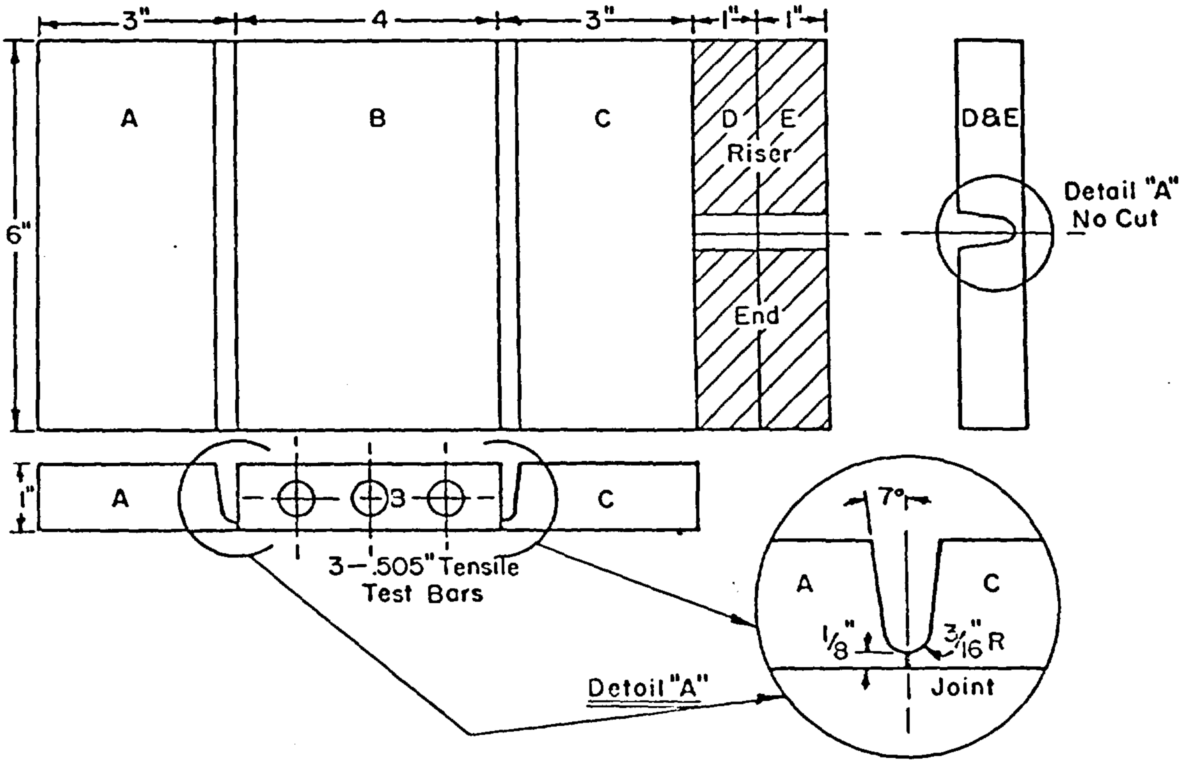

Figure 2. Sectioning and Joint Design for Cast Slabs.

TABLE 2

Chemical Compositions of Parent Metal

Melt No.	Elements, Per Cent				
	Cu	Sn	Zn	Pb	P
401	85.71	6.30	4.95	2.11	0.025
419	87.17	10.21	2.34	0.10	0.06
492	88.60	9.54	1.78	0.06	0.015
493	88.05	9.87	2.14	0.02	0.005
513	86.48	9.32	2.12	1.80	0.011
550	84.66	5.19	4.88	4.82	0.04
551	88.39	9.40	2.64	0.02	0.001

TABLE 3

Chemical Composition of Filler Materials

Type	Elements, Per Cent						
	Cu	Sn	Si	Fe	P	Al	Mn
A Silicon Bronze (Nominal)	96.0	-	3.0	-	-	-	1.0
B Phosphor Bronze (Nominal)	91.8	8.0	-	-	0.2	-	-
C Aluminum Bronze (Nominal)	90.0	-	-	0.8	-	9.2	-
D IX Experimental Bronze* (Actual)	91.6	7.7	0.19	0.07	0.30	-	-
E 2X Experimental Bronze* (Actual)	91.04	7.74	0.57	0.14	0.25	-	-

*Patent applied for.

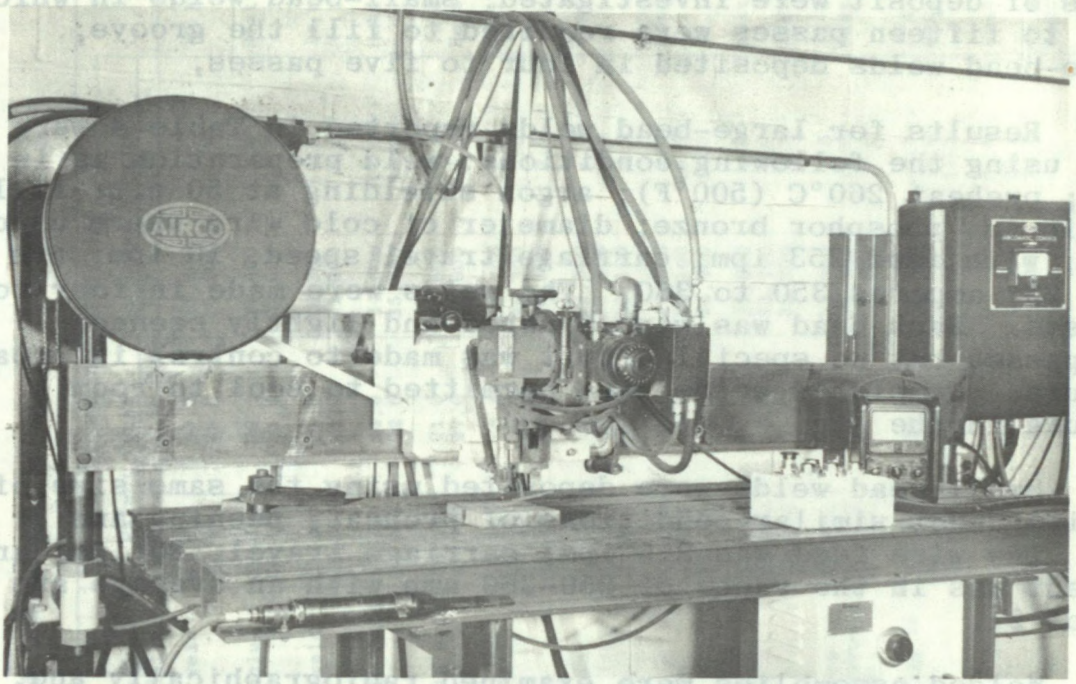

Figure 3. General View of Equipment

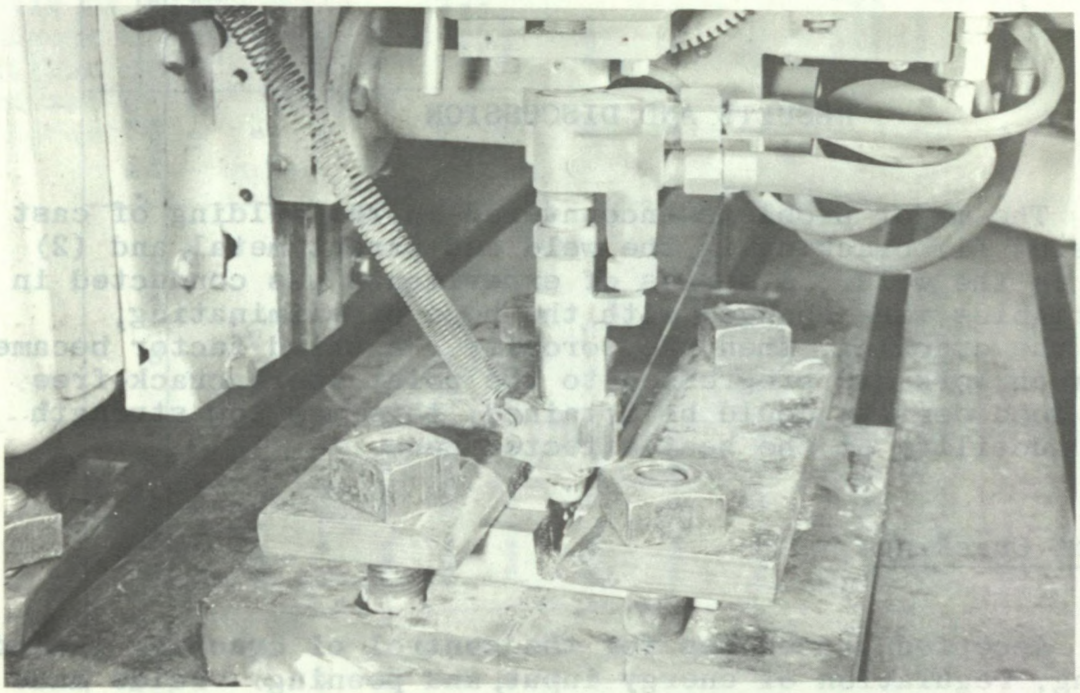

Figure 4. Close-up View Showing Jigging and Cold Wire Feed.

Variations in bead size were obtained by changing the voltage setting, wire-feed speed, and carriage travel. In general, two types of deposit were investigated: small-bead welds in which fourteen to fifteen passes were required to fill the groove, and large-bead welds deposited in four to five passes.

Results for large-bead welds reported in Table 4 were obtained using the following conditions: weld preparation as in Figure 2; preheat 260°C (500°F); argon shielding at 50 cfh; filler wire, 1/16 in. phosphor bronze; diameter of cold wire where used, 3/32 in.; wire feed, 253 ipm; carriage travel speed, 10 ipm; arc voltage, 23; amperes, 350 to 360. The welds were made in four to five passes. Each bead was wire-brushed and lightly peened between passes, but no special effort was made to control interpass temperature. Completed welds were permitted to cool to room temperature in the jig.

Small-bead welds were deposited using the same size of filler wire under similar conditions of preheat, peening, and cooling. The wire feed was 215 ipm; carriage travel, 20 ipm; and the current was in the range of 250-260 amp with an average arc voltage of 21.

Welded assemblies were examined radiographically and, if no serious cracking had occurred, were sectioned to provide three 0.505 in. tensile test bars machined transverse to the direction of welding so that the weld was in the centre of the gauge length. A cross-section for metallographic examination was taken from the specimen in the region between the second and third test bars.

RESULTS AND DISCUSSION

The major problems encountered in the welding of cast bronze were: (1) cracking in the weld and parent metal, and (2) porosity in the weld. A series of experiments was conducted in which variables were changed with the hope of eliminating, firstly, the cracking, then the porosity. A third factor became evident when work had progressed to the point where crack-free welds of good density could be obtained; this was low strength and poor ductility of the heat-affected zone.

Control of Cracking

Accepted procedures for the control of cracking include preheating, regulation of energy input, and peening. Welds made without preheat and peening using silicon bronze filler wire, cracked longitudinally and transversely, regardless of bead size.

TABLE 4

Test Results from Second Stage

Test No.	Melt No.	Filler Wire	Cold Wire	No. of Beads	X-ray Results		Mechanical Properties				Location of Failure
							Parent Metal		Weld Cross Section		
					Cracks	Porosity	UTS	% El. in 2 in.	UTS	% El. in 2 in.	
59A1	401 NC(1)	Si Bronze		15	Many small in weld	Light, weld	43,600	40.5	15,200	2.0	In weld.
							39,900	28.0	16,800	1.0	" "
59A5	419 C(2)	Phos. Bronze	Flux(3)	5	None	Many inclusions	39,600	28.5	21,400	2.5	Heat-affected zone.
							36,600	25.0	22,600	3.5	" "
59A15	401 NC	Si Bronze		15	None	Light, weld	35,500	21.0	16,300	4.0	In weld.
							34,300	24.0	21,000	7.5	" "
60A8	492 NC	Phos. Bronze	3/32 in. Si Bronze	4	None	Minor in weld	40,700	24.0	34,800	14.0	Heat-affected zone.
							38,900	22.0	35,700	13.0	" "
60A9	492 C	Phos. Bronze	3/32 in. Si Bronze	4	3 small transverse in parent metal	Minor in weld	45,100	21.0	25,600	7.5	In weld.
							47,700	27.0	31,600	6.0	Heat-affected zone.
60A11	492 C	Phos. Bronze	Nil	4	None	Very heavy	43,400	17.0	33,700	8.0	Heat-affected zone.
							46,300	28.0	28,300	7.0	" "
							42,100	19.0	19,100	6.0	" "
60A14	493 NC	Phos. Bronze	3/32 in. Si Bronze	4	None	Slight in weld	39,900	26.0	19,500	7.5	Heat-affected zone.
							37,500	23.0	23,000	9.6	" "
							38,800	24.0	19,100	9.0	" "
60A15	493 C	Phos. Bronze	3/32 in. Si Bronze	4	None	Slight in weld	40,600	15.0	17,600	8.0	Heat-affected zone.
							43,700	19.0	33,100	16.5	" "
							43,700	24.0	24,700	10.0	" "
60A16	493 NC	Phos. Bronze	3/32 in. Phos. Bronze	4	None	Very heavy in weld	34,700	14.0	29,600	4.5	Heat-affected zone.
							35,600	13.0	33,700	6.0	" "
							36,500	20.0	35,200	6.5	5/8 in. from weld.
60A19	513 NC	Phos. Bronze (not peened)	3/32 in. Si Bronze	5	Many small transverse in parent metal	Stringers of small porosity in weld	39,600	34.0	23,500	7.0	In weld.
							39,700	34.0	35,200	14.0	Heat-affected zone.
							37,600	31.5	33,300	10.0	" "
60A20	513 NC	Phos. Bronze (peened)	3/32 in. Si Bronze	5	None	Less than in 60A19	37,500	28.5	18,200	4.5	3/4 in. from weld.
							39,200	27.5	29,600	9.0	Heat-affected zone.
							36,600	25.0	32,500	11.5	" "
61A1	551 NC	2X wire	Nil	4	Small transverse in weld; lack of fusion	Very slight in weld	40,800	30.0	43,700	24.0	Heat-affected zone.
							40,000	30.0	41,500	23.0	" "
							41,600	32.0	36,600	14.0	In shoulder of test piece.
61A2	550 NC	2X wire	Nil	4	2 small transverse in parent metal	Very heavy	35,200	27.0	11,200	Could not be determined N.d.	All failures in weld. Many small cracks between pores.
							37,800	30.0	12,800		
							38,000	31.5	10,000		

(1) The letters NC following melt number indicate that casting was not chilled.
(2) C after melt number indicates chilled casting.
(3) Weld groove and passes were painted with flux.
N.d. = Not determined.

Those made with phosphor bronze filler wire were free from cracks in the weld, but longitudinal and transverse cracking occurred in the parent metal adjacent to the weld. Extreme porosity was present in the phosphor bronze welds and this may have made it difficult for cracks to form. When welds were made using a 260°C (500°F) preheat, with either filler wire, longitudinal cracking in the weld and the parent metal was reduced, but transverse cracks persisted and with aluminum bronze filler these frequently extended into the parent metal.

Variation in bead size was controlled by means of the energy input. For convenience in assessment, two levels were chosen; one approximately 20,000 joules per inch and requiring fourteen to fifteen passes to complete the weld, the other 50,000 joules per inch, requiring four to five passes to fill the weld groove. When small beads were deposited using silicon bronze filler wire, centre-line cracks occurred within individual beads but these did not extend into adjacent beads. When large beads were deposited with the same filler wire, cracks propagated from one bead to another and resulted in cracking through the whole thickness of the weld.

The use of phosphor bronze filler wire reduced the incidence of cracking in the weld, but seemed to increase the size and number of cracks in the parent metal. Because of the erratic arc characteristics common to the phosphor bronze filler, some difficulty was experienced in maintaining a constant energy input, especially in the smaller beads. As a result, attempts to deposit welds at the lower energy level were unsuccessful.

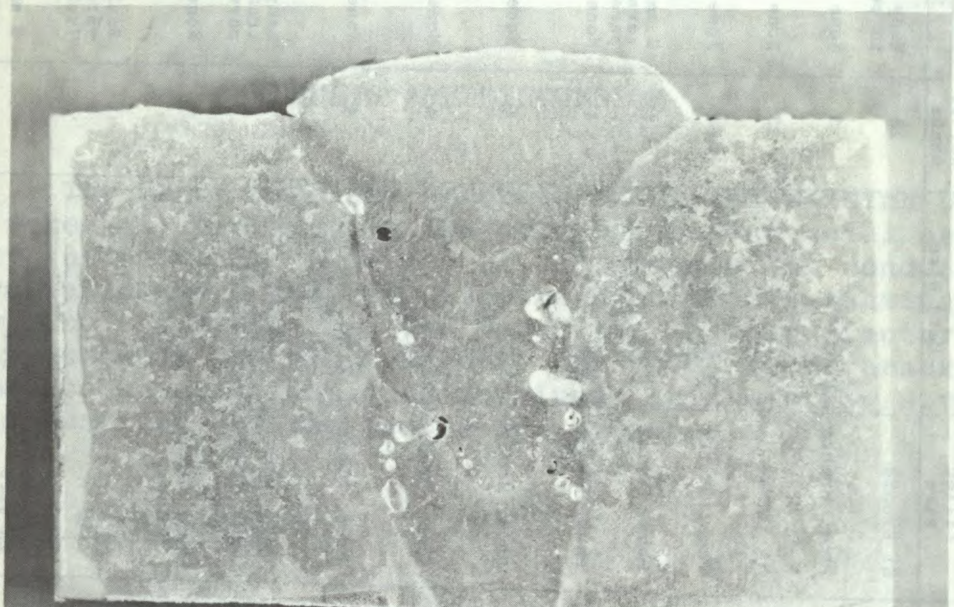

Figure 5. Phosphor Bronze Weld Showing Porosity Close to Fusion Line. X2 1/2

Peening, which was performed using a light air-driven descaling hammer with a rounded chisel-shaped tool, caused some reduction in transverse cracking in welds made without preheat, but had no noticeable effect on longitudinal cracking, particularly the throat cracking characteristic of silicon bronze welds. When used in conjunction with the 260°C (500°F) preheat, peening eliminated the transverse cracking in the parent metal associated with phosphor bronze welds, except in those areas where a definite casting defect existed, in which case a crack formed from this defect. It was not possible, however, to prevent longitudinal cracking in welds made with silicon bronze, even by the use of preheating and peening. It was decided, therefore, to use only phosphor bronze filler wire for all subsequent welds.

Control of Porosity

Macroscopical examination of cross-sections taken from several multipass welds revealed two interesting facts concerning porosity: (1) regardless of the filler wire used, porosity was concentrated in the weld close to the fusion zone (Figure 5); (2) considerably less porosity occurred in welds made with silicon bronze wire. The location of porosity close to the fusion zone was confirmed by stereoscopic X-ray examination. Since most of the porosity was located close to the fusion line, it appeared that the source could be the parent metal. Weld beads deposited on machined surfaces of castings showed porosity at the fusion line, whereas subsequent passes deposited on top of these contained little or no porosity. Autogenous welds, made by fusing clean surfaces of castings with the tungsten-inert gas torch without the addition of filler rod, were very porous (Figure 6). The conclusion was drawn, therefore, that the parent metal was the source of porosity.

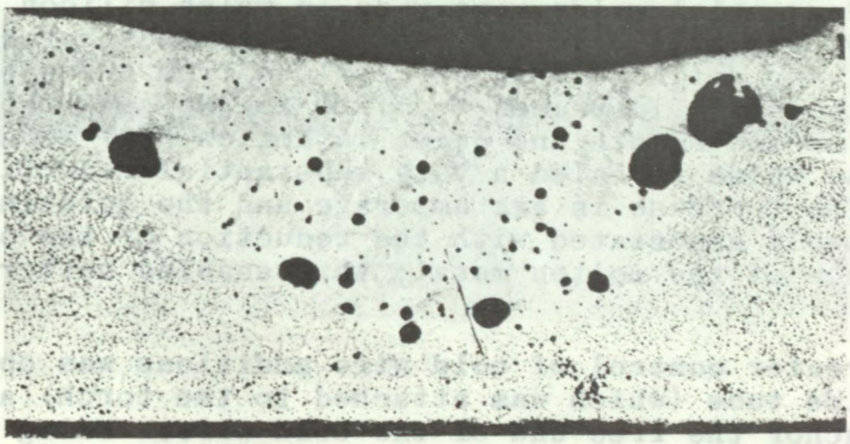

Figure 6. Cross-Section of Autogenous Weld Showing Extreme Porosity. X4

It was at first thought that the cast plates might have picked up moisture during handling, either in storage or in transportation, or from water-soluble lubricants during machining. The decomposition of such moisture during welding could be the cause of porosity. However, when cast slabs, which had been heat-treated to drive off free moisture, were welded, no reduction in porosity was evident. Porosity also occurred in welds made on cast slabs which had been carefully protected from any form of oil or grease contamination. Finally, melting practice was checked and it was found that all heats had been thoroughly degassed before pouring into sand moulds. However, regassing may have occurred by reaction of the hot metal with moisture associated with the binder used to make the sand moulds. This is a common cause of hydrogen in cast metals. It is suggested that gas is evolved from the surrounding metal into the weld pool and is trapped there as a result of the rapid cooling. Alternatively, the hydrogen might react with oxides in the weld metal, if deoxidation were incomplete, giving rise to steam porosity at this location.

The fact that there was less porosity in welds made with silicon bronze as compared with phosphor bronze welds (Figures 7a and 7b) may be explained by the better deoxidation with considerable silicon present. Similar reduction in porosity occurred when the weld groove was coated with a flux, presumably due to removal of freshly-formed oxides. However, flux residue was difficult to remove and flux inclusions were found in multipass welds. Welds made with an aluminum bronze filler wire were free from porosity, but lack of fusion between weld and base metal made these welds unacceptable.

The realization that major reduction in porosity occurred only when metal containing a strong deoxidant was used suggested that the addition of some deoxidizing element to welds made with commercially available phosphor bronze wire might reduce porosity. Some trial welds were made in which silicon bronze wire was added by hand as a cold wire addition to phosphor-bronze welds. Two very definite changes resulted from these experiments: (1) the arc amperage increased from 250 to 350, and the formerly erratic arc became smooth and quiet in action; (2) X-ray examination of these welds revealed a very substantial reduction in porosity. The increase in arc amperage and the quieting of the arc are probably associated with the reduction of the oxide layer on the surface of the molten metal; this enabled better ionization in the arc.

Greater control of cold wire additions was obtained by making a guide tube (which was attached to the torch) and a holding device to anchor the free end of the cold wire. Using this equipment, the cold wire was threaded through the guide tube and located in the weld groove slightly in advance of the phosphor bronze filler wire; the free end of the cold wire was attached to the holding device. As the weld was deposited, the movement of the head caused the cold wire to be forced into the molten pool, so

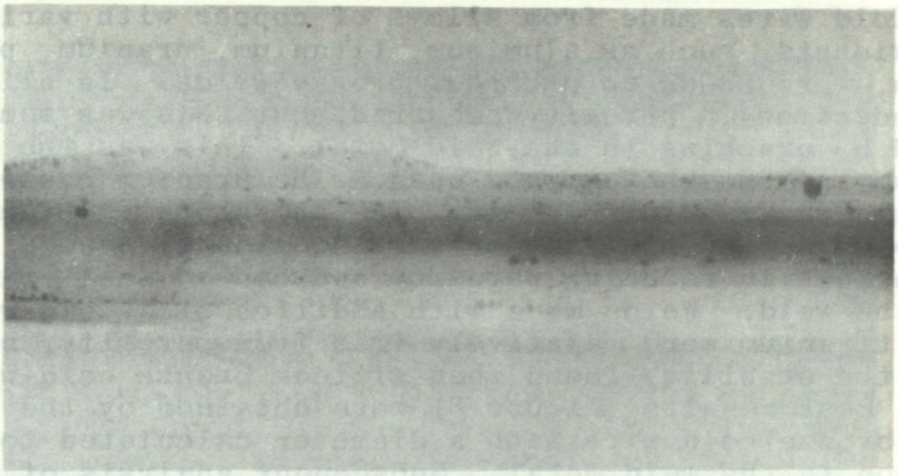

Figure 7a. Positive X-ray Print Showing Porosity in Silicon Bronze Weld Metal.

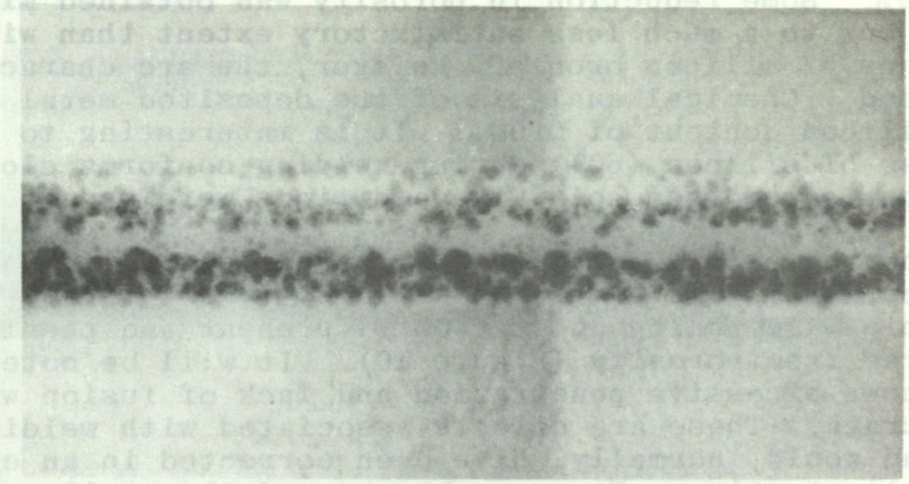

Figure 7b. Positive X-ray Print Showing Porosity in Phosphor Bronze Weld Metal.

that the length of cold wire added was roughly equivalent to the length of the weld. Variation in the amount of cold wire added was accomplished by changing the diameter of the wire used.

Cold wires made from alloys of copper with various strong deoxidants, such as aluminum, titanium, uranium, phosphorus and silicon, were added to phosphor bronze welds. In all instances some reduction in porosity occurred, but this was sometimes accompanied by cracking in the weld metal. This was the case when uranium and phosphorus were used. The uranium caused extensive longitudinal cracking in the weld. The phosphorus, which is believed to be a poor high-temperature deoxidant, seemed to have the least effect in reducing porosity and caused small random cracks in the weld. Welds made with addition of a cold wire containing titanium were relatively free from porosity, but the arc lacked the stability found when silicon bronze cold wires were used. Best results (Figure 8) were obtained by the addition of silicon bronze cold wire with a diameter calculated to provide 0.30% silicon in the weld metal. Subsequent analysis of metal deposited in this manner showed an actual silicon content of 0.10%, indicating that two-thirds of the silicon was lost by oxidation. It was evident that some of this silicon had gone into the formation of the very light slag that was apparent on weld beads.

In order to obviate the necessity for a cold wire addition, an experimental phosphor bronze wire was made with a normal phosphorus content of 0.2% and an intended silicon content of 0.30%. Analysis of the resultant billet showed a silicon content of 0.19%. Some reduction in porosity was obtained with this (Figure 9), but to a much less satisfactory extent than with cold wire additions of silicon bronze. However, the arc characteristics were very good. Chemical analysis of the deposited metal revealed an actual silicon content of 0.06%. It is interesting to note that the loss of silicon (60%) during welding conforms closely to the loss experienced when cold wire additions were made.

Another experimental phosphor bronze wire was made with an actual content of 0.57% silicon and 0.25% phosphorus. Welds made with this wire, using 260°C (500°F) preheat and peening, were generally free from porosity (Figure 10). It will be noted that Figure 10 shows excessive penetration and lack of fusion with an associated crack. These are defects associated with welding technique and would, normally, have been corrected in an example chosen for illustration. However, because of the small amount of experimental wire available, few welds could be made and it was not possible to eliminate defects due to procedure. Mechanical properties obtained from such a weld are reported under test No. 61A1 in Table 4. It can be seen that these results compare very favourably with those for the parent metal, and indicate that the use of phosphorus and silicon in combination provides sufficient deoxidation to prevent excessive porosity and results in resistance to cracking in the weld metal. The strength and ductility of the weld metal are comparable to those of cast tin bronze, when used with lead-free parent metal.

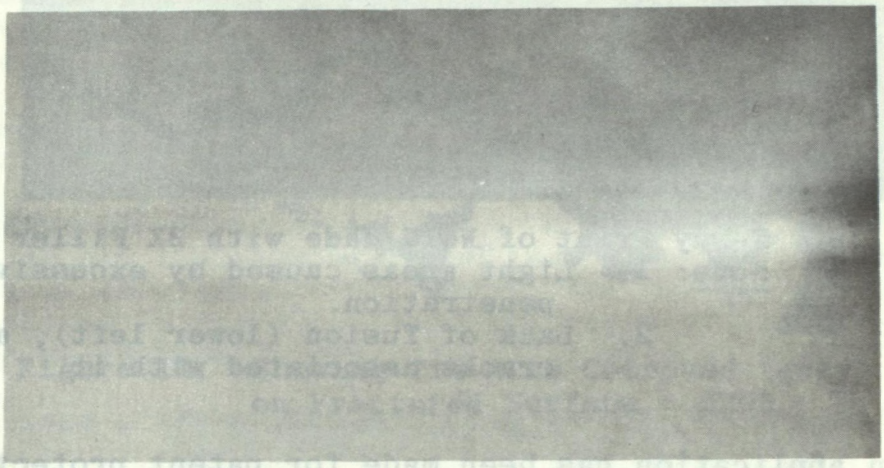

Figure 8. Positive X-ray Print of Phosphor Bronze Weld Made with Silicon Bronze Cold Wire Addition.

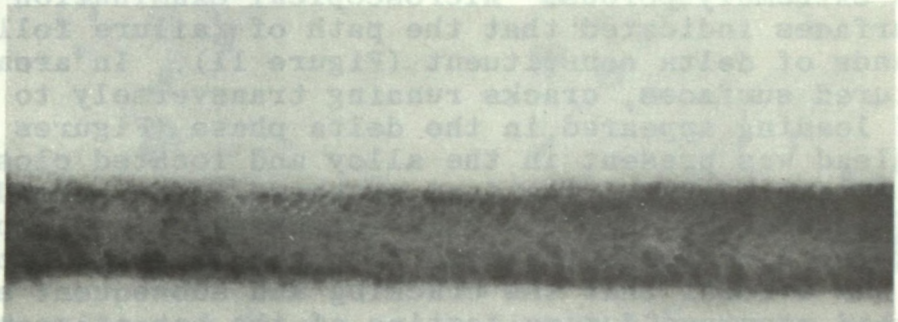

Figure 9. Positive X-ray Print Showing Porosity in Weld Made with IX Filler Wire.

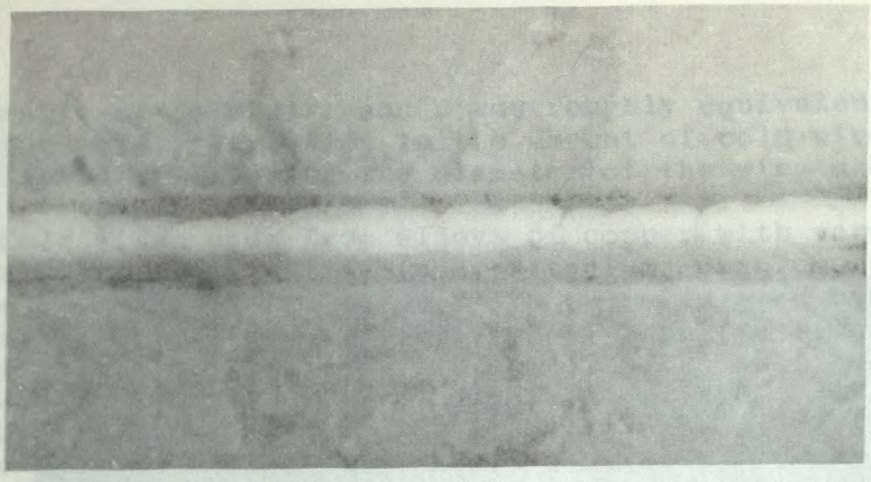

Figure 10. X-ray Print of Weld Made with 2X Filler Wire.
Note: 1. Light areas caused by excessive penetration.
2. Lack of fusion (lower left), and cracks associated with it.

An application has been made for patent protection respecting the compositions of filler wires discussed above and given in Table 3.

Weakness in Heat-affected Zone

Tensile test bars were machined from cross-sections taken from those tests that had not shown cracking in the radiographic examination. The weld was located in the centre of the gauge length. In the great majority of cases these test bars failed in the heat-affected zone of the parent metal, even when the weld was extremely porous. Microscopical examination of the fractured surfaces indicated that the path of failure followed through islands of delta constituent (Figure 11). In areas close to the fractured surfaces, cracks running transversely to the direction of loading appeared in the delta phase (Figures 12 and 13). Where lead was present in the alloy and located close to the islands of delta phase, the lead appeared to be extruded into the cracks (Figure 12). Since similar cracks were not apparent in samples taken from welds that had not been subjected to tensile testing, it was evident that the cracking and subsequent extrusion of the lead had occurred during testing of the bar at room temperatures. This fact, considered in conjunction with the presence of the delta-constituent on the fractured surfaces, indicated that the zone of weakness must be caused by some increase in the tin-rich compound in this zone. Microscopical examination showed that the various zones had different structures as illustrated in Figure 14, the most important being an increase in amount of delta in the heat-affected zone.

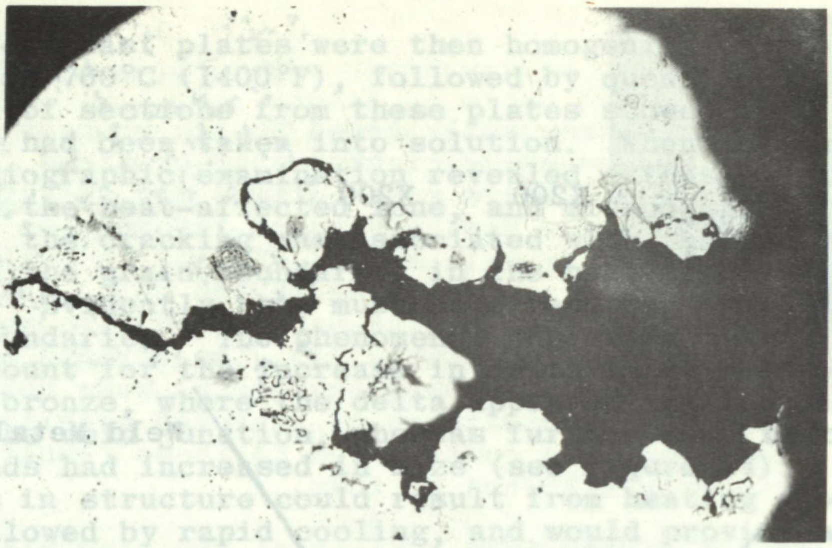

Figure 11. Showing Tin-Rich Compound (grey) on Fractured Surface. X200

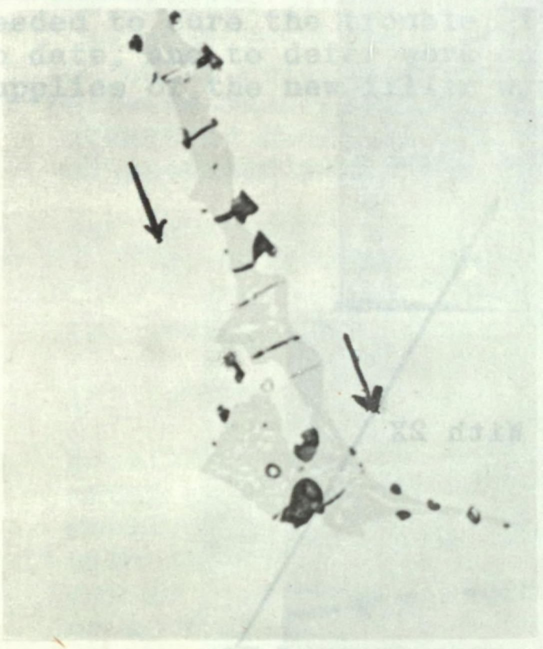

Figure 12. Showing Cracks in Delta Phase Section taken from Failed Tensile Bar. X600. Arrows show direction of loading.

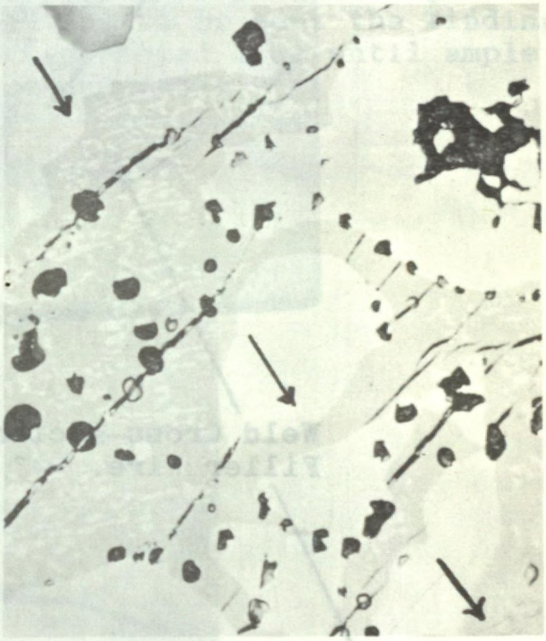

Figure 13. As in Figure 12. X600. Arrows show direction of loading.

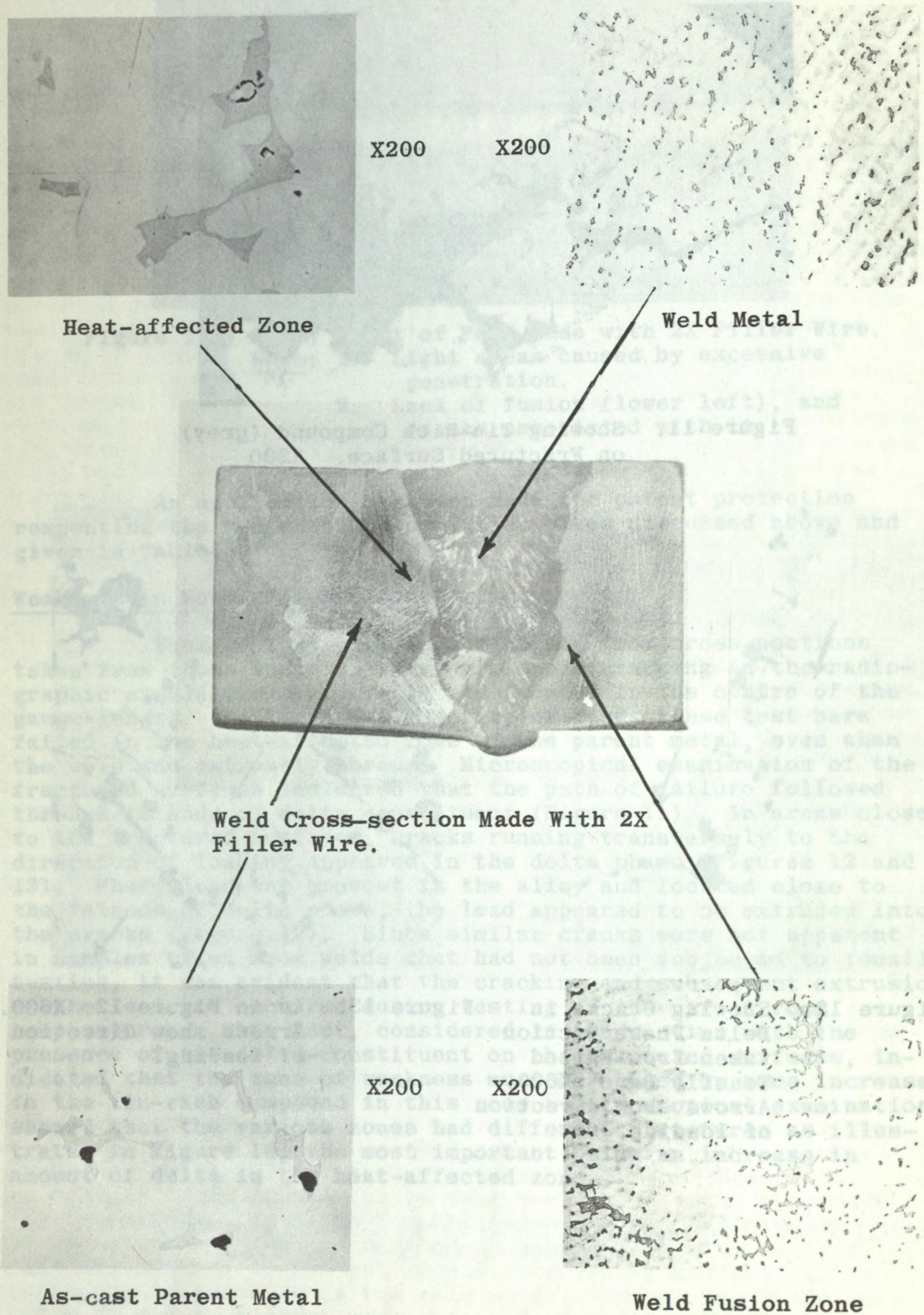

Figure 14. Composite of Various Microstructures in Weld and Base Plate.

Some cast plates were then homogenized by heating for five hours at 760°C (1400°F), followed by quenching in water. Examination of sections from these plates showed that the delta constituent had been taken into solution. When this material was welded, radiographic examination revealed extensive random cracking in the heat-affected zone, and microscopical examination showed that the cracking was associated with the presence of films of delta on the grain boundaries in the heat-affected zone (see Figure 15). Evidently this must have resulted from partial melting near the boundaries. The phenomenon suggested a similar explanation to account for the increase in delta in the heat-affected zone of as-cast bronze, where the delta appeared in fine dendritic form near the weld junction, whereas further away the original delta islands had increased in size (see Figure 14). Here again the changes in structure could result from heating above the solidus followed by rapid cooling, and would provide more continuous paths of weak delta constituent in which cracking can occur.

Since a weakened heat-affected zone appeared to be characteristic of tin bronzes, and an extensive program might be needed to cure the trouble, it was decided to present the findings to date, and to defer work on the heat-affected zone until ample supplies of the new filler wire became available.

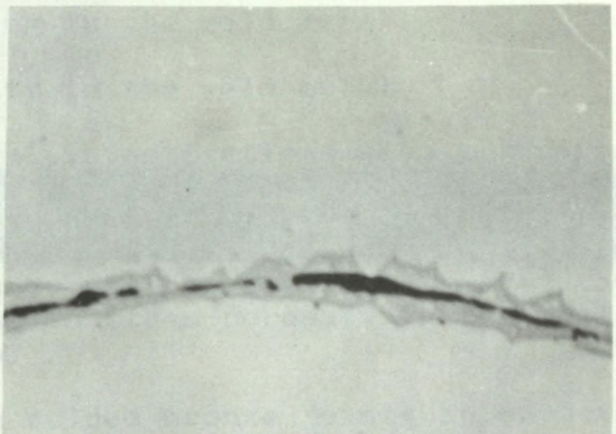

Figure 15. Crack in Grain Boundary Precipitation of Delta Phase. X600.

Effects of Lead

Since lead is frequently added to tin bronzes as a means of increasing the pressure tightness of castings, any consideration of a repair procedure must include the effect of this constituent on weldability. Most published information indicates that the presence of even a small amount of lead in a tin bronze results in extreme porosity or cracking in the weld. In order to investigate these claims, many of the melts used were made with lead contents ranging to 4.82% (Table 2). The effects of these additions on the properties of the parent metal were not clear. In some melts there were indications of improved consistency, but, since other factors may have contributed to these results, no special significance is attached to them.

The effect of the lead content of the base plate on the quality of welds produced seems to be equally obscure. It had been noted, in examination of radiographic films, that welds made on plates containing lead seemed to be slightly more porous, and that this porosity increased as the lead content increased, but the effect on strength and ductility as determined by tensile testing is not clear. Certainly, lead contents below 2% do not seem to weaken the weld below the strength of the heat-affected zone, whereas lead greatly in excess of 2%, as shown in 61A2, Table 4, seems to cause extreme porosity and great weakness in the weld.

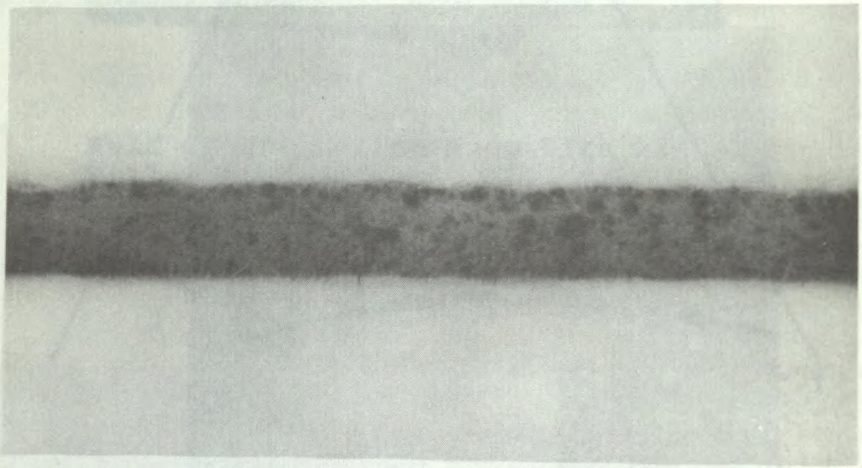

Figure 16. Positive X-ray Print Showing Porosity and Cracking in Weld Made on High Lead Base Plate Using 2X Filler Wire.

Examination of the fractured surfaces of tensile test bars containing weld metal deposited on plates from melt 550 showed that failure occurred in areas where lead films had formed on cracks extending between pores.

Since many of the observations concerning the effects of lead could have been caused by other factors that were not controlled at the time, it would seem unwise to generalize on its influence in these experiments. There can be little doubt, however, of the role of lead in test 61A2 (Figure 16), which was made using the newly developed filler wire. Here, with a lead content of 4.82%, welds were porous and weak. In order to study the problem further, it will be necessary to obtain a sufficient supply of the new filler wire. However, on the basis of results to date, it seems that lead in amounts less than 2% causes some porosity but little weakening of the weld, whereas lead in excess of this percentage could cause serious weakness in welded joints.

CONCLUSIONS

1. The mechanical properties of cast bronzes vary within individual plates, and also among plates from the same heat. The properties are usually better in thin sections and when chills are used.

2. The preliminary work established that the conventional welding processes yielded poor mechanical properties in the joints, often associated with serious welding defects such as:

   (a) cracking in the parent plate, usually in or near the heat-affected zone;

   (b) cracking in the weld metal;

   (c) porosity in the weld metal.

3. Metallurgical investigations seem to indicate that the weld metal porosity may derive from hydrogen present in the cast metal. This could result from reaction of the molten metal with the binder used in the sand moulds. The hydrogen may appear subsequently as gas pockets near the weld junction, or give rise to steam porosity in the weld metal by reaction with oxides.

4. Cracking in welded bronze joints appears to be associated with the tin-rich delta constituent, which is increased in amount in the heat-affected zone.

5. Lead in large amounts (around 5%) may increase somewhat the susceptibility to porosity and cracking, but in smaller amounts (up to about 2%) it seems to have little influence.

6. Butt-welded joints were made under restraint on 1-in.-thick cast bronze slabs of various compositions, and the welding conditions were experimentally varied. The following conditions were found to be helpful in minimizing the occurrence of welding defects:

   (a) Preheating to 260°C (500°F).

   (b) Light mechanical peening of the welds.

   (c) Argon shielding with a flow of about 50 cfm.

   (d) Large bead size.

   (e) Use of supplemental deoxidants through the agency of cold wire additions.

7. Based on tests with cold wire additions, experimental filler wires were made with the following compositions:

   (a) phosphorus 0.2%, silicon 0.19%, tin 7.7%;

   (b) phosphorus 0.25%, silicon 0.57%, tin 7.74%.

The second composition, with higher deoxidants, was found to be very satisfactory. Welds made with this wire were generally free of porosity and gave mechanical properties in the joint comparable with those of the parent metal except when used on high lead castings.

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