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TENSILE TESTS AND METALLURGICAL STUDIES OF WELDED COPPER JOINTS

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Tensile Tests and Metallurgical Studies of Welded Copper Joints

Mechanical properties and metallurgical studies of a number of types of welded copper joints at various temperatures and by different welding processes

by R. J. Mosborg, R. W. Bohl, F. L. Howland and W. H. Munse

INTRODUCTION

THIS investigation, sponsored by the Copper and Brass Research Association at the University of Illinois, is a part of a program to determine the mechanical properties of a number of types of welded copper joints at various temperatures.

Thus far static tension tests have been completed on welds made by the inert-gas shielded-arc (deoxidized copper rod and argon shield) and the oxyacetylene (brass rod) processes. Three base materials, electrolytic tough-pitch, deoxidized high-phosphorus, and oxygen-free high-conductivity (OFHC) coppers, in $^1/_8$ and $^1/_4$ in. thicknesses, were welded with each of these two processes. From these tests, values of yield strength, ultimate strength, per cent elongation, and per cent reduction of area were determined at testing temperatures of −321, 70 and 400° F. for each combination of base metal and type of welded joint.

To supplement the mechanical test data obtained on these welded copper joints, a metallurgical examination was made of a section cut from each type of joint. This examination consisted of microscopic, macroscopic and micro-hardness surveys of the base metal, heat-affected base metal and weld metal.

TESTING EQUIPMENT AND PROCEDURES

A 30,000-lb. Riehle universal testing machine was used for the duplicate tests conducted at room temperture and 400° F. These test specimens were 10 in. long with a $1^1/_2$-in. wide net section and conformed to the A.S.T.M. Designation E8-46 for standard rectangular tension test specimens with a 2-in. gage length.

The 400° F. testing temperature was provided by a 2000 watt electrical tube-type furnace for which previous calibrations indicated that a uniform temperature was obtained over the entire length of the specimen. During each test the temperature was measured with a chromel-alumel thermocouple located at the center of the specimen and was recorded continuously with a recording self-balancing potentiometer. The specimen was maintained at the test temperature for ten minutes prior to the start of the test to insure uniform temperature distribution along the specimen. This temperature was then maintained within ±2° F. throughout the test.

The −321° F. tests were conducted in a 120,000-lb Baldwin-Southwark hydraulic universal testing machine. For these low-temperature tests quadruplicate specimens, 10 in. long and with a net section $^1/_2$ in. in width, were tested. This smaller section permitted the use of special equipment already available for tests at this temperature and also reduced the size of the apparatus to be cooled. Before changing to this reduced width, however, a series of tests was conducted at room temperature in which the results from $^1/_2$- and $1^1/_2$-in. wide specimens were compared. This comparison indicated that this change in width of the specimen had no significant effect on the mechanical properties. In order that all the specimens would be similar and comparable to one another, the weld reinforcement was removed from each specimen.

The testing temperature of −321° F. was obtained by immersing the specimen and pullheads in a bath of boiling liquid nitrogen. Thus they were maintained at a constant temperature of −321° F. throughout the entire test. The testing chamber for these low-temperature tests consisted of a multiple-walled container. One of the spaces between these walls was filled with Santocel, a commercial insulating material, and the other contained a dead air space. The problem of insulating the test assembly from the rest of the testing machine was solved by using felt and plastic insulating joints above and below the test assembly.

For each specimen tested, an autographic recording

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Table 1—Details of Welding Procedures

	Inert-gas shielded-arc						*Oxyacetylene*					
Filler metal	American brass alloy 372						Oxweld 25M bronze					
Type of flux	....						Oxweld brazo flux (paste form)					
Make and type of torches	Aircomatic gun model 2S						Oxweld W17, Airco No. 800					
Size of tips	....						No. 40, No. 7					
Gas used	....						Oxygen and acetylene (slightly oxidizing)					
Current	Reversed d. c.						....					
Electrode size, in.	1/16						....					
Shielding gas	Argon (35 C.F.H.)						....					
Joint position	Flat						20 deg. angle					
Backing	Shallow groove copper						Grooved copper, 1/16 in. deep by 1/4 in. wide					
Clamping	2 C-clamps						None					
Plate thickness, in.	1/8			1/4			1/8			1/4		
Filler metal size, in.	1/16			1/16			3/16			1/4		
Edge preparation	Square butt			60° Incl. angle			90° Incl. angle			90° Incl. angle		
Root face, in.	....			None			1/32			1/16		
Root space, in.	1/16			None			3/32—Starting end 1/4—Finishing end			3/32—Starting end 1/4—Finishing end		
Preheat, ° F.	....			About 250			....			....		
Base metal	T.P.	Deox.	OFHC	T.P.	Deox.	OFHC	T.P.	Deox.	OFHC	T.P.	Deox.	OFHC
Amount of gas used, cu. ft.	..	..	..	..	..	..	50	43	45	64	68	60
Current, amp.	330	330	300	370	350	370	..	.	..	..	..	..
Time to complete pass, min.	21	22	23	13	13	12	..	..	..	..	..	..

unit was used to obtain a complete load-elongation curve. From these curves the yield load, maximum load and the final maximum elongation were obtained.

The metallurgical specimens for the welded joint studies consisted of a section cut normal to the joint. One of the specimen faces containing the weld section was ground with successively finer grit emery papers through 3/0 grit, and the surface was electrolytically polished in an electrolyte of phosphoric acid (900 g./l.). A micro-hardness survey was then made across the polished surface along a straight line traverse parallel to the surface of the plate. This hardness survey was made with a Tukon Hardness Tester, using a 136-degree Vickers diamond pyramid indenter under a load of 1000 gm. All tests were made along a line extending 36 mm. from the center of the joint and included the weld metal, heat-affected base metal and unaffected base metal. The first twenty tests were

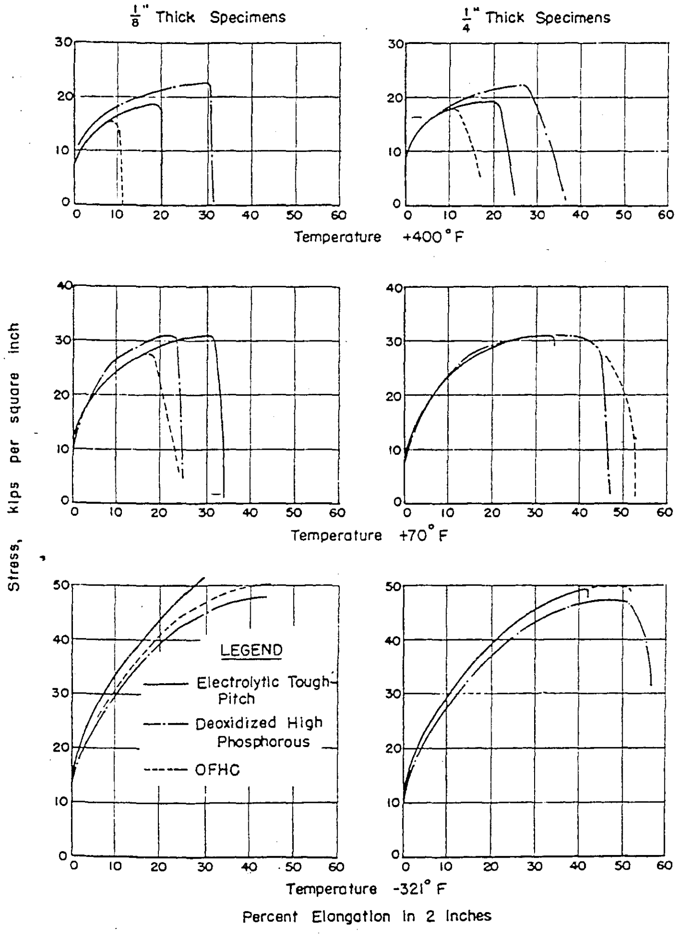

Fig. 1 Stress-elongation curves for copper joints welded by the inert-gas shielded-arc process, deoxidized copper rod

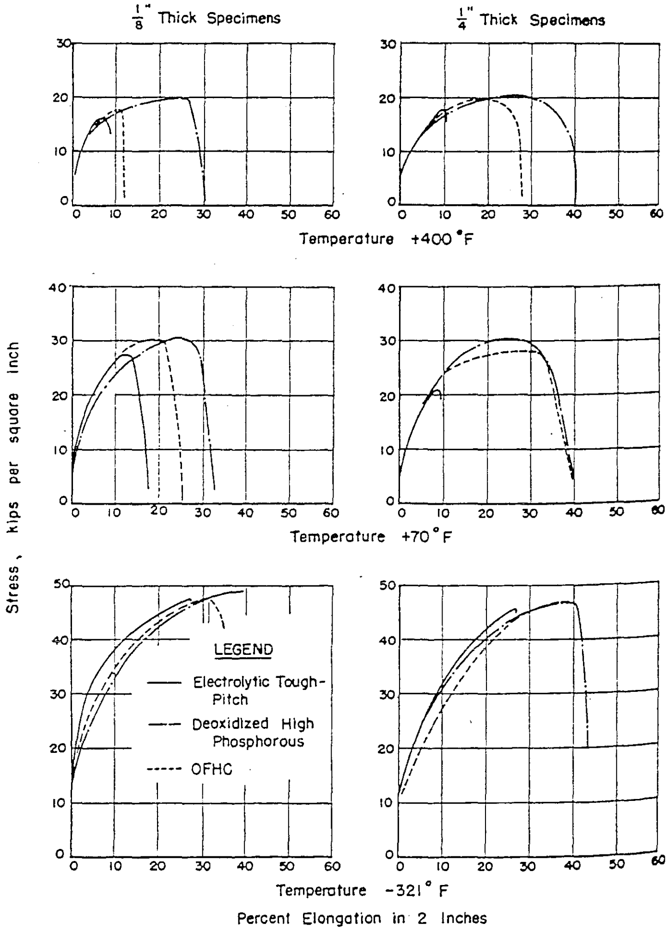

Fig. 2 Stress-elongation curves for copper joints welded by the oxyacetylene process, brass rod

made at 1-mm. intervals in the weld metal and the base metal. This was followed by eight readings at 2-mm. intervals in the unaffected base metal.

Upon completion of the hardness surveys the specimens were etched with an acid potassium dichromate reagent to reveal the microstructure of the base metal and weld metal. Upon completion of the microscopic examination, all specimens were repolished and etched with nitric acid for a macroscopic examination.

DISCUSSION OF TEST RESULTS

As stated previously, the object of the investigation was to determine the mechanical properties of welded joints in copper at various temperatures. The details of the welding procedures used to prepare the test specimens are given in Table 1. (The joints were prepared by a highly qualified commercial fabricator.)

Stress-Elongation Curves

The average stress-elongation curves for each of the various types of joints are shown in Figs. 1 and 2 and make it possible to compare the behavior of the different joints when tested at the various temperatures. In these figures the curves for each of the two thicknesses, the two welding processes and the testing temperatures have been presented separately.

For joints prepared by either welding process, the influence of the testing temperature on the ultimate strength of the specimen was more pronounced than on any of the other properties. The curves of Figs. 1 and 2 show also that in the tests at −321° F. failure of the specimen (the end point of the curves) occurred at loads very close to the maximum load on the specimen, while at the other temperatures a considerable drop-off of the load usually occurred before final failure of the specimen. This abrupt or sudden type of failure occurred also at room temperature and 400° F. for the $^1/_4$-in. tough-pitch specimens welded by the oxyacetylene process.

The deoxidized copper joints were usually stronger and underwent greater elongations than the other base metals. However, in general, the differences between these joints and the joints of tough-pitch and OFHC coppers were small.

Yield Strength

For the two welding processes studied, the yield strength, as determined by an elongation of 0.5%, was not greatly affected by the temperature, and at 70° F. varied only slightly from an average of 10,000 psi. As the temperature was decreased from 400 to −321° F., the yield strength increased about 4000 psi. This trend is shown in the lower part of each diagram of Fig. 3. It is evident that neither the welding process, the thickness, nor the base metal produced a distinguishable variation in the yield strength.

Ultimate Strength

One of the most important properties considered in

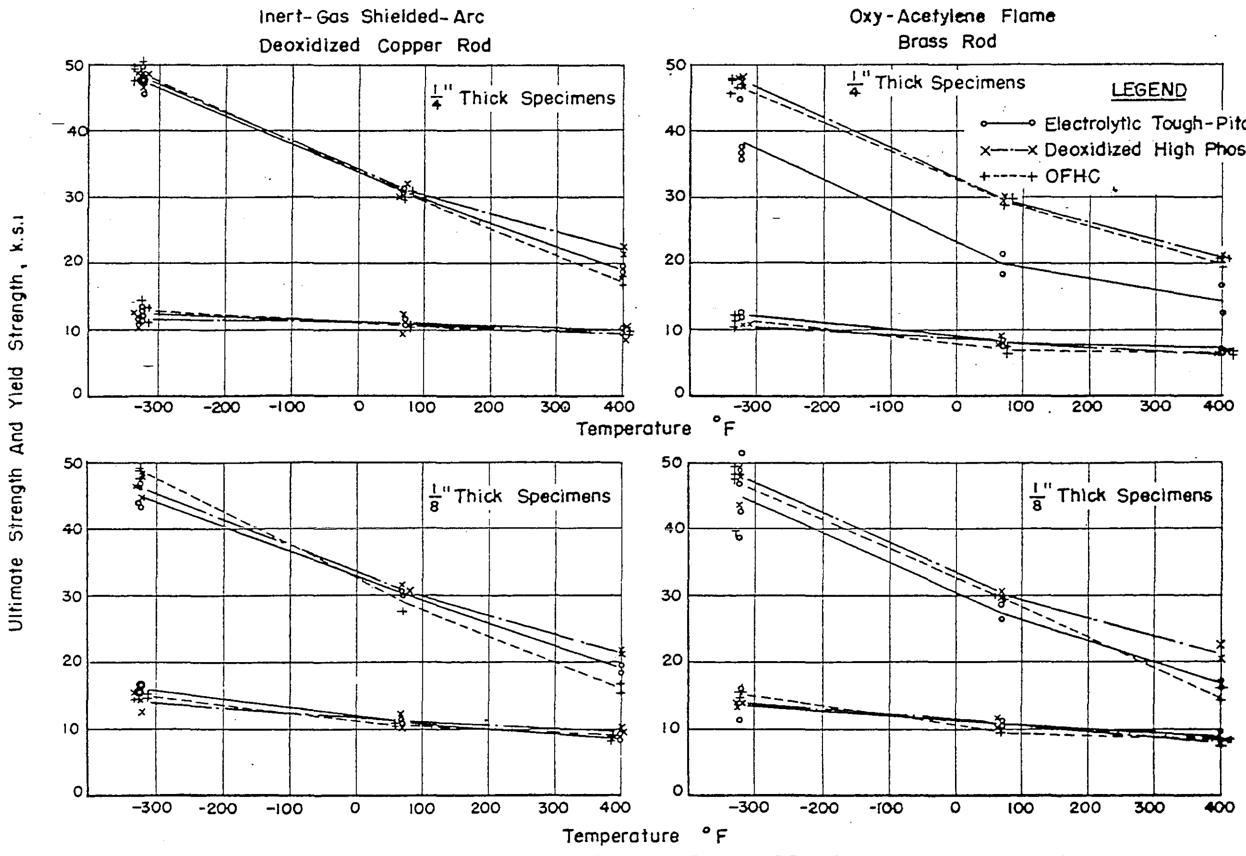

Fig. 3 Variation of ultimate strength and yield strength of welded joints in copper with temperature

these tests was the ultimate strength. It was this property which exhibited the greatest variation with temperature and base material.

For specimens welded by the inert-gas shielded-arc process the ultimate strength decreased, as shown in Fig. 3, from an average value of 48,000 psi. at −321° F. to 31,000 psi. at 70° F., and to 20,000 psi. at 400° F. The type of base metal did not noticeably affect the ultimate strength of the $^1/_4$-in. specimens; most of the strengths fell within a relatively small band. For the $^1/_8$-in. specimens, however, the ultimate strength varied somewhat more at all temperatures. Variations in the location of the fracture along the specimen axis are believed responsible for much of this scattering.

The effect of the testing temperature on the strength of the joint was, in general, the same for the welds prepared by either process. However, the strength of the joints prepared by the oxyacetylene process depended, to a greater extent, upon the type of base metal in the joint. This base metal dependence was demonstrated clearly by the $^1/_4$-in. specimens. In this case the joints of deoxidized and OFHC coppers had ultimate strengths which approached the base metal strengths of 51,000, 31,000 and 22,000 psi. at −321, 70 and 400° F., respectively.[1] However, the joints of tough-pitch copper had ultimate strengths which were between 6000 and 10,000 psi. lower, for each testing temperature, than those of the base metals. The $^1/_8$-in. specimens did not exhibit the same degree of base metal influence, but the tough pitch copper joints tended again to have the lowest strength except at 400° F. where the OFHC copper joints were slightly weaker.

Microhardness Surveys

As a result of the nature of the microhardness test, some scatter exists in the results of these tests because of the effects of variables such as local segregation, grain size and orientation, surface condition, small amounts of plastic flow and residual stresses. The specimen preparation and testing procedure, however, were designed to minimize, as far as possible, the effect of external variables on the test results.

Because of the familiar relationship between hardness and grain size of annealed copper, it was anticipated that the hardness contour would reflect the increase in grain size of the base metal adjacent to the weld with lower hardnesses. Examination of the hardness data (see Figs. 4 and 5), however, failed to reveal any systematic relation between the hardness values and their distance from the site of the weld, in spite of the very pronounced grain coarsening which was evident, in general, in most of the welded joints.

This lack of softening suggests that some work hardening may have offset the expected softening due to grain growth. That the plates have, in fact, suffered some plastic deformation was evident in the distortion and warpage caused by uneven heating during the welding process. The net result of these two opposing effects could be either an increase or a decrease in hardness, and could account for the fact that the tests show considerable variation. In spite of this irregularity, lower values of hardness were noted generally when excessive grain growth occurred in the base metal. This was particularly true in the joints for which an oxyacetylene flame was used to make the weld.

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[1] From "Mechanical Properties of Copper at Various Temperatures" by W. H. Munse and N. A. Weil. Presented at the Fifty-Fourth Annual Meeting of the A.S.T.M., June 1951.

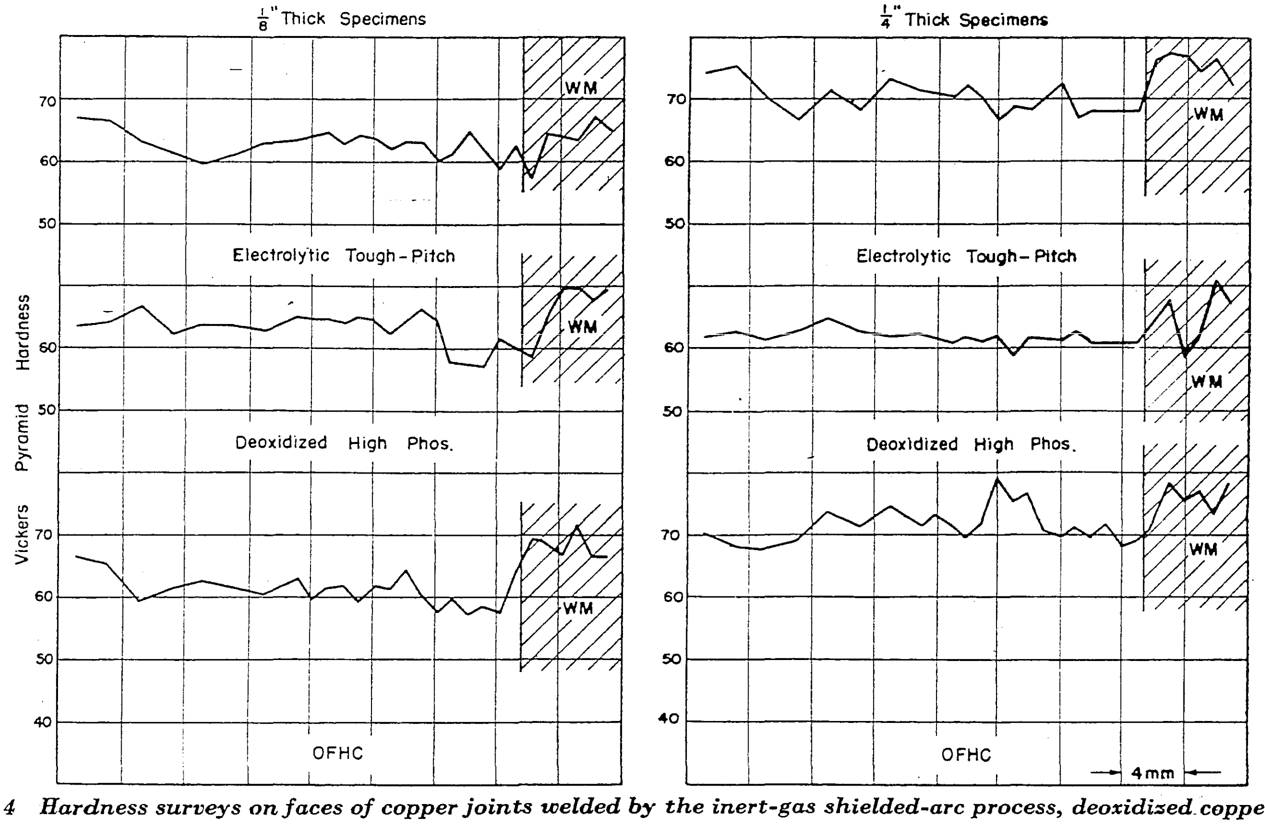


Fig. 4 Hardness surveys on faces of copper joints welded by the inert-gas shielded-arc process, deoxidized copper rod

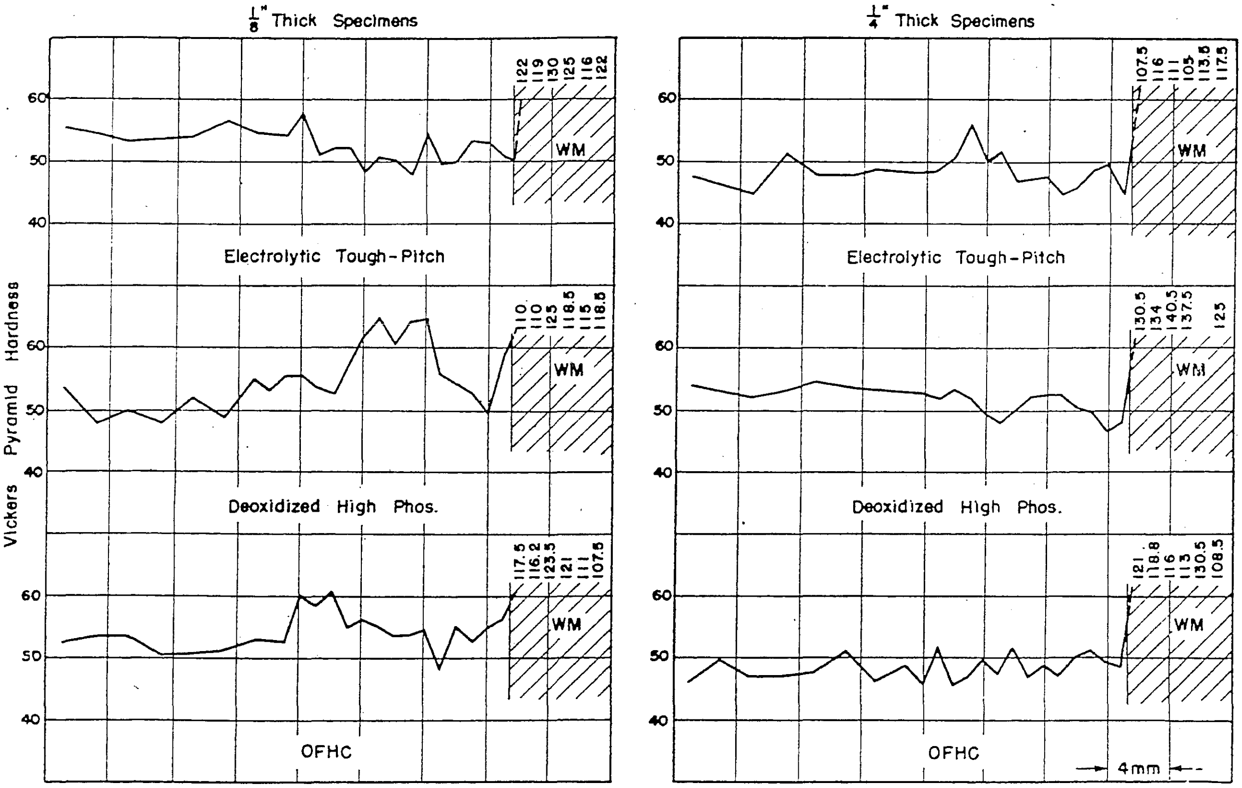


Fig. 5 Hardness surveys on faces of copper joints welded by the oxyacetylene process, brass rod

The hardness values in the weld metal were quite uniform for cast structures, and indicated that the weld deposits were, in most cases, uniform and sound.

Elongation and Reduction of Area

The per cent elongation and per cent reduction of area for the welded joints can well be treated together since they are somewhat interrelated and their magnitudes were noted to have similar patterns. For the welding processes studied these properties were sometimes highly scattered for duplicate specimens. This large scatter was a result, primarily, of the variation in the location of fracture, and consequently the tem-

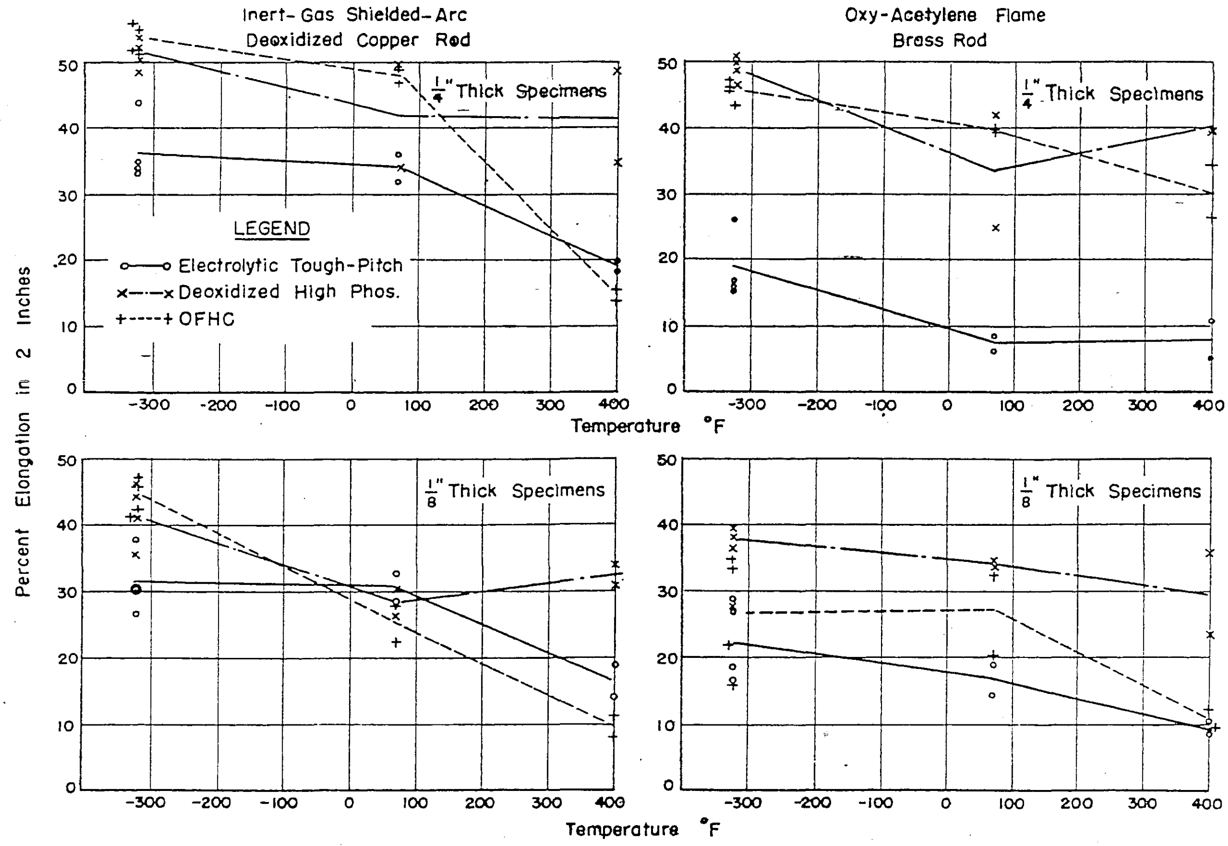


Fig. 6 Variation of per cent elongation in 2 in. of welded joints in copper with temperature

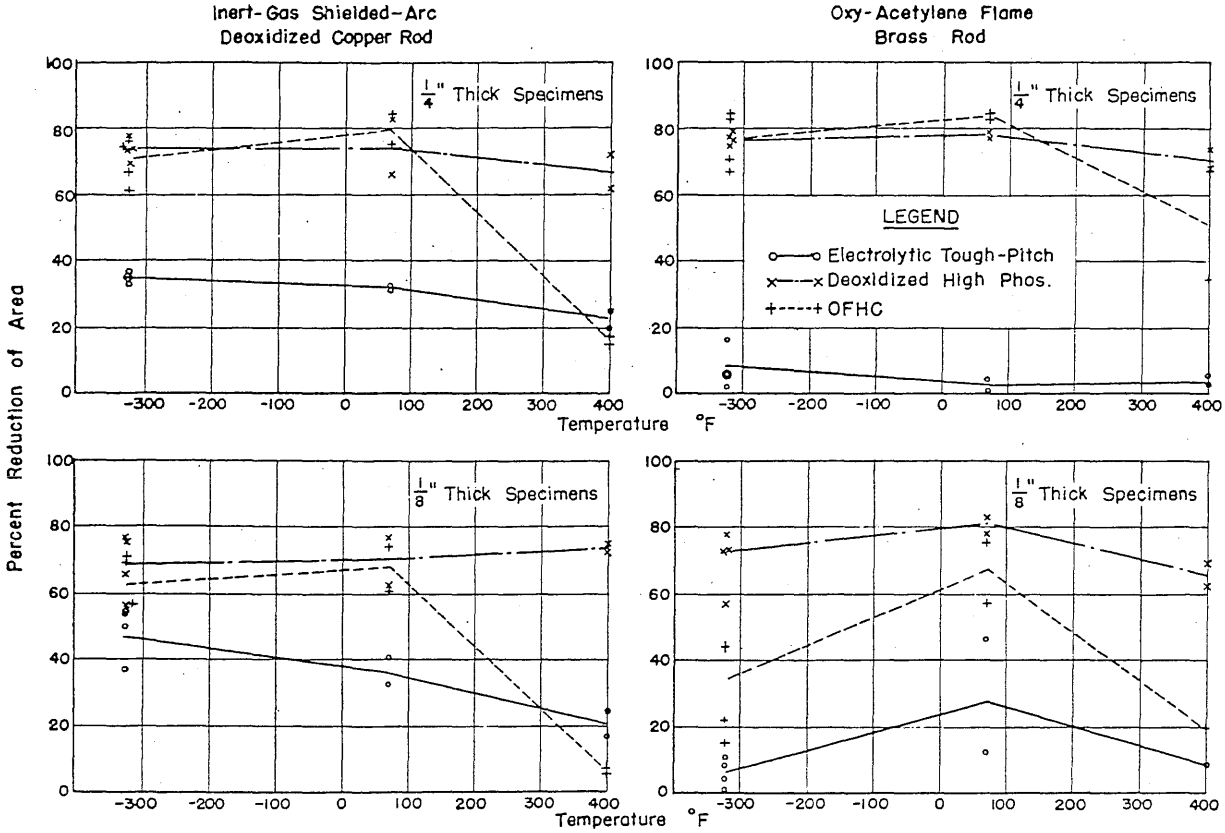


Fig. 7 Variation of per cent reduction of area of welded joints in copper with temperature

perature, base metal and plate thickness influences were difficult to determine.

Because of this significant effect of fracture location, the conclusions which may be drawn from the results shown in Figs. 6 and 7 are limited. Nevertheless some base metal differences are apparent. For both processes the specimens welded from tough-pitch copper generally produced the lowest values of elongation and reduction of area. However, at 400° F. the OFHC copper specimens gave smaller values occasionally.

INTERPRETATION OF TEST RESULTS

It has been pointed out that some of the mechanical properties of the joints tested varied markedly with the location of the fracture relative to the weld site. These fracture locations can generally be predicted from a consideration of the metallurgical structures of the joints. In the series of specimens tested, however, some deviation of the fracture locations, from those indicated by the metallurgical structures, was observed. These deviations are believed to be related to difficulties encountered in attempting to prepare identical test specimens from the original welded plates. These welded plates contained such irregularities as variations in plate alignment, undercutting, and residual thermal stresses which, when relieved by machining, caused warpage and distortion of the specimens. Variations of this nature influence the measured properties of the joints and increase the difficulty of interpreting the data.

To help in the interpretation of the data, arbitrary zones of failure were defined in the specimens, and the locations of the fractures were analyzed in terms of

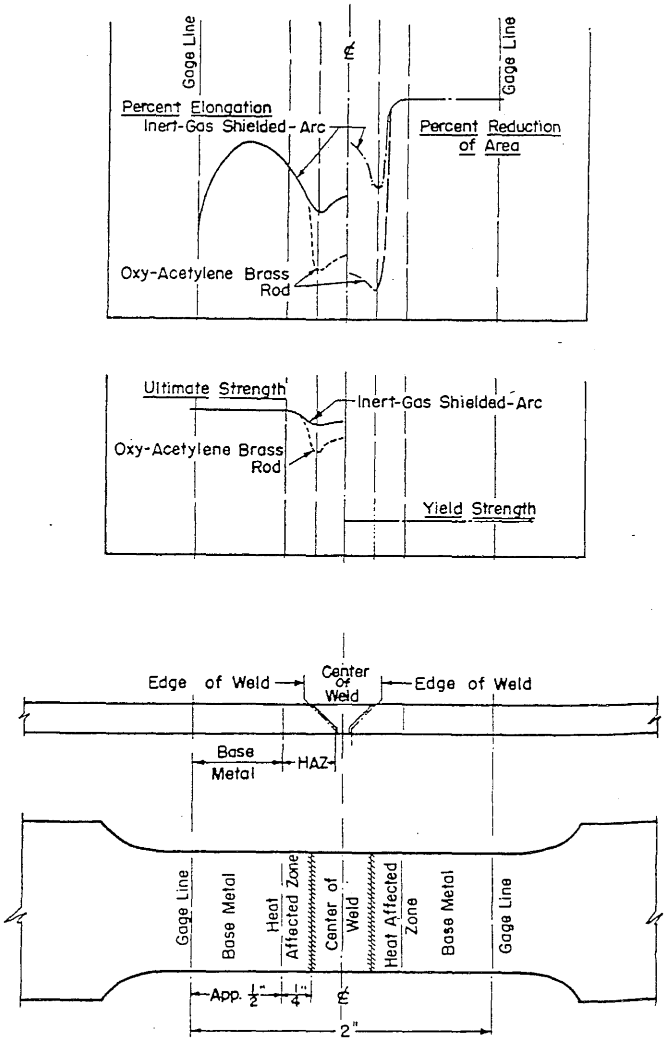
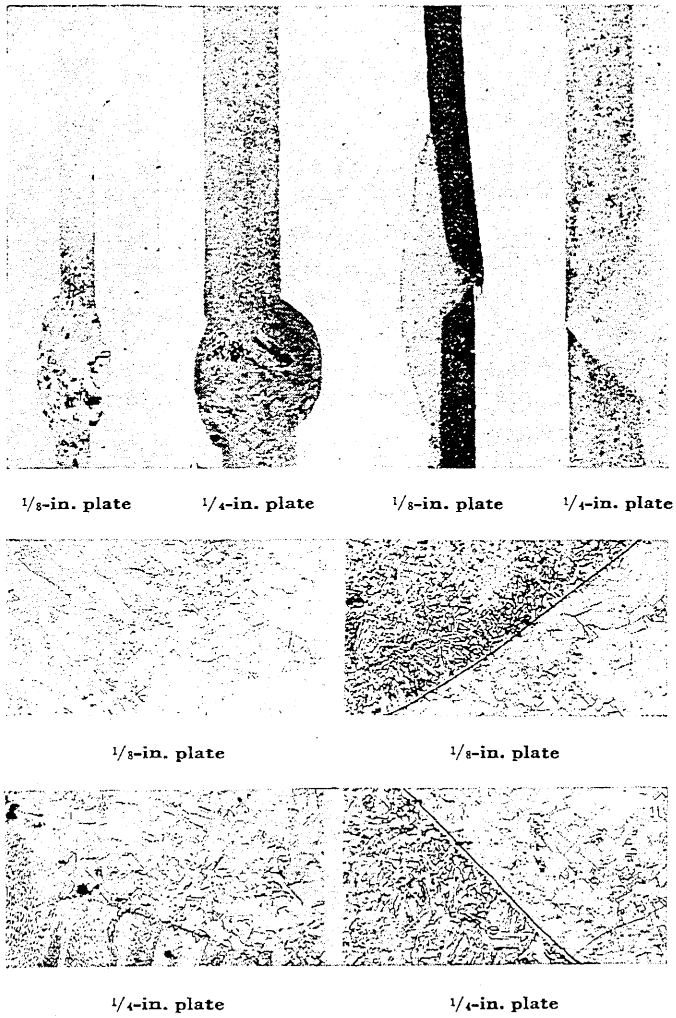


Fig. 8 Fracture locations and approximate variations of the mechanical properties with fracture location

these zones as indicated in Fig. 8. These arbitrary zones may not accurately describe the actual metallurgical structure in all of the joints but were selected to standardize the notation and approximate the structures. The upper part of the same figure shows the approximate mechanical properties for the different fracture locations. These curves were plotted from the values of the mechanical properties determined at −321° F. but are representative also of the variations obtained at the other testing temperatures.

From these data it is evident that the yield strength was not influenced by different fracture locations. This was true also for the ultimate strength and per cent reduction of area when the fractures occurred in the unaffected base metal. The values of the per cent elongation reached a maximum near the center of the base metal zone and decreased as the fracture approached the gage lines. This decrease occurred because, as the fracture approached the gage lines, a greater portion of the elongation took place outside of the 2-in. gage length. In general, however, when fractures occurred in regions removed from the weld, the mechanical properties approached those of the base metal.

For joints welded by the inert-gas shielded-arc process, wherein the deposited metal is similar to the base metal, only a slight variation in ultimate strength occurred if the fracture was in the weld metal rather than in the base metal. However, a fracture in the deposited metal caused a decided decrease in the values of elongation and reduction of area. This influence of the weld metal was even more noticeable when brass was used for the filler metal.


1/8-in. plate 1/4-in. plate 1/8-in. plate 1/4-in. plate

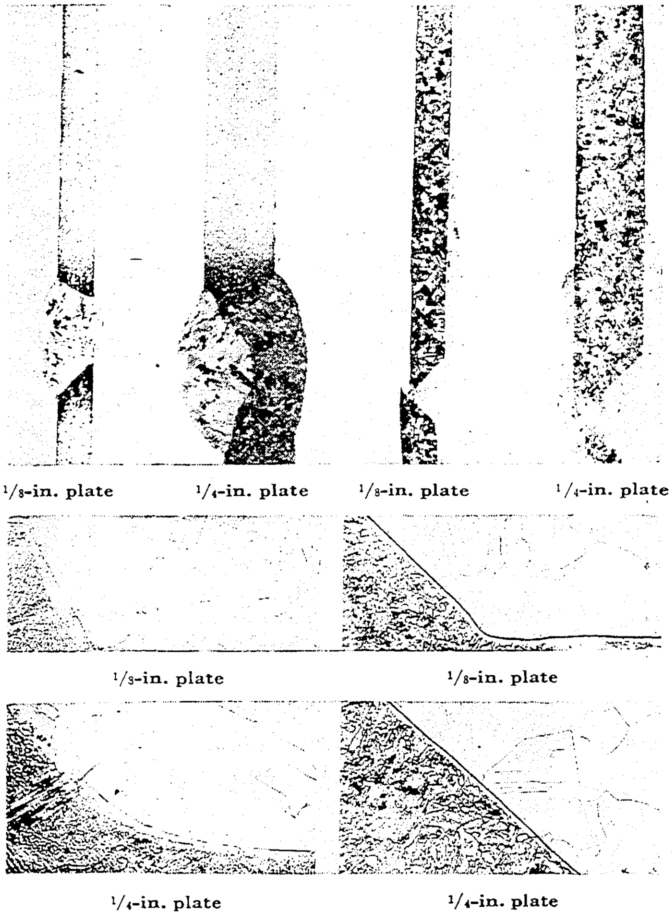
1/8-in. plate 1/8-in. plate

1/4-in. plate 1/4-in. plate

(a) Inert-gas shielded-arc, deoxidized copper rod (b) Oxyacetylene flame, brass rod

Fig. 9 Welded joint structures in tough-pitch copper. Macrostructures 1 1/2 ×. Microstructures 25 ×

Typical macrographs and micrographs of the joints in the tough-pitch, deoxidized high-phosphorus, and OFHC coppers are given in Figs. 9, 10 and 11, respectively. By a careful consideration of the metallurgical structures produced by the two welding processes, the joints having the best mechanical properties could usually be selected. Among the several factors which are inherent to the structures of welded copper joints and which affect their quality are the formation of oxides, grain growth in the base metal, porosity in the weld metal, and poor penetration and flow of the filler metal resulting from rapid heat conduction away from the joint during welding. The formation of copper oxide during welding, or the redistribution of copper oxide already present when tough-pitch copper is the base metal, has a pronounced effect on the quality of welds produced if the oxide is located in continuous masses. However, small amounts of copper oxide, when distributed uniformly throughout the structure, have little effect on the properties of a joint.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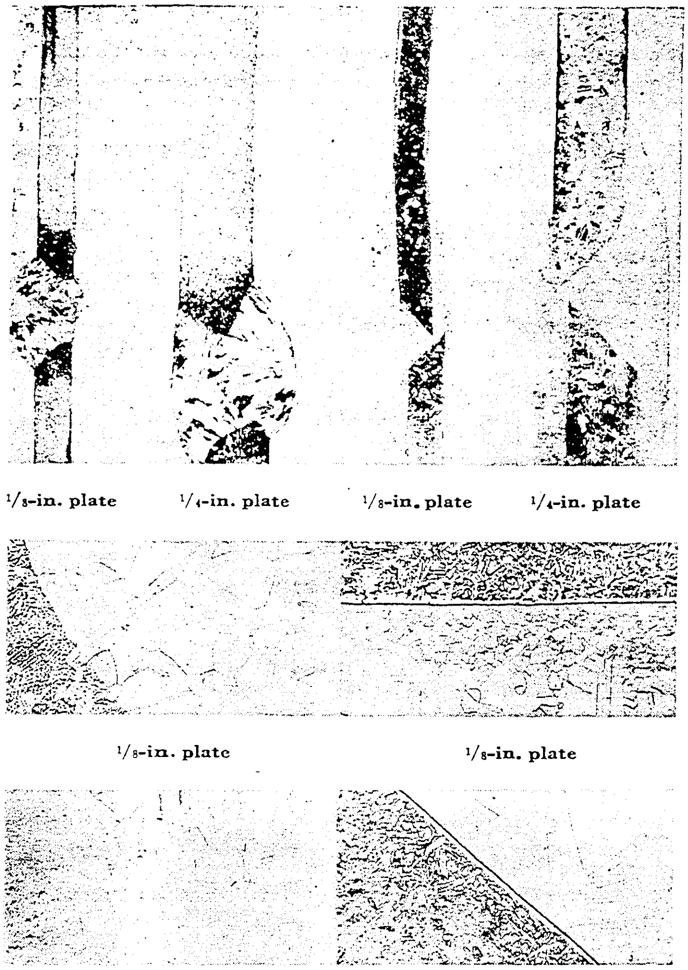
1/8-in. plate 1/8-in. plate

1/4-in. plate 1/4-in. plate

(a) Inert-gas shielded-arc deoxidized copper rod (b) Oxyacetylene flame, brass rod

Fig. 10 Welded joint structures on deoxidized copper. Macrostructures 1 1/2 ×. Microstructures 25 ×


$^1/_8$-in. plate $^1/_4$-in. plate $^1/_8$-in. plate $^1/_4$-in. plate

$^1/_8$-in. plate $^1/_8$-in. plate

$^1/_4$-in. plate $^1/_4$-in. plate

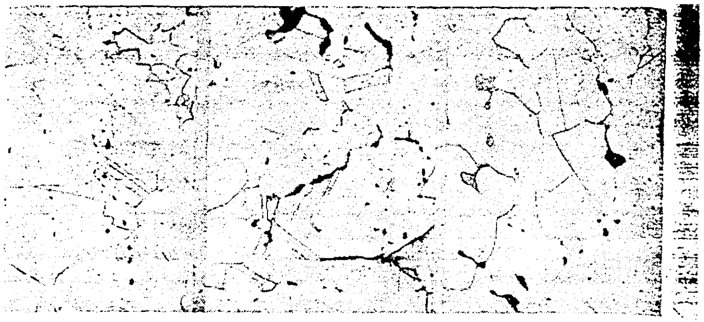
(*a*) Inert-gas shielded-arc, deoxidized copper rod (*b*) Oxyacetylene flame, brass rod

Fig. 11 Welded joint structures in OFHC copper. Macrostructures $1^1/_2$ ×. Microstructures 25 ×

The oxidizing flame of the oxyacetylene torch is, of course, an excellent source of oxygen for absorption by the base metal. Oxides can be formed also through contact of the atmosphere with a highly heated copper. However, careful welding with the inert-gas shielded-arc process can prevent the oxygen and moisture of the atmosphere from coming into contact with the metal, and thereby produce a weld free of oxides.

When welds are made in tough-pitch copper, the oxides already present in the base metal are redistributed from a relatively harmless random occurrence to a semi-continuous network at the grain boundaries, which is deleterious to the mechanical properties of the joint. Copper oxide, being slightly soluble at high temperatures, goes into solution during heating, and upon subsequent cooling, precipitates in the grain boundaries. The appearance of this type of precipitation is shown in Fig. 12 (*a*). In Fig. 12 (*b*), the oxides outline a dendritic, or cast structure, and show fusion and oxygenation of the base metal resulting from the welding process.

In addition to the detrimental effect of the precipitation of oxides in the grain boundaries, copper oxide can also be responsible for another serious condition known as "gassing." If oxide-bearing copper is introduced to a reducing gas, namely hydrogen, at moderate temperatures, the oxide will be reduced to form copper and water vapor. This vapor is insoluble and creates an extremely high internal stress which can lead to premature failure under load, or actually disrupt intergranular cohesion. Evidence of such an occurrence is noted in the $^1/_8$-in. plate shown in Fig. 12 (*a*).


$^1/_4$-in. plate $^1/_8$-in. plate

(*a*) Copper oxide precipitation in boundaries showing disruption of grain boundary continuity, oxyacetylene process. 150 ×

(*b*) Fusion of $^1/_8$-in. plate with Cu-Cu_2O eutectic in boundaries shielded-arc process. 150 ×

Fig. 12 Welds in tough-pitch copper

Welding tough-pitch copper with an oxyacetylene flame, because of the slower rates of heating and cooling, allows more time for solution and reprecipitation of copper oxide. As a consequence of the presence of this copper oxide it was observed that the joints in tough-pitch copper had a much lower ductility than did the joints in which the oxygen had been excluded. Failures in these joints occurred in the base metal at the edge of the weld where the precipitation took place.

More extensive copper oxide precipitation was noted in the $^1/_8$-in. plates than in the $^1/_4$-in. plates of tough-pitch copper and, as a result, a greater reduction in the ultimate strength was observed in the joints of the thinner material. Because of the lower thermal capacity of the $^1/_8$-in. plates, slower heat dissipation occurred through the plate, and this permitted more migration of the copper oxide to the grain boundaries. This thermal effect resulted also in a greater degree of grain coarsening of the base metal in the $^1/_8$-in. plates.

A low ductility was obtained also for joints in the $^1/_8$-in. OFHC copper welded by the oxyacetylene process. The explanation for this lies in the presence of an oxide grain boundary precipitate as shown in Fig. 13 (*a*). The same welding procedure but on the $^1/_4$-in. plate (Fig. 13 (*b*)), showed only slight traces of oxide precipitation. This difference may be ascribed partly to the operator's technique and partly to the

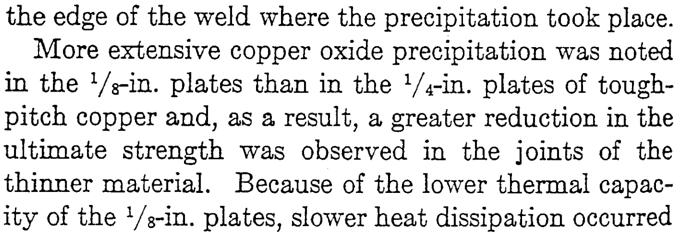

(*a*) $^1/_8$-in. plate (*b*) $^1/_4$-in. plate

Fig. 13 Oxides in OFHC copper welded by the oxyacetylene process. 150 ×

difference in thermal capacity of the plates. Welding OFHC copper entails the risk of introducing oxygen and the formation of copper oxide, while welds in deoxidized copper by the oxyacetylene process can be made relatively free of copper oxide.

The temperatures of the base metal during welding are sufficiently high to cause grain growth and thereby a lowering of the mechanical properties, particularly the ductility. In tough-pitch copper grain growth is not a serious problem because of the presence of copper oxide particles which act as barriers to grain boundary migration. Similarly, in OFHC copper welded by the oxyacetylene process, grain growth is restricted in areas of the base metal which have absorbed oxygen during welding. This is demonstrated in Fig. 11, where regions adjacent to the weld have absorbed oxygen and no coarsening has occurred. Beyond the region of oxygen penetration, however, unrestricted grain growth has taken place. In the deoxidized copper the presence of phosphorus gives this material somewhat lower coarsening characteristics.

The oxyacetylene flame is a less intense source of heat than the arc but requires that the metal be at high temperatures for a longer period of time with a consequent greater coarsening. Failures in this weaker coarsened zone predominated in the joints made under conditions favorable for grain growth.

The joints in OFHC copper which were tested at 400° F. showed a large drop in ductility as compared to the values for this material when tested at lower temperatures. However, a similar drop in ductility was not found when the other base metals were tested at this temperature. Therefore, a metallographic examination was made of the OFHC joints after they had been tested at 400° F. The fractures were found to be intercrystalline and occurred in the base metal at a distance of about one grain diameter from the weld metal. A typical section of one of the joints examined is shown in Fig. 14 (*a*). The base metal on the side of the weld which had not failed showed the presence of numerous grain boundary cracks penetrating from the edge of the plate and the presence of some grain boundary precipitation (Fig. 14 (*b*)).

This embrittlement was probably the result of copper oxide precipitation in the grain boundaries. Although no oxides were observed in the metallurgical specimen from the as-welded plate, it is very possible that the region from which the test specimens were taken had absorbed some oxygen during welding. The possibility of oxygen absorption during testing is questionable and although the literature reports some oxidation of copper in air at 400° F. the embrittling effect is uncertain. The immunity of the deoxidized copper to loss of ductility can be explained by the action of the excess deoxidizer in preventing the formation of copper oxide. The tough-pitch copper, with oxide initially present, was already in a state of low ductility and any such additional loss was not evident.


(*a*) Edge of specimen showing fracture in base metal

(*b*) Edge of specimen showing incipient cracks and precipitate in base metal

Fig. 14 Fracture of joint in 1/4 in. OFHC copper tested at 400° F., shielded-arc process. 100 ×

The macroscopic examination of the welds made with a brass filler rod revealed relatively shallow penetrations. Because of the lower melting point of brass, it is possible to fill the weld site without attaining a high enough temperature for a great deal of fusion and penetration of the base metal. However, the examination of these joints at high magnification indicated that adequate continuity had been established across the interface.

When all of the specimens prepared by each welding process were grouped according to their fracture location, the variations in elongation and reduction of area resulting from a change in base metal and plate thickness largely disappeared, and the influence of temperature on these properties became apparent. Thus, it was found that the per cent elongation increased slightly with a decrease in temperature and the per cent reduction of area was not influenced in a consistent manner by a change in the testing temperature.

SUMMARY AND CONCLUSIONS

The results of the tests on welded joints fabricated by the inert-gas shielded-arc and the oxyacetylene processes, as reported herein, may be summarized as follows.

An increase in the testing temperature from 70 to 400° F. decreased the ultimate strength of the joints by about 32%, whereas a decrease in the testing temperature from 70 to −321° F. increased the ultimate strength approximately 60%. Except for a few joints welded in tough-pitch copper by the oxyacetylene process, all the ultimate strengths obtained in tests at room temperature were between 28,000 and 31,000 psi.

The elongation and reduction of area, measures of ductility, were only slightly affected by the 720° change in the testing temperature, with the exception of OFHC copper. In this case oxides, either introduced during welding or absorbed during testing, are believed to be responsible for the lower ductility.

The location of the fracture along the specimen axis and its effect upon the properties, regardless of the testing temperature, makes the analysis of this series of tests difficult.

The conclusions that can be drawn regarding base metal effects are relatively clear. The mechanical properties of the welded joints in the deoxidized copper plates approached the properties of the base metal. For the joints in tough-pitch copper, the fracture generally occurred in regions of oxide precipitation at the weld edge, particularly when the oxyacetylene welding process was used, thereby causing the mechanical properties to be low and somewhat scattered. The joints prepared by OFHC copper exhibited a great deal of scatter in properties, due primarily to the changes in fracture location.

With the welding procedures reported in this study, very sound weld metal deposits were obtained. Both the macrostructures and radiographs of the welded joints indicated very little porosity. The structures of the joints showed excellent continuity at the weld metal-base metal interface, and excellent flow and penetration characteristics. Any failures occurring at the junction were due to the presence of copper oxide, and not to a lack of bonding between the base metal and weld deposit.

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