Properties of Weld Metal in a Lead-Calcium Alloy

Gas tungsten-arc welding with alternating current is proved capable of joining a lead-calcium alloy without loss of base metal properties

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ABSTRACT. An investigation was made to determine (1) the welding parameters necessary to produce a metallurgically sound weld having a chemistry similar to the nominal 99.92% Pb-0.06% Ca base metal and (2) to determine the effect of heat treatment on metallurgical and mechanical properties of the weld metal and heat-affected zone.

The gas tungsten-arc alternating current welding process was determined to be capable of welding the lead-calcium alloy without producing calcium losses in the weld metal. The process permitted the addition of filler metal, promoted complete fusion, and resulted in a smooth weld bead. Welding parameters were developed for single-pass welds in ¼ in. thick material.

Mechanical properties, including hardness and tensile strength, were first characterized on base metal solution heat treated and room temperature aged, and solution heat treated and aged at 100 C. Weld metal was determined to respond in a manner similar to base metal when similarly heat treated and aged. Weld metal in the as-welded and room temperature aged condition was also found to exhibit properties similar to the base metal and to weld metal which had been solution heat treated and room temperature aged. Mechanical property degradation did not occur in the weld metal or heat-affected zone as a result of thermal excursions during welding. Therefore, a solution heat treatment is not required after welding to achieve maximum and identical mechanical properties in all weld zones.

Introduction

Lead is one of the oldest metals known to man. This metal probably has more varied fields of application than any other. Some outstanding characteristics of lead include heavy weight, high density, softness, malleability, flexibility, low melting point, low strength, high resistance to corrosion under a wide variety of conditions, and the ability to shield nuclear radiation. The disadvantages of using pure lead in some engineering applications include low fatigue resistance, extreme softness, low tensile strengths, and inability to have its mechanical properties enhanced by heat treatment.

Alloying is the only effective means available to enhance the properties of lead. A desirable solution to the problem, then, is to develop an alloy that is (1) rich in lead for nuclear properties, (2) corrosion resistant, and (3) capable of having its mechanical properties enhanced by heat treatment.

A number of binary and ternary systems have been investigated. Generally, the lead-calcium alloys have exhibited the best combination of fatigue resistance, tensile strength, and hardness without degradation of corrosion resistance and nuclear properties (Refs. 1-4). A lead-calcium phase diagram including the range of interests is shown in Fig. 1. Because of the enhanced combinations of mechanical properties of the lead-calcium alloys it is of special interest for use as cable sheathing, battery plates, and nuclear radiation shielding.

A method for welding lead-calcium alloys which maintains superior mechanical properties in the weld metal has not been developed (Refs. 4, 6-9). Therefore, when machined parts are required, the part must be machined from special castings. Molds for such castings can become very expensive when large or complex shaped parts are required. Also, long machining times are required because of excessive stock required for castings. It is, therefore, economically desirable to produce welded assemblies.

This paper describes a study (Ref. 10) that was made (1) to determine the parameters necessary to produce metallurgically sound weld with chemistry similar to the lead-0.06 wt % calcium base metal and (2) to determine the effect of heat treatment on metallurgical and mechanical properties of the weld metal and heat-affected zone in the lead 0.06 wt % calcium alloy.

Experimental Procedure

Material Preparation

The material used in this investigation was prepared from a premium grade of corroding lead. The calcium was added as a 1 wt % calcium master alloy. The gross chemical and impurity analysis of the alloy used is reported in Table 1.

Table 1 — Gross Chemical and Impurity Analysis of the Nominal Lead-0.06 Weight Percent Calcium Used in this Investigation (a)

Lead	99.92 %
Calcium	0.059%
Aluminum	15
Antimony	<6
Arsenic	<20
Bismuth	5
Cadmium	< 6
Chromium	< 1
Copper	< 1
Iron	< 1
Lithium	< 1
Magnesium	10
Manganese	< 1
Nickel	< 4
Phosphorus	< 100
Silver	2
Sodium	< 20
Tin	1

(a) All values in ppm, except where noted.

After the ingot was removed from the mold, it was cold rolled to ¼-inch thick plate. The plate was cut into samples 8 by 2 by ¼ in. thick. No effort was made to preserve the identity of the individual samples until after welding. This permitted samples to be selected for welding on a purely random basis with respect to any composition variation that might be present in the plate.

Strips ¼ in. square were sheared from the base metal and swaged to 0.100 in. diam for filler metal. Heat treatments were not used between swaging operations. Just prior to

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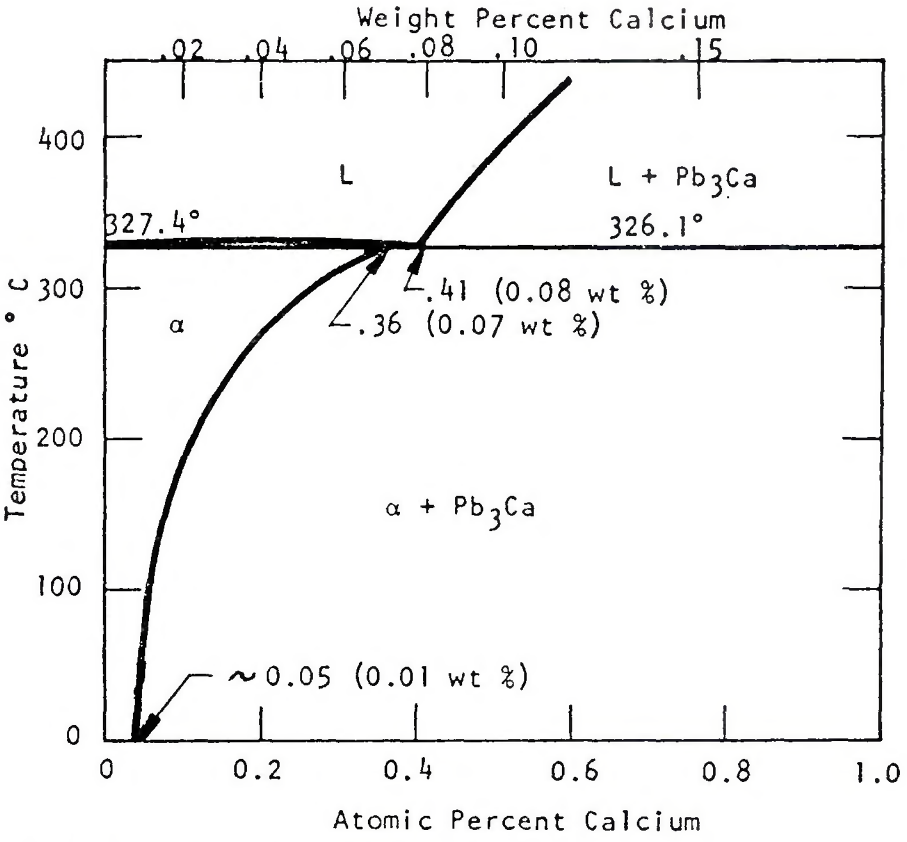

Fig. 1 — Lead-calcium binary phase diagram

Table 2 — Parameters Used to Weld Lead-Calcium Plate

Process	Gas tungsten-arc
Current (mode)	Alternating current
Current (amperes)	270
Travel speed (ipm)	6.6
Type of arc starting device	High frequency
Shielding gas	Argon
Flow rate (cfh)	20
Pre-flow time (seconds)	5
Electrode holder	500 A, water cooled
Electrode type	2% Thoriated Tungsten
Electrode diameter	⅛ inch
Arc voltage (volts)	8
Wire feed rate (ipm)	56
Work Slope (in./in.)	+0.02

welding, the filler metal was chemically cleaned in a 50 vol. % nitric acid-water solution and then swaged to 0.094 in. diam.

Welding Procedure

A welding procedure was developed for welding ¼ in. thick plate using the gas tungsten-arc welding process with filler metal addition. The welding procedure was developed using a single Vee-groove weld in a butt joint having a 60 deg included angle, zero width root face and no root opening. Immediately before welding, the plates were mechanically cleaned by scraping the surface to be welded.

The welding parameters for a single pass weld, shown in Table 2, were developed using a 600 A, single phase, ac/dc welding power supply. A voltage control head was used to maintain a constant arc voltage. Filler metal was automatically fed into the arc at a constant feed rate with a wire feeder. A welding manipulator was used to move the welding torch at a constant travel speed.

Chemical Analysis

Calcium analysis of the lead-calcium alloy was obtained by the atomic absorption method. Base metal and weld metal sampling was accomplished by drilling, using a ½ in. drill and collecting the chips. The filler metal sampling was accomplished by cutting sections from the beginning and end of each length of filler metal. The accuracy of determinations for calcium at 95 % confidence limits was reported to be ±0.004 wt %.

Heat Treatment and Aging

The specimens used in this study were heat treated in a box-type resistance heated furnace. Specimens used to obtain hardness data were heat treated and aged under the following schedules:

1. Solution heat treated at 300 C for 1 to 24 hr, water quenched and room temperature aged for up to two weeks
2. Solution heat treated at 300 C for two hr, water quenched and aged at 100 C for up to 96 hr followed by a two-week room temperature age
3. As-deposited weld metal room-temperature aged for up to two weeks

Specimens used for tensile strength evaluation were heat treated and aged under the following schedules:

1. Solution heat treated for two hr at 300 C, water quenched and room temperature aged for up to two weeks
2. Solution heat treated for two hr at 300 C, water quenched and aged at 100 C for up to 48 hr.
3. As-deposited weld metal room-temperature aged for two weeks

Hardness and Tensile Strength Measurements

Macrohardness numbers used in this work were obtained using a Rockwell hardness tester with a ½ in. diam steel ball for a penetrator and a 60 kg load applied for 45 sec. The depth of penetration as indicated by the Rockwell dial was used as a measure of the impression diameter and converted to a Brinell hardness (HB) number.

Microhardness values were determined on several solution heat treated and aged samples and samples in the as-welded condition. Diamond pyramid hardness values were obtained using a 100 g load on a Tukon microhardness tester. Readings were taken by traversing from the base metal to the weld metal on a specimen section transverse to the weld.

Tensile strength values were obtained using a strain rate of 0.25 in./in./min. Flat tensile specimens were used with a ¼ in. square cross section. Elongation was determined over a 1 in. gage length. Longitudinal weld metal specimens contained all weld metal while transverse weld specimens contained weld metal, heat-affected zone and base metal.

Metallography

Longitudinal and transverse cross sections of welded specimens were examined metallographically. The

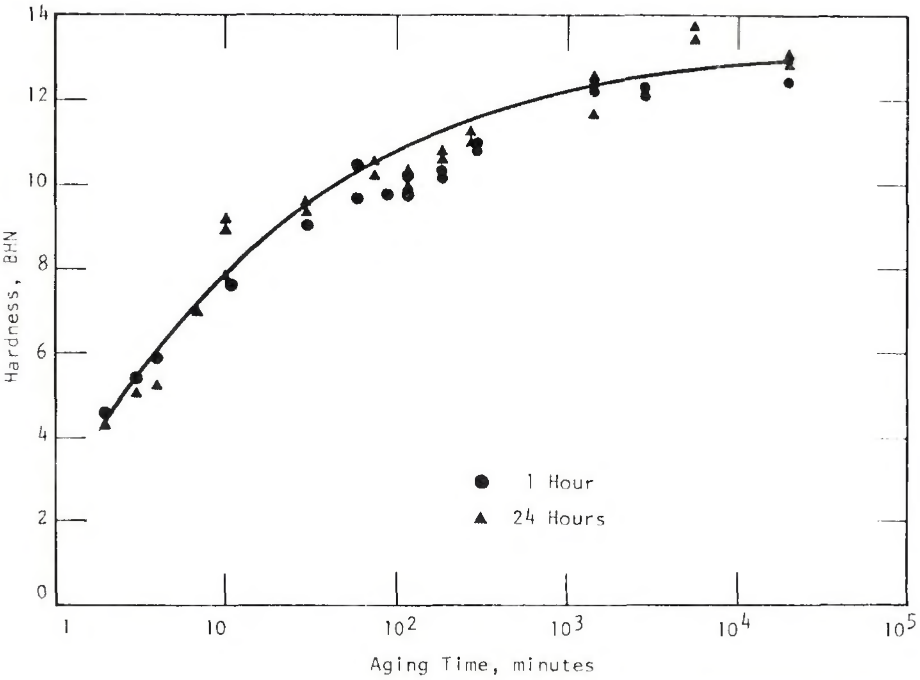

Fig. 2 — Hardness versus aging time for base metal sample solution heat treated at 300 C for different times, water quenched, and room temperature aged

specimens were mounted in epoxy, ground through 600 grit silicon carbide paper impregnated with paraffin and kerosene as a lubricant. Polishing and etching was accomplished by using a solution containing 60 vol. % acetic acid, 20 vol. % hydrogen peroxide and 20 vol. % ethyl alcohol. A swab etch method was used. Etching times of approximately 10 sec were required.

Safety

A ventilation system was required during welding to remove the lead vapors formed during welding. A 6 in. diam exhaust vent with an air flow velocity of 4000 fpm was positioned 16 in. from the arc. The air flow velocity at the arc was approximately 40 fpm. Also, during welding, a respirator was worn by the welder to prevent accidental inhalation of lead vapors. After welding of each sample, the fixture and sample were wire brushed near the exhaust vent to prevent the deposited lead vapors from becoming airborne during handling. Care was taken by the welder to wash prior to eating or drinking after handling samples covered with lead vapors.

Results and Discussion

Welding the Lead-Calcium Alloy

A number of welding processes including oxyacetylene, gas tungsten-arc, electron beam and plasma arc were evaluated to determine if these processes could produce a weld in the lead-calcium alloy without significant calcium losses. Further evaluations were carried out to insure that a weld with no objectionable defects and adequate mechanical properties could also be obtained with these candidate processes.

The oxyacetylene gas welding process was evaluated utilizing an oxidizing, carburizing and neutral flame. With each of the three flames used, a thick oxide layer quickly formed on the surface of the molten weld metal. This oxide prevented fusion by inhibiting the melting and mixing of the material from both sides of the joint. For this reason the further evaluation of the oxyacetylene welding process was discontinued.

The plasma-arc welding process was evaluated and during welding an oxide film, similar to that which formed during oxyacetylene welding, also occurred. The same lack of fusion resulted from this oxide. The oxide film which formed during plasma welding did not appear to be as thick as that produced by gas welding but still effectively inhibited proper fusion. Likewise, this process was eliminated from further evaluation.

The electron beam welding process, even though it did not cause oxidation of the alloy, was not evaluated for welding because of the difficulty of adding filler metal in the closed chamber. A welding process which permits filler metal additions is highly desirable in most applications. Thus, the electron beam process was eliminated from any further consideration.

The final welding process evaluated was gas tungsten-arc welding. Direct current reverse polarity, direct current straight polarity and alternating current were used in the evaluation.

Direct current straight polarity permitted a thin oxide layer to form which inhibited proper fusion. The oxide layer formed was very similar to the oxide layer formed with the plasma-arc process. Direct current reverse polarity caused the arc to be very erratic and unstable. The weld metal, however, was free of oxide films during welding and adequate fusion resulted. The erratic arc produced a weld with a rough uneven surface. Welding with an alternating current caused the thin oxide layer to break up which permitted fusion and resulted in a smooth weld bead. Thus, the gas tungsten-arc alternating current process appeared to be adequately suited to welding the lead-calcium alloys.

In order to simplify the metallurgical analysis of the weld metal and heat-affected zone a single pass weld was deemed desirable. Welding parameter studies showed that single pass welds could be made in ¼ in. thick plate. Therefore, the remaining metallurgical and mechanical studies were carried out using ¼ in. thick plate with a single pass weld sequence.

Chemical analysis of the filler metal and base metal plates used for each weld were performed. The resulting fusion zone on each of the assemblies was also analyzed. The calcium content in the base metal, all of which came from a single heat, ranged between 0.042 and 0.077 wt % with an average of 0.058 wt %. The filler metal, which was from the same heat as the base metal, ranged in calcium content from 0.046 to 0.066 wt % with an average of 0.055 wt %. The weld metal calcium content ranged between 0.046 and 0.075 wt % with an average of 0.059 wt %. All of these average values are in a range which can be considered to fall within the limits of experimental error. Thus, these data indicate that the lead-calcium alloy can be welded without calcium losses.

Mechanical Properties

The initial phase of the mechanical property evaluation was the characterization of the properties of the base metal attainable by heat treatment. The properties used for primary evaluation were hardness and tensile strength. Base metal characterization served as a bench mark for comparison and evaluation of the heat-affected zone and weld fusion

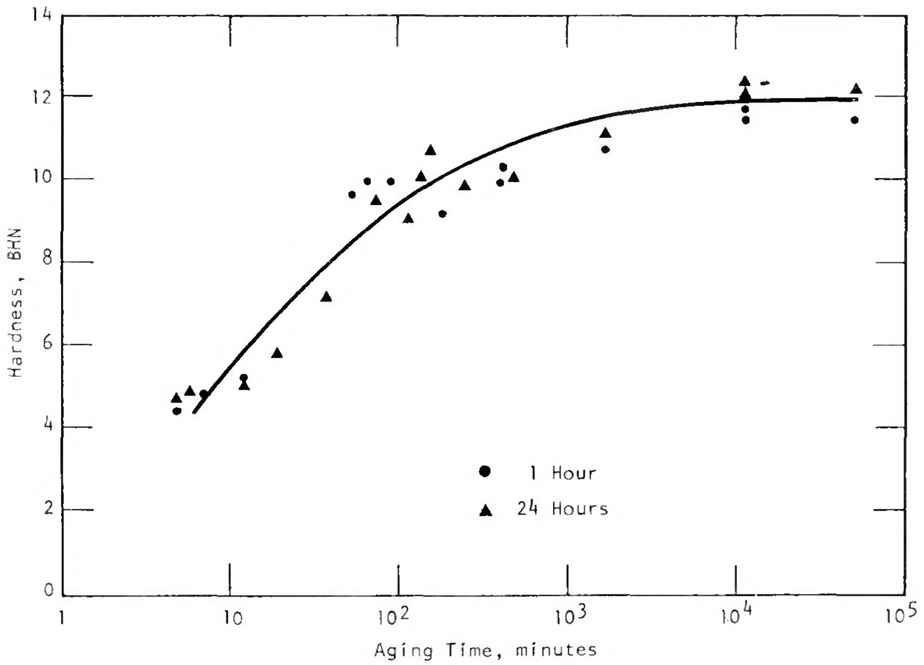

Fig. 3 — Hardness versus aging time for weld samples solution heat treated at 300 C for different times, water quenched, and room temperature aged

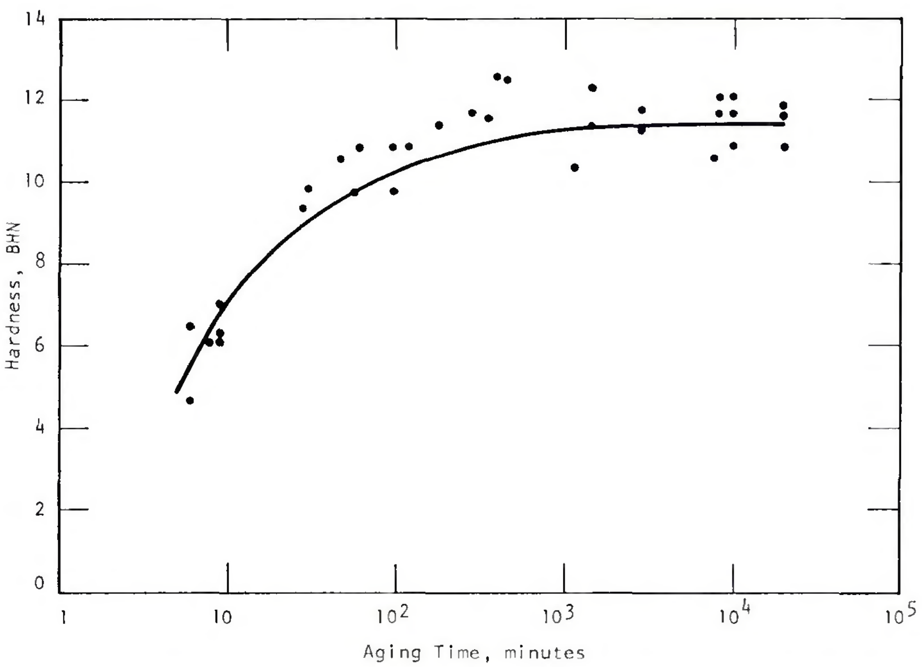

Fig. 4 — Hardness versus aging time for weld metal in the as-welded, and room temperature aged condition

zone properties.

Hardness. In order to determine the minimum time to achieve essentially complete solid solubility of calcium in lead, base metal samples in the completely overaged condition were used. The hardness was checked on all of the samples after overaging and averaged 6.9 BHN with a range of 6.0 to 7.4 BHN. These data compare with the hardness of cast and cold rolled base metal which averaged 6.4 HB with a range of 5.1 to 6.4 HB. No increase in hardness of the overaged samples was noted over a period of several months.

The overaged samples were heated to 300 C for periods of 1 to 24 hr followed by a water quench and room temperature age. The hardness was measured immediately after the water quench and then monitored at various time intervals to determine if the samples had responded to precipitation hardening. A similar response to precipitation hardening would indicate that the samples had achieved a similar solid solubility level of calcium in lead during the solution treatment.

A plot of the data obtained for 1 hr and 24 hr solution times is shown in Fig. 2. The data for time intervals between these limits are not shown since they were virtually identical to the 1 and 24 hr data. These data indicate that solution heat treatment times of 1 and 24 hr will produce identical hardness after aging at room temperature. These data also indicate that the hardness can be increased approximately two fold over the completely overaged material from 6.9 HB to 12.5 HB after a room temperature age of one week and three fold over the solution heat treated and as-quenched hardness from 4.5 HB to 12.5 HB.

Based on these data and the fact that 1 hr at the solution heat treatment temperature may be a minimum time, a solution heat treatment time of 2 hr was chosen for all further base metal samples.

In order to determine the effect of elevated temperature aging, additional overaged base metal samples were solution heat treated at 300 C for 2 hr, water quenched and immediately aged at 100 C in boiling water. Aging times of 15 min, 1, 12, 24, 48, and 96 hr were used. Hardness data was obtained on each sample immediately following the time interval at the 100 C aging temperature. Following the elevated temperature age, the samples were allowed to remain at room temperature and hardness data was obtained at various time intervals for a two week period. The hardness did not change during the room temperature age following completion of the elevated temperature age for any of the samples.

These data indicated that an aging time of 24 hr is adequate for an elevated temperature age which is a much shorter time than the one week required for the room temperature age. A maximum hardness of 13.0 HB achieved for the 100 C age compares favorably with the 12.5 HB achieved with the room temperature age. Overaging did not appear to occur at 100 C with aging times up to 96 hr.

In order to determine if weld metal would respond to solution heat treatment in a manner similar to the base metal, weld metal samples were solution heat treated, water quenched, and room temperature aged in a manner similar to the base metal samples. A plot of the hardness versus aging time is presented in Fig. 3.

The weld metal was found to respond to solution heat treatment in much the same manner as the base metal and the hardness reached at similar aging times is essentially identical to that achieved in the base metal.

To determine if weld metal would respond in a manner similar to the base metal during an elevated temperature age, additional weld metal samples were solution heat treated and aged in a manner similar to the base metal samples. As with the base metal, the hardness did not change during the room temperature age following completion of the elevated temperature age. An aging time of 24 hr, the same as for the base metal, was required to achieve a maximum hardness of 12.0 HB. Again, the weld metal specimens had hardness values slightly lower than the base metal by approximately 1 HB.

To determine if weld metal, allowed to room temperature age after welding, would respond in a manner similar to solution heat treated and room temperature aged weld metal, additional weld metal samples were prepared. Hardness data was obtained immediately after welding and subsequently monitored at various time intervals for a two week period. A plot of the data obtained for this study is shown in Fig. 4. The maximum hardness of 12.0 HB is essentially the same as the base metal hardness of 12.5 HB and weld metal hardness of 12.0 HB achieved by solution heat treating at 300 C for two hours, water quenching and room temperature aging for one week. Thus, weld metal would not be expected to require a solution heat treatment and water quench subsequent to welding to achieve a hardness similar to that of solution heat treated and aged weld metal or base metal.

To determine if base metal, fully hardened prior to welding, would indicate a decrease in hardness in the heat-affected zone after welding, microhardness data were obtained. Measurement data were obtained by traversing from the base metal to the weld metal on transverse cross sections of as-welded samples room temperature aged two weeks. A plot of the data obtained is shown in Fig. 5. These data do not indicate a decrease in hardness in the base metal heat-affected zone. Thus, welds can be made on previously fully hardened base metal without causing a degradation of the base metal hardness and these welds do not require subsequent solution heat treatment to obtain maximum hardness in the weld.

Tensile Strength. To determine if the tensile strength of the lead-calcium alloy would respond to heat treatment in a manner similar to that indicated by hardness tests, tensile coupons were prepared and tested. Tensile properties were first characterized on base metal to provide data for later comparison with the tensile properties of weld metal and heat-affected zone. The yield strength and ultimate tensile strength was determined at various room temperature aging times following the solution heat treatment and water quench. A plot of the ultimate tensile strength and yield strength is shown in Fig. 6. The yield and ultimate tensile strength increase for longer aging times at a rate similar to hardness increases. Also, the yield strength is approximately one-half the ultimate strength at all aging times. The ultimate tensile strength and weld strength approached a maximum after room temperature aging one week. This is similar to the time required for base metal samples, similarly heat treated and aged, to approach maximum

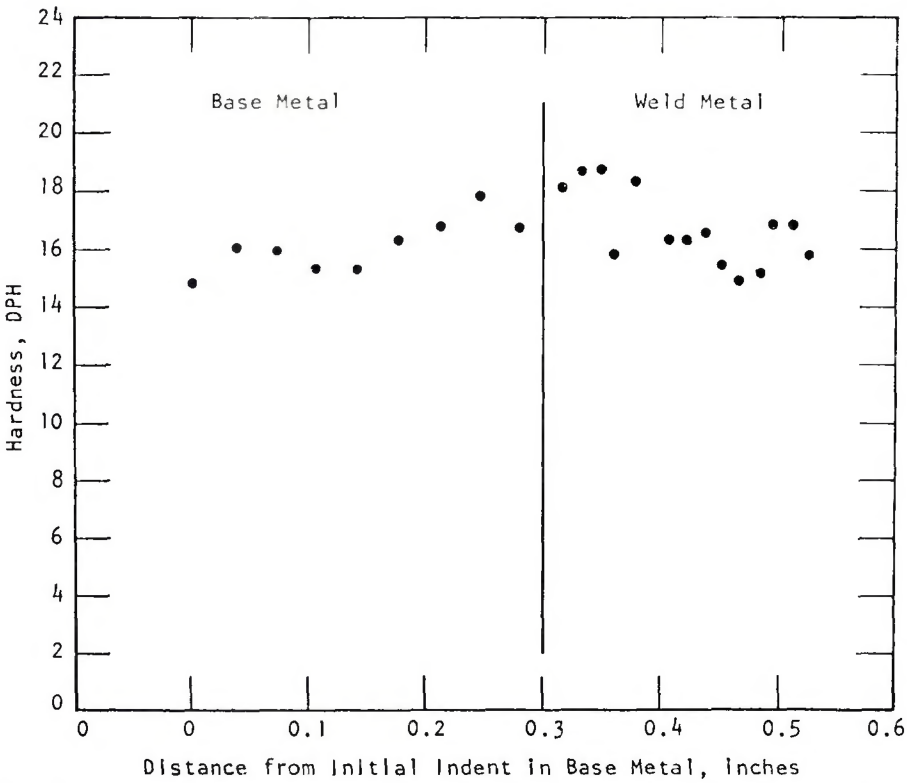

Fig. 5 — Hardness traverse in initially fully hardened base metal in the as-welded condition, two weeks after welding

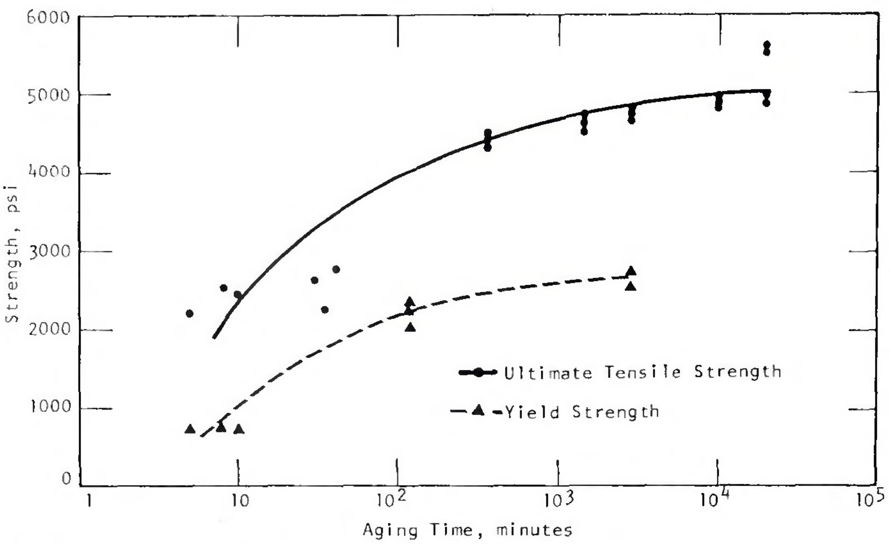

Fig. 6 — Tensile strength versus aging time for base metal samples solution heat treated at 300 C for two hours, water quenched, and room temperature aged

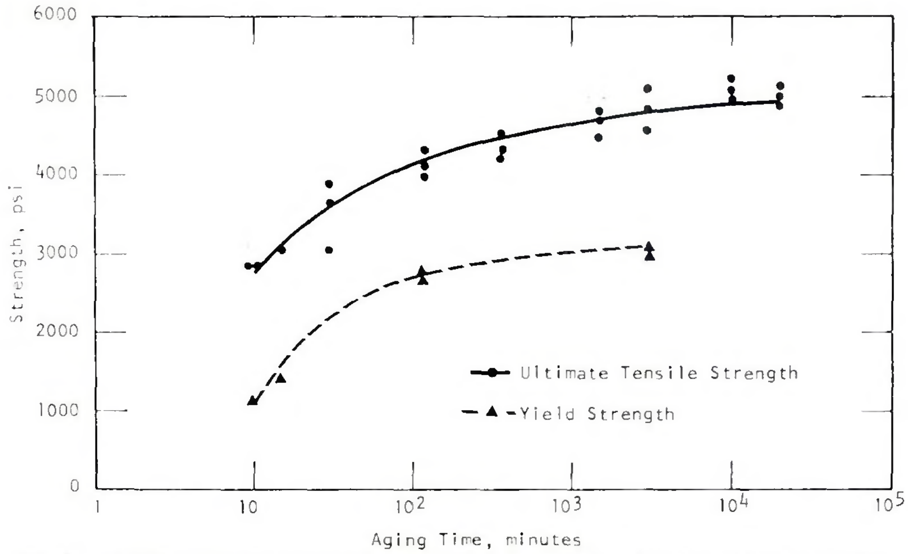

Fig. 7 — *Tensile strength versus aging time for longitudinal weld metal samples solution heat treated at 300 C for two hours, water quenched, and room temperature aged*

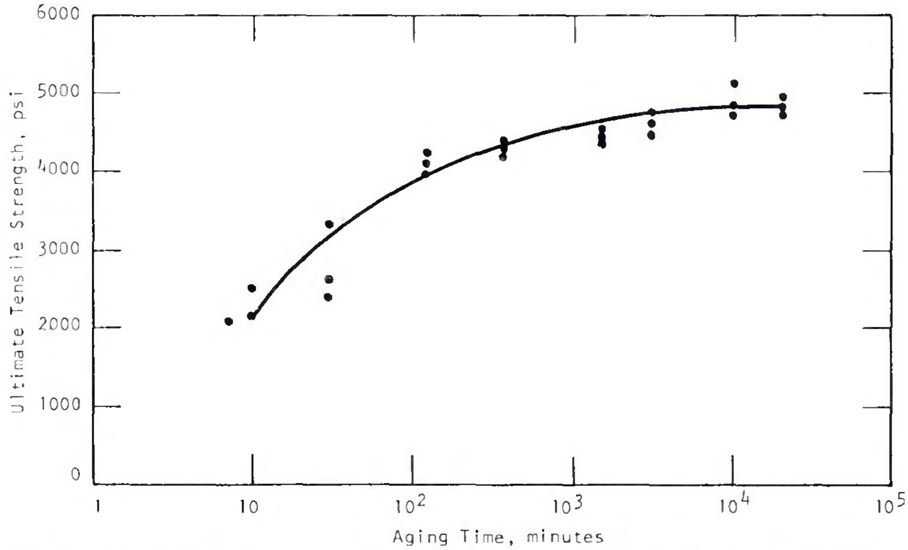

Fig. 8 — *Tensile strength versus aging time for transverse-weld metal samples solution heat treated at 300 C for two hours, water quenched, and room temperature aged*

hardness. Thus, the tensile strength of lead-calcium base metal increases in a manner similar to hardness when similar solution heat treatment and room temperature aging are used.

In order to determine the effect of elevated temperature aging, additional base metal tensile samples were solution heat treated, water quenched, and immediately aged at 100 C. Tensile strength data was obtained immediately following the 100 C aging temperature. The ultimate tensile strength showed a slight increase in strength from 4100 psi after a 30 min aging time to 4600 psi after a 48 hr aging time. Hardness data indicated a similar gradual increase in hardness with longer aging times. These data indicate similar increases in tensile strength in response to both room temperature and 100 C aging.

In order to determine if weld metal would respond to increases in tensile strength in a manner similar to the base metal, longitudinal weld tensile samples were solution heat treated, water quenched and room temperature aged. The ultimate tensile strength and yield strength were determined at various times following the water quenching. A plot of the longitudinal weld tensile data is shown in Fig. 7. The ultimate tensile strength approaches a maximum strength of 5000 psi after a one week room temperature age which is identical to the maximum strength and time required to reach maximum strength in base metal. The yield strength approaches a maximum of 3000 psi after an aging time of 48 hr which is greater than the maximum yield strength of 2600 psi reached in the base metal samples in the same time interval.

To determine if weld metal would respond to an elevated temperature age in a manner similar to the base metal, longitudinal weld tensile coupons were solution heat treated, water quenched and aged at 100 C. Immediately following the elevated temperature age, the ultimate tensile strength was determined. These data were virtually identical to that obtained for base metal samples similarly heat treated and aged. Thus, weld metal can be expected to respond to solution heat treatment and room temperature or elevated temperature age in a manner similar to base metal.

In order to determine if weld metal, room temperature aged immediately after welding, would respond in a manner similar to solution heat treated and room temperature aged weld metal, additional longitudinal weld tensile coupons were prepared. Ultimate tensile strength data were obtained after a room temperature age of two weeks. The as-welded and aged coupons had an ultimate tensile strength of 5800 psi. This value is approximately 800 psi greater than similar samples given a solution heat treatment and room temperature age. The tensile data indicates that the solution heat treatment and room temperature age causes a slight degradation in the as-welded and room temperature aged weld metal. Hardness data, however, did not show indications of degradation in the base metal hardness caused by the solution heat treatment and room temperature aging.

To determine the tensile properties of the heat-affected zone, transverse weld tensile coupons were prepared. Again, the tensile coupons were solution heat treated, water quenched and room temperature aged. A plot of the transverse weld tensile data is presented in Fig. 8. The maximum ultimate tensile strength of 5000 psi reached after room temperature aging one week compares favorably with similarly heat treated and aged base metal and weld metal. However, in all but three of the transverse weld tensile coupons tested, each failed in the heat-affected zone. The specimens apparently failed in the heat-affected zone because the weld metal has a slightly higher yield strength than the base metal when similarly heat treated and aged as previously indicated.

In order to determine the effect of an elevated temperature age on the heat-affected zone, transverse weld

Fig. 9 — Photomicrograph of base metal in a welded specimen treated at 300 C for two hours, water quenched, and room temperature aged for two weeks (acetic acid, hydrogen peroxide and ethyl alcohol). X750, reduced 8%

Fig. 10 — Photomicrograph of weld metal solution heat treated at 300 C for two hours, water quenched, and room temperature aged for two weeks (acetic acid, hydrogen peroxide and ethyl alcohol). X750, reduced 8%

tensile coupons were solution heat treated, water quenched and immediately aged at 100 C. Immediately following completion of the elevated temperature age, the samples were tested. These data indicate a gradual increase in ultimate tensile strength, similar to the longitudinal weld coupons and base metal coupons similarly solution heat treated and aged. Thus, the tensile strength in the heat-affected zone of the welded lead-calcium alloy can be expected to respond to solution heat treatment and aging at room temperature or 100 C in a manner similar to the weld metal and base metal.

To determine if the heat-affected zone, room temperature aged immediately after welding, would show a lowering of the tensile strength caused by the thermal cycling of the weld, transverse weld tensile coupons were prepared. Ultimate tensile strength data were obtained after a room temperature age of two weeks. The as-welded coupons had an ultimate tensile strength of 4700 psi. This value compares with the ultimate tensile strength of the solution heat treated and room temperature aged base metal and weld metal samples. Also, these data indicate that the heat from welding does not cause a reduction in tensile strength of initially fully hardened base metal. Therefore, base metal, solution heat treated and aged prior to welding, can be welded and be expected to reach the initial base metal tensile strength after a two week room temperature age without a solution heat treatment subsequent to welding.

Metallography

The lead calcium alloy was found to be very difficult to prepare for metallographic examination. Because of the alloy's softness, polishing compounds became embedded in the sample. Also, if excessive pressure was applied during polishing, the sample tended to smear. These two problems created artifacts in the sample.

Oxidation of the etched surface also created many problems. Approximately one hour after etching, the etched surface was oxidized severely enough to mask the microstructure. Therefore, observation of the microstructure and obtaining of photomicrographs had to be accomplished within approximately one hour following etching. Some of the samples, even when observed immediately following etching, showed indications of light interference fringes apparently caused by a thin oxide forming on the surface. Thus, it was extremely difficult to characterize the microstructure.

To characterize the base metal and weld metal, a sample was solution heat treated for 2 hr at 300 C, water quenched and room temperature aged for two weeks. A photomicrograph of the base metal is shown in Fig. 9 and a weld metal photomicrograph is shown in Fig. 10. In both micrographs, a lamellar structure can be observed. The lamellar structure may be present for two reasons. First, the solidification structure, which could have been a lamellar eutectic structure, may have not been homogenized during the solution heat treatment. This seems unlikely since the material was within approximately 27 C of the melting temperature for a relatively long time at the solution heat treating temperature. Second, the lamellar structure may be caused by the lead-calcium precipitate forming on certain habit planes which in turn causes preferential attack by the etching solution.

To substantiate this argument an electron microprobe analysis was performed on the sample. The lamellar width is approximately that of the diameter of the electron beam. However, calcium rich areas (Pb_3Ca eutectic phase and/or precipitate) were not observed. In addition, the rather low calcium level in the alloy may be approaching the lower limit of detection by the electron microprobe.

Metallographic analysis was also performed on a sample solution heat treated at 300 C for 2 hr, water quenched and aged at 100 C for 48 hr. The base metal and weld metal appeared to have the same structure as that in the previously discussed sample. Thus, as would be expected, the different aging treatments did not have any apparent influence on the microstructure.

To determine if the weld metal in the as-welded condition would indicate the solidification history, an as-welded sample room temperature aged for two weeks was prepared for metallographic analysis. Again, the base metal and weld metal had a structure which was essentially identical to the structure of the solution heat treated and aged samples. Since all of the structures are identical it appears that aging with or without prior solution treatment is obscuring any solidification history. Solidification in the planar growth mode is occurring or the metallographic techniques are such that structures resulting from solidification are not revealed. The former and the latter may be operating in concert to obscure the prior solidification history since the

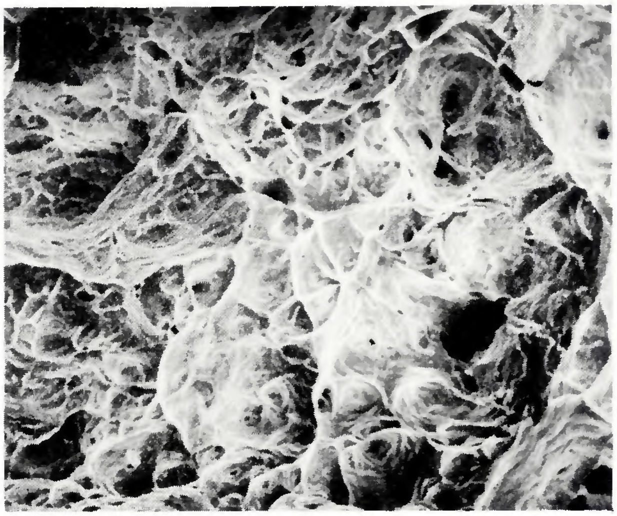

Fig. 11 — Scanning electron micrograph of a fractured weld metal tensile coupon, X300, reduced 8%

planar growth mode would not be expected in this alloy.

Electron Microprobe. To determine the distribution of calcium in the lead-calcium alloy and to identify the lamellar structure observed in the optical metallographic analysis, samples were subjected to electron microprobe analysis. There was no apparent difference in the calcium distribution on any of the samples in the base metal, weld metal or heat-affected zone. The calcium appeared to be uniformly distributed throughout the samples with no enriched inclusions apparent. The calcium content was observed to vary from 0.04 to 0.07 wt % which was essentially identical to the calcium variation determined by the atomic absorption technique.

Scanning Electron Microscopy. Most of the tensile coupons failed in a ductile knife-edge manner. However, a few of the coupons fractured before complete necking. These fractured surfaces appeared to exhibit porosity and were therefore examined by scanning electron microscopy. Figure 11 represents a fractograph from the weld metal. As can be observed, the fractographs indicate that porosity was not present. Failure appeared to occur in a ductile-dimple manner. The dark holes appearing in the fractographs were too deep to be observed with the scanning electron microscope. The deep holes may be caused by localized premature ductile-dimple failure followed by a large amount of plastic yielding prior to the sample failure.

Conclusions

Welding

1. The gas tungsten-arc alternating current welding process was determined to be capable of welding the lead-nominal 0.06 wt % calcium alloy without producing calcium losses in the weld metal. The welding process also permitted fusion of the molten metal and resulted in a smooth weld bead.

2. Welding parameters were developed for single pass welds in ¼ in. thick lead-nominal 0.06 wt % calcium.

3. Material thicknesses greater than ¼ in. require multiple pass welds.

4. A backing material is required during welding to prevent molten metal drop through.

5. The material should be positioned such that the weld is made with a slight up-hill slope. This is to prevent the molten metal from flowing under the joint ahead of the arc and solidifying in the backing groove. This causes an effective increase in material thickness which prevents proper penetration.

Properties

1. The lead-nominal 0.06 wt % calcium alloy responds to solution heat treatment and aging.

2. Room temperature aging and 100 C aging produce a hardness approximately three times that of solution heat treated and quenched material and approximately two times that of overaged material.

3. Room temperature aging and 100 C aging produce essentially identical hardness and tensile strength characteristics.

4. For material room temperature aged, two weeks are required to reach maximum hardness, ultimate tensile strength and yield strength.

5. For material aged at 100 C only 48 hr are required to reach hardness and strength.

6. Two hours at 300 C was determined to be adequate for solution heat treating.

7. Weld metal mechanical properties responded in a manner identical to the base metal mechanical properties when the material was solution heat treated and aged.

8. As-deposited weld metal (room temperature aged) mechanical properties also responded in a manner identical to solution heat treated and aged base metal and weld metal.

9. Mechanical property degradation did not occur in the weld metal or heat-affected zone as a result of thermal excursions during welding.

10. A solution heat treatment is not required after welding to achieve maximum and identical mechanical properties in all weld zones if a two-week aging time is permitted.

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