Welding 99.9999 Percent Pure Aluminum

Fusion welding of ultrahigh purity aluminum produces only small changes in electrical properties at cryogenic temperatures

BY D. L. CHEEVER, D. G. HOWDEN AND R. E. MONROE

ABSTRACT. Gas tungsten-arc welding was selected for making butt joints in 99.9999+% pure aluminum with minimal decrease in the high electrical conductivity of the aluminum at cryogenic temperatures. The conductivity of welded aluminum was no less than 84% of the base metal. Welding procedures are detailed along with properties of the aluminum that are required for designing magnets with a high field intensity.

Introduction

High purity aluminum is being used increasingly at cryogenic temperatures where high electrical current density is required. Applications include power transmission lines and ultrahigh field strength magnets. The high electrical conductivity of high purity aluminum can be increased more than 10,000 times by cooling from room temperature to liquid helium temperature (4.3K). At this low temperature, the decreased thermal vibration of the aluminum atoms results in the higher electrical conductivity. Superconducting materials such as Nb_3Sn are also candidates for similar applications. However, the superconductors are much poorer conductors of heat and become less conductive as the magnetic field surrounding them increases (magnetoresistance).

Present methods of preparing high purity aluminum can produce ingots with a maximum weight of 100 lb. Since about 8000 lb of continuous ultrahigh-purity aluminum strip would be required in certain applications of particular high field strength magnets, the Air Force* sponsored a program at Battelle-Columbus to develop the necessary joining and rolling procedures. This paper discusses the welding procedures in detail. For further details on ingot preparation, rolling, chemical milling, cleaning, annealing, resistivity ratio determination and magnetoresistance determination, the literature should be consulted.[1, 2]

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Table 1—Electron Beam Welding Parameters

Sheet thickness, in.	Beam voltage, kv	Beam current, milliamp	Travel speed, ipm
0.06	20	45 to 47	60
0.24	28	105	20
0.24	28[a]	90[a]	20[a]

[a] Second pass—used only for one specimen.

Experimental Program

Gas tungsten-arc, electron beam, and roll welded joints were made in ultrahigh-purity aluminum for evaluation in this program.

Materials

Ultrahigh-purity aluminum with a specified minimum resistivity ratio† of 7000 was used for most of the program. Initially, some work was conducted using aluminum with a resistivity ratio of 5000.

Welding Equipment and Procedures

The welding equipment and procedures used for each of the three welding processes evaluated are summarized below. The ingots were rolled to an intermediate thickness, welded, rolled to 0.03 in. thick, and chemically milled to final thickness.

Gas Tungsten-Arc Welding

Gas tungsten-arc welding was performed in a chamber evacuated to 10^{-5} torr before it was backfilled with inert shielding gas. An electronic feedback, voltage-controlled gas tungsten-arc head operated a torch in the welding chamber. The current was d-c straight polarity (electrode negative). Welds were made both in 0.24 and 0.06 in. thick material. For the 0.06 in. thick aluminum, welds were made both at 10 and 50 ipm. The 0.24 in. thick material was welded at a travel speed of 7.5 ipm. Joints were chemically cleaned and assembled and then placed in the welding chamber. The chamber was evacuated within 30 min after chemical cleaning to minimize oxide formation and oxide hydration on the joint surfaces.

Electron Beam Welding

Electron beam welds were made in 0.24 and 0.06 in. thick material. Two welds were made in each thickness of ultrahigh-purity aluminum. The welding machine was a continuously variable 9 kw, 30 kv, triode-gun electron beam unit. Welding was conducted in a vacuum of about 10^{-6} torr. Joint preparation prior to electron beam welding was the same as that used for gas tungsten-arc welding. The electron beam welding parameters for the four welds evaluated are given in Table 1.

Roll Welding

Roll welding was evaluated only for the lower resistivity ratio (3000 to 6000) 99.9999% aluminum. An 8 × 12 in., two-high laboratory mill was used for the rolling experiments. The rolls were carefully cleaned with crocus cloth followed by an acetone rinse to remove loose contaminating particles. The evaluation considered joint

* Sponsor was the Manufacturing Technology Division of the Air Force Materials Laboratory. The Air Force project engineer was Mr. Gabe Campbell.

† To measure the purity of contamination of ultrahigh-purity aluminum, it is experimentally easiest and least ambiguous to determine the resistivity ratio:

$$\text{Resistivity Ratio} = \frac{\text{Resistivity at Room Temperature}}{\text{Resistivity at Liquid Helium Temperature}}$$

$$R/R = \frac{\rho 273K}{\rho 4.2K}$$

The higher the resistivity ratio, the more desirable is the aluminum for use as a high current density conductor.

design, preweld preparation, and rolling reduction sequence. Three different lap joint designs were evaluated. Preweld preparation consisted of various chemical cleaning and annealing or baking procedures. One-pass reductions ranging from 70 to 87% were evaluated.

Subsequent Processing of Welds

Once the aluminum was welded, the strip was rolled to a thickness of 0.030 in. using 10% rolling reduction for each pass. The strip was chemically milled in a sodium hydroxide bath (40 grams NaOH per liter water) at 160°F for about 30 min to remove 0.005 in. from the thickness. The final strip was then annealed for 1 hr at 800°F in air to restore the initial high resistivity ratio to the heavily cold-worked material.

Results

Figure 1 shows the fabrication sequence selected for fabricating satisfactory continuous ultrahigh-purity aluminum strip from ingots. The selection of specific procedures is detailed in the literature.[1, 2]

Welding

Gas tungsten-arc welding and electron beam welding were satisfactory processes for joining ultrahigh-purity aluminum to produce joined strip with a 7000 resistivity ratio. Electron beam welds had a satisfactory resistivity ratio but the fixturing required in this program to make continuous lengths of strip 30 in. wide was more complicated than would be required for gas tungsten-arc welding. Gas tungsten-arc welding was therefore selected for making the final welds. Roll bonding produced suitable resistivity ratios but

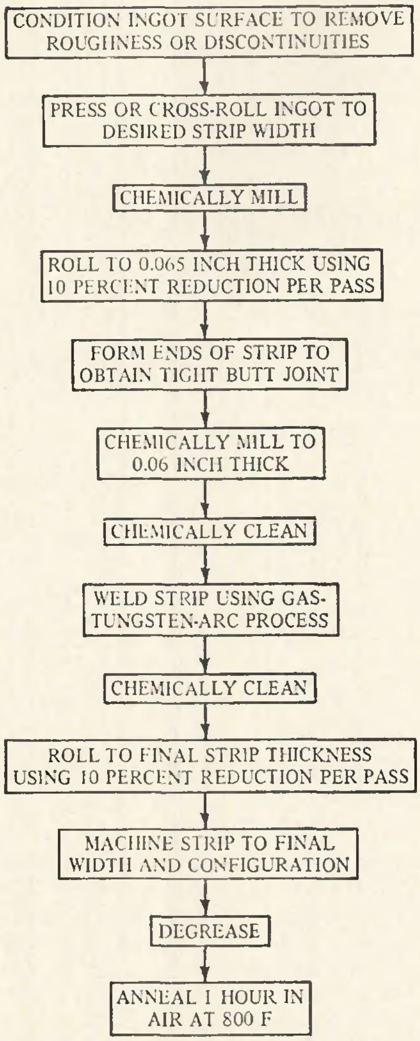

Fig. 1—Manufacturing procedure selected for fabricating continuous ultrahigh-purity aluminum strip from ingots.

the oxide particles at the joint interface acted as locations for gas to form blisters (delaminations) during annealing. These blisters were deemed undesirable because they cause poor heat flow and could contribute to mechanical failure. Figure 2 shows the distribution of resistivity ratios of weld specimens evaluated during the program.

The data in Fig. 2 shows appreciable scatter for each joining procedure evaluated. Scatter was probably caused by:

1. Differences in initial purity of the ingot (7000 to 12,000 resistivity ratio).
2. Differences in material purity due to contamination during processing.
3. Differences due to contamination due to the specific joining procedure.

Gas Tungsten-Arc Welding

Gas tungsten-arc welding was selected as the most suitable process for joining ultrahigh-purity aluminum strip. As shown in Fig. 2, gas tungsten-arc welded strip could have resistivity ratios greater than the minimum target value of 5000. Using the final gas tungsten-arc welding conditions developed, the resistivity ratio of the welded strip was greater than 84% of the resistivity ratio of the ingot before it was processed to strip. Figure 3 compares the resistivity ratio of the gas tungsten-arc welded specimens to the base metal resistivity ratio in an ingot that had a higher resistivity ratio at one end than the other. Electron beam welding produced welds that had good resistivity ratios, but was not considered further because the process required more complicated fixturing than did gas tungsten-arc welding.

Final Welding Conditions. The welding conditions used to make the final gas tungsten-arc welds were ap-

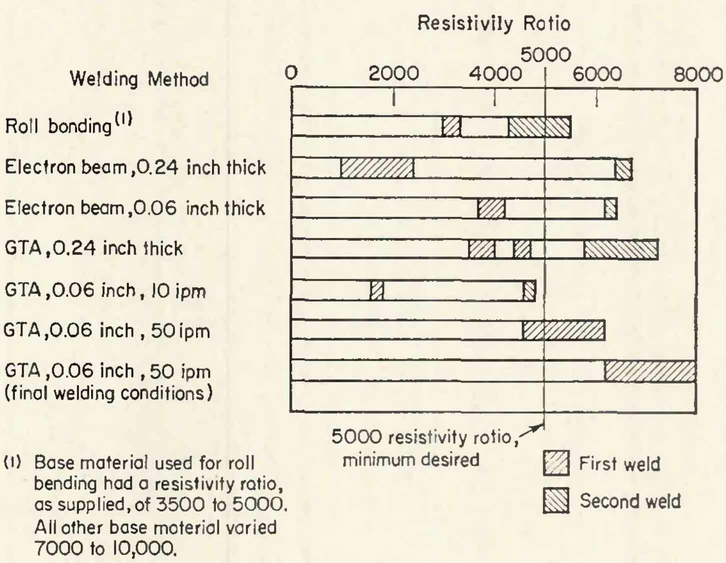

Fig. 2—Comparison of range of weld resistivity ratios for the joining processes evaluated

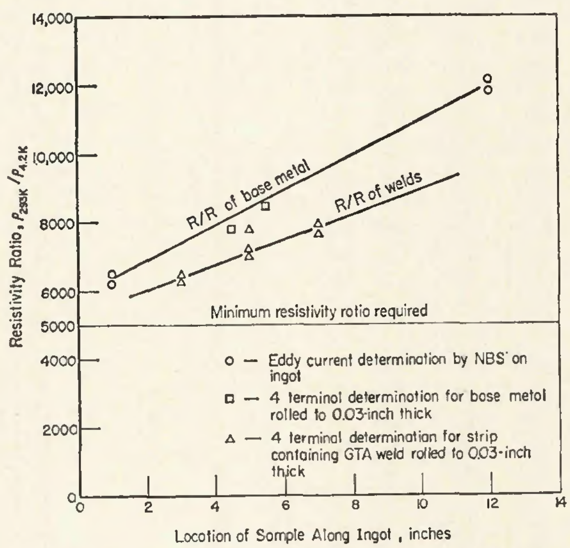

Fig. 3—Illustration of how resistivity ratio of final gas tungsten-arc welds compared favorably to that of the ingot

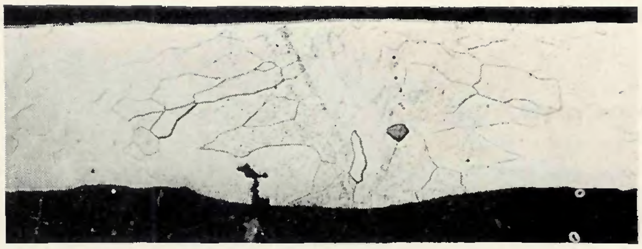

Fig. 4—Transverse section of gas tungsten-arc weld in 0.06 in. thick ultrahigh-purity aluminum showing crack-like defect associated with insufficient joint cleaning at lower left of fusion zone. 20% HF etchant. X20 (reduced 33% on reproduction)

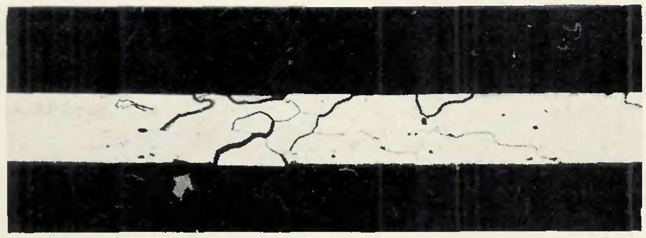

Fig. 5—Completed strip 0.025 in. thick containing a transverse gas tungsten-arc weld section in the center. 20% HF etchant. X20 (reduced 33% on reproduction)

proximately 8.6 v, 156 amp, 50 ipm, —80°F dewpoint argon shielding gas, and a 1/16 in. diameter, 1% thoriated tungsten electrode. The joint configuration was a tight butt. Factors that affected weld quality were the use of heat sinks, high-purity argon, and procedures to provide good fit-up.

Rigid copper tooling provided a heat sink on both sides of the joint. The tooling contacted the aluminum starting 0.15 in. from the joint. This tooling helped assure a uniform weld width.

The purity of the argon shielding gas was critical. Conventional welding-grade argon tended to produce a rough, discolored weld surface. With —80°F dewpoint argon, the weld surface was bright with no trace of discoloration. Fit-up and cleaning of the butt weld joint was a more difficult factor to control.

Fit-Up and Cleaning. Poor fit-up and cleaning resulted in burnthrough, porosity, and a crack-like defect (see Fig. 4) that extended only partly through the weld and was open to the bottom surface. It was believed that this crack-like defect was caused by the oxide film on the joint surfaces. The film apparently was not completely broken up in the pool (particularly at the bottom surface).

The most satisfactory cleaning procedure evaluated was to cut the joint, chemically mill 0.007 in. from the surface, smooth the joint area with a vixen file, and chemically mill the remaining 0.003 in.

Final Processing. Once the final gas tungsten-arc welds were made, the specimens were cleaned, rolled to 0.03 in. thickness, chemically milled to 0.025 in. thickness and annealed in air at 800°F for 1 hr. The final chemical milling resulted in localized pitting attack at the edge of the gas tungsten-arc fusion zone. (Electron beam welds also were susceptible to this type of pitting attack.) Figure 5 shows pitting in a transverse section of a final gas tungsten-arc weld after annealing had been completed. It was determined later in our evaluation that this final chemical milling treatment did not improve the resistivity ratio. The final procedure selected for processing eliminated this last milling step thereby eliminating the problem of preferential pitting.

If postweld chemical milling was desirable, different welding conditions or different chemical milling procedures would be needed to prevent pitting. We found that welding thicker specimens (0.1 in. thick) or two pass (one from each side) welding techniques reduced the pitting tendency.

Electron Beam Welding

Electron beam welds produced satisfactory results as shown in Fig. 2. The low resistivity ratios reported in some cases were partly due to prior contamination of the base material. Certain precautions are needed to prevent contamination during electron beam welding. The beam should not be allowed to touch material other than ultrahigh-purity aluminum. This means that tooling immediately beneath the weld should be ultrahigh-purity aluminum. When the beam was focused on a molybdenum starter block, molybdenum inclusions in the weld resulted. Weld porosity was also detected in some cases and was attributed to inadequate cleaning procedures that allowed excessive oxide formation and hydration.

Electron beam welding was eliminated from further consideration since the complexity of the tooling that would be required to fabricate continuous strip in this program was greater than that required for gas tungsten-arc welding.

Roll Welding

Roll welding conditions were developed only for the lower resistivity ratio aluminum. The results indicated:

1. A single-pass reduction of about 80% is required to weld high-purity aluminum prepared by chemical cleaning.
2. The best joint design evaluated was a 30 deg bevel, $^{1}/_{4}$ in. thick lap joint (overlap of $^{1}/_{4}$ in.) with an electron beam seal weld (Fig. 6).
3. The strip width before roll welding must be slightly greater than the final desired width because the welding process produces small tears at the edges of the joint.

The results were inconclusive as to the effects of baking or annealing prior to welding. However, these treatments may have some benefit in removing some of the moisture ab-

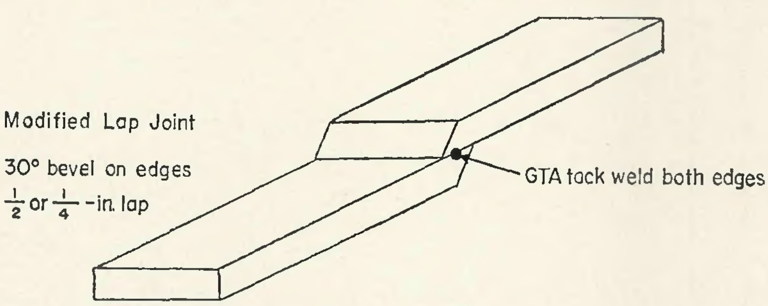

Fig. 6—Final joint design for roll welding

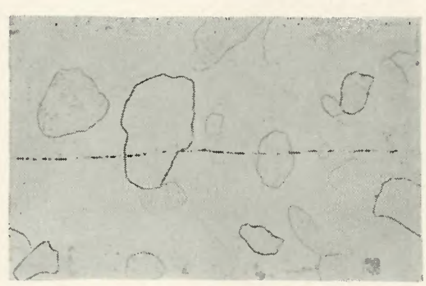

Fig. 7—Transverse roll weld sections showing undesirable oxide inclusions at joint interface. Keller's etchant. X100 (reduced 45% on reproduction)

sorbed on the strip surfaces during chemical cleaning. As pointed out in the literature,[3] chemical cleaning is not the best surface treatment for preparing aluminum for roll welding. The method recommended in the literature—wire brushing—was not evaluated in this program because of concern over possible metallic contamination from the brush.

Subsequent annealing of roll welded strip caused blistering in the joint area. This was believed to be due to the collection of hydrogen around the oxide inclusions typically found at the joint interface (Fig. 7). The blisters were undesirable discontinuities.

Discussion of Results

It was believed that the use of metallic electrodes in electron beam and gas tungsten-arc welding would cause significant metallic contamination of the weld. Fusion welding processes were considered, at first, only as repair techniques. As the data indicate, there was evidence that contamination from the welding electrode was not significant for either process if suitable procedures were used. Because the presence of fusion welds caused no more than a 16% decrease in any of the electrical properties of interest, the anticipated problem clearly did not develop. This program has therefore determined that no serious manufacturing problems exist in fabricating large (8000 lb), continuous coils of ultrahigh-purity aluminum strip (providing that suitable procdures are followed).

Structure of Final Gas Tungsten-Arc Welds

Observations were made about the metallurgical nature of fusion welds that suggest possible reasons for the program results. The transverse weld section in Fig. 4 contains U-shaped bands of etch pits that corresponded in location to the surface ripples visible both on the top and bottom of this weld. The ripples are shown in profile clearly on the bottom right.

The ripples are believed to be related to a ±10% voltage ripple (180 cps) of the d-c power source used. The etch pits are indicative of dislocation types of defects. The presence of ripples in a weld in 99.9999% pure aluminum suggests that the evidence of cyclic variations in weld solidification is not due to the periodic formation of a constitutionally supercooled liquid ahead of the solidification interface.[5] This is also the first experimental indication we are aware of that dislocation or vacancy condensation distribution in welds can be macroscopically discontinuous and is strongly related to weld surface ripples.

Etch Pit Concentration

The photomicrograph in Fig. 5 shows a completely processed weld with pronounced grain boundaries (compared to less heavily etched boundaries in the base metal) that could be indicative of higher angle grain boundaries. At a higher magnification etch pits could be seen in the weld zone clearly delineating subboundaries indicative of polyganization. The higher angle grain boundaries and the large number of subboundaries in the weld area may have been the principal reason that weld resistivity ratios were 10 to 15% less than that of the base metal. The resistivity ratio values for welds may be most strongly affected by dislocation density than by chemical contamination. Solidification rates of a welding process may be more important than the inherent "cleanliness" of the welding process.

Further Study of Weld Solidification

The ease with which etch pits can be produced in ultrahigh-purity aluminum welds and the number of observations about lattice defect concentration that can be made without resorting to the transmission electron microscope makes this material a strong candidate for more basic studies of welding metallurgy. The most obvious field of study would be an evaluation of welding conditions on weld solidification and the resulting dislocation and vacancy condensation distribution.

Future Work

In the year since the program was completed, the highest resistivity ratio aluminum available commercially has moved from values of 7,000 to 15,000. It is believed that values as high as 45,000 can be achieved regularly in the near future due to better purification techniques.

The work reported here is applicable only to 7,000 resistivity ratio aluminum. This reservation may be necessary, since, as shown in Fig. 3, the fusion weld resistivity ratios might not increase linearly with the base metal resistivity ratio. This may mean that a more contaminant-free form of fusion welding such as laser welding is necessary for joining aluminum with resistivity ratios above 7,000. Or, the solution may lie in obtaining more favorable dislocation or vacancy distributions in welds by using special weld power supplies or a series of mechanical and thermal treatments after gas tungsten-arc welding to decrease the final crystalline defect density and distribution.

Conclusions

1. Manufacturing procedures now exist to fabricate continuous ultrahigh-purity aluminum strip for magnet windings with a minimum resistivity ratio of 5,000.
2. Fusion welding processes are a suitable way to joint the strip. Gas tungsten-arc and electron beam welding produced similar results. Gas tungsten-arc welds were evaluated more extensively than electron beam welds because the tooling required for this application was simpler.
3. Roll welded joints could be made at room temperature with an 80% reduction to obtain a good resistivity ratio. The oxide at the interface caused undesirable delaminations during annealing.
4. The etch pit density in the weld formed U-shaped bands that were related to weld surface ripples.
5. To obtain satisfactory resistivity ratios of 15,000 or higher, different or additional welding, rolling, and annealing procedures may be necessary.

Acknowledgments

Valuable contributions to this program were made by other Battelle personnel. H. G. Leonard and D. W. Joseph supplied the resistivity ratio and magnetoresistance determinations under the supervision of Dr. J. J. Duga. T. Buyers performed the processing and joining experiments. Mechanical testing was supervised by J. E. Campbell. Dr. K. C. Brog provided calculations for coil design. P. A. Kammer, formerly of Battelle, and now with the McKay Company supervised the roll bonding. Valuable assistance was also received from Dr. Vincent Arp of the Cryogenics Branch of the National Bureau of Standards, Boulder, Colo. J. C. Laurence and W. R. Hudson of NASA-Lewis, Cleveland, Ohio, supplied the facilities for the magnetoresistance determinations.

This report is based on work sponsored under Contract AF33(615)5270 under the guidance of Mr. Gabe Campbell of the Air Force Materials Laboratory.

References

1. Cheever, D. L., Monroe, R. E., and Campbell, G.; "Fabrication of Ultrahigh-Purity Aluminum Strip for Use in Cryogenic Magnets"; Proceedings, 15th National Symposium of Society of Aerospace Material and Process Engineers; pages 479 to 490 (May, 1969).
2. Cheever, D. L., Howden, D. G., and Monroe, R. E.; "A Manufacturing Process for Producing High-Quality Electrical Strip from Ultrahigh-Purity Aluminum for Magnet Applications," Battelle Memorial Institute, Columbus, Ohio; Contract AF33

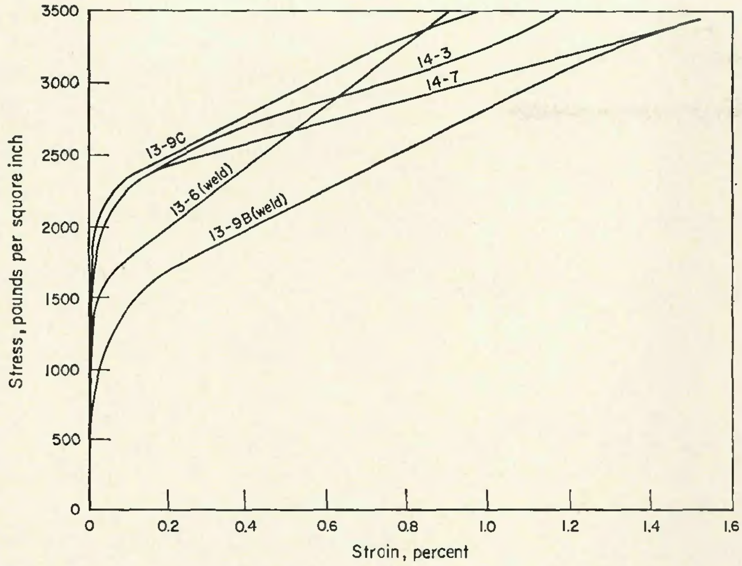

Fig. 8—Stress-strain curves for typical base metal and transverse gas tungsten-arc weld specimens at 4.2K

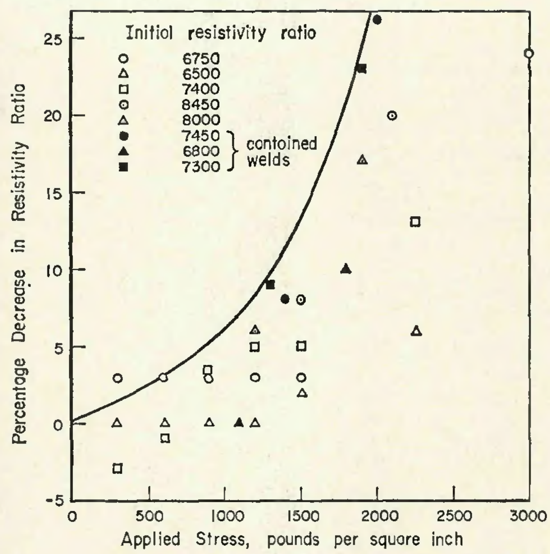

Fig. 9—Effect of stressing specimens at 4.2K on resistivity ratio

(615)-5270; Air Force Report AFML-TR-68-358 (December 1968).

3. Milner, D. R., and Rowe, G. W.: "Fundamentals of Solid Phase Welding," Metallurgical Reviews 17, (28); pages 435 to 480 (1962).

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Appendix: Design Data for Magnet Coil

Because the ultrahigh-purity aluminum strip produced in this program was to be used for the coil of a high field intensity magnet, data were needed on the mechanical and electrical properties of the final 0.02 in. thick strip. These data are reported below and include data for the welded and unwelded strip.

Experimental Procedures

In most cases, the resistivity ratio was measured for thin pieces of strip by determining the voltage drop for a known current. Measurements were made at room and liquid helium temperature to yield a resistance ratio.

Evaluation of Mechanical Properties. The yield strength, ultimate strength, and total elongation were determined at liquid helium temperature for samples 0.5 in. wide and 0.028 in. thick over a 1.5 in. gage length.

Evaluation of Effect of Stress on Resistivity Ratio. The interaction between the magnetic field developed by the magnet and current flowing through the coil results in a circumferential tensile stress on the aluminum coil. For design purposes, it was necessary to determine the stress magnitude that reduced resistivity ratio significantly. Then a suitable stress backing assembly could be designed to keep the circumferential stress in the aluminum at a suitably low level.

Magnetoresistance Determinations. The magnetoresistance determinations were essentially resistivity ratio measurements made while transverse magnetic fields of up to 50 kilogauss were imposed on the specimen. Loads of up to 3000 psi also were applied to the specimen while the field was operating.

Results

Mechanical Properties. The mechanical property data for the aluminum showed some scatter primarily due to the large grain size (about 0.05 to 0.10 in. diameter in the base metal) as compared to the 0.028 in. thick specimen thickness. Typical stress-strain curves obtained are plotted in Fig. 8. The two specimens containing gas tungsten-arc welds made at final conditions showed lower proportional limits and offset yield strengths. The mechanical-property data indicated the following values at 4.2K:

1. Proportional limit: ~ 1,400 psi
2. 0.2% offset yield strength: ~ 2,400 psi
3. Ultimate tensile strength ~ 30,000 psi
4. Elongation in 1 in.: ~ 35%

Effect of Stress on Resistivity Ratio. The experimental results for the effect of stress at 4.2K on the resistivity ratio are plotted in Fig. 9. Specimens containing welds apparently showed a slightly greater sensitivity to stresses than did the base metal specimens. A possible explanation for this effect may lie in the difference in grain

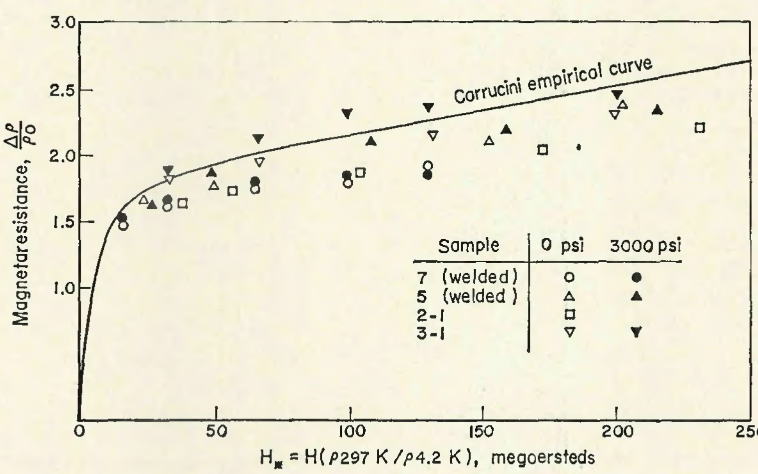

Fig. 10—Illustration of agreement between Corrucini empirical curve and program results for magnetoresistance of specimens

size between the base metal and the welds.

Cycling base metal and weld specimens from room temperature to 4.2K showed that the presence of welds made little difference in the resultant resistivity ratio.

Magnetoresistance Determination. Corrucini[4] plotted an empirical magnetoresistance curve for aluminum with resistivity ratios below 5000. The data points for the magnetoresistance determinations of the present work made on base metal and weld metal specimens correlated quite well with his predictions in Fig. 10. The data show little difference in magnetoresistance due to the presence of welds.

Eastern European Welding Research News

BY RUDOLPH O. SEITZ

CZECHOSLOVAKIA

Zvaranie 19, No. 4 (April 1970)

• Vrbensky, J.: Aspects of the weldability of rolled plates under stress in the direction of thickness (98-103).—The results of a study on the relation between plate thickness and weldability are reported. The causes of lamellar tearing are analyzed and measures of determining the presence of and the susceptibility to lamellar tearing are described.

• Ruza, V.: Proposal for a complex brazability test based on the service requirements of the brazed joint (103-07).—Methods of testing the tensile and shear properties, the electrical conductivity and the corrosion resistance of brazed joints in sheets and rods are described.

• Minarik, R., et al.: Combination of spot welding and adhesive bonding in joining aluminum sheets (107-11).—The problem of producing moisture-proof flanged seams in large decorative aluminum panels with minimum deformation was solved by the combined application of condenser discharge spot welding and epoxy resin bonding.

• Holasek, J.: Spot welding of zinc coated sheet metal (111-16).—The author discusses the problem of producing sound spot welds in zinc coated sheet metal and presents recommendations, based on the results of his investigations, for the spot welding of zinc coated sheets 0.8-2.0 mm in thickness with various thicknesses of the zinc layer applied by electroplating, dipping or metallizing.

• Plachy, A.: Designing protective shields for semiautomatic arc welding installations (116-18).—The incorporation of semiautomatic arc welding stations in a production line necessitates the protection of the operators against arc radiation. Several examples of the design of shields assuring the desired protection are described.

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Zvaranie 19, No. 5 (May 1970)

• Satoh, H.: Thermal stresses in high-strength steels developed by thermal cycles simulating the heat-affected zone of the weld (129-36).—Transient thermal stresses in the HAZ were determined by means of a method in which cylindrical specimens are held in a rigid frame and subjected to a thermal cycle simulating the conditions in the weld zone. A comparison of the thermal stresses in HY80 and in mild steel showed that in the case of the HY80 steel the transformation characteristics had an effect on the transient and residual stresses.

• Jesensky, M.: Welded gear boxes (136-41).—The results of a study of welded gear boxes are reported. The design and the fabrication procedures are described and the results of stress and noise measurements on cast and welded gear boxes are given. The two types of gear boxes are compared from the technical and the cost angle.

• Plachy, A.: Solid backings for joining strips by gas-shielded butt welding (141-47).—Gas-shielded arc welding is frequently used for joining sheets or strips by straight butt welds made from one side only. This requires the use of solid backings to assure uniform joint quality. The various aspects of this problem have been studied by the author in his investigation of different backing systems.

EAST GERMANY

ZIS Mitteilungen 12, No. 6 (June 1970)

• Pluschke, W. W.: One-sided submerged arc welding with a shaped strip electrode (666-74).—A new method of submerged arc welding from one side has been developed in which a strip electrode is formed into a V-shape during the welding process. The arc moving along the bottom edge of the strip electrodes safely fuses the joint edges and produces a good root weld.

• Pluschke, E. W.: Weld pool backups for welding from one side (675-80).—At the present state of development, welding from one side is possible only with the aid of some backup to secure the weld pool. A survey of known backup systems is given.

• Weisselberg, A. and Ratzsch, H.: Deposition efficiency of the various submerged arc welding methods (681-98)—The general burn-off characteristics of the different submerged arc welding processes are discussed from the point of view of maximum permissible current load. For filler pass welding, the indirect arc method which utilizes I_2Rt heating of the free end of the electrode at high welding currents is considered particularly effective. Numerous data are presented to arrive at an objective estimate of the economics of the different processes with respect to electrode cost and productivity of labor.

• Weillelberg, A. and Ratzsch, H.: The efficiency of submerged arc filler pass welding in the case of butt and fillet welds (701-14)—The maximum attainable welding speeds for the filler pass welding of one-sided butt joints (V-edge preparation) and of filler joints are reported. The maximum deposition rates are compared with the deposition volumes required as a function of edge preparation and the data are used to determine the maximum welding speeds for different plate thicknesses and fillet sizes.

• Kruppa, M. and Weiser, G. Electromagnetic clamping bench for welding flat plates in shipbuilding (715-21).—A method is described for reducing the time and effort for determining by trial and error the optimum distance between the magnets of an electromagnetic bench for clamping flat plates at right angles to the weld

(*Continued on page* 38-s)