Fluxless Induction Brazing of Aluminum in Air

A 12-strand testpiece of EC grade aluminum straps is successfully brazed using a specific brazing filler metal and a clamping fixture

BY K. C. LIN

ABSTRACT. Fluxless brazing of aluminum in air was once considered extremely difficult and not practical. The development work conducted at Westinghouse proved that aluminum can be fluxless induction brazed in air with MD-110 filler material. Conductor cleaning or etching was not mandatory, but the cleaned work pieces were shown to have a better bonding between the filler material and the base metal than the uncleaned work pieces.

Some formation of Mg_2Si precipitates and diffusion of silicon were observed at the joint which led to subsequent aging after brazing. However, fluxless lap brazed aluminum joints were electrically and mechanically satisfactory for conductor application.

Introduction

Brazing is defined as a welding process employing filler material having a liquidus above 800 F (427 C) and below the solidus of the base metal (Ref. 1).

Since the melting point of aluminum is 1220 F (660 C) and copper is 1981 F (1083 C), aluminum has a smaller temperature difference between the liquidus of the filler material and the solidus of the base metal than that of copper.

During brazing, aluminum has poor capillary action, because the oxide formed on the aluminum surface interferes with the spread of the molten metal. A chemical flux, the metallic halide salt, can help to promote the wetting action (Ref. 2) but fluxes generally are hygroscopic. After brazing, the flux trapped in the joint may cause corrosion.

The use of mechanical abrasion by wiping the conductor surface during heating has been a recommended method for soldering aluminum (Ref. 3). Mechanical abrasion will remove aluminum oxide to promote the spread of the molten metal without the use of a chemical flux. Nevertheless, it is impractical to apply the method on brazing aluminum at elevated temperatures.

Heating aluminum in a vacuum or in controlled gas atmospheres has been an alternative method of fluxless brazing. In 1940, P. H. Brace brazed aluminum in a vacuum along with a "getter" metal (Ref. 4). The getter metal, magnesium, lithium, or calcium, was heated to a vaporizing temperature prior to heating the part for brazing. Subsequently, several workers including C. I. Miller (Ref. 5) found that the active metallic vapor used for brazing could be supplied from the filler material.

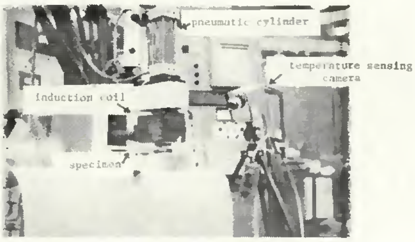

Fig. 1—Arrangement of brazing equipment

In 1965, C. A. Anderson welded 2250 MCM aluminum cable in a sealed movable mold with induction heating (Ref. 6). Aluminum work pieces were cleaned and melted in the mold with the induced high current. During solidification, the movable mold squeezed the molten metal to complete a compact sound welded aluminum joint.

Recently, development work conducted at Westinghouse has found that aluminum can be fluxless brazed in air with induction heating without a sealed mold. Conductor cleaning or etching is not mandatory. The method is feasible for lap joining aluminum straps to straps, bus bar to bus bar, straps to bus bar, and strips to strips.

Brazing

Aluminum work pieces to be joined were clamped between two brazing tongs under a moderate pressure from a pneumatic cylinder. The brazing tongs consisted of two shell form induction coils and two stainless steel plates which were placed between two coils for use as heating plates.

Filler material, MD-110 (Ref. 7) from the Reynolds Aluminum Company, was preplaced between each layer of aluminum for brazing. The brazing temperature was controlled with a temperature sensing camera which picked up the radiation signal from the two stainless steel plates to control the induction power source. Brazing, however, can also be monitored with a fiber optic temperature control equipment (Ref. 8).

During brazing in air, pressure from the pneumatic cylinder held work pieces tightly intact without introducing external gases, such as oxygen to the joint interface. The applied pressure also aided the capillary action of brazing and prevented the lifting of the aluminum work pieces due to the surface tension of the molten filler material. The excess filler material which flowed out from the interface was removed during flowing to complete a compact sound metallurgical joint. Figure 1 illustrates the arrangement of brazing equipment.

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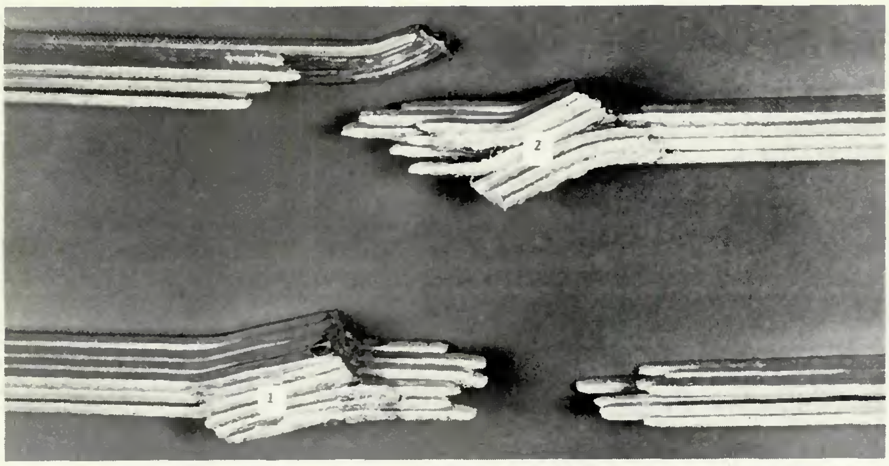


Fig. 2—Results of pull tests made on brazed samples

Fig. 4—Etched cross section of conductors showing joint details

Fig. 3—Destructive test made on a brazed sample by chipping the joint interface with a chisel

Joint Evaluation

Bare EC-grade aluminum straps, 0.091 × 0.162 in. (2.3 × 4.1 mm) each, in a lap configuration, three high, four wide per group, lap length versus a strap thickness ratio of three to one, were clamped between two brazing tongs for making induction brazed samples. MD-110, 0.008 in. (0.20 mm) thick sheet, was used as a brazing material.

Mechanical Tests

Joint samples approximately ten inches in length were tensile tested using a Tinius Olson Tensile Testing Machine at two inches per minute speed at room temperature and at 200 C (392 F) after 30 minutes aging at 200 C.

Figure 2 shows results of pull tests made on brazed samples. Sample No. 1 was pulled at 200 C and Sample No. 2 was pulled at room temperature. The average breaking strength of four test samples pulled at 200 C was 5240 and 6210 psi (36 and 43 MPa) at room temperature. Most of the test samples broke in the conductors adjacent to the joint. These conductors were softened during induction brazing; therefore, the breaking strength was about the strength of dead soft EC-grade aluminum.

In addition to the pull tests, a destructive test was made on brazed samples by chipping the joint interface with a chisel to examine bonding of brazing. Figure 3 shows that the joint interface was chipped with a chisel in a direction parallel to the strap length. No sign of cracking was found at the chipped end.

Electrical Tests

Four brazed samples connected in a series loop were run for twelve cycles in air with 400 amperes current (2200 A/in.^{2} or 3.41 A/mm^2). Each cycle consisted of three hours current on and one hour current off. Joint resistances in microhms were measured before and after the test and joint temperatures were measured during the test.

After the current cycling test, samples were further annealed in an oven without any current load at 125 C (257 F) for 30 days to study the effect of silicon diffusion and magnesium precipitation at the joint. No change in the joint resistance was observed due to the current cycling and the oven aging.

Microstudies

Cross sections of the joint samples were examined with a microscope to study the effect of sample preparation on the joint structure. Conductors chemically etched or mechanically cleaned prior to brazing evidenced a good metallurgical bonding (Fig. 4). Some voids were observed, however, in the filler material, and at the interface between the filler material and the base metal, for the samples made up of uncleaned or unetched conductors.

Fig. 5—Microstructure of the brazing material, MD-110, ×400 (reduced 64% on reproduction)

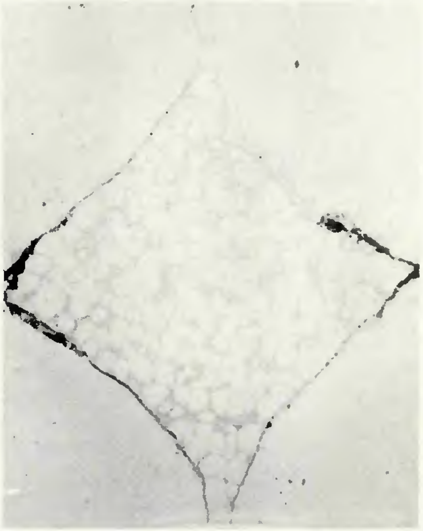


Fig. 6—Microstructure of the joint as brazed. ×400 (reduced 64% on reproduction)

Figure 5 shows a microstructure of the brazing material, MD-110. Figure 6 shows a microstructure of the joint as brazed. The microstructure consisted of a solid solution of silicon and magnesium in aluminum (light), and eutectic aluminum silicon (dark gray).

Figure 7 shows coarsening of the solid solution as a result of one hour aging at 350 C (662 F). Figure 8 shows the formation of dendrites resulting from 72 hours aging at 350 C. A similar structure of dendrites was observed on the sample which was heated under the 400 amperes current cycling and in an oven at 125 C for 30 days.

Microprobe analyses were made on the sample aged 72 hours at 350 C. Figures 9 through 12 show x-ray intensity images of aluminum, magnesium, silicon and iron, respectively. Figure 9 shows an even distribution of aluminum (light dots) across the joint. Figures 10 and 11 indicate that the distribution of silicon and magnesium across the joint was in the same pattern. It is possible that silicon and magnesium formed Mg_2Si dendrites. However, there were some excess silicon distributions which were free from the magnesium pattern. The excess silicon indicated that silicon could also form with aluminum in the eutectic structure across the joint. Figure 12 shows a distribution of iron across the joint. No significant pattern of the distribution of iron across the joint was observed.

Figures 13 through 15 illustrate results of x-ray profiles of aluminum, silicon and magnesium across the joint for samples as brazed, aged for one hour at 350 C and aged for 72 hours at 350 C. After 72 hours aging at 350 C, some diffusion of silicon was observed from the brazed zone to the aluminum matrix (see the parabolic curves across the joint interface in Fig. 14 c).Some noticeable change in magnesium profile was observed between the sample aged one hour and 72 hours at 350 C. The change of magnesium profile (from Fig. 15 b to Fig. 15 c) could be attributed to the formation of dendrites structure from the solid solution in aluminum matrix.

Discussion

The use of magnesium as a "getter" environment for aluminum brazing has been postulated, since under an active vapor (Ref.16), the rate of aluminum oxidation slows. Because thermal expansion of the aluminum based metal is two or three times that of aluminum oxide, the oxide which is a barrier to wetting and flow will crack and spall. When repair elements, mainly oxygen, are not available from the environment, the filler metal will melt and flow readily onto those metallic areas unprotected by the oxide to complete fluxless brazing (Ref. 9).

However, an alternative postulation given by W. Schultze et al (Ref. 10) was that at the brazing temperature, the active vapor reduces the aluminum oxide. Thermodynamically, a reduction of aluminum oxide with magnesium at a brazing temperature of 1148 F (620 C) is illustrated as the following

Fig. 7—Microstructure of the joint after one hour aging at 350 C (662 F). ×400 (reduced 63% on reproduction)

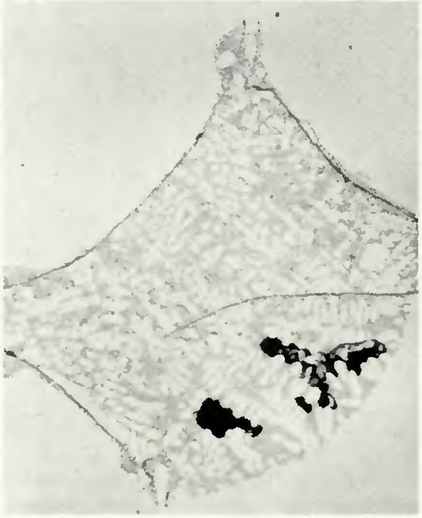


Fig. 8—Microstructure of the joint after 72 hours aging at 350 C (662 F). ×400 (reduced 63% on reproduction)

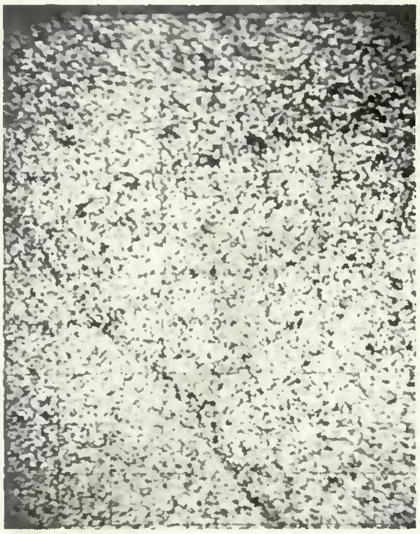


Fig. 9—X-ray intensity image of aluminum. ×600 (reduced 55% on reproduction)

Fig. 10—X-ray intensity image of magnesium. ×600 (reduced 57% on reproduction)

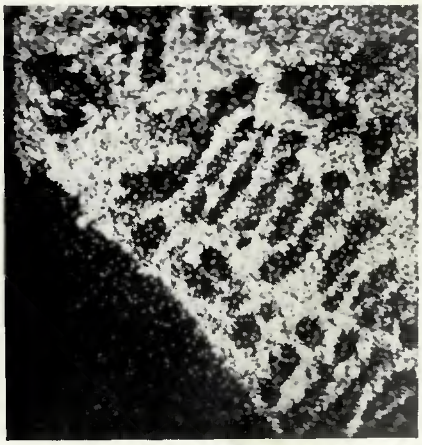


Fig. 11—X-ray intensity image of silicon. ×600 (reduced 57% on reproduction)

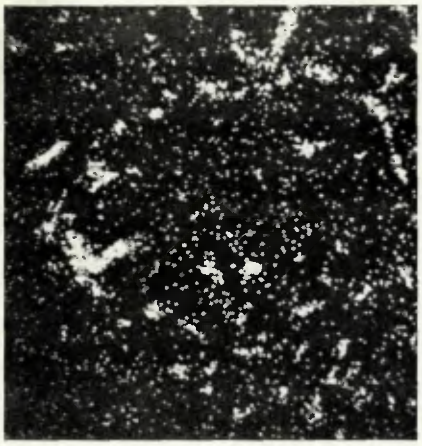
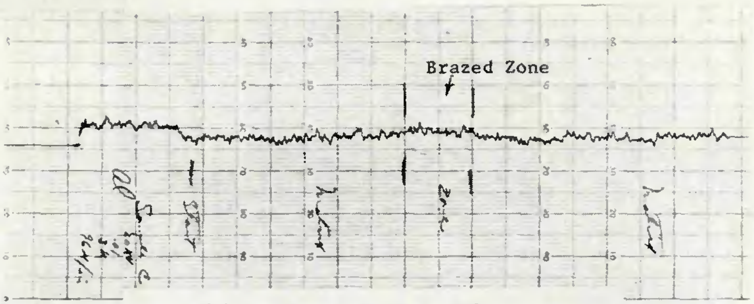
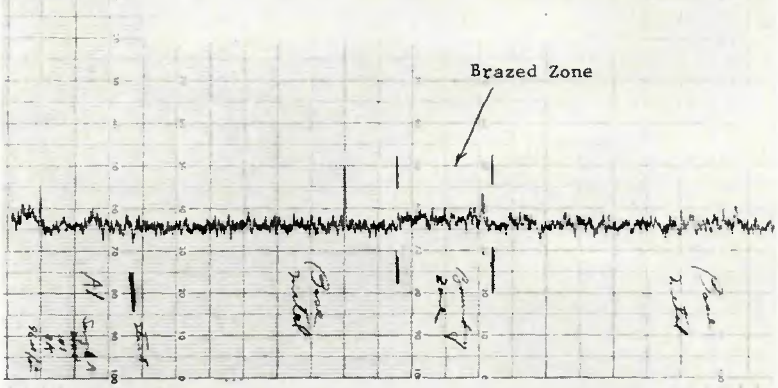


Fig. 12—X-ray intensity image of iron. ×600 (reduced 51% on reproduction)

(a) As Brazed



(b) One Hour Aged at 350°C



(c) 72 Hours Aged at 350°C

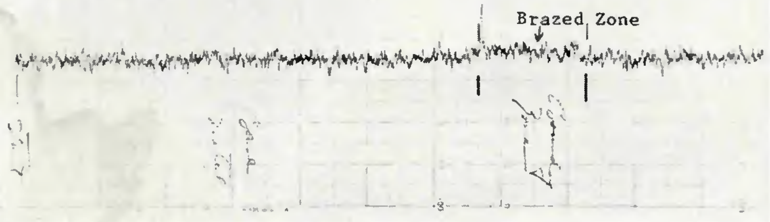


Fig. 13—Results of X-ray profile of aluminum across the joint

operations (Ref. 11):

$$4/3\ \mathrm{Al} + \mathrm{O_2} \rightarrow 2/3\ \mathrm{Al_2O_3}$$
$$\Delta G = \mathrm{RT\ in\ PO_2} = -225\ \mathrm{K\ cal}$$

$$2\ \mathrm{Mg} + \mathrm{O_2} \rightarrow 2\ \mathrm{MgO}$$
$$\Delta G = \mathrm{RT\ in\ PO_2} = -245\ \mathrm{K\ cal}$$

$$2\ \mathrm{Mg} + 2/3\ \mathrm{Al_2O_3} \rightarrow 2\ \mathrm{MgO} + 4/3\ \mathrm{Al}$$
$$\Delta G = -26\ \mathrm{K\ cal}$$

The negative sign of the free energy in the reaction shows that a reduction of aluminum oxide with magnesium is feasible. However, it is doubtful that a complete reaction could take place within the brazing period. O. R. Singleton (Ref. 9) expressed his doubt in reduction of the aluminum oxide because of the normal desorption and dehydration of surface oxides during heating. Tests made at the Reynolds Aluminum Company on the induction brazed sample found that some aluminum oxides were trapped in the brazing zone (Ref. 12).

At 350 C, the diffusion coefficient of silicon and magnesium are both about 10^{-12} cm^2/s (Ref. 13). Diffusion of silicon from the brazing zone across the joint interface to the aluminum base metal was observed. The similar depletion of silicon from the Alcoa's No. 12 to 3003 base metal was reported by J. R. Terrill (Ref. 14). No diffusion of magnesium was noted. Mg_2Si has been reported to be a stable precipitate (Ref. 15).

The Reynolds Aluminum Company's MD-110 brazing material which provides solidus at 1030 F (554 C) and liquidus at 1120 F (610 C), has a chemical composition of 6.8 to 8.2% Si, 2.0 to 3.0% Mg, 0.8% maximum Fe, 0.045% maximum impurities and remainder of aluminum. The MD-110 alloy has a chemical composition that is similar to alloy Nos. 333 (8 to 10% Si, 0.8% Mg), 359 (8.5 to 9.5% Si, 0.1% Mg), and 356 (6.5 to 7.5% Si, 0.2 to 0.4% Mg). These alloys which have many desirable characteristics including moderately high strength and good resistance to corrosion have been reported to be heat treatable and are used for both wrought and cast products (Ref. 17).

Dendritic structures were observed in brazed areas after the joint was aged at elevated temperatures. Dendritic structures were also found for the joint which had a prolonged heating during brazing.

Some voids were observed in the filler material and the interface between the filler material and the base metal for the samples when conductors were uncleaned or unetched prior to brazing. There was no evidence, however, that voids affected the mechanical and electrical properties of a lap brazed joint.

Conclusions

Aluminum can be fluxless induction brazed in air with Reynolds Aluminum Company's MD-110 filler material. The lap brazed aluminum joints were electrically and mechanically satisfactory.

Acknowledgments

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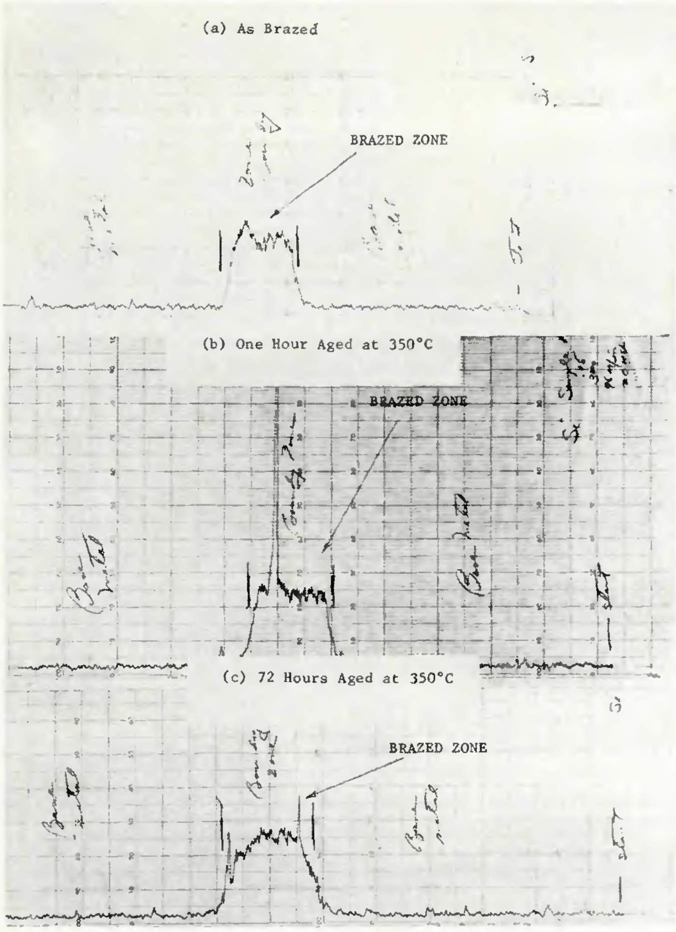

Fig. 14—Results of X-ray profile of silicon across the joint

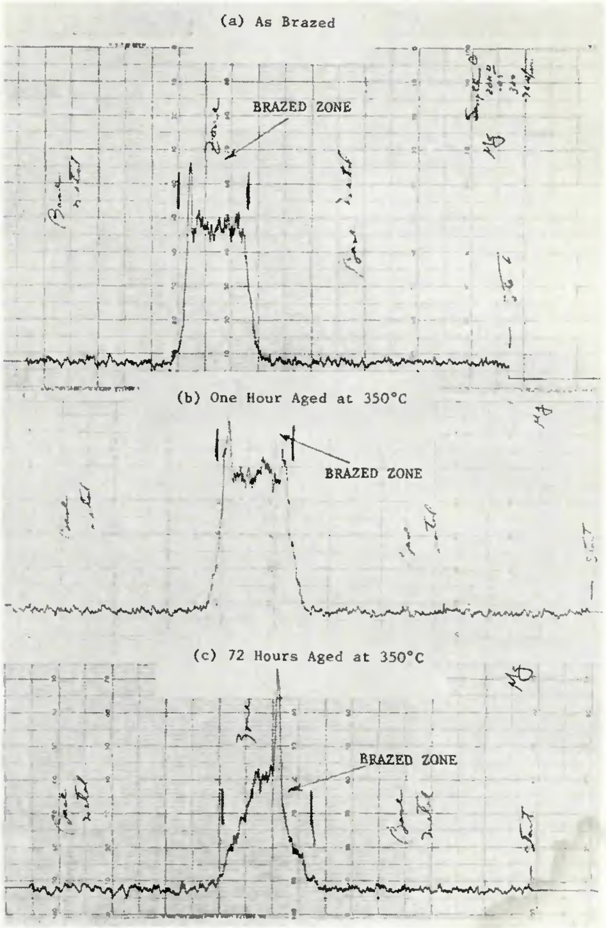

Fig. 15—Results of X-ray profile of magnesium across the joint

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