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Fluxless Diffusion Brazing of Aluminum Castings

Copper can be used as a eutectic former with aluminum and silicon to provide strong diffusion brazed joints in A356.0 aluminum alloy

BY. J. T. NIEMANN AND G. W. WILLE

ABSTRACT. This study was undertaken to determine if the A356.0 aluminum alloy could be diffusion brazed by electroplating one of the joint members with copper to form a eutectic with the aluminum and silicon in the casting alloy when heated to 975 F (524 C). The feasibility was demonstrated by brazing, heat-treating and testing small pin/face sheet sandwich specimens. Braze strength averaged 34.5 ksi (237.9 MPa).

To ensure optimum joint properties, the copper thickness, brazing temperature and time-at-temperature must be selected to promote isothermal solidification during brazing and thereby prevent the formation of the compound $CuAl_2$. Proper balancing of these variables results in strong joints that can withstand quenching from above the ternary eutectic temperature which is required for heat-treating A356.0 to the T61 condition. Brazing parameters were defined for a specific demonstration article—pin-fin type cold plates which may be incorporated in structural castings to cool electronic components. Electroplating the cover sheets with 150 to 200 microinches of copper and holding between 980 and 1000 F (527 and 538 C) for 1 h were the parameters selected for this demonstration.

Braze tooling was designed so that the forces generated by the different thermal expansion rates of steel and aluminum tooling details would bring the joint surfaces into close contact during brazing. A cold plate section cut from a production casting was brazed, heat-treated and pressure-tested successfully.

Introduction

As cost became a driving factor in selecting materials and processes for missile applications, the attention of aerospace designers was directed toward casting as an economical method for fabricating high-strength, aluminum alloy components. This, in turn, led to situations where versatility, cost savings, or both could be increased further through the use of welding or brazing.

Welding of the more popular casting alloys such as A356.0 is well within the present state-of-the-art but brazing is not. Most casting alloys melt below the brazing temperatures recommended for the commercial aluminum-silicon brazing filler metals. However, low temperature diffusion brazing appeared to offer a solution to this dilemma, and its potential was evaluated under a company-funded research and development study.

The program was concerned first with demonstrating the feasibility of the process, refining process parameters and determining joint strengths. Then, the ability to scale up the process was demonstrated by brazing a face sheet onto a cold plate which was cut from a production casting.

Evolution of the Joining Process

Diffusion brazing and conventional brazing are essentially the same except for the manner in which the liquid filler metal is formed during the brazing thermal cycle. In conventional brazing, a metal or alloy which melts at a lower temperature than the base metal is placed in, or adjacent to, the joint. Diffusion brazing, on the other hand, relies on the interdiffusion of a thin surface layer of metal and the underlying base metal to form a liquid phase when the eutectic temperature of the combination is reached.

The advantage of diffusion brazing aluminum and its alloys is that joining

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J. T. NIEMANN and G. W. WILLE are with the Materials and Processes Department, McDonnell Douglas Astronautics Company, St. Louis, Missouri.

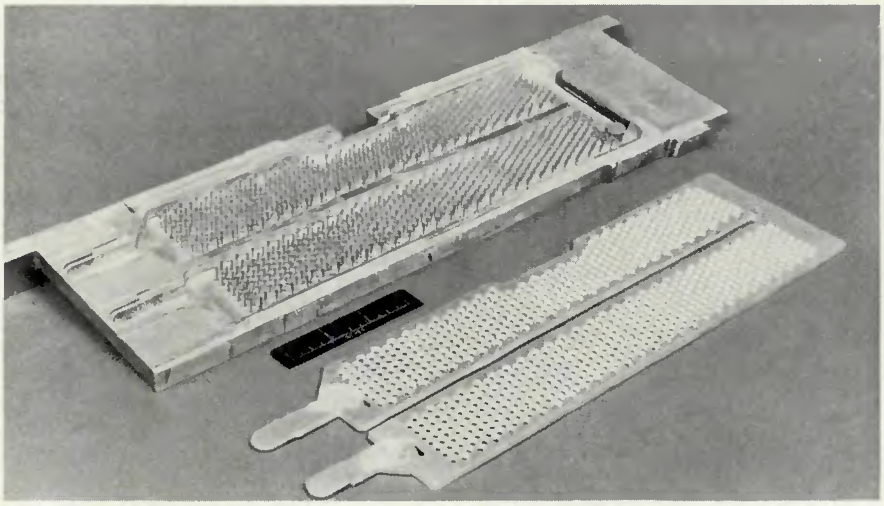

Fig. 1—Cold plate section of A356.0 alloy investment casting

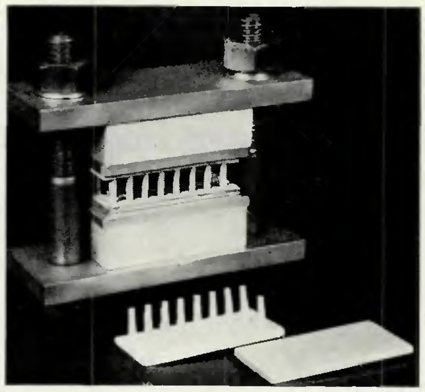

Fig. 2-Test specimen and brazing tool

can be accomplished at temperatures well below the normal brazing temperatures. This feature led McDonnell Douglas Astronautics Company, St. Louis, to develop a diffusion brazing system for fabricating boron-aluminum structural components in order to minimize filament degradation which occurs during elevated temperature processing.[1,2] Our approach was to coat the surfaces of boron-1100 aluminum matrix monolayer foils with a 20 microinch layer of copper. Structural shapes and flat laminates were built-up from these monolayers by heating, under pressure, above the copper-aluminum eutectic temperature of 1018 F (548 C). During the period from 1968 through 1973, several hundred pounds of monolayer foil were processed successfully by this technique.

As boron-aluminum technology advanced, it was recognized that secondary fabrication processes such as brazing would have to be developed in order to fully utilize the weight savings potential of this new material. However, the need to maintain low processing temperatures was a major stumbling block. Application of the conventional Al-Si brazing filler metals was not acceptable. Exposure to temperatures of 1100 F (593 C) or higher for even short periods results in drastic reductions in boron fiber strength.

Diffusion brazing offered a solution to this problem. In this case, the approach was to plate the commercial Al-7.5Si alloy (4343) with copper. A ternary Al-Cu-Si eutectic, with a nominal composition of Al-27.5 Cu-5.2 Si, will form when this system is heated to 975 F (524 C). This technique was used to braze boron-aluminum assemblies below 1000 F (538 C).

The Al-Cu-Si system seemed ideally suited for brazing the popular A356.0 and A357.0 cast alloy compositions because of their similarity to the Al-7.5 Si braze alloy. These casting alloys are basically the 4343 composition with minor additions of magnesium and zinc. Their solidus temperature, at approximately 1035 F (557 C), is well above the Al-Cu-Si eutectic formation temperature. It was obvious from the boron-aluminum experience that these alloys could be copper-plated directly and brazed by heating above 975 F (524 C). However, a study was necessary to refine processing parameters and to demonstrate that diffusion brazed joints were sufficiently strong for consideration in missile applications.

Procedure and Results

The objective of this program was to demonstrate that integrally cast pin-fin type cold plate cavities could be completed by diffusion brazing. Figure 1 shows a cold plate section that was cut out of a complex A356 investment casting and its cover sheet. The purpose of the cold plate is to provide cooling for electronic components, and the cavities are completed with the attachment of the cover sheet.

Currently, the cover sheets are attached by manual gas tungsten arc welding; the pins and bosses extend through and are welded into the cover sheets. All the welds are finished flush with the cover plate, and the casting is then heat-treated to the T61 condition. The heat treatment consists of holding in the temperature range from 980 to 1010 F (527 to 543 C) for 6 to 18 h followed by quenching in 150 to 212 F (66 to 100 C) water. Aging is carried out at 310 F (154 C) for 1 to 6 h.

The parameters are selected to meet the minimum specified mechanical properties of 28 ksi (193 MPa) yield strength, 38 ksi (262 MPa) tensile strength and 3% elongation. After straightening and machining operations are completed, the cold plates are pressurized to 1.5 times their operating pressure to verify weld integrity.

This program was directed toward demonstrating that a nonperforated cover sheet could be brazed around the periphery of the cavity and to the pins. A two phase program was carried out. Phase I was concerned wih showing that sound, strong joints could be made in aluminum castings by diffusion brazing. In Phase II, processing parameters were refined, tooling concepts developed and a cold plate cut from a production casting was brazed, heat-treated and proof-tested.

Phase I—Preliminary Tests

The objective of this phase of the

Table 1—Evaluation of Differential Expansion Tooling Concept

	Pin dimensions, in.[a]		
	Max.	Min.	Avg.
Before Heating:			
outer rows	.4300	.4288	.4292
inner rows	.4247	.4230	.4238
ΔH	.007	.0041	.0054
After heating:			
outer rows	.4207	.4195	.4201
inner rows	.4206	.4195	.4202
Δ H	.0012	0	.0001
Permanent set:			
outer rows	.0105	.0082	.0090
inner rows	.0050	.0024	.0036

[a] 1 in. = 25.4 mm.

study was to verify that the A356.0 casting alloy could be diffusion brazed successfully. Samples of the type shown in Fig. 2 were machined from the chassis casting. The samples were approximately ¾ × 1¾ in. (19 × 44.5 mm); the simulated cover sheets were 0.090 in. (2.3 mm) thick and the pins were about ⅜ in. (9.5 mm) high. Also, the cover sheets were electroplated with copper on the joint side only.

Selection of a Tooling Concept

The first problem area to be addressed was the probability that in practice there would be a variation in the height of the cast pins. It was assumed that such a condition would be detrimental to brazing because the amount of liquid formed from the eutectic reaction might not be sufficient to fill wide gaps. Therefore, contact between the pins and cover sheet was considered a prerequisite to obtaining sound, strong joints by diffusion brazing.

To accomplish this, tooling was designed so that the differential expansion between metals could be used to apply pressure to the cover

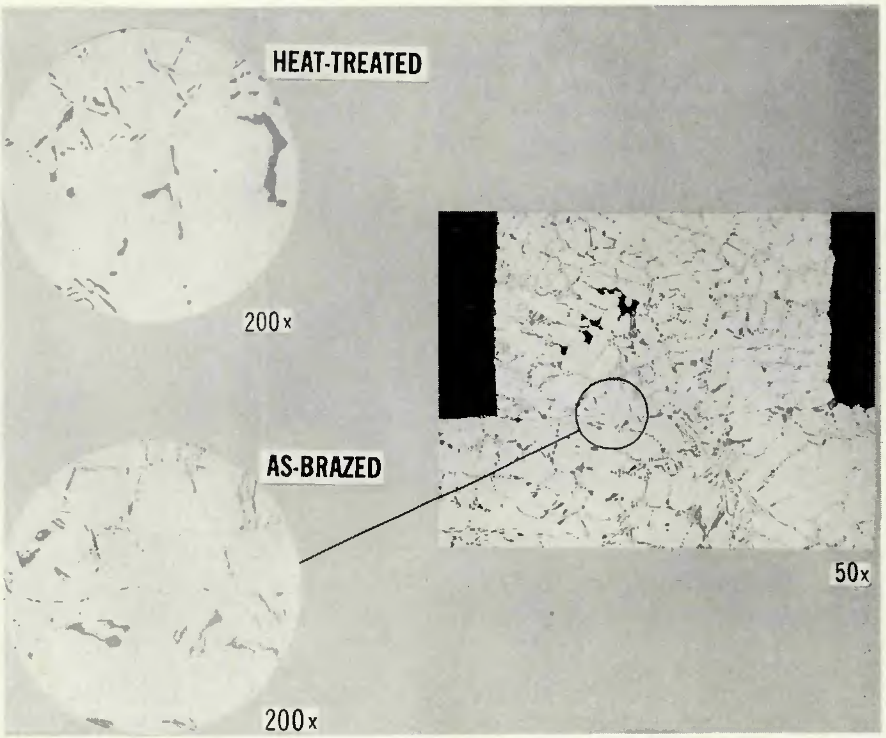

Fig. 3—Microstructure of sample diffusion brazed with 150 μin. thick copper coating on face sheet (reduced 46% on reproduction)

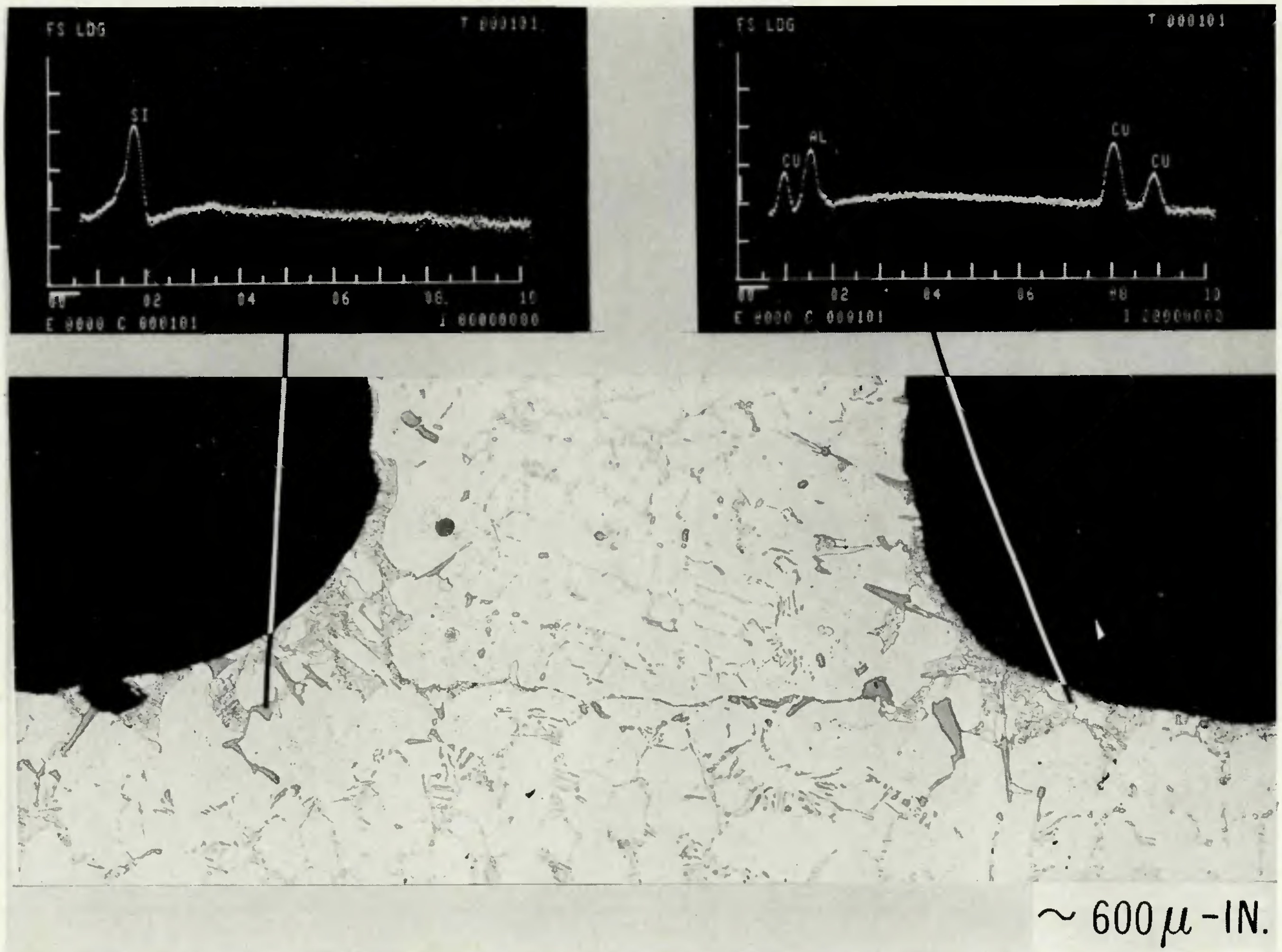

Fig. 4—Microstructure of sample diffusion brazed with 600 μin. thick copper coating on face sheet (reduced 7% on reproduction)

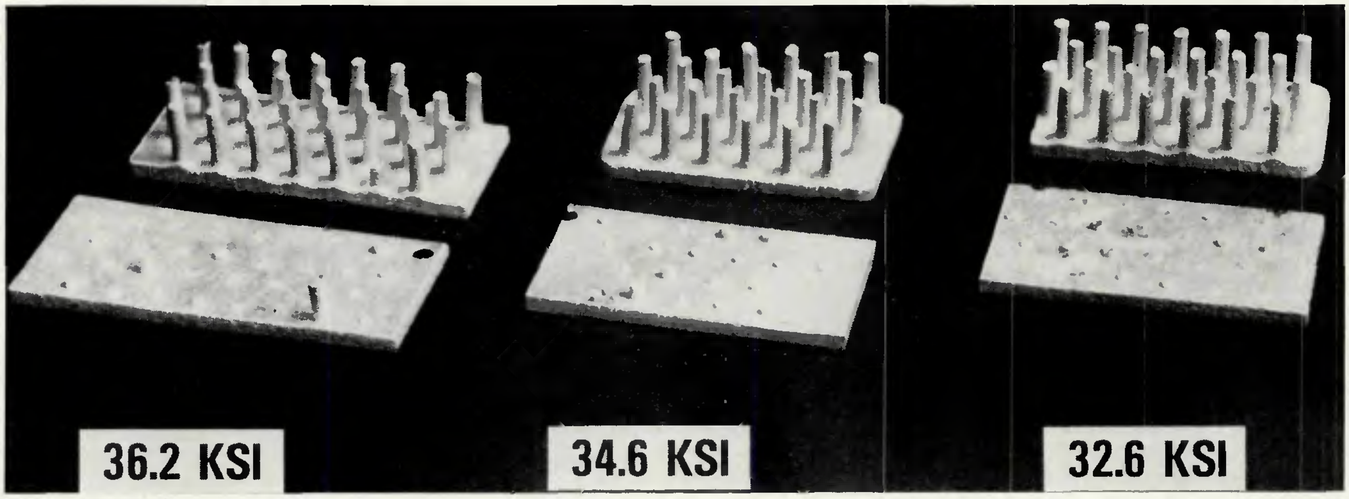

Fig. 5—Flatwise tension test results

plate and ensure overall contact by local yielding during heat-up. Figure 2 shows how this was accomplished on the preliminary test specimens. In this arrangement, the difference in expansion between the aluminum and the steel details applies compressive forces to the aluminum pins.

Before samples were brazed, a run was made to test the tooling concept. For this test, the two inner rows of pins on one of the specimens were machined to be about 0.005 in. (0.13 mm) shorter than the outer rows. Also, a steel cover sheet was used rather than an aluminum cover. The test sample was heated in the steel brazing fixture to the brazing temperature (1000 F, 538 C) and then furnace cooled. The height of each pin was measured both before and after heating.

These measurements are summarized in Table 1 and show that the tooling approach was successful in establishing contact between the pins. The permanent set measured in the higher, outer-row pins indicated a height variation of about 0.01 in. (0.25 mm) could be corrected by the tool designed for the preliminary brazing tests. Even greater variations could be tolerated by increasing the thickness of the aluminum blocks in the tool.

Effect of Copper Thickness

Experience with diffusion brazing boron-aluminum showed that, for a given thermal cycle, the final microstructure and joint properties were determined by the amount of copper available. The brazing parameters were selected to ensure that $CuAl_2$ would not be formed during cooling, because this compound was believed to adversely affect mechanical properties. Avoidance of this constituent was also considered important when brazing castings.

The most direct way to achieve compound-free joints is to limit the amount of liquid formed; this, in turn, is determined by the thickness of the copper plating. At the same time, however, filleting was considered desirable in the pin/face sheet joints selected for this study and would require some surplus liquid. Therefore, a study was needed to determine if filleting could be obtained without the intermetallic being formed during cooling.

The first evaluation of coating thickness was made on samples electroplated with either 150 or 600 μin. of copper. These values were selected in an attempt to define a range of thickness encompassing both filleting and nonfilleting. Subsequent tests then would be made during Phase II to evaluate the effects of copper thicknesses within this range on microstructure and filleting and to select parameters for brazing a full size casting.

Test samples were assembled in the brazing fixture (Fig. 2) with the bolts

Table 2—Effect of Diffusion Brazing Thermal Cycle on Tensile Properties of A356.0 and 6951 Alloys

Material	Copper thickness, μ in.	Condition	0.2% offset yield strength, ksi[a]	Tensile strength, ksi[a]	Elongation, %
A356	0	STA[b]	39.5	47.7	5.0
			39.9	47.6	5.0
			40.2	47.6	5.0
			AVG 39.8	AVG 47.6	AVG 5.0
	0	Braze cycle[c]	38.8	47.1	6.0
		+ STA	39.6	47.0	5.0
			AVG 39.2	AVG 47.1	AVG 5.5
No. 21 braze sheet[d]	170	Braze cycle	35.8	41.9	8
		+ STA	35.9	42.7	11
			AVG 35.9	AVG 42.3	AVG 9.5
No. 21 braze sheet	250	Braze cycle	35.7	41.9	7
		+ STA	36.4	42.1	7
			AVG 36.1	AVG 42.0	AVG 7

[a] Multiply by 6.894757 to convert ksi to MPa.
[b] 1000 F (538 C)/14 h, quench 150 F (66 C) water, age 310 F(154 C)/4 h.
[c] 1000 F (538 C)/1 h, slow cool
[d] 6951 alloy clad one side with 4343

finger-tight and then heated in a 6 in. (152.4 mm) diameter, argon purged and evacuated (<0.1 torr) retort. Heating to the brazing range (985-1000 F, 529-538 C) required about 30 min. The brazing temperature was maintained for 4 h to promote diffusion and thereby avoid or minimize the formation of $CuAl_2$. These tests were successful in establishing a range where copper thickness could be selected to either produce or suppress fillet formation.

Photomicrographs of the 150 μin. sample are shown in Fig. 3. This sample was well bonded even though vestiges of the original interface were discernible in the as-brazed condition. After heat treatment, the original interface is indistinguishable from the adjacent base metal. No fillets were formed with a 150 μin. thick coating nor was there any evidence that $CuAl_2$ was formed through eutectic decomposition of the liquid phase. This microstructure is the result of complete depletion of the copper plating through formation of the liquid phase and subsequent diffusion into the base metal.

Holding at the brazing temperature promoted interaction between the liquid and solid phases, and this reduced the copper content of the liquid. Eventually, isothermal solidification occurred producing a two-phase microstructure composed of Al-Cu-Si solid solution and free silicon. During cooling to room temperature, the solubility of Cu and Si in aluminum decreased, and $CuAl_2$ and Si were precipitated from the solid solution.

Figure 4 shows that fillets were formed in the 600 μin. sample. However, both the fillets and bond line contain $CuAl_2$. This microstructure occurred because cooling was initiated while the fillets and bond line still contained a liquid phase. At 975 F (524 C) the remaining liquid underwent the eutectic reaction, yielding Al-Cu-Si solid solution, silicon and $CuAl_2$. At the bond line, the solid solution blended into the base metal leaving the $CuAl_2$ and Si isolated at the bond line with the $CuAl_2$ in stringer form. This microstructure was considered undesirable from the standpoint of possible effects on joint strength and also because remelting would occur during heat treatment since the solution annealing temperature is above the Al-Cu-Si eutectic temperature.

Joint Strength

Three additional samples, plated with 150 μin. of copper, were prepared to determine the tensile strength of diffusion brazed joints. These samples were machined with the inner rows of pins 0.005 in. (0.13 mm) shorter than the outer rows. After brazing and heat-treatment, the samples were adhesively bonded between 2 in. (50.8 mm) square aluminum blocks and tension tested in the flatwise direction.

Based on the heat-treated microstructure it was believed that the brazed joints would be as strong as the cast material with minimum tensile strengths of 38 ksi (262 MPa). However, the specimens failed at an average stress of 34.5 ksi (238 MPa), based on the assumption that the pin diameter was 0.07 in. (1.8 mm), which was the drawing requirement. The individual pins were not measured and a difference of only 0.003 in. (0.08 mm) between the actual and assumed diameters would account for the lower than expected strength. Also, any misalignment of the specimens on the 2 × 2 in. (50 × 50 mm) test blocks would lower the joint strength as would the notch effect caused by the lack of fillets.

Results of the tension tests are shown in Fig. 5. For the most part, the fractures occurred at, or near, the braze joints. This can be attributed to the fact that the pins taper from a nominal 0.09 in. (2.3 mm) diameter at the tangent point of the cast radius to a nominal 0.07 in. (1.8 mm) at the joint. However, it is significant that the failures are about evenly divided between the braze joints and parent pin material. This observation suggests that the braze joints were essentially as strong as the base metal and that the measured strengths were imprecise because of test conditions, differences between assumed and actual braze areas, or both.

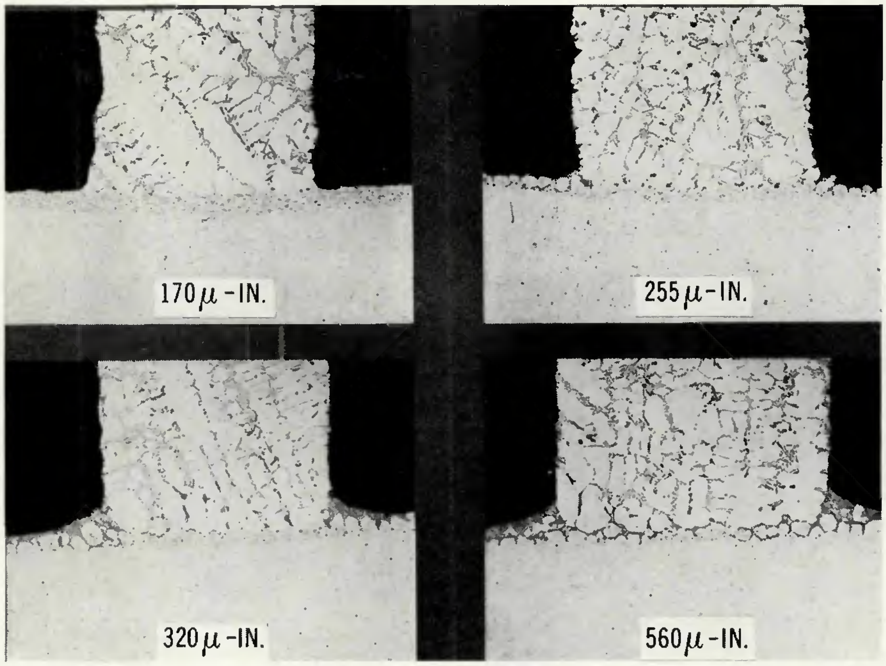

Fig. 6—Effect of copper thickness on fillet formation and microstructure. ×50 (reduced 49% on reproduction)

Phase II—Refinement of Processing Parameters

The Phase I study was encouraging in that it showed sound, strong joints could be made in A356.0 cast alloy by diffusion brazing. During Phase II, the study of coating thickness effects was expanded and a cold plate section was brazed to further evaluate the tooling concept.

Selection of Copper Thickness

The effect of copper thickness on joint microstructure was studied using specimens of the type shown in Fig. 2. However, the cover plates were made from 0.090 in. (2.3 mm) thick No. 21 brazing sheet rather than being machined from a casting. This change was made to facilitate material procurement by eliminating the need to obtain cast and machined sheets of an appropriate thickness. No. 21 brazing sheet is 6951 alloy clad on one side with Al-7.5% Si braze alloy. This type was chosen because the basic 6951 alloy is heat-treatable to about the same strength level as A356.0.

In the first step, a series of tests was run to determine the combined effects of copper coating, brazing thermal cycle and A356.0 heat-treatment on the strength of 6951 brazing sheet. Samples of brazing sheet were plated on the braze alloy side and then subjected to a braze cycle which consisted of holding 1 h at 1000 F (538 C) followed by furnace cooling. These samples then were heat treated in the same manner as A356.0 castings and then tension tested. Unplated round

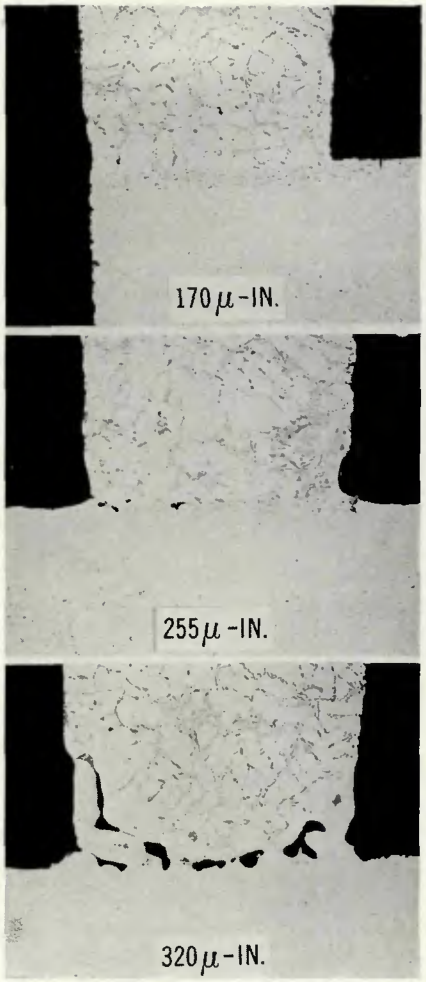

Fig. 7—Effect of copper thickness and heat treatment on microstructure of diffusion brazed joints. ×50 (reduced 43% on reproduction)

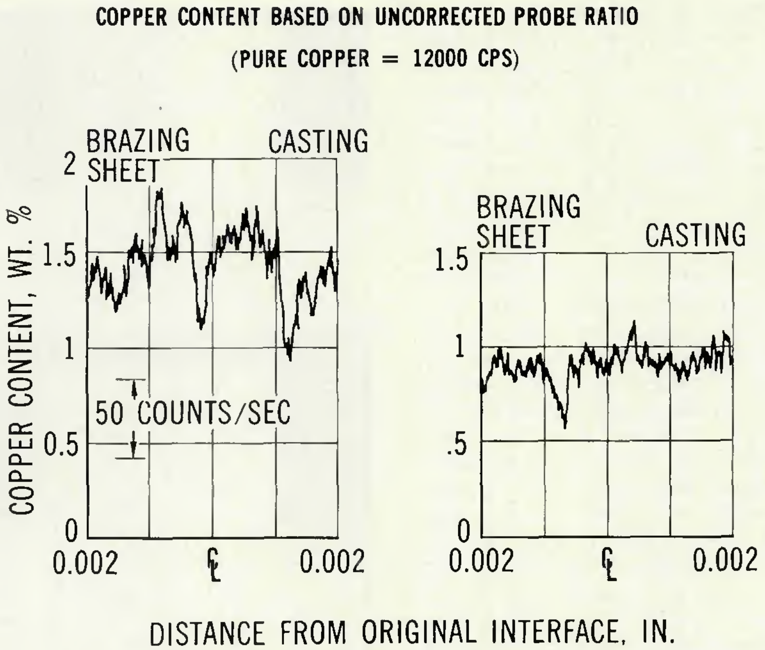

Fig. 8—Copper distribution across joint diffusion brazed with 150 μin. thick copper coating

cast tensile-bars of A356.0 alloy accompanied the braze sheet samples through the thermal treatments.

The results of these tests are summarized in Table 2. Although the copper plated braze sheet specimens were about 5 ksi (34.5 MPa) lower in strength than the A356 casting specimens, they were above the 38 ksi (262 MPa) minimum required by the casting specification. The No. 21 braze sheet was considered to be a satisfactory substitute for cast sheet for this study effort.

Eight coating thicknesses ranging from 150 to 600 μin. were evaluated to determine the effect of copper thickness on filleting and microstructure. Sheets of the No. 21 braze sheet, measuring 0.090 in. × 8 in. × 8 in. (2.3 × 203 × 203 mm), were plated on the clad side only with the desired thickness of copper. The central portion of each sheet was cut into eight specimens, each ¾ × 1¾ in. (19 × 44.5 mm). One specimen from each sheet was weighed to the nearest 10 milligrams, immersed in a 50% HNO_3 solution to remove the copper and then re-weighed to determine the actual copper thickness.

Samples of the type shown in Fig. 2 were brazed with each coating thickness following the same general procedure used in Phase I, except that the time at temperature was reduced from 4 to 1 h to simulate a more economical and more representative production cycle. Examination of these samples showed that fillets and $CuAl_2$ were present in the samples plated with 255 μin. or more of copper. As shown in Fig. 6, fillet size and the amount of $CuAl_2$ present increased with increasing copper content.

The presence of $CuAl_2$ in the microstructure indicated that remelting would occur if the casting was heated above 975 F (524 C) for solution annealing. However, it was not known for certain that this would always be detrimental. Perhaps some remelting could be tolerated, provided isothermal solidification occurred during the 6 to 18 h hold above 980 F (527 C) prior to quenching. Three samples representing 170, 255 and 320 μin. were heat-treated to determine the effect of solution annealing and aging on joint quality and microstructure.

Figure 7 shows the results of the heat treatment. There was no appreciable change in the microstructure of the 170 μin. sample. The 255 μin. sample, which had small fillets, showed evidence that some remelting occurred during heat treatment and that it resulted in minor void formation at the bond line. This effect was greatly accentuated in the 320 μin. sample, which originally showed heavier concentrations of $CuAl_2$ in the fillets and along the bond line. Apparently, the liquid phase which formed on reheating flowed away from the joint, thereby depleting the fillets and leaving large void areas within the joint.

Small islands of very fine eutectic structure are visible in the 320 μin. heat-treated sample indicating there was still some liquid present at the time of quenching. Even 16 h at 990 F (532 C) was not long enough to complete the liquid-solid interaction necessary for isothermal solidification. Therefore, it was concluded that the copper coating thickness should be maintained below 200 μin. to avoid the possibility of detrimental remelting within the joint during postbraze heat treatment.

Figure 8 shows the change in copper concentration in the bond line area that accompanied the heat-treatment of the 170 μin. sample. In the as-brazed condition, the maximum copper content reached about 1.75% at the joint centerline and then tapered off to the content of the base metals. The probe scan indicated the copper content of the casting and brazing sheet to be about 0.25% and 0.42% respectively with corresponding diffusion zone depths of 0.008 and 0.006 in. (0.20 and 0.15 mm).

Heat-treatment lowered the maximum copper content to about 0.8%. The extent of the diffusion zone was not determined, but the copper content remained constant for at least 0.01 in. (0.25 mm) on each side of the joint. If the joint had been cooled from the brazing temperature immediately after isothermal solidification, the copper content would have been near 5%. The actual maximum was less than 2%

which indicates that the holding time at the peak brazing temperature could be shortened considerably and still avoid eutectic decomposition.

Brazing of a Cold Plate Section

The final task in Phase II consisted of brazing, heat-treating and evaluating a half-section of the forward cold plate cut from a production casting as shown in Fig. 9. This section was 3.7 × 12 × ½ in. (94 × 205 × 12.7 mm) overall and contained five bosses and approximately 600 pins. The 0.090 in. (2.3 mm) thick cover sheet was machined from a cast slab and the joint side was electroplated with a 100 to 200 μin. thick layer of copper.

A major objective of this test was to determine whether or not the tooling principle used to prepare the preliminary specimens could be adapted to brazing larger assemblies. For the preliminary tests, steel bolts were used to apply a very light initial force to the assembled specimen and aluminum blocks which were contained between steel plates and to resist the forces set up by the differential expansion of the aluminum and steel details. The cold plate half-section tool also utilized differential expansion forces to load the assembly during brazing. However, the part and aluminum blocks were placed in a rectangular steel frame and steel wedges were used in place of bolts, as shown in Fig. 10.

The cold plate section was brazed in the same manner as the preliminary samples except that the rate of heating to the brazing temperature was slower because of the larger mass of the tool. Heating the cold plate section required about 4 h compared to 30 min for the small, preliminary specimens.

After brazing, the cold plate section was heat treated to the T61 condition and then pressure tested. The cold plate was pressurized to its design burst pressure without failure. Metallographic sections then were cut from the assembly and examined to evaluate joint quality. As shown in Fig. 11, both pins and bosses were well bonded.

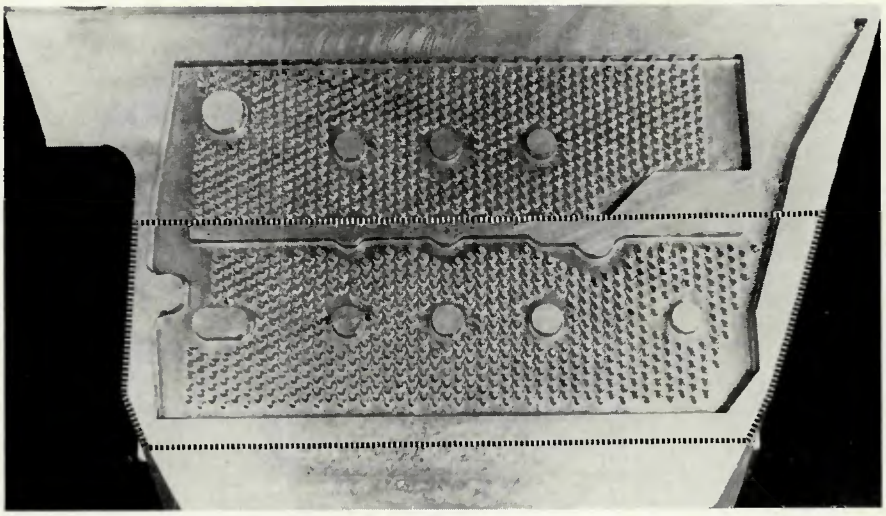

Fig. 9—Cold plate test section

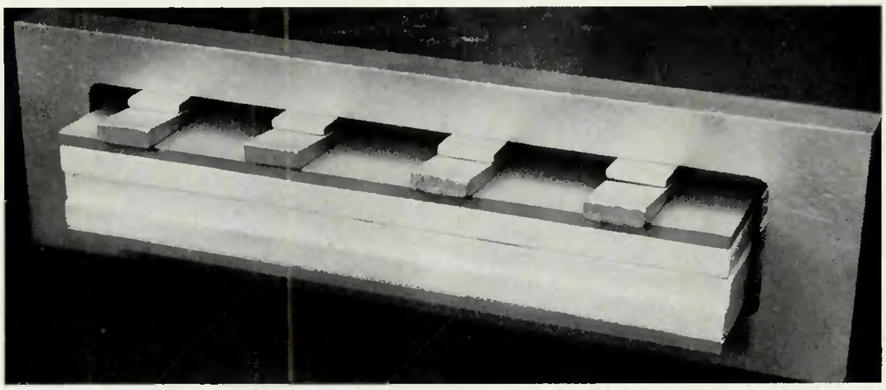

Fig. 10—Cold plate test section in brazing tool

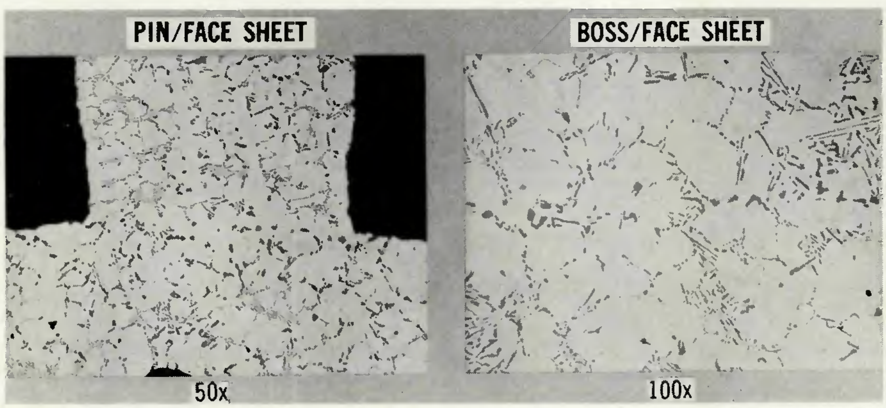

Fig. 11—Microstructure of brazed and heat-treated cold plate test sections (reduced 49% on reproduction)

Conclusion

The results of this investigation show that the A356.0 casting alloy can be diffusion brazed by plating one of the joint members with copper. A liquid phase is formed at the Al-Cu-Si eutectic temperature of 975 F (524 C) through diffusion of copper into the casting alloy during heating.

The critical processing parameters are copper thickness and time at the peak temperatures. These parameters can be balanced to ensure that the liquid phase will solidify isothermally at the peak temperature. Under these conditions, eutectic decomposition will be avoided and the joint will not contain stringers of the copper-aluminum intermetallic compound. Also, the brazed joint can subsequently be solution annealed above the Al-Cu-Si eutectic temperature without remelting.

After quenching and aging, the joint strength will equal that of the casting itself. Microstructurally, the brazed joint will be indistinguishable from the casting.

References

1. Niemann, J. T., and Garrett, R. A., "Eutectic Bonding of Boron-Aluminum Structural Components—Part I," *Welding Journal*, 53 (4), April 1974, Research Suppl., pp. 175-s to 184-s.

2. Niemann, J. T., and Garrett, R. A., "Eutectic Bonding of Boron-Aluminum Structural Components—Part II," *Welding Journal*, 53 (8), August 1974, Research Suppl., pp. 351-s to 359-s.