SOLID-STATE BONDING OF SUPERPLASTIC ALUMINUM ALLOY 7475 SHEET

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ABSTRACT

Experimental works were carried out to study the feasibility of solid-state bonding of superplastic aluminum 7475 sheet. Amount of deformation, bonding time, surface cleaning method and intermediate layer were the process parameters investigated. Other parameters, held constant by the superplastic forming condition which is required to obtain a concurrent solid-state bonding, are bonding temperature, bonding pressure and atmosphere. Bond integrity was evaluated through metallographic examination, x-ray line scan analysis, SEM fractographic analysis and lap shear tests. The early results of the development program indicated that sound solid-state bonding was accomplished for this high strength 7475 alloy with significant amounts of deformation. A thin intermediate layer of the soft 5052 aluminum alloy aided in achieving a solid-state bonding by reducing the required amount of plastic deformation at the interface. Bond strength was substantially increased by a post bond heat treatment.

INTRODUCTION

Superplastic forming of titanium combined with solid-state bonding (frequently called SPF/DB) has demonstrated substantial cost and weight savings in fabri-cating aircraft structures. Superplastic forming aluminum is a new technology emerging in aerospace industries to form complex net formed parts of high strength aluminum. While the aluminum superplastic forming technology is ready for implementation into production, to date only limited success has been realized in solid-state bonding of aluminum especially high strength aluminum alloy. The major difficulty in the solid-state bonding of aluminum comes from its tenacious surface oxide film which cannot be avoided under normal manufacturing conditions. As a result, methods should be developed to achieve intimate metallic contact between faying surfaces in the presence of this film.

A company-funded program was started to study the feasibility of solid-state bonding as a concurrent process with superplastic forming of aluminum. The early phase of this program concentrated on obtaining solid-state bonding of alloy 7475 sheet at superplastic forming temperature. Bonding experiments were conducted using methods to disrupt the surface oxide film to expose a clean metal surface prior to bonding. Some of the bonding parameters includ-ing an intermediate layer as a bonding aid were evaluated for use in the later phase of this program. Since there are no standard test procedures which apply to solid-state bonding, reliable tools had to be selected to measure bond quality.

FEATURES OF SOLID-STATE BONDING
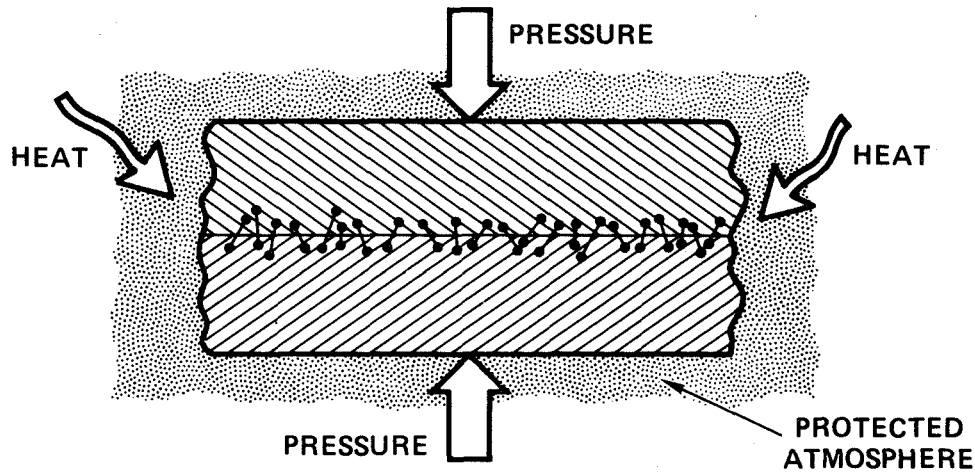
- JOINT PROPERTIES ARE SAME OR VERY SIMILAR TO THOSE OF BASE ALLOY

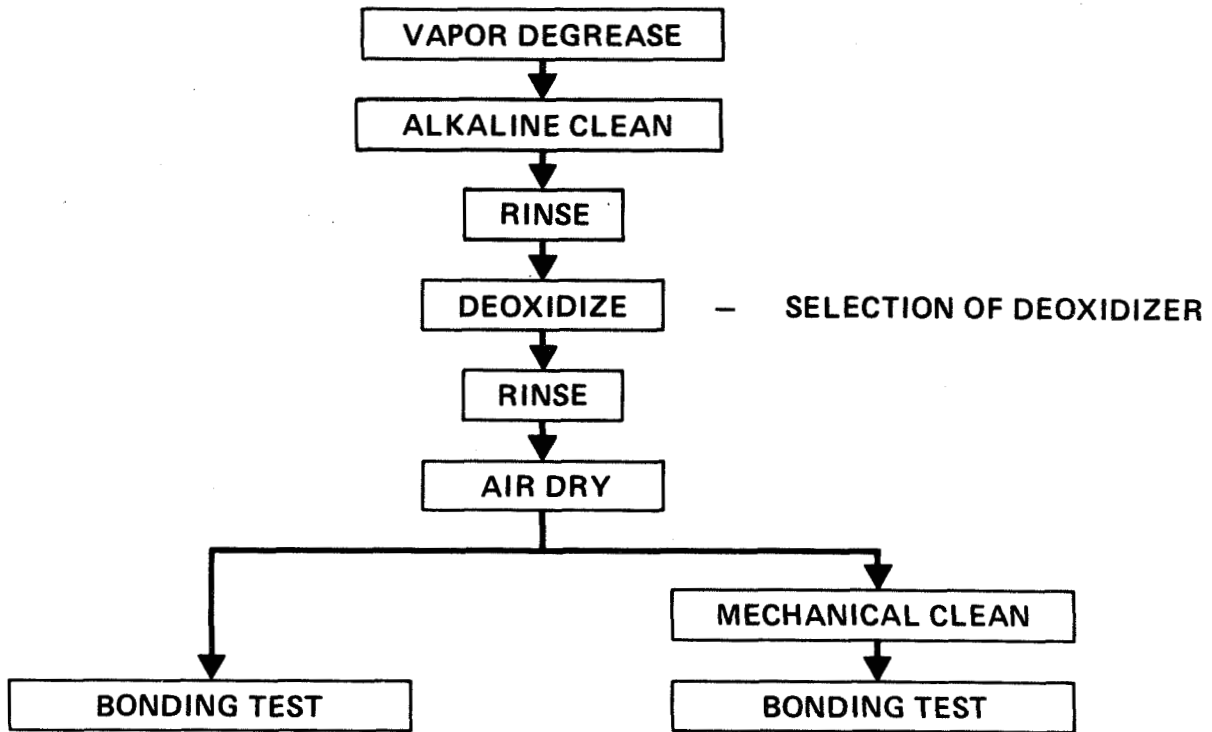- IT IS APPLICABLE TO UNWELDABLE ALLOYS

In solid-state bonding two cleaned pieces of metals are put together with pressure applied normal to the bond interface at elevated temperature. Bond interface has to be protected from oxidation in either vacuum or inert gas. It is generally believed that solid-state bonding is completed through two stages. At the first stage plastic flow disrupts oxide film to expose the clean metallic surface and produces intimate contact. Bonding is established by atomic inter-diffusion and recrystallization and/or grain growth across bond interface at the second stage.

PROCESS PARAMETERS FOR SOLID-STATE BONDING

- SURFACE CLEANING

- AMOUNT OF DEFORMATION

- INTERMEDIATE LAYER

- BONDING TIME

- POSTBOND HEAT-TREATMENT

- BONDING TEMPERATURE

- BONDING PRESSURE

- ATMOSPHERE

The process parameters investigated are surface cleaning, amount of deformation, intermediate layer and bonding time. Besides these parameters there are three more important variables in the solid-state bonding process: bonding temperature, bonding pressure and atmosphere; these were kept constant by superplastic forming conditions in our bond experiments.

SURFACE CLEANING PROCEDURE

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                    ┌─────────────────────┐
                    │   VAPOR DEGREASE    │
                    └─────────────────────┘
                               │
                               ▼
                    ┌─────────────────────┐
                    │   ALKALINE CLEAN    │
                    └─────────────────────┘
                               │
                               ▼
                        ┌──────────────┐
                        │    RINSE     │
                        └──────────────┘
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                    │    DEOXIDIZE     │   ─   SELECTION OF DEOXIDIZER
                    └──────────────────┘
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                        ┌──────────────┐
                        │    RINSE     │
                        └──────────────┘
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                  │                       │
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                  │            │  MECHANICAL CLEAN   │
                  │            └─────────────────────┘
                  ▼                       ▼
      ┌─────────────────────┐  ┌─────────────────────┐
      │   BONDING TEST      │  │    BONDING TEST     │
      └─────────────────────┘  └─────────────────────┘
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Surface cleaning of the as-received aluminum alloy 7475 sheets was started with vapor degreasing followed by alkaline cleaning to remove oil and other dirts. Surface oxide film was removed through a deoxidizing process. Mechanical cleaning subsequent to chemical cleaning was beneficial to solid-state bonding of alloy 7475.

LAP SHEAR SPECIMEN

FLAT BOTTOM NOTCHES (1/16 INCH WIDE)

0.5 INCH

3.0–3.5 INCHES
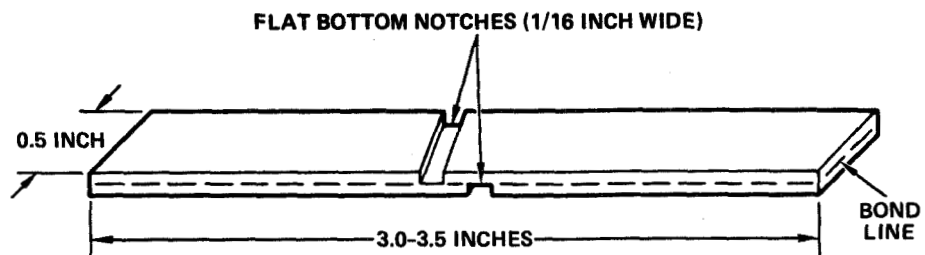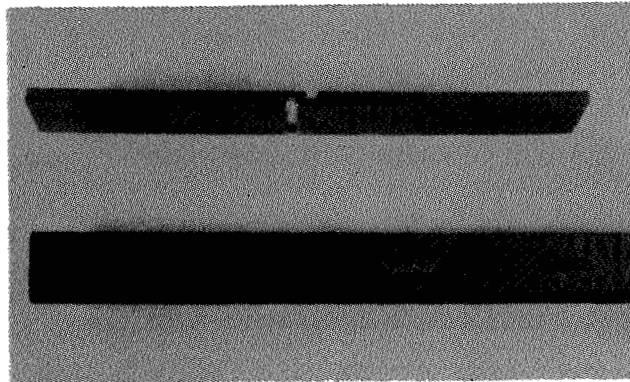
BOND
LINE

A single shear test was chosen to measure bond equality. The test specimen
was designed to break at lap joint between two flat bottom notches when it was
pulled lengthwise.

EFFECTS OF INTERMEDIATE LAYERS AND AMOUNT OF DEFORMATION ON BOND STRENGTH

BOND SHEAR STRENGTH (PSI X 1,000)
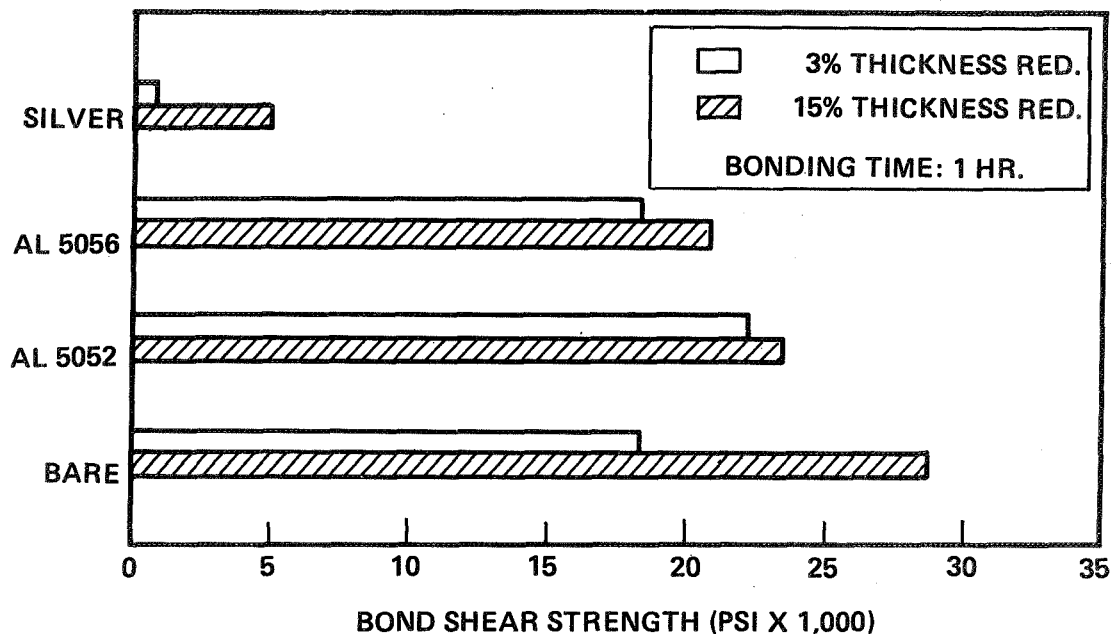
Three different types of intermediate layers were investigated as bonding aids, and the bond strength results were compared with self-bonding of alloy 7475. With low bond deformation a thin layer of alloy 5052 produced the highest bond strength. Electroplated silver did not aid solid-state bonding of alloy 7475. Bond quality with alloy 5056 foil as an interlayer was slightly lower than that with alloy 5052 intermediate layer.

Bond lap shear strength was significantly increased with increasing bond deformation from 3% to 15% in terms of total thickness reduction. This deformation effect on bond strength was most pronounced in self-bonding without using any intermediate layer. Since bonding with high deformation was considered to limit the application, solid-state bonding of alloy 7475 with alloy 5052 intermediate layer which reduced the amount of required bond deformation was selected for further investigation.

COMPLETION OF SOLID-STATE BONDING

AS-POLISHED   100X   KELLER'S   100X

BOND LINE
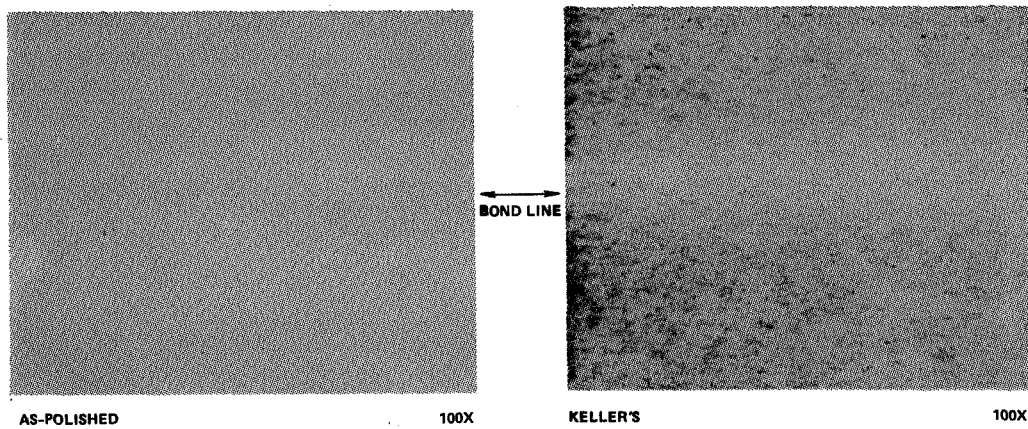
The photomicrographs show a solid-state bond of alloy 7475 with the inter-
mediate layer of alloy 5052 foil as a bonding aid. Microstructure is
continuous over bond interface without showing any significant interface voids
or detectable original bond line.

CHEMICAL COMPOSITION OF BASE
AND FILLER ALLOYS

ELEMENTS	ALLOY 7475 (WT. %)	ALLOY 5052 (WT. %)
SILICON	0.04	0.12
COPPER	1.45	0.04
MANGANESE	0.01	0.04
MAGNESIUM	2.50	2.35
CHROMIUM	0.20	0.20
ZINC	5.70	0.06
TITANIUM	0.02	0.01
ALUMINUM	REMAINDER	REMAINDER

When the chemical composition of filler alloy 5052 is compared with that of base alloy 7475, the major differences between two alloys are the contents of copper and zinc. Therefore, concentrations of these two elements were analyzed at the joint area.

ELEMENT DIFFUSION PROFILE
ACROSS BOND INTERFACE
(INTERMEDIATE LAYER: Al 5052)

COPPER   ZINC
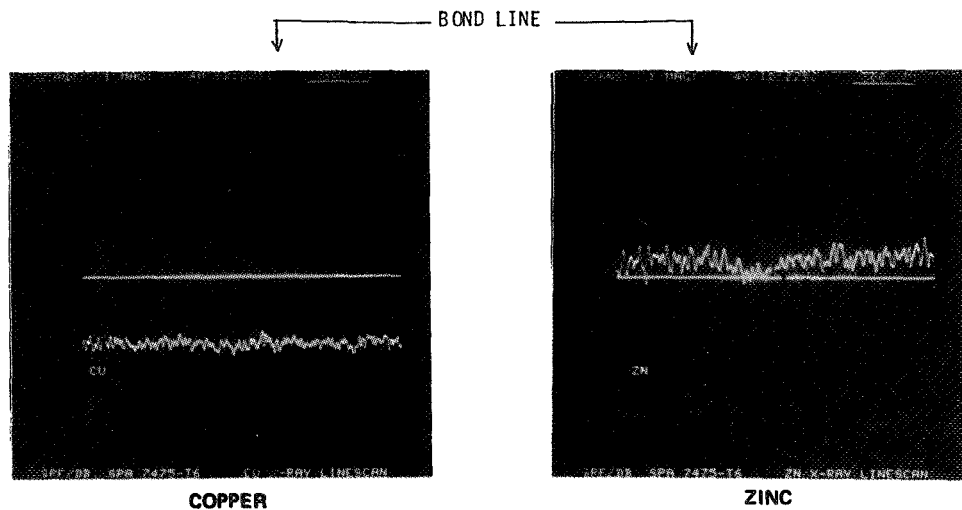
X-ray line scan analyses were made for the elements copper and zinc to obtain qualitative diffusion profiles. A bonded specimen was placed on a scanning electron microscope. Using an x-ray line scan system, diffusion profiles for copper and zinc were determined across the bond interface. The solid white lines in the photos show the electron beam path for each analysis. The line profile for the element zinc shows a concentration decrease at the bond area where alloy 5052 was interlayed while the line profile for the element copper does not indicate any change across the bond line.

QUANTITATIVE ANALYSIS OF ZINC
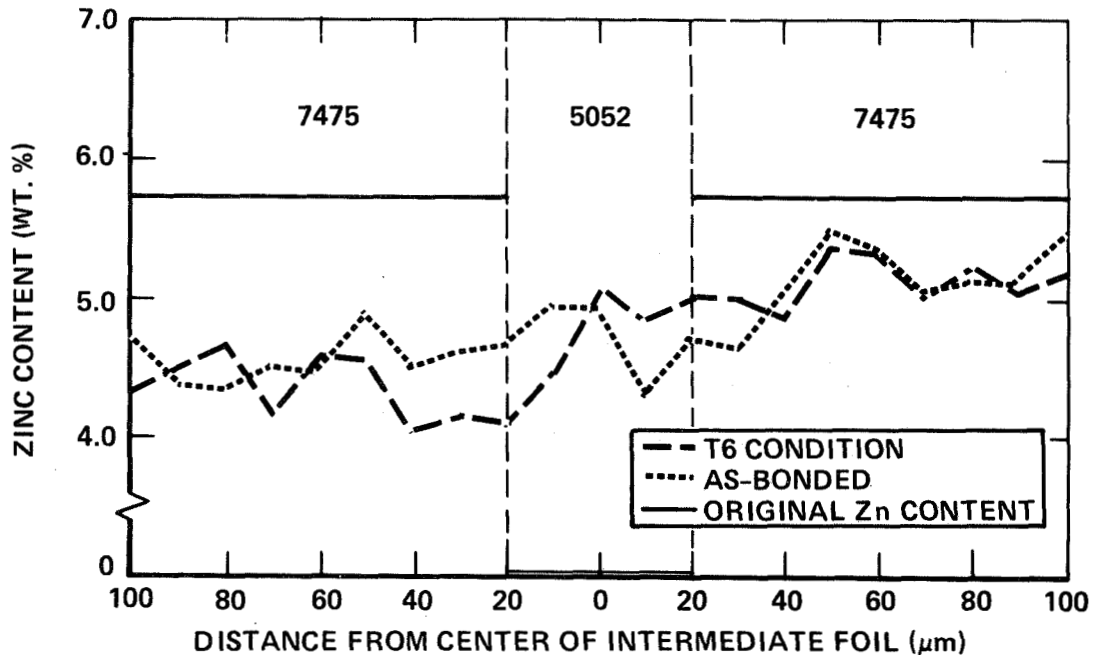
With concern over the concentration drop of zinc as seen, quantitative
analyses were performed. Energy dispersive x-ray analyses were conducted
at 10 μm steps, then the data obtained were reduced by a computer to give
quantitative weight percent. Zinc contents ranged from 4.5 wt % to
5.5 wt % while the original zinc content was 5.7 wt % in alloy 7475 and
0.06 wt. % in alloy 5052. The diffusion profiles clearly indicate elements
inter-diffused across interfaces during the solid-state bonding. Post bond T6
heat treatment did not significantly change the diffusion profile of zinc at
the joint.

MICROSTRUCTURE AND MICROHARDNESS
OF SOLID-STATE BONDED SPA 7475
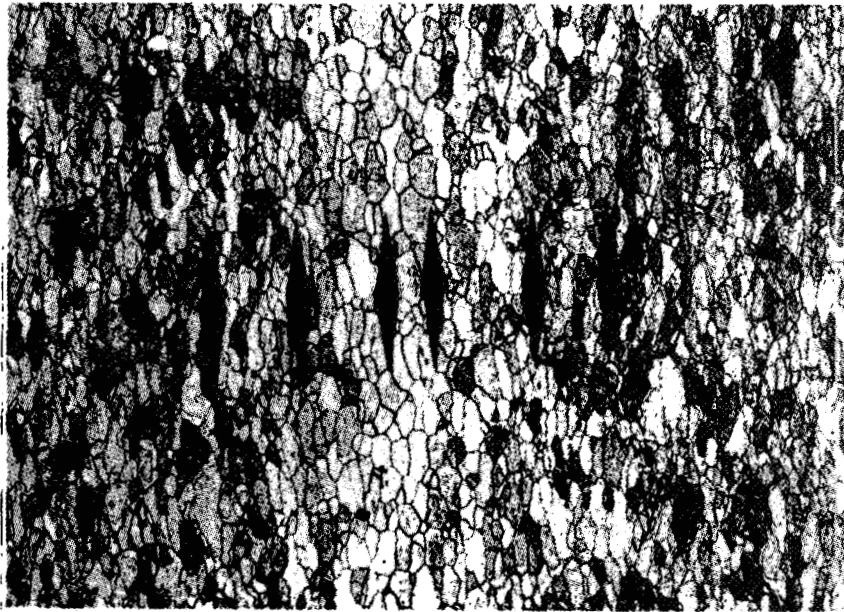
| KELLER'S | | | | | | | 200X |

KNOOP HARDNESS NUMBER   120   112   113 114   110   108

Knoop hardness numbers at the joint ranged from 108 to 120, which are somewhat
lower than the hardness number that one can expect from the base alloy 7475.
The microhardness numbers were closely related to the content of zinc. The
photo shows the details of microstructure for perfectly bonded alloy 7475 as
well as dark indentations from microhardness testings.

BONDING TIME VS. BOND STRENGTH
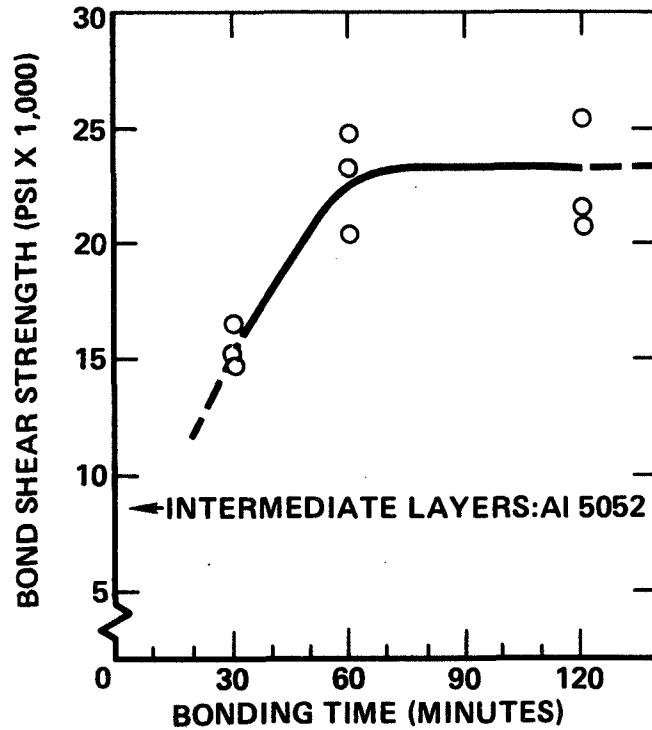
The bond experiment started with 60 minutes bonding time. Bond shear strength sharply decreased with reducing the bonding time from 60 minutes to 30 minutes. When the bonding time was increased from 60 minutes to 120 minutes, no change of bond strength was observed. Although the data are not enough to determine the optimum bonding time, 60 to 90 minutes is considered to be enough bonding time to produce sound bonding of alloy 7475.

EFFECT OF POSTBOND HEAT-TREATMENT
ON BOND STRENGTH
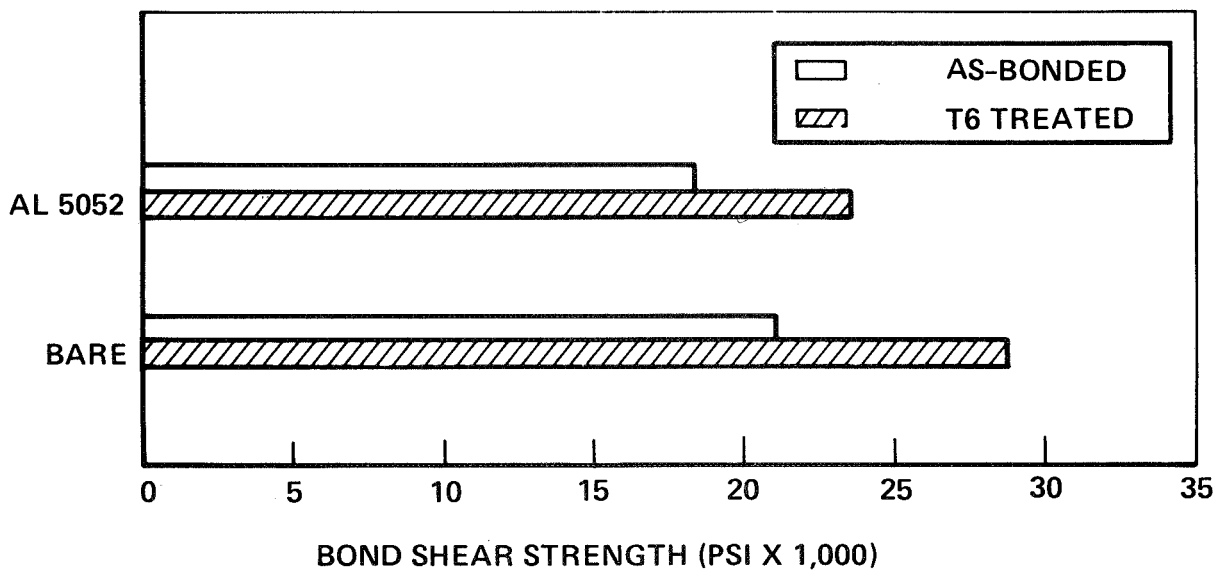
Solid-state bonded structure responded well to postbond T6 heat-treatment with substantial increase of bond strength. The heat-treatment response was more distinct in self-bonding than in the bonding with the intermediate layer. This can be explained by the zinc concentration decrease at the joint when alloy 5052 was used as bonding aid.

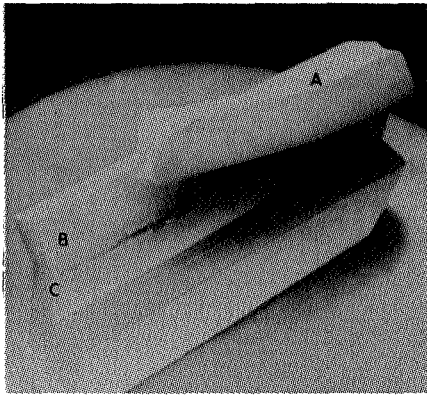# SEM FRACTOGRAPHS OF BONDING INTERFACE
(BOND SHEAR STRENGTH:15,000 PSI)
SHOWING INSUFFICIENT BONDING
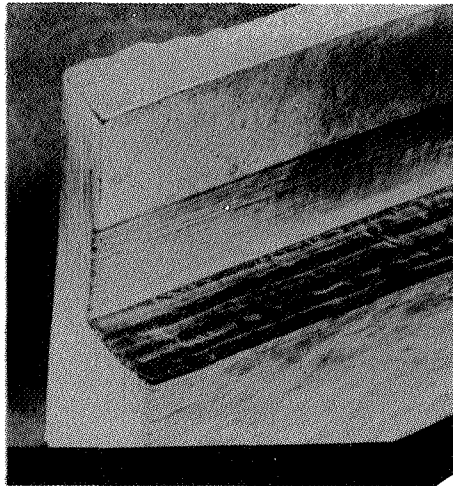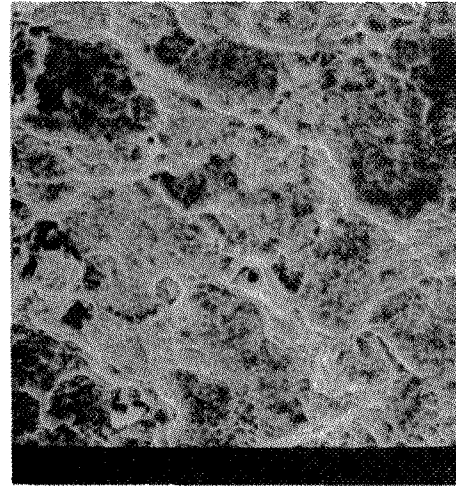

20X   1000X

Fractographic analysis of the failed bond interface characterizes integrity of the solid-state bond. Lap-sheared bond specimens were examined on a scanning electron microscope for this purpose. In the above fractographs fracture occurred along the bond interface, and significant areas of the fractured surface are essentially featureless. These fractographic features indicate that the bonding was not sufficient. The bond strength of the shear specimen used here was 15,000 psi.

SEM FRACTOGRAPHS OF BONDING INTERFACE SHOWING SOUND BONDING
(BOND SHEAR STRENGTH: 30,000 PSI)


10X

BONDING PLANE = B
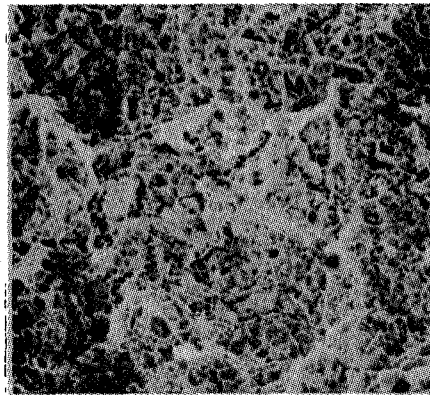
1000X

PLANE B

Another lap sheared specimen which represents 30,000 psi bond strength was chosen for SEM fractographic analysis. Here fracture occurred both at bond interface (Plane B) and at parent alloy (Plane A). A secondary crack, which is indicated as C, was also observed at the corner of a machined notch. Examination of Plane B with higher magnification revealed a typical failure mode of overload dimpled rupture by microvoid coalescence. This failure mode of ductile rupture is a good indicator for a completed bonding with good integrity.

246

APPLICATIONS FOR SOLID-STATE BONDING

- ELECTRONIC COMPONENTS

- NUCLEAR REACTORS

- MISSILES

- AIRCRAFT STRUCTURES

    - AS A JOINING METHOD FOR
      UNWELDABLE ALLOYS

    - AS A CONCURRENT PROCESS
   WITH SUPERPLASTIC FORMING

The applications of solid-state bonding are found in the industries where
stringent joint requirement is necessary and high joint efficiency is re-
quired. Solid-state bonding or diffusion bonding of titanium has been uti-
lized for aircraft structural parts. The ultimate goal of this program is to
develop solid-state bonding technology as a concurrent process with superplas-
tic forming of high strength alloy 7475 for aircraft structural application.

GRAIN STRUCTURE OF SUPERPLASTIC ALUMINUM 7475

LT   L

MAG 250X

ST
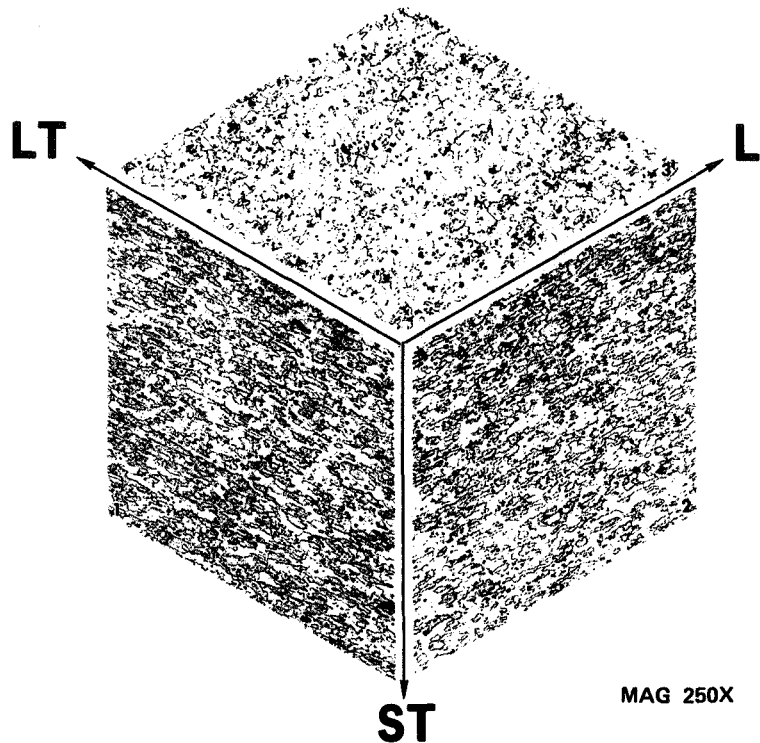
The photomicrograph shows a three-dimensional grain aluminum 7475 alloy sheet, which was used in the bonding experiments. Conventional aluminum alloy sheets are not superplastic because of coarse grains. Thermo-mechanical process can effectively reduce the grain size of the 7475 alloy to a sufficiently small size and stable state to permit the development of superplastic deformation. The grain size of the alloy shown in the photo is approximately 10 μm.

248

DEFORMATION CHARACTERISTICS OF SUPERPLASTIC ALUMINUM 7475
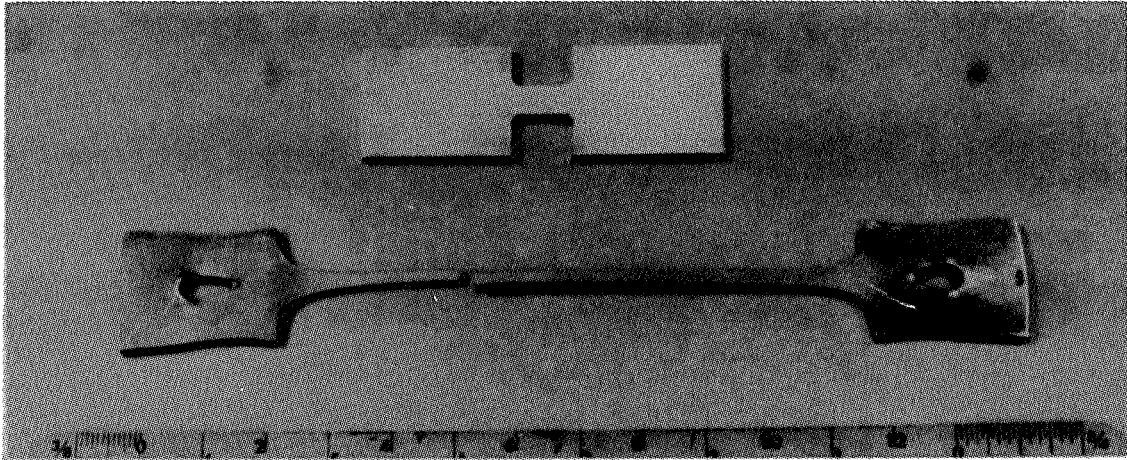
Superplastic behavior is characterized by extremely high elongation before necking occurs. When a tensile specimen of fine-grained 7475 alloy was tested at 960° F at a controlled strain rate, the total elongation was approximately 950% at fracture.

INTEGRALLY STIFFENED STRUCTURES
FOR POTENTIAL SPF/SSB APPLICATION
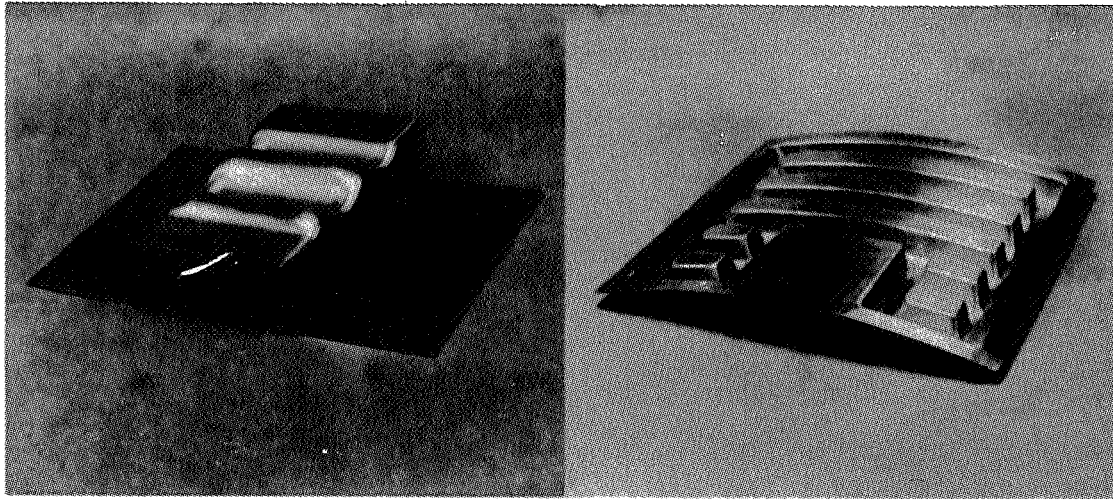
Superplastic forming of aluminum will result in reduction of number of details and fasteners, which consequently leads to cost and weight savings. When the solid-state bonding is combined with the superplastic forming process, further gains will be realized. Two integrally stiffened structures of high strength aluminum which were superplastically formed are the examples of potential superplastic forming solid-state bonding because these formed parts have to be eventually joined to skin sheet.

CONCLUSIONS

1. Feasibility of solid-state bonding was demonstrated for superplastic aluminum 7475 sheet.

2. Plastic deformation was required to obtain solid-state bonding, and bond strength increased with an increase in the amount of deformation.

3. A thin intermediate layer of alloy 5052 aided the solid-state bonding in reducing the required bond deformation.

ACKNOWLEDGMENT