Using Solid-State Joining in Gas Turbine Engines

D. C. MARTIN
Section Manager,
Materials Processing and Fabrication,
Battelle Memorial Institute,
Columbus, Ohio

F. R. MILLER
Senior Project Manager,
Air Force Materials Laboratory,
Manufacturing Technology Division,
Fabrication Branch,
Wright-Patterson Air Force Base,
Columbus, Ohio

The ability to fabricate materials and components needed to improve gas-turbine engine performance depends on an ability to achieve reliable joints. Solid-state joining provides this ability. Diffusion bonding of compressor blades, friction welding of engine rotors, and solid-state bonding of turbine shafts by coextrusion of dissimilar metals are discussed as examples of applications of solid-state bonding. Parts made by these techniques have successfully completed engine tests.


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INTRODUCTION

The continuing development of advanced aircraft gas turbine engines with emphasis on improved thrust-to-weight ratios and specific fuel consumptions, resulting in increased turbine inlet temperatures, imposes a requirement for continued development of new manufacturing processes for producing the advanced engine designs. Higher engine performance through the utilization of advanced materials at reduced weight and a reduction in the complexity of engine cooling requirements are worthy design objectives. The ability to utilize the advanced materials throughout the engine where specific benefits will be gained from their application is generally known in the engine design phase. The ability to fabricate the particular material to the optimum component design to ultimately attain the design objectives requires an ability to reliably join the material with consistently reproducible joint properties acceptable for the design criteria of the component.

Solid-state joining processes have been studied in considerable detail for use in aircraft gas turbine manufacture over the past few years. Design and material requirements, which could not be met by conventional, established joining processes, instigated these studies.

1 High-strength, cast nickel-base superalloys, such as used in turbine blades and vanes, are unweldable by conventional fusion processes. The microstructure and properties of dispersion-strengthened materials (TD-Ni or TD-Ni-Cr) are destroyed by fusion welding processes. Yet, high-strength reliable joints are often required in components made from these alloys.

2 Solid-state joining eliminates the cast structure found in fusion welds. This permits the solid-state processes to be used in critical applications and where dissimilar metals are joined.

3 Many designs, such as hollow turbine wheels and hollow blades, have complex, inaccessible joints which, nevertheless, require high-strength, efficient weld joints. Such joints can be made by solid-state welding.

4 Quality assurance in critical joints is mandatory. Since no molten metal is formed during joining, solid-state joints are not subject to shrinkage cracks, voids, or large residual welding stresses. Improved process control can be a significant contributor to quality assurance in the solid-state processes.

Inertia welding, diffusion bonding, and co-extrusion are examples of solid-state joining processes which have achieved pilot production or production status. Each has unique advantages and limitations with respect to specific applications, but all are solid-state joining techniques and have the capability of producing joints indistinguishable from the base metal.

SOLID-STATE JOINING

Solid-state joining processes can be divided into two types — diffusion bonding and deformation bonding. Both types are represented in the processes discussed in this paper.

All solid-state joining processes have one problem in common — overcoming the barriers presented by metal surfaces to producing welds by atomic forces acting across the weld interface. The major problem in solid-state bonding is to put...
clean metal surfaces into contact so that the interatomic forces can act. To understand the difficulties involved requires an understanding of a metal surface.

To adequately describe a real surface, there are two dominant characteristics, roughness and impurities, which must be considered. Both of these present the intimate metal-to-metal contact required to produce a solid-state bond. Both must be eliminated if satisfactory bonds are to be achieved. A schematic diagram of a real surface is shown in Fig. 1. On a microscopic scale, surfaces are extremely rough (1, 2). Mechanically prepared surfaces consist of grooves or scratches (3). In addition to these first-order scratches, secondary ridges exist on the faces of the primary scratches. Both the primary and secondary forms of roughness have an obtuse included angle at the peaks of the asperities. FINELY polished, abrasively prepared surfaces are topographically similar to rough surfaces, although the included apex angle of the scratch is believed to be more obtuse. The most highly polished surfaces, for example, will have peak-to-valley distances of roughly 500 Å. Ground surfaces will be many times rougher than this. The initial contact area produced when metallic surfaces are brought together will be very much less than the nominal surface area, possibly 10^-6 times the nominal area. Because of surface roughness, a load, normal to the interface, will be supported by asperities that will plastically deform until the actual area of contact is capable of supporting the applied force. The true area of contact is proportional to the load and is independent of the size or shape of the surfaces.

All metallic surfaces exposed to air are covered with an oxide film 10 to 10^5 Å thick. The thickness of this film will vary with the chemical properties of the metal and the environment. The oxide film on noble metals may only be several atomic layers thick while, on most other metals, it is much thicker. In air, at atmospheric pressure, a monolayer of oxide will form on a surface in about 4 x 10^-9 sec., while at a pressure of 10^-6 torr, approximately 3 sec., are required (4). In addition, occluded layers of gases will be present on the oxide film, and the surface may be contaminated with water, grease, oil, or solid materials which prevent intimate contact of uncontaminated metal.

**Diffusion Bonding**

The welding barrier is overcome in diffusion bonding in two ways — by careful surface preparation prior to welding and by using extended times under load at elevated temperatures. Surface preparation can include polishing to provide smooth surfaces and cleaning to minimize surface oxide layers and surface contaminants. In some cases, electroplates or other thin coatings may be used to drastically change surface conditions. Time under load at elevated temperature is used to rupture surface films, induce asperity collapse, and provide time for diffusion to occur.

**Deformation Bonding**

In deformation bonding, gross plastic flow is used to prepare surfaces for bonding. Surface conditioning may be accomplished by plastic flow alone. Increasing the surface area of the faying surfaces breaks up the oxide skin into islands. Between these islands, uncontaminated metal is brought into intimate contact and welding occurs. The interface area may be heated to make it easier to deform plastically. A thin skin of metal on the faying surfaces may be heated to a high temperature or melted and expelled from the interface. This expelled layer carries with it undesirable surface features.

**Fabricating Hollow Titanium Compressor Blades**

A program carried out by General Electric (5) had as its objective the development of a diffusion-bonding process for assembling hollow titanium compressor blades.

The program was designed to: (a) determine the diffusion-bonding parameters for joining Ti-6Al-4V and determine the mechanical properties of single- and multi-bond joints, (b) manufacture compressor blades with no midspan support and compare with conventionally processed hollow blades, and (c) manufacture compressor blades with midspan support and establish the strength of the blades and the usefulness of the manufacturing technique for a large size blade.

**Diffusion-Bonding Process Parameters**

To establish the bonding parameters for the mechanical test specimens and the fabricated blades, titanium 6Al-4V specimens of various configurations were prepared. The initial bond trial specimens were made from 1 in. square bar stock cut to 1-in. length and the two ends ground parallel with a 32-rms finish. Based on previous bonding work, the surfaces were prepared by light sanding, vapor hone, cleaned in methyl ethyl ketone (MEK), pickled in 5%HF-15%HNO — balance H2O water rinsed, air dried, then heated in a vacuum of 9 x 10^-6 torr. The specimens were bonded using two pressure levels, various combina-
tions of time and temperature, and at different amounts of upset. Metallographic examinations were used to evaluate the bonds obtained.

The maximum temperature used was just below the beta transformation temperature of the material, and the maximum time evaluated was established as an economical consideration. The pressure, or its resultant upset, was limited by the end product tolerances and finished shape and controlled by positive stops. In general, the test showed that, as the temperature was decreased, the quality of the bond joint became unacceptable even with times up to 2 hr.

The results of these investigations are summarized in Fig. 2. This figure shows that the total upset required for 100 percent bonding increases as thickness increases, but that 100 percent bonding is obtained at about 2 percent upset regardless of thickness. Other experiments showed that for surfaces finished rougher than 32 rms, higher deformations were required to obtain 100 percent bonding.

Evaluation of Mechanical Properties of Diffusion-Bonded Specimens

After the preliminary tests were completed, a number of specimens were made to compare the mechanical properties of diffusion-bonded material and parent material.

The following bonding procedure was used with titanium 6-4Al alloy. The mating surfaces to be bonded were prepared by:

1. Grinding to a 32 rms (or better) surface finish
2. Lightly sanding
3. Vapor honing
4. Cleaning in methyl ethyl ketone (MEK)
5. Pickling in 5%HF-15%HNO₃-80%H₂O solution followed by a water rinse and air dry.

The blocks were then:

1. Diffusion bonded at 1650°F for 1 hr in vacuum under an initial applied pressure of 1000 psi to result in a 5 percent height deformation.
2. Then given a 1650°F vacuum heat treatment for 16 hr, although this step was deleted on some specimens to determine the effect on properties.
3. The desired specimens machined
4. These specimens given the 1300°F vacuum standard anneal for 1 hr.

Some samples were given a post-bonding heat treatment of 16 hr at 1650°F to improve the fracture toughness of the welds.

A large number of mechanical-property tests
were made. Included were:

1. Tensile
2. WOL fracture mechanics
3. Static shear
4. Torsional shear
5. Shear bend fatigue
6. 45-deg angle bond fatigue
7. Rotating beam fatigue
8. Axial fatigue.

The data obtained from these tests indicated that the mechanical properties of the diffusion-bonded specimens were nearly equivalent to those of the parent material.

**Large Compressor Blades**

The final objective of this program was the application of the information generated in the preceding work to the manufacture of a large compressor blade with a mid-span support.

Figs. 3, 4, and 5 depict the fabrication approach. Fig. 6 shows a bonded and machined blade. This figure also depicts the parts and steps used to produce the blade.

The blades produced on this program were tested to establish the integrity of a fabricated diffusion-bonded airfoil by:

1. Ballistic impact
2. Bench fatigue
3. Whirligig fatigue
4. Stress deflection
5. Microexamination.

A primary requirement for compressor blading is to be able to withstand impact of particles which the blade is likely to encounter in service. To evaluate this characteristic, two blades manufactured by the fabricated technique were impact tested. Although rigid examination of ballistic impact limits was not attempted, critical areas of the test blades were subjected to impact. This was accomplished by firing 1/4-in.-dia steel projectiles at a velocity of 600 fps at the desired impact locations. The angle of impact was approximately 90 deg to the leading edge. In no case did the impacts cause any separation of the bond joint but exhibited plastic deformation as a solid homogeneous material. The critical area for F.O.D.
A cost comparison shown in Table 1 was made between the previous method of manufacturing hollow titanium blades and the fabricated method as established under this program. The values used for the fabricated method of manufacture have been adjusted by a 90 percent learning curve on labor to bring the actual cost incurred to the same quantity cost level as exist for cost data on the forged and bonded method.

**FRICITION WELDING OF GAS TURBINE ENGINE ROTORS**

The use of integral multi-stage rotors, rather than individual stages bolted together, provides significant weight savings and reliability improvement in gas turbines.

Present methods of manufacturing integral rotors start with a bulky forging and machine away the excess metal to obtain the desired configuration. This practice is extremely wasteful of material for as much as 90 weight percent of the forging can be converted to chips and turnings. In a program carried out at General Electric (6), inertia welding (friction welding) was used to fabricate experimental multi-stage rotors. Other work on friction welding of gas turbine parts has been carried out by Pratt and Whitney (7). The principal objective of the General Electric program was to develop an improved fabrication method based on inertia welding individual disks together to form an integral multi-stage rotor. The benefits anti
cipated were:

1. Maximum utilization of expensive material produced at minimum cost by using cross-rolled plate for disk fabrication
2. Solid-state bonded joints with mechanical properties equal to or better than parent metal
3. More uniform properties throughout the rotor by using heavily worked cross-rolled plate in place of bulky forgings.

Inertia Welding Process

Inertia welding is a solid-state bonding process which produces bonding by upsetting parts heated by friction obtained from rubbing two mating surfaces. The process is based on rotating one part at relatively high controlled speeds against a stationary member to which it is to be joined.

Inertia welding uses a stored and predetermined amount of rotational kinetic energy applied to one workpiece, plus axial pressure to weld onto a stationary second workpiece. Most of the energy is converted to heat by frictional rubbing of the workpieces at the interface; the balance is converted to mechanical energy in forging an upset weld. Any melted metal produced is expelled along with surface oxides, contaminates, and the most plastic solid metal into a flash formed by the upset.

With an established flywheel size, there are only two parameters to control, thrust and speed, which leads to good process reproducibility. Once correct weld conditions have been established based on mechanical property tests, microexamination, visual examination of the size and nature of the flash and nondestructive inspections, the amount of weld upset by length reduction of the weldment is the basic quality control technique for welds. Any large differences in upset will usually indicate a machine malfunction or some change in the workpieces.

Parametric Studies

A statistical testing plan designed to analyze the interactions of the process variables with a minimum of testing was used in parametric studies of inertia welding Inconel 718, Udiment 700 and Ti-6Al-4V. The plan was based on a $3 \times 2 \times 3$
factorial experiment with the factors tested at unequally spaced levels. The variables selected were three levels of flywheel moment of inertia, two levels of surface speed, and three levels of pressure. The significant results for each alloy studied are presented in the following:

1 Inconel 718: The parametric study of Inconel 718 was done on 1-in. OD x 0.100- and 0.200-in. wall cylinders using the following parametric ranges:
   a. Moment of inertia, 4.4 to 19.5 lb-sq ft
   b. Angular velocity, 1600 to 7200 rpm
   c. Surface velocity, 420 to 1900 sfm
   d. Upset pressure, 32 to 48 ksi
   e. Actual energy input, 23,300 to 38,900 ft-psi

   Statistical analysis of the test data showed that flywheel moment of inertia had little influence on the amount of upset or weld quality. The best welds were made with angular velocity and ram pressure at the low end of their ranges, i.e., actual energy inputs of 23,300 to 24,400 ft-psi and upset pressures of 32 and 38 ksi.

2 Udimet 700: One-in. OD x 0.100-in. wall cylinders of Udimet 700 were inertia welded using the following parametric ranges:
   a. Moment of inertia, 3.9 to 19.0 lb-sq ft
   b. Angular velocity, 1600 to 5200 rpm
   c. Surface velocity, 420 to 1400 sfm
   d. Upset pressure, 32 to 48 ksi
   e. Actual energy input, 25,100 to 38,800 ft-psi

   Similar to the Inconel 718 results, statistical analysis of the data showed moment of inertia was not very significant, and the best welds were made with the low energy inputs and upset pressure, 25,000 ft-psi and 32 to 38 ksi respectively.

3 Ti-6Al-4V: One-in. OD x 0.300-in. wall cylinders were inertia welded using the following parametric ranges:
   a. Moment of inertia, 1.8 to 3.9 lb-sq ft
   b. Angular velocity, 5000 to 8000 rpm
   c. Surface velocity, 1310 to 2100 sfm
The statistical analysis indicated upset pressure was least significant while moment of inertia and angular velocity were significant. Best welds were made at low energy levels, 6700 to 12,800 ft-psi.

Inconel 718 Diameter and Wall Thickness Study

To determine the effect of diameter and wall thickness on the amount of upsetting obtained under various energy inputs and contact pressures, 4-, 12-, and 24-in.-dia cylinders of various wall thicknesses were prepared. Inertia welding parameters were varied by changing ram loads, flywheel moments of inertia, and contact...
welding speeds. Wall thicknesses ranged from 0.070 to 0.375 in. All cylinders were solution treated and aged before welding.

Initial attempts to correlate upset, diameter, and wall thickness with energy input and contact pressure led to the plots of upset as a function of unit energy input.

These plots showed: (a) for a given diameter, wall thickness and contact pressure, the total upset appeared to be a straight line function of the unit energy input; (b) the slopes of the straight lines appeared to be nearly the same; and (c) upset pressure and unit energy input varied inversely for a given upset. Since energy and pressure appeared to vary inversely with total upset, the product of total load and total energy

Fig. 8 Load X energy for zero upset versus weld joint area — Inconel 718
Table 1 Cost Comparisons

<table>
<thead>
<tr>
<th>Operation</th>
<th>Stage 1 Blade Current Method</th>
<th>Fabricated Method</th>
<th>Stage 3 Blade Current Method</th>
<th>Fabricated Method</th>
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<tr>
<td></td>
<td>% of total cost</td>
<td>% of total cost</td>
<td>% of total cost</td>
<td>% of total cost</td>
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<tr>
<td></td>
<td>cumulative</td>
<td>cumulative</td>
<td>cumulative</td>
<td>cumulative</td>
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<td>Airfoil raw stock</td>
<td>23</td>
<td>3</td>
<td>11</td>
<td>5</td>
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<td>Machine airfoil raw stock</td>
<td>36</td>
<td>9</td>
<td>23.5</td>
<td>5</td>
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<td>Form airfoil</td>
<td>2</td>
<td>1</td>
<td>2</td>
<td>2</td>
</tr>
<tr>
<td>Machine cavity</td>
<td>2</td>
<td>7</td>
<td>4</td>
<td>6</td>
</tr>
<tr>
<td>Machine mean camber</td>
<td>20</td>
<td>N.R.</td>
<td>24.5</td>
<td>N.R.</td>
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<tr>
<td>Bond airfoil</td>
<td>3</td>
<td>3</td>
<td>6</td>
<td>24</td>
</tr>
<tr>
<td>D/T and M/S raw stock</td>
<td>N.R.</td>
<td>2</td>
<td>N.R.</td>
<td>2</td>
</tr>
<tr>
<td>Machine D/T &amp; M/S raw stock</td>
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<td>8</td>
<td>N.R.</td>
<td>7</td>
</tr>
<tr>
<td>Bond D/T and M/S</td>
<td>N.R.</td>
<td>6</td>
<td>N.R.</td>
<td>6</td>
</tr>
<tr>
<td>Finish machine blade</td>
<td>14</td>
<td>14</td>
<td>30</td>
<td>69</td>
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</table>

Table 2 Summary of Weld Parameters and Results For Rotor No. 5

<table>
<thead>
<tr>
<th>Run No.</th>
<th>Stage Nos.</th>
<th>Weld RPM</th>
<th>Speed SFM</th>
<th>Weld Pressure PSI</th>
<th>Weld Time Sec.</th>
<th>Max. Energy Ft-Lbs/in²</th>
<th>Total Upset Inch</th>
<th>Total Indicated Face (in)</th>
<th>Run Out Dia. (in)</th>
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</thead>
<tbody>
<tr>
<td>400-0-102</td>
<td>Test Rings</td>
<td>246</td>
<td>1550</td>
<td>35,800</td>
<td>2.8</td>
<td>25,200</td>
<td>0.091</td>
<td>0.0055</td>
<td>0.005</td>
</tr>
<tr>
<td>400-9-103</td>
<td>Test Rings</td>
<td>245</td>
<td>1540</td>
<td>35,100</td>
<td>2.5</td>
<td>24,500</td>
<td>0.069</td>
<td>0.004</td>
<td>0.020</td>
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<tr>
<td>400-9-104</td>
<td>Test Rings</td>
<td>250</td>
<td>1570</td>
<td>35,200</td>
<td>2.6</td>
<td>25,600</td>
<td>0.092</td>
<td>0.007</td>
<td>0.020</td>
</tr>
<tr>
<td>400-9-105</td>
<td>Test Rings</td>
<td>252</td>
<td>1585</td>
<td>36,000</td>
<td>2.9</td>
<td>26,000</td>
<td>0.092</td>
<td>0.007</td>
<td>0.012</td>
</tr>
<tr>
<td>400-9-106</td>
<td>14-15</td>
<td>251</td>
<td>1580</td>
<td>35,500</td>
<td>2.8</td>
<td>26,000</td>
<td>0.084</td>
<td>0.002</td>
<td>0.0065</td>
</tr>
<tr>
<td>400-9-107</td>
<td>14-15-16</td>
<td>249</td>
<td>1560</td>
<td>37,500</td>
<td>2.8</td>
<td>25,500</td>
<td>0.072</td>
<td>0.011</td>
<td>0.004</td>
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</table>

Flywheel WR² = 32,500 lb-ft²

input (corrected for efficiency) was plotted for each diameter and wall thickness as a function of total upset on semi-logarithmic coordinate paper. As shown in Fig. 7, most of the data points for a given diameter and wall thickness (weld joint area) fall on straight lines of the same slope having the general equation:

\[ y = C \cdot 10^{mx} \]

where

\[ y = \text{load total energy} = L \cdot E_t \]
\[ x = \text{total upset} = U \]
\[ C = \text{value of } y \text{ at } x = 0 \]
\[ m = \text{slope} = \text{scale value of the paper} = \frac{0.126}{0.09} = 1.4. \]

Values of C for each diameter and wall thickness were then plotted on logarithmic coordinate paper.
as a function of weld joint area, Fig. 8. The equation of the straight line was determined to be:

\[ y = Kx^n \]  

(2)

where

- \( y \) = load total energy for 0 upset
- \( x \) = weld joint area = \( A \)
- \( K \) = value of \( y \) at \( X = 1 \)
- \( n \) = slope = 1.987.

By substituting "y" from equation (2) for "C" in equation (1), a single equation relating upset to joint area and the load and energy product was obtained.

\[ L.E_t = k A^n \cdot 10^mU \]  

(3)

or

\[ E_t = \frac{6.45 \times 10^8 A^{1.987}}{L} \cdot 10^{1.40} \]  

(4)

where

- \( E_t \) = total energy input (corrected for efficiency), ft-lb
- \( L \) = total ram load, lb
- \( A \) = weld joint area, sq in.
- \( U \) = total upset, in.

The values of the constants, \( k \), \( m \), and \( n \), in equation (3) reflect not only Inconel 718 material properties, such as strength, thermal conductivity, coefficient of friction, etc., but are also somewhat dependent on the tubular joint geometry, including weld prep design which was quite similar for all diameters and wall thicknesses studied. While the general form of equation (3) should be applicable to the inertia welding of materials other than Inconel 718, the values of \( k \), \( m \), and \( n \) would have to be determined from welding studies similar to those herein described.

**Compressor Rotor Fabrication**

Rotors were experimentally fabricated from both Inconel 718 plate which had been cold flanged to provide outside edge preparation and from Inconel 718 forged disks. Rotors made from plate stock were found to contain cracks after machining. While the cause of the cracking was not conclusively determined, it is believed that the following were all contributing factors:

1. Excessive grain size of cross-rolled plate
2. Improper machining of weld flash
3. Improper acid etch cleaning.

All of these factors can be controlled or modified, and, therefore, the cracking should be preventable.

Sound experimental rotors were made from forged disks. Since previous metallographic studies had shown the presence of liquated phases in Inconel 718 inertia welds made at high angular velocities, the flywheel moment of inertia was increased from 26,038 to 32,500 lb-sq ft, thereby allowing some reduction in welding speed. Three sets of 24-in.-dia test rings welded in the wall thickness-diameter study were cut apart and remachined for additional test piece welds.
Welding of the three ring sets and test disks from two forgings showed no significant changes in the welding parameters, maximum input energy and welding pressure, from those used for cross-rolled plate. The two rotor welds were then made with good dimensional and upset results. Table 2 summarizes the parameters and results. The welded rotor is shown in Fig. 9. A close-up view of the two weld joints is shown in Fig. 10.

The rotor was machined and then aged in vacuum using controlled heating and cooling rates of 200°F/hr to reduce any possibility of warpage or distortion of the nearly finished machine rotor. The standard Inconel 718 aging cycle of 8 hr at 1325°F + 8 hr at 1150°F was used. Dimensional inspection after aging showed that no significant changes or distortion had occurred, and x-ray inspection showed no defect indications. The finished machined rotor is shown in Fig. 11.

Other rotors have been successfully welded, spin tested, and run in a test engine.

DEVELOPMENT OF METHOD OF MANUFACTURING BIMETAL SHAFTS

Modern military aircraft engines are dual-axial compressor engines (twin-spool engines) and consist essentially of two independent rotor systems. One turbine stage or a set of turbine stages drives the high-pressure compressor, and the balance of the turbine stages drive the low-pressure compressor. The low-pressure compressor is joined to the rear stages of the turbine by a shaft (the low-pressure turbine shaft) passing through the center of the high-pressure compressor and turbine assembly drive shaft (the high-pressure turbine shaft). This arrangement is illustrated in Fig. 12.

The ideal low-pressure turbine shaft would be made from two joined materials — an alloy with high fatigue and high yield strength at the cold end, and a material with high fatigue strength, high creep strength, and corrosion resistance at...
the hot end. Such a bimetal shaft would be lighter in weight, and, with no cooling requirement, the complexity of the cooling air system would be effectively reduced.

In the past, bimetal joints have been avoided in high-performance parts for a number of good reasons — a major one being the lack of a suitable method of making the joint. A successful method of making and heat treating a bimetal engine shaft was developed at Pratt and Whitney Division, United Aircraft Corporation (8).

Joining and Testing of Bimetal Joints

Five processes were evaluated for making bimetal shafts from AMS6304 and Inconel 718. These were:

1. Coextrusion, including seal welding plus coextrusion
2. Inertia welding
3. Friction welding
4. Flash-butt welding
5. Electron-beam welding.

Data on a number of the mechanical properties of a material, over the temperature range it will encounter, are needed to complete a shaft design. It would have been impractical (in terms of time and expense) to obtain these data each time parameters were varied during optimization. A single, easily measured criterion was required. The ultimate strength of the joint was selected, and a value of 130 ksi in tension at room temperature was assigned as the acceptance level. This value was expected to provide a joint suitable for engine-operating conditions.

Specimens were joined and tested to see if they met the criterion. Some initial joints were rejected by visual examination or by visual examination after breaking. Joints which were visually acceptable were tested in tension or shear to measure their strength.

The results of these evaluations showed that coextrusion was the best method for making bimetal shafts.

Coextrusion Process

The coextrusion process produces a metallurgical bond between the two materials being joined by forcing the materials through an extrusion die at an elevated temperature and reducing the cross-sectional area. This forms a characteristic tapered joint interface and provides the shearing force between the two materials necessary to make a strong joint. It is important that the surfaces which form the joint interface be protected from contamination during the heating and extruding cycles. This protection is accomplished by placing the chemically cleaned billets into a steel can which is then evacuated. If additional protection is needed when the billets are canned, a "getter" material, such as tantalum foil, is wrapped around the billets.

When extruding two different materials, as this program required, the material with the most resistance to plastic flow at the extrusion temperature enters the die first. The process is shown schematically in Fig. 13. If the material which is softer at extrusion temperature enters the die first, the joint will not be tapered. It will maintain essentially the flat face that existed between the billets before extrusion, and no bond will take place. A reduction ratio of at least 6:1 between the billet and extrusion cross-sectional areas is considered necessary to produce a good bond.

Two techniques were considered to produce bimetal joints by extrusion:

1. The two materials would be sealed in a mild-steel can and evacuated to protect the surface to be joined, heated to the extrusion temperature, and extruded.
2. The two materials would be seal welded to protect the surface to be joined, heated to the extrusion temperature, and extruded.
The advantage of the second approach is the elimination of the somewhat costly canning and evacuation procedure required to keep the interface between the two materials clean. However, in this program, the seal-welded parts were also canned to maintain consistent diameters, and, therefore, extrusion ratios were maintained without the need of duplicate tooling.

Billets were prepared for extrusion as follows:

1. The can details were machined from heavy wall tubing and cold-rolled plate of AISI 1010 material.
2. The nose section of the can was heliarc welded in place and helium leak checked.
3. The can components were rinsed in trichloroethylene and then out gassed for a total furnace time of 16 to 18 hr at 1800 F with a vacuum of 0.5 microns.
4. The can components were then finish machined and stored in sealed plastic bags with desiccant until required.
5. To assemble the can, the material to be joined and the can components were rinsed in trichloroethylene, washed in detergent and warm water, rinsed in warm water, dipped in alcohol and dried.
6. Inconel 718 and AMS 6304 materials were wrapped in tantalum foil and slipped into the can with the Inconel 718 at the nose end.
7. The rear plate was then heliarc welded in place, and the assembly was helium leak checked.
8. The assembly was heated to 600 F for the \(\frac{3}{4}\)-in.-dia billets, and 1000 F for the 8-in.-dia billets, and held until a vacuum of 0.05 micron was obtained; the evacuation tube was then sealed.
9. The outer surface of the can was nickel-plated to protect it from oxidation during the extrusion cycle.

The seal-welded billets were prepared the same way, except that both sizes were seal welded before going into the can and not wrapped in tantalum foil, and the larger size was not evacuated.

Fig. 14 shows a typical extrusion bonded joint.
Fabrication of coextruded final shafts was started with three sets of billets measuring (before extrusion) 11\(\frac{1}{2}\) in. in diameter by 16 in. in length (10 in. of AMS 6304 and 6 in. of Inconel 718 at the centerline). For extrusion, the billets were heated in an 1800 F furnace and were soaked for one-half hour after the jackets reached 1800 F. A low limit of 1625 F was established for the temperature of the jackets at the time of insertion in the die. The jacket temperatures were monitored with optical pyrometers. All three shafts were extruded and the jackets removed. The maximum press force during extrusion was 4200 tons for the Inconel 718 portion of the shaft and 2560 tons for the AMS 6304 section. The extrusions were turned to 4 9/16 in. dia, except at the joint interface, which was turned to 4 in. The joint taper was established by measuring the location of the interface after each cut. The taper of the joint proved to be that predicted when the billets were shaped.

The extruded shafts were upset on the Inconel 718 and heat treated, then machined to final dimension. Fig. 15 shows a finished shaft.

Engine Testing

One of the shafts was assembled into an engine and successfully completed an engine test. This is the first known fabrication and operation of a bimetal shaft for a critical application.

The shaft was assembled into a TF30-P-3 engine which was run in a 150-hr endurance test. The test consists of 25 six-hr cycles. The testing was done in a sea level static stand, i.e., atmospheric inlet pressure and no inlet air velocity simulating aircraft motion. A total of 172 hr were run, 32 of these were with afterburning. The shaft was inspected after test:

1. Shaft bow at room temperature and with the joint at 600 F was the same as before test.
2. Shaft unbalance at the front and rear was the same as before test.
3. Wink zyglo of the oil holes and rear section of the shaft, including the joint, showed no indications.
4. No defects or discrepancies of any kind were found.

REFERENCES