Activated Diffusion Bonding

A new joining process produces high strength joints in difficult-to-weld superalloys, including René 80

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ABSTRACT. "Activated diffusion bonding" is the name given a joining process for high strength nickel base superalloys which involves the marriage of the best current knowledge of conventional brazing and solid state diffusion welding technology. This process combines the manufacturing ease of brazing with the high joint strengths achievable by solid state diffusion bonding. This new process basically involves vacuum furnace brazing with an ultra high strength bonding alloy (nearly identical in chemical composition to the base metal being joined), followed by diffusion and aging heat treatments to produce maximum joint strength.

Joint quality has been critically assessed by exhaustively testing butt joints in elevated temperature tensile, stress rupture, and high cycle fatigue. These tests have demonstrated that butt joint efficiences of 70-90% can be developed in both cast and wrought nickel base superalloys that are extremely difficult to fusion weld. This represents an eight-fold increase in strength over the strongest joints producible by conventional brazing with nickle-base brazing filler metals.

Introduction

The continuing evolution of aircraft gas turbines to produce engines with improved thrust-to-weight ratios and specific fuel consumptions has resulted in ever-increasing turbine inlet temperatures, since the thermodynamic efficiency of the engine cycle invariably increases with this critical temperature. These continually increasing turbine inlet temperatures have imposed increasingly stringent requirements on the rotating and stationary components (wheels, buckets and vanes) used in the primary turbine of single spool engines and in the high pressure turbines of multiple spool engines. Initially, these requirements were met by evolutionary improvements in the high temperature strengths of the cobalt and nickel-base alloys used in turbine airfoils and wheels.

Figure 1 indicates progressive increases in 100 hr/1500° F stress rupture strength from the "17W" used in 1939 superchargers to today's René 100 and René 80. Compositions of these alloys plus some others of current interest are given in Table 1. Over 30 years, 100 hr/1500° F stress rupture strength has increased nearly seven-fold; but it is clear that the bulk of this strength improvement had occurred by about 1960. The modern gas turbines of today and foreseeably for the next decade, do and will employ increasingly sophisticated schemes of air-cooling to accommodate the requirements of increasing turbine inlet temperatures. These air cooling designs often require high strength joints for successful operation. However, the alloys developed to meet the strength requirements of advanced turbine components are difficult to weld by conventional fusion welding processes, because the alloys are subject to both strain-age and hot cracking.

To overcome this drawback, General Electric has developed a new joining process—activated diffusion bonding—which produces in ultra high strength gas turbine alloys, crack-free joints with strengths approaching base metal properties. This process combines the manufacturing ease of brazing with the high joint efficiencies of solid state diffusion bonding—or preferably, diffusion welding by definition.* The process involves joining nickel-base superalloy components with a specially designed bonding alloy that completely melts at some elevated temperature below the incipient melting point of the alloy or alloys being joined. Subsequent to this, the joined component is given a diffusion heat treatment to effect homogenization of the bonding alloy and base metal. This is followed by an appropriate aging heat treatment. The process differs radically from solid state diffusion bonding in that only nominal pressures (0—10 psi) are required to produce a sound joint. The low pressure used in this process allows it to be used for joining relatively fragile parts of complex configuration without risking deformation during joining.

The process provides a *major advance* in metal joining technology and is far superior to conventional welding, brazing, or solid state diffusion bonding of superalloys because of its ability to produce sound, strong, crack-free joints in complex configurations. The feasibility of the activated diffusion bonding process has been proven in the laboratory and in pilot

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Table 1—Compositions of Alloys, %

	C	Cr	Mo	Co	W	V	Fe	Ni	Al	Ti	Cb
17W	0.50	12	1.0	—	2.2	—	Bal	19	—	—	—
HS 21	.25	27	6.0	Bal	—	—	—	2	—	—	—
Nimonic 80A	—	20	—	—	—	—	—	Bal	1.2	2.2	—
Hastelloy B	—	—	28.0	—	—	0.3	5	Bal	—	—	—
S-816	.40	20	4.0	Bal	4.0	—	—	20	—	—	4
M-252	.15	19	10.0	10	—	—	—	Bal	1.0	2.5	—
René 41	.10	19	10.0	11	—	—	—	Bal	1.5	3.1	—
René 77	.07	14	4.2	15	—	—	—	Bal	4.3	3.4	—
René 100	.18	9.5	3.0	15	—	1.0	—	Bal	5.5	4.2	—
René 80	.15	14	4.1	9.4	4.0	—	—	Bal	3.0	5.0	—

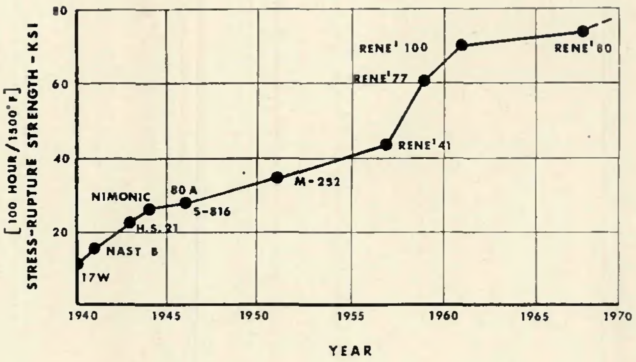

Fig. 1—Evolutionary increases in strength through alloy development

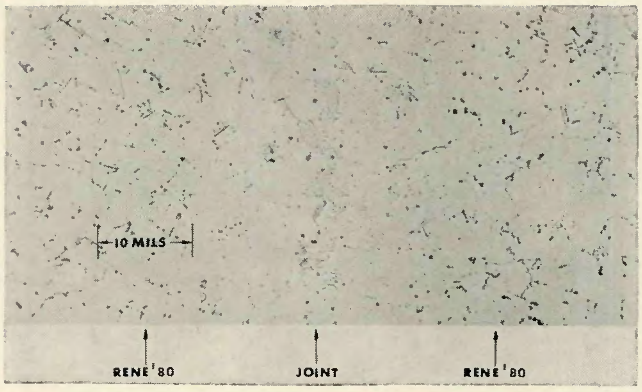

Fig. 2—Typical activated diffusion bonded joint in René 80

production of selected engine components.

The bonding alloy and heat treatment development and resultant high joint mechanical properties are the subject of this paper.

Experimental Procedure and Results

Development of the activated diffusion bonding process has progressed through these basic steps: bonding alloy development, establishing joining parameters, and determining mechanical properties.

Bonding Alloy Development

The concept of activated diffusion bonding required the development of suitable bonding alloys with melting points lower than those of the alloys to be joined. The bonding alloys are placed at or near the faying surfaces to be joined such that nil or minimum pressure would be required during bonding. Alloys for elevated temperature bonding of superalloys can be developed using either of two basic approaches:

1. Use a relatively simple ternary or quaternary alloy or nickel or cobalt near an eutectic point.

2. Use an existing super strength alloy as a base composition and add *melting point depressants* to produce a bonding alloy with a desired melting point.

Brazing filler metals for elevated temperature service have historically been relatively simple ternary or quaternary alloys of the base elements nickel, cobalt, gold, or other precious metals. The precious metal based filler metals have often been preferred for applications where minimum base metal interaction was a prime consideration, but the nickel-based filler metals have produced the strongest joints. Even though one of the prime strengthening mechanisms in nickel-based superalloys is the precipitation-hardening effect of "gamma prime" Ni_3 (Al, Ti), brazing filler metals containing aluminum and titanium have not been employed commercially. The prime causes of this are two in nature:

1. Aluminum and titanium are highly reactive elements, and it has been extremely difficult to produce oxide-free filler metal powders containing Ti and Al, particularly by conventional water atomization processes for processing alloy powders.

2. The reactivity of filler metal powders containing Ti and Al is such that the powders will oxidize and not flow properly in the dry hydrogen atmospheres commonly used for high temperature brazing.

Therefore elevated temperatures brazing alloys, up to now, have been simple alloys low in strength. The development of bonding alloys for activated diffusion bonding, however, was not faced with many of the previous limitations because of three recent technological developments:

1. Many modern high strength, high temperature resistant cast nickel base superalloys can be heated very close to their incipient melting points without impairing their mechanical properties. This was not true of the wrought alloys used previously. Thus high melting bonding alloys, very similar chemically to the cast alloys, can be used.

2. Sophisticated equipment for inert gas atomization of reactive superalloys to bonding alloy powders has become commercially available in the past few years.

3. Ultra-high vacuum "cold-wall" furnaces in production sizes have become commercially available only recently. Vacuum equipment of this type is required to perform the initial brazing step in activated diffusion bonding.

The development of complex, high-strength bonding alloys by the addition of small amounts of melting point depressants to ultra-high strength super-alloy-base compositions has been successfully demonstrated. Melting point depressants such as silicon, boron, manganese, aluminum, titanium, and columbinum have been added to the base alloys, René 77, René 80, and René 100. The base alloy is simply "doped" with increasing amounts of depressants such that the resultant alloy is liquid at a temperature that does not impair the properties of the alloy to be joined. Ideally, bonding is accomplished at the normal solution heat treatment temperature for a giv-

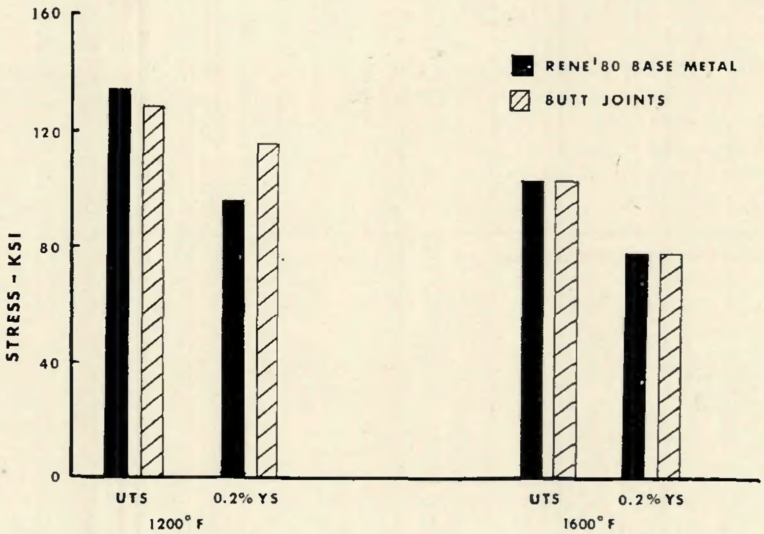

Fig. 3—Tensile properties of activated diffusion bonded butt joints in René 80 vs. those of the base metal

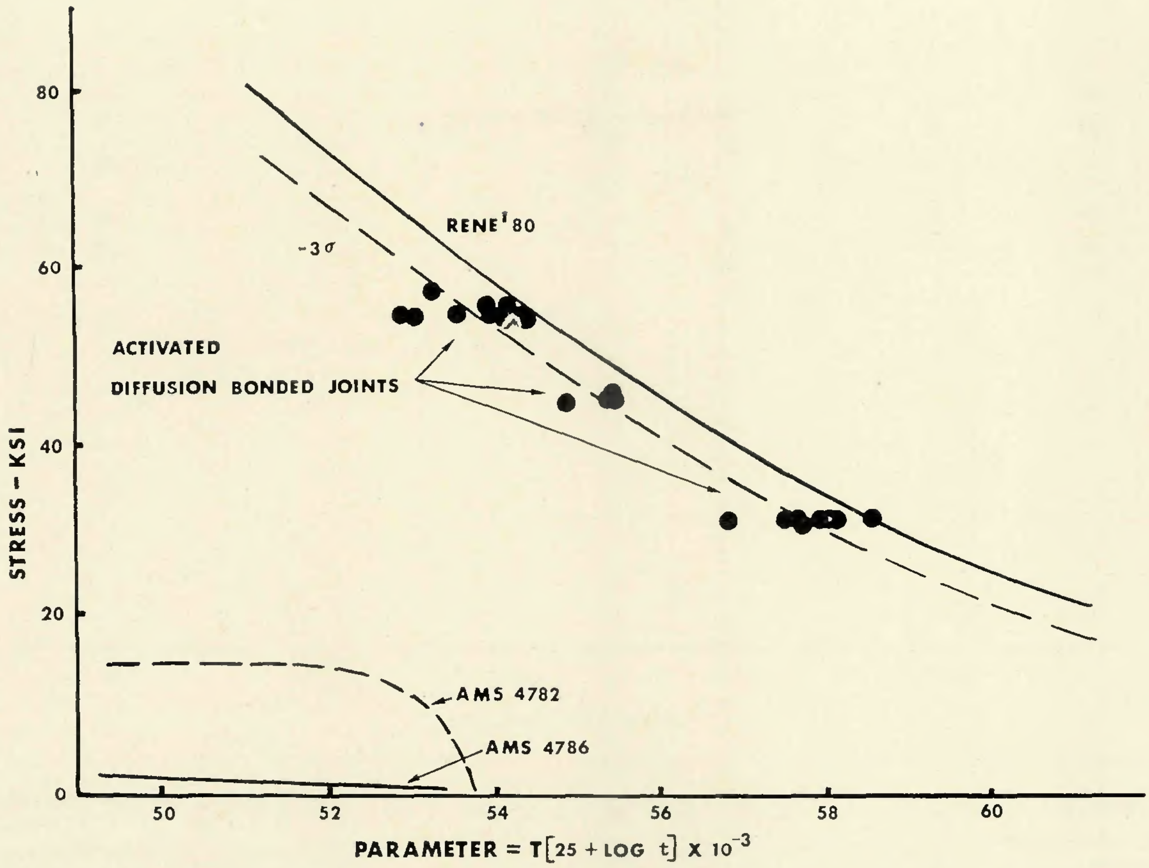

Fig. 4—Stress rupture properties of activated diffusion bonded joints in René 80 compared with those of conventional brazed joints

en cast superalloy.

Bonding alloys were initially produced as 50 gram buttons, using virgin starting materials melted under an argon atmosphere (using conventional gas tungsten-arc welding equipment) and mechanically crushed to powder. These candidate bonding alloys were then screened by determining their melting point and flow characteristics in high vacuum. The most promising alloys were further screened, primarily by stress rupture tests of butt joints in superalloys. Tensile tests, particularly room temperature tests, were found to be misleading when testing butt joints—apparent joint strength is greatly increased by the base metal strength. Stress rupture is a far more sensitive test of actual joint strength. This relatively simple screening procedure allowed a large number of potential bonding alloys to be evaluated rapidly.

A typical microstructure of an activated diffusion bonded joint made with a selected bonding alloy is shown in Fig. 2. Normally some evidence of the "melting point depressant element" remains at the joint center. All the normal strengtheners (Al, Ti, etc.) are present in the joint region which accounts for its high strength.

Although the bonding alloys were initially developed primarily for joining René 80 to itself, the activated diffusion bonding process has been used to successfully join many other nickel base superalloys, including Hastelloy X, René 41, Waspalloy, René 100, and dissimilar metal combinations of these. The work described herein, however, is confined to activated diffusion bonded joints in the current high strength, cast superalloy for turbine blades and vanes, René 80.

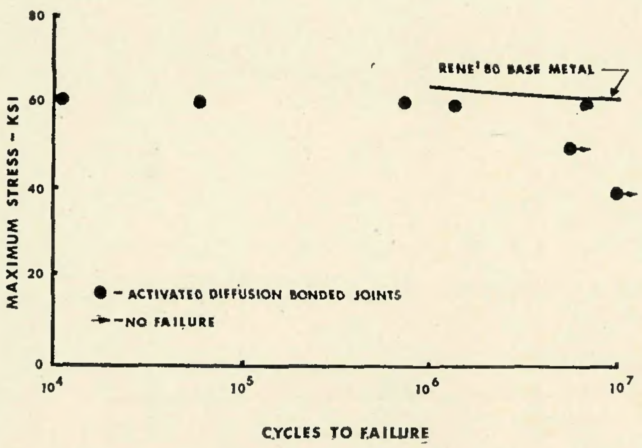

Fig. 5—1400° F high cycle fatigue strengths of activated diffusion bonded butt joints in René 80

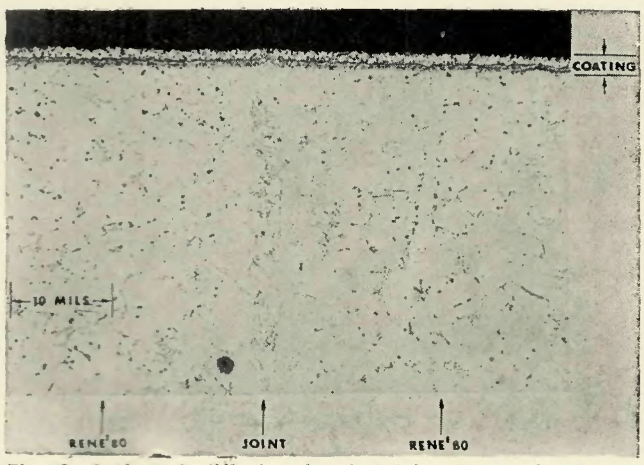

Fig. 6—Activated diffusion bonded joint in René 80 after coating and static oxidation at 1800° F

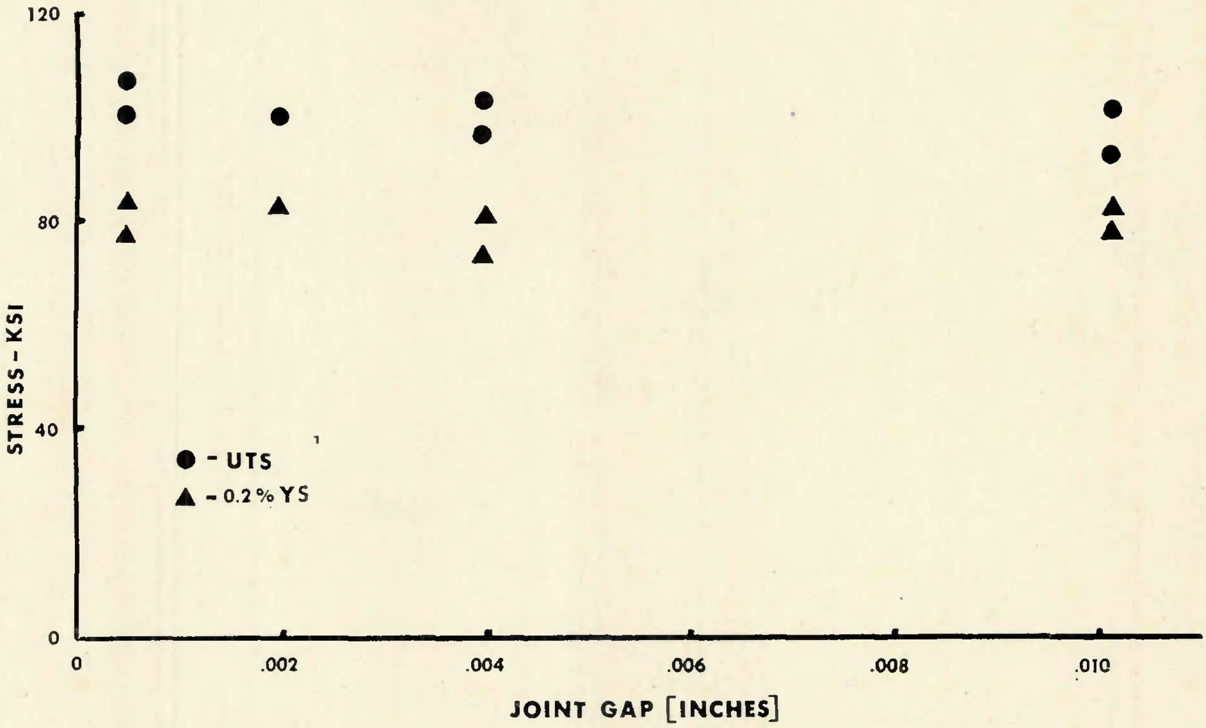

Fig. 7—Effect of joint gap on 1600° F tensile properties of activated diffusion bonded butt joints in René 80

Bonded Joint Mechanical Properties

Following initial bonding alloy development, exhaustive mechanical testing was conducted to verify the integrity of the activated diffusion bonded joints. Testing was conducted using butt joints to critically evaluate joint properties.

Tensile properties of activated diffusion bonded butt joints in René 80 are shown in Fig. 3. In all specimens failures occurred in the joint at strength levels comparable to average René 80. Ductilities, however, were low.

Stress rupture properties of butt joints are given in Fig. 4. Both René 80 base metal and conventional brazing alloy butt joint strengths are included as a basis of comparison. Again joint strengths comparable to those of the base metal were achieved.

Results of similar stress-rupture tests on René 80 brazed with AMS 4782 (Ni–19% Cr–10% Si) and "AMS 4786" (Au 8% Pd–22% Ni) are included in Fig. 4 for comparative purposes.

Since the activated diffusion bonded joints tests exhibited low ductilities, there was concern that their fatigue strengths would be low. Therefore, high cycle fatigue tests were conducted on butt joint specimens. Some typical results are shown in Fig. 5. This critical mechanical property further defined the integrity of activated diffusion bonded joints.

Homogenization of the activated diffusion bonded joint is further evidenced by the identical resistance as the base metal to environment effects —oxidation and sulfidation. A typical photomicrograph of an activated diffusion bonded joint after extended oxidation exposure is shown in Fig. 6.

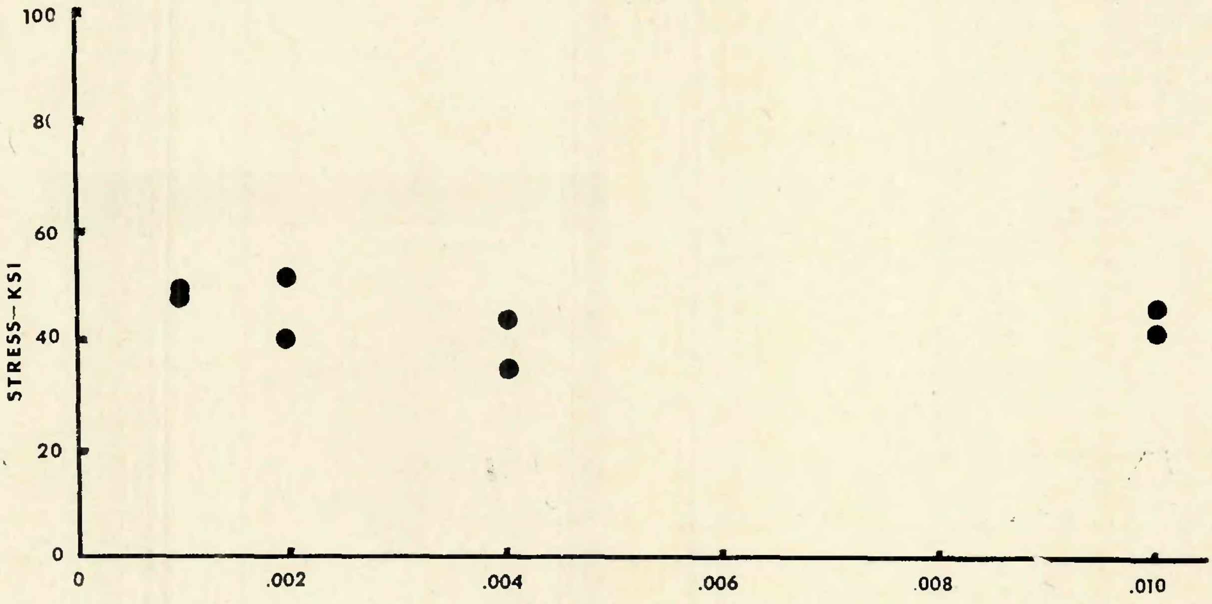

Fig. 8—Effect of joint gap on 1600° F/50 hr stress rupture properties of activated diffusion bonded butt joints

Oxidation occurred uniformly in the René 80 base metal and joint regions. Sulfidation tests of activated diffusion bonded joints revealed identical results.

Joining Parameter Limits

In combination with the development of relatively low melting bonding alloys which have chemical compositions virtually identical to the base metal except for the melting point depressant, joint gaps and post bond heat treatment were controlled to produce high joint strengths.

Since the manufacturing success and inherent process cost is highly dependent on the process parameter tolerance, both joint gaps and post bond heat treatments were varied to define acceptable limits.

Joint gaps in René 80 butt joint specimens were varied from 0.0005 to 0.010 in. and tested at 1600° F in tensile and stress rupture. The results are shown graphically in Figs. 7 and 8. These results reveal the tolerance of the activated diffusion bonding process for mismatch and poor fit-up, while maintaining high joint strengths.

Evaluation of several post bond homogenization heat treatments showed that these were benefical, but that the precise time-temperature cycle employed was not critical. Such cycles will, naturally, vary with the superalloy being joined.

Discussion

The mechanical properties of activated diffusion bonded joints (summarized in Figs. 3–5) are several times greater than those achievable in joints brazed with conventional filler metals. This represents a major advance in metallurgical joining of nickel base superalloys which are difficult to weld (such as René 80, René 100, or René 77).

The process is inherently applicable to complex joint designs and experience to date with the process has shown it to be no more difficult a manufacturing process to control than conventional high vacuum furnace brazing.

Conclusions

A new process—activated diffusion bonding—has been developed for joining difficult to weld nickel base superalloys. It combines the manufacturing ease of conventional vacuum furnace brazing with high joint strengths. Elevated temperature tensile, stress rupture, and high cycle fatigue testing of butt joints has demonstrated that joints strengths 70–90% of those of the base metal can be achieved.

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The four reports in this Bulletin are an assembly and summary of data made available to or generated for the Subcommittee on Reinforced Openings and External Loadings of the Pressure Vessel Research Committee. It is by no means a complete guide to the design of nonradial nozzles, but it should give good direction to those who must design and use nonradial nozzles.

"Interpretive Report on Oblique Nozzle Connections in Pressure Vessel Heads and Shells Under Internal Pressure Loading" by J. L. Mershon

The purpose of this report is to present, discuss and interpret the available data from analytical and experimental studies of oblique nozzles under internal pressure loading. Covered are skewed holes in flat plates, hillside connections in a sphere, lateral connections on a cylinder, and hillside connections on a cylinder.

"Elastic Stresses Near a Skewed Hole in a Flat Plate and Applications to Oblique Nozzle Attachments in Shells" by F. Ellyin

This report is divided into three parts, the first of which covers the theoretical analysis of a skewed hole in a flat plate. The second part summarizes the results of an experimental investigation of plates containing skew circular cylindrical holes. It is shown that good agreement exists between theory and experiment. In the third part, an approximate approach is suggested for computing an elastic stress concenration factor for oblique openings in spherical and cylindrical shells.

"Photoelastic Determination of the Stresses at Oblique Openings in Plates and Shells" by M. M. Leven

Data on stresses in photoelastic models are presented, in four tables and 96 figures, for an oblique hole ($\alpha = 45°$) in a flat plate for oblique openings in cylindrical pressure vessels, and for oblique openings in spherical pressure vessels.

"A Photolastic Analysis of Oblique Cylinder Intersections Subjected to Internal Pressure" by R. Fidler

Elementary considerations of the stresses existing around an opening in a pressurized cylinder lead one to expect a less severe distribution around the elliptical opening than around a circular opening for that case where the major axis of the elliptical opening is normal (transverse) to the longitudinal axis of the vessel. This note deals with a photoelastic analysis of oblique cylinder intersections, which produce elliptical openings of ratios typical of header/tube joints, and shows the prediction to be true. The optimum obliquity is found to be approximately 56 deg which results in a lowering of the peak stress (circumferential bore) by 40%.

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