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Diffusion Bonding Aeroengine Components

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1. INTRODUCTION

Over recent years, Rolls-Royce plc has committed significant research resources to the development of diffusion bonding processes for the manufacture of existing and advanced titanium alloy aeroengine components and structures. Both aspects of the joining technique, i.e. 'solid-state' and 'liquid phase' have been utilised in the production of both simple static fabrications and complex rotating parts.

A pre-requisite for the use of diffusion bonding in a production environment is the determination of the process parameter 'operating windows' which can repeatedly guarantee the formation of diffusion bonds with joint strengths approaching those of the titanium alloys being joined. Variables examined include temperature, pressure, time, surface roughness and, in the case of liquid-phase diffusion bonding, interlayer composition, consistency and thickness. Primarily, metallography and mechanical testing – particularly tensile, fatigue and impact testing – have been used to optimise the allowable variants within the process parameters in order to economically manufacture suitable aeroengine components with the required levels of bond properties and bond quality.

Rolls-Royce plc has specifically developed a liquid-phase diffusion bonding process called 'activated diffusion bonding' for the manufacture of its unique and revolutionary hollow titanium wide chord fan blade. The development of a high integrity bond has been fundamental to the design concept of this component. Solid-state diffusion bonding is being utilised by Rolls-Royce plc in the manufacture of hollow vane/blade aerofoil constructions mainly in conjunction with superplastic forming and hot forming techniques.

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2. PROCESS PARAMETERS OF DIFFUSION BONDING

British Standard 499 defines diffusion bonding as a process in which the mating faces are held intimately in contact, by a pressure which does not cause detectable plastic material flow at a temperature below the melting-points of the materials being joined, for a period of time which does not degrade material properties significantly until a metallurgical bond is formed by solid-state diffusion.

For solid-state diffusion bonding, all reactions involved in bond formation occur in the solid-state whereas liquid-phase diffusion bonding utilises an interlayer between the mating faces in order to promote the formation of a liquid-phase by solid-state interdiffusion. In the latter case, after solidification of the joint, subsequent solid-state diffusion can be used to enhance the mechanical properties of the bond.

Heat-treatment cycles, therefore, require detailed study in order to satisfy the potentially contradictory requirements of promoting the bonding mechanisms while maintaining the mechanical properties of the alloys being joined.

2.1 Temperature

For both solid-state and liquid-phase diffusion bonding, Rolls-Royce plc limits the temperature of the joining process to just below the beta transus of the titanium alloys being joined and maintains a constant and uniform temperature by furnace microprocessor control. The higher the bonding temperature, the lower is the pressure required and/or the shorter is the time necessary to effect a fully developed joint.

2.2 Pressure

For a given bonding temperature, the higher the pressure that can be applied, the shorter is the time needed to form the bond. The primary advantage of liquid-phase diffusion bonding relative to the solid-state method is the much reduced applied pressures associated with the former process.

2.3 Time

The time necessary for the formation of sound joints by both the solid-state and liquid-phase processes has economic and metallurgical implications. This is a particularly significant factor if grain-growth in the titanium alloys being joined is time-dependant, especially if superplastic forming is to be utilised subsequently in the manufacturing sequence.

2.4 Surface Roughness

Rolls-Royce plc has determined that the mating surfaces to be joined by either of the diffusion bonding methods need to be as smooth as possible within practical limits in order to permit the good contact demanded by both processes. Chemical machining techniques have been developed to provide the required surface finish, with a typical surface roughness (Ra) of 0.8 to 1.0 μm.

2.5 Interlayer for Liquid-Phase Bonding

All known liquid-phase joining media for titanium and its alloys have been extensively reviewed to assess their suitability for identified product fabrications.

2.5.1 Interlayer Composition

Titanium joining systems evaluated include aluminium-manganese, silver-aluminium, aluminium-magnesium, copper, nickel, titanium-copper-nickel, and copper-nickel. Titanium-6 per cent aluminium-4 per cent vanadium alloy specimens utilising these interlayer alloys have been thermally processed to determine joint properties and microstructural details. The copper-nickel system was identified as the most promising for further research which ultimately developed the activated diffusion bonding process specifically for the fabrication of the Rolls-Royce plc wide chord fan blade.

2.5.2 Interlayer Thickness

Extensive development work has been carried out to establish the critical relationship between interlayer thickness and the heat-treatment cycle in order to guarantee the formation of joints with optimum properties. This programme of work not only established interlayer thickness criteria but also defined the preferred temperature-pressure-time heat-treatment cycle, including heating and cooling rates for activated diffusion bonding.

3. DIFFUSION BONDING APPLICATIONS FOR AEROENGINE COMPONENTS

3.1 Rolls-Royce plc Wide Chord Fan Blade

By generating some 75 per cent of the total take-off propulsive thrust, the fan significantly influences the fuel efficiency of an aeroengine. Rolls-Royce plc has designed and developed an advanced, highly efficient fan for all its civil engine applications in the thrust range 22,000 to 61,000 lbs[1,2].

3.1.1 Design Philosophy

This fan is based on a radical concept for a major rotating component by being clapperless to provide an aerodynamically efficient aerofoil shape, hollow to reduce total weight effects, and of wide chord for natural aerodynamic stability. Its position at the front of the aeroengine demands an operational capability of developing adequate thrust for aircraft safety after suffering impacts from all types of foreign objects (birds, ice and pebbles). The fan blades are also subjected to the effects of low cycle fatigue stresses during every flight cycle and potentially from high cycle fatigue stresses at specific flight conditions due to air intake disturbances.

3.1.2 Construction

In order to satisfy the design criteria. Rolls-Royce plc has developed a wide chord fan blade with a low density honeycomb core in order to provide optimised aerodynamics together with low weight and mechanical integrity.

The basic construction of the Rolls-Royce plc wide chord fan blade is shown schematically in Fig. 1 as a three-piece titanium fabrication. The external titanium alloy skins are separated and supported by a thin-walled small cell titanium honeycomb core, and are tapered radially from root to tip and axially from leading to trailing edge for the optimum compromise between component weight and integrity. The capability of the fabrication to resist the effects of fatigue and impact requires that both panel-to-panel and honeycomb-to-panel joints exhibit parent material properties.

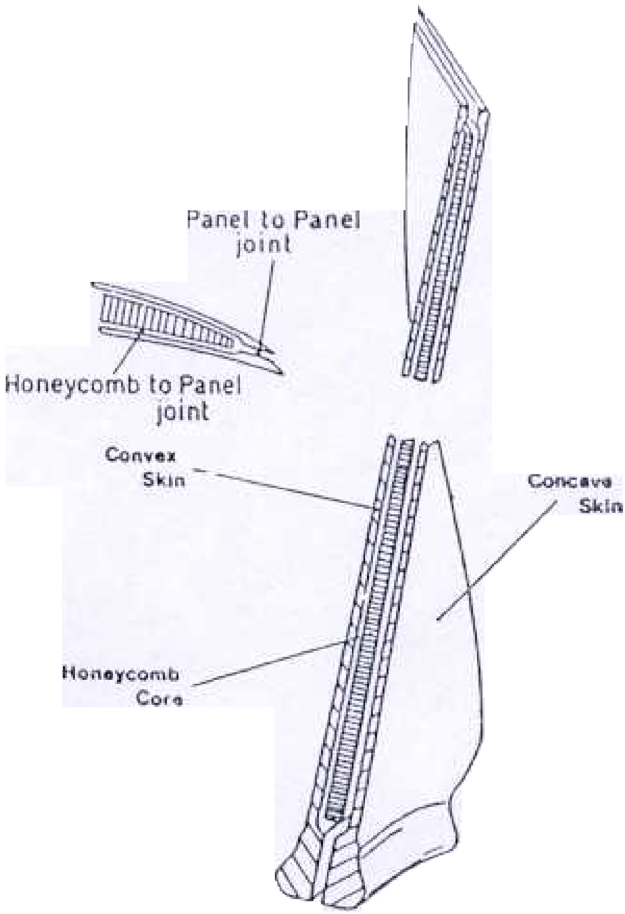

Figure 1. Wide chord fan blade fabrication.

This design has demanded the development of novel metal forming, metal joining and inspection techniques to consistently manufacture wide chord fan blades which meet the engineering specification requirements[3].

3.1.3 Activated Diffusion Bonding

Activated diffusion bonding transforms the three-piece fabrication into an integral component. The activating interlayers for the process, copper and nickel, are pre-placed onto the inner surface of the two external panels by a microprocessor controlled electroplating technique. A microprocessor-controlled heat-treatment operation at elevated temperature with the concurrent application of low pressures in a custom built vacuum furnace completes the joining process.

Activated diffusion bonding occurs in three stages during the heat-treatment cycle : firstly, as neither the fan blade panels nor the interlayer elements will melt of their own accord at the bonding temperature, prior solid-state inter-diffusion between the *Cu* and *Ni* layers and the surfaces of the fan blade panels during the heating cycle provides the correct *Ti-Cu-Ni* alloy composition for melting at the diffusion bonding temperature, which also eliminates the original mating surfaces; in the second stage, rapid isothermal solidification cccurs at the diffusion bonding temperature and forms the joint; finally, subsequent solid-state diffusion at the same temperature develops a sound, tough, high strength joint compatible with the properties of the fan blade panel material.

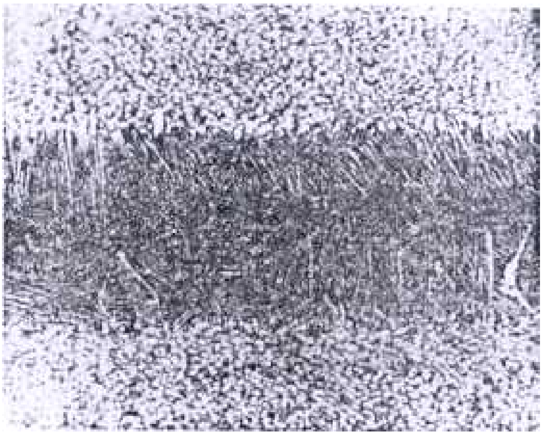

Figure 2. ADB joint microstructure-plate/plate

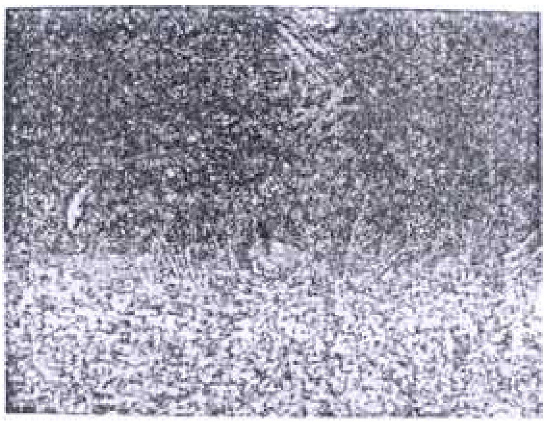

Figure 3. ADB joint microstructure-honeycomb/plate.

Figures 2 and 3 show that fully transformed acicular beta microstructures are developed for panel-to-panel and honeycomb-to-panel joints in the wide chord fan blade. Corresponding mechanical property data for both the bond constructions is presented in Figs. 4 and 5 which clearly indicate that the optimised activated diffusion bonding process produces the equivalent of parent material properties.

Impact testing is considered to provide a sensitive assessment of bond quality. Figure 4 shows that good impact strength is associated with full diffusion of the interlayer elements with low concentration of *Cu* and *Ni* at the centre of the joint. The low cycle fatigue properties of honeycomb-to-panel joints are similarly dependent on degree of transformation and surface chemical composition.

ACTIVATED DIFFUSION BONDING – JOINT PROPERTIES :
DERIVED FROM PICTURE FRAME (PANEL TO PANEL) SPECIMENS

ROOM TEMPERATURE TENSILE	0.2%PS	UTS	E1%	RA%
ADB Ti-6Al-4V	840MPa	965MPa	15	3
DIFFUSION BONDED Ti-6Al-4V	845	970	10	2
PARENT MINIMUM	830	930	8	2
UNDIFFUSED ADB Ti-6Al-4V	830	960	8	1

2. ROOM TEMPERATURE IZOD IMPACT	AVERAGE IMPACT STRENGTH ft-lbs
ADB Ti-6Al-4V	
DIFFUSION BONDED Ti-6Al-4V	12
PARENT	12
UNDIFFUSED ADB Ti-6Al-4V	5

LOW CYCLE FATIGUE	FATIGUE STRENGTH
ADB Ti-6Al-4V	EQUIVALENT TO PARENT AT 10^5
UNDIFFUSED ADB Ti-6Al-4V	REDUCED BY 10% AT 10^5 CYCLES COMPARED WITH PARENT

Figure 4. ADB joint properties-plate/plate.

ACTIVATED DIFFUSION BONDING – JOINT PROPERTIES
DERIVED FROM HONEYCOMB/PANEL SPECIMENS

ROOM TEMPERATURE TENSILE (SHEET SPECIMEN)	UTS	E1%
ADB Ti-6Al-4V PANEL/Ti CORE	1065	10
DIFFUSION BONDED Ti-6Al-4V PANEL/Ti CORE	990	9
UNDIFFUSED ADB Ti-6Al-4V PANEL/Ti CORE	900	5

LOW CYCLE FATIGUE
DEPENDENT ON THE DEGREE OF DIFFUSION OF Ni AND Cu

HIGH CYCLE FATIGUE (4 POINT BEND)
DEPENDENT ON THE HOLDING TIME AT THE ADB TEMPERATURE

SHEAR
HONEYCOMB CORE FAILURES ONLY. NO FAILURE OF THE HC/PANEL BOND

FLAT WISE COMPRESSION
DEPENDENT ON HC CORE MATERIAL AND ITS THICKNESS AND GEOMETRY

Figure 5. ADB joint properties-honeycomb/plate.

3.1.4 Engine Applications

Rolls-Royce plc has demonstrated significant improvements in aeroengine fuel consumption by the adoption of wide chord fan technology and, to date, it has been selected for four civil aeroengine applications in the thrust range 22,000 to 61,000 lbs.

The first Rolls-Royce plc aeroengine to benefit from this technology is the RB 211–535 E4 powerplant which was certified in 1984 to power the Boeing 757 civil airliner. Rolls-Royce plc is contributing the wide chord fan blade to its latest collaborative venture, the IAE V2500 scheduled for certification in 1988 to power Airbus Industries' A320 aeroplane. Recently, this design concept has been applied to the latest versions of the RB211 series of engines, the –524G (Fig. 6) and the –524H which are both scheduled for certification in 1988 to power the Boeing 747–400 and Boeing 767 airliners respectively.

3.2 Hollow Vane/Blade Constructions

Solid-state diffusion bonding is a joining process which is being utilised by Rolls-Royce plc for the manufacture of selected titanium fabrications. Examples to date include panel structures with varying internal configurations and hollow vane/blade constructions (Fig. 7) which have incorporated solid-state diffusion bonding in their manufacturing sequence prior to superplastic forming or hot forming.

Chemically machined surfaces with a surface roughness better than 1.0 μm, high applied pressure of the order of 300 psi and elevated temperatures below the beta transus of the titanium alloys being joined have been found necessary to effect a

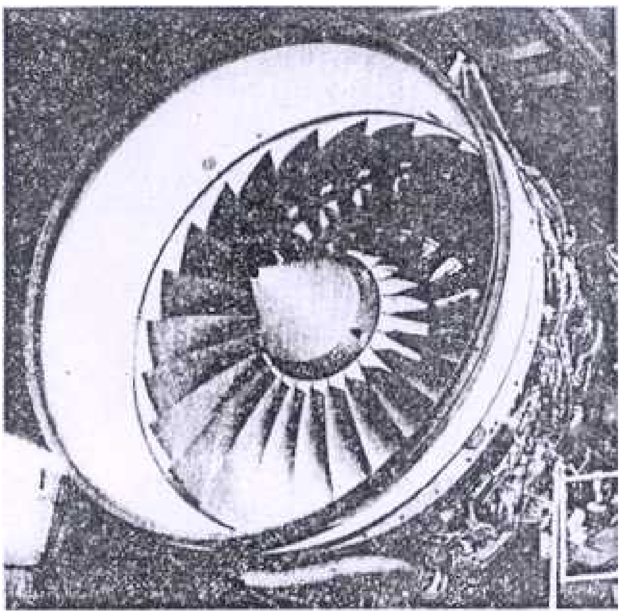

Figure 6. RB211-524G aeroengines showing wide chord fan blades.

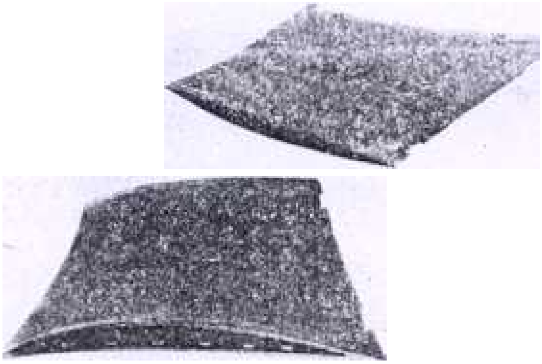

Figure 7. Hollow vane constructions via DB/SPF.

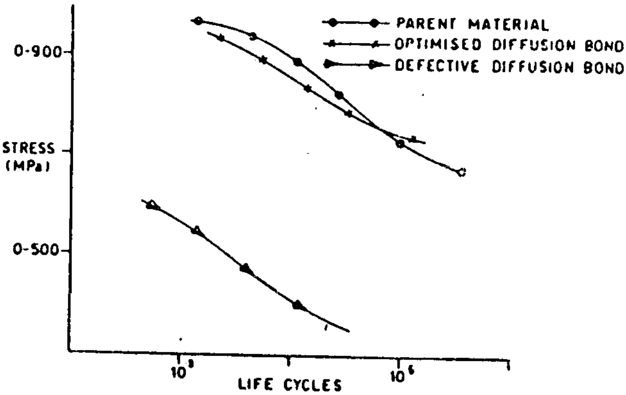

Figure 8. Effect of diffusion bond quality on low cycle fatigue behaviour of Ti-6% Al-4% V.

solid-state diffusion bond in these fabrications. Extensive development work has determined the optimum parameter operating window which guarantees full diffusion bonding.

Solid-state diffusion bonds in titanium alloys are considered to be more sensitive to the presence of microporosity than are joints formed by activated diffusion bonding. However, with suitable control of the processing parameters, solid-state diffusion bonds exhibiting parent alloy properties can be produced. Figure 8 schematically presents the tensile low cycle fatigue behaviour of a diffusion bonded titanium-6 per cent aluminium-4 per cent vanadium alloy emphasising this sensitivity.

To overcome the established difficulties of inspecting solid-state diffusion bonds by non-destructive testing methods, further work programmes have been, and are being, carried out in order to verify the quality of such joints by process control.

As the understanding of the manufacturing control of solid-state diffusion bonding and its effect on bond performance in titanium alloy components are established, Rolls-Royce plc will utilise the process for the production of other aeroengine components, particularly light-weight fabrications which incorporate other advanced fabrication processes and/or advanced materials.

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