THE DIFFUSION BONDING OF AEROENGINE COMPONENTS

G.A. FITZPATRICK and T. BROUGHTON*

Manufacturing Engineering Project Manager Rolls-Royce plc, Barnoldswick, LANCS, Great-Britain
**Director of Manufacturing Engineering Rolls-Royce plc, GB-DERBY, Great-Britain*

1.0 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 - "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 - "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.

2.0 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 whilst 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 to Rolls-Royce plc 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 1,0µm.

2.5 Interlayer for "Liquid-phase" Bonding

All known "liquid-phase" joining media for titanium and its alloys have been extensively reviewed by Rolls-Royce plc 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% Aluminium-4% 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

Rolls-Royce plc has carried out extensive development work 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".

3.0 DIFFUSION BONDING APPLICATIONS FOR AEROENGINE COMPONENTS

3.1 Rolls-Royce plc Wide Chord Fan Blade

By generating some 75% 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 22,000lbs to 61,000lbs (References 1 and 2).

3.1.1 Wide Chord Fan 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 Wide Chord Fan Blade 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 Figure 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.

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 (Reference 3).

3.1.3 "Activated Diffusion Bonding" the Wide Chord Fan Blade

"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 surfaces 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 - this also eliminates the original mating surfaces; in the second stage, rapid isothermal solidification occurs 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.

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 bond constructions is presented in Figures 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.

3.1.4 Wide Chord Fan Blade 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 lbs to 61,000 lbs.

The first Rolls-Royce plc aeroengine to benefit from wide chord fan 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, Rolls-Royce plc has applied its wide chord fan design concept to the latest versions of the RB211 series of engines, the -524G (Figure 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 (Figure 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 pressures 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 "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% Aluminium-4% 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, then 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.

4.0 REFERENCES

1. R E Dawson, D G Pashley, J E Melville.
"Technology of the Wide Chord Fan Blade", American Institute of Aeronautics and Astronautics/ASME/SAE/ASEE, 22nd Joint Propulsion Conference, Huntsville, Alabama, USA
June 1986.

2. D J Nicholas
"The Wide Chord Fan Blade - a Rolls-Royce First"
8th International Symposium on Air Breathing Engines Conference, Cincinatti, Ohio, USA
June 1987

3. G A Fizpatrick and T Broughton
"The Rolls-Royce Wide Chord Fan Blade"
Titanium Development Association. International Conference on Titanium Products and Applications, San Francisco, California, USA
October 1986

5.0 ACKNOWLEDGEMENTS

The authors would like to thank Rolls-Royce plc for permission to publish this paper and to acknowledge the contributions made by many colleagues to the developments reported.

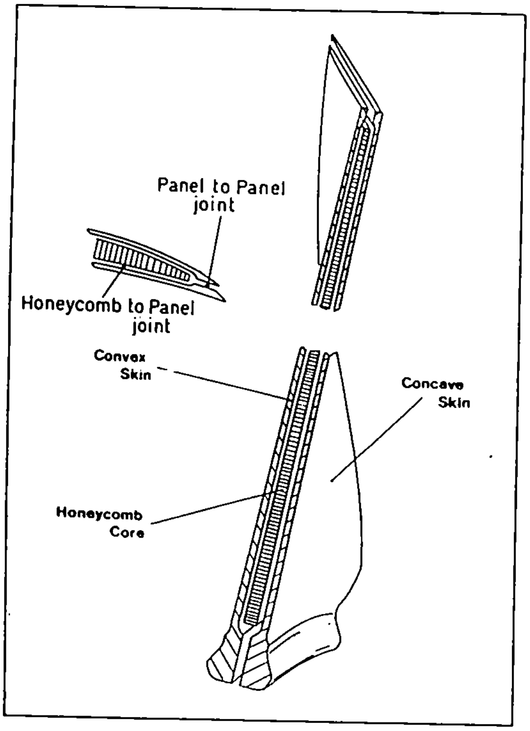

FIGURE 1. WIDE CHORD FAN BLADE FABRICATION

FIGURE 2. ADB JOINT MICROSTRUCTURE - PLATE/PLATE

FIGURE 3. ADB JOINT MICROSTRUCTURE - HONEYCOMB/PLATE

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

1.	ROOM TEMPERATURE TENSILE	0.2%PS	UTS	E1%	RA%
	ADB TI-6AL-4V	840MPa	965MPa	15	35
	DIFFUSION BONDED TI-6AL-4V	845	970	10	25
	PARENT MINIMUM	830	930	8	25
	UNDIFFUSED ADB TI-6AL-4V	830	960	8	11
2.	ROOM TEMPERATURE IZOD IMPACT		AVERAGE IMPACT STRENGTH FT-LBS		
	ADB TI-6AL-4V		11		
	DIFFUSION BONDED TI-6AL-4V		12		
	PARENT		12		
	UNDIFFUSED ADB TI-6AL-4V		5		
3.	LOW CYCLE FATIGUE		FATIGUE STRENGTH		
	ADB TI-6AL-4V	EQUIVALENT TO PARENT AT 10^6 CYCLES			
	UNDIFFUSED ADB TI-6AL-4V	REDUCED BY 10% AT 10^6 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	EL%
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
DEPENDANT ON THE DEGREE OF DIFFUSION OF NI AND CU.

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

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

FLAT WISE COMPRESSION
DEPENDANT ON HC CORE MATERIAL; AND ITS THICKNESS AND GEOMETRY.

FIGURE 5. ADB JOINT PROPERTIES - HONEYCOMB/PLATE

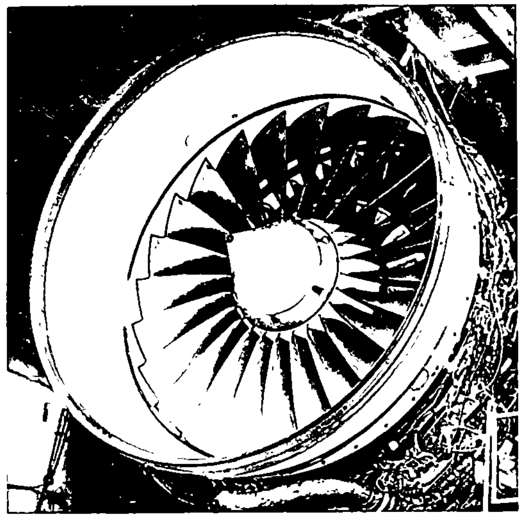

FIGURE 6. RB211-524G AEROENGINE SHOWING WIDE CHORD FAN BLADES

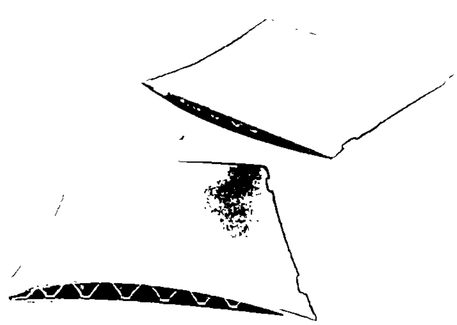

FIGURE 7. HOLLOW VANE CONSTRUCTIONS VIA DB/SPF

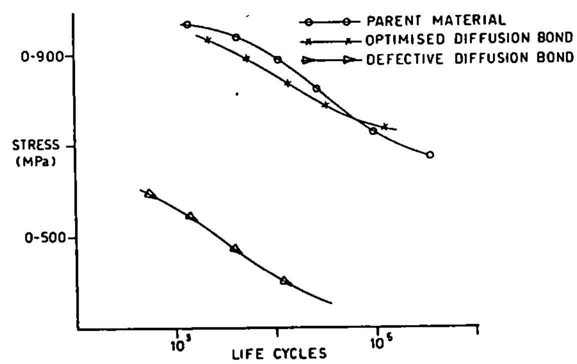

FIGURE 8. EFFECT OF DIFFUSION BOND QUALITY ON LOW CYCLE FATIGUE BEHAVIOUR OF $Ti-6\%Al-4\%V$