A SOLID-TO-SOLID HIP-BOND PROCESSING
CONCEPT FOR THE MANUFACTURE OF DUAL-PROPERTY
TURBINE WHEELS FOR SMALL GAS TURBINES

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Some of Detroit Diesel Allison's early experiences with the fabrication of small-engine dual-property turbine wheels in which both cast Mar-M246 airfoil doublers and integrally cast airfoil rings were HIP-bonded to near-net-shape PA101 (PM IN 792) disks are discussed. Details of the HIP-Bonding process, post-HIP heat treatment, and mechanical property testing as well as the successful results of component fatigue and full-scale engine testing are presented. Future trends in the dual-property technology area are also discussed.

INTRODUCTION

The growth of small gas turbines into designs which exhibit the high-temperature/long-life characteristics commonplace to larger gas turbine engines has been hampered in large measure by the complexities imposed by the small sizing of rotating hot section gas generator components. Specifically, the small diameters of these wheels (typically on the order of 15.2 cm (6 in.) to 20.3 cm (8 in.) diameter) have made it very difficult to utilize the mechanical attachment schemes which have worked so well in larger engine designs. This is primarily due to the high centrifugal stresses developed in the rims of the disks which rotate at much higher speeds than large turbine engines, the large thermal gradients developed in the rims of the disks, and the limited amount of space available to support highly stressed airfoil attachments.

Because of these complexities and cost considerations, the trend in small gas turbine design has been to use superalloy integral wheel castings which have performed well in numerous applications. Unfortunately, however, integral wheel castings limit the life and temperature growth potential of small turbines.

In particular, low cycle fatigue (LCF) life in bore regions is much less than would be possible if the disk were a conventional wrought or powder metallurgy (PM) product because of the inherently

reduced capability of cast superalloys. It also becomes difficult to attain an increase in airfoil temperature capability in uncooled designs with conventional cast equiaxed airfoil structures because, in most cases, the designs are already operating at their limits. Basic, then, to the contemporary integral wheel casting is limited bore life and growth in airfoil temperature capability.

An attractive monolithic type of substitution for an integral wheel casting in a small turbine engine design is a dual-property turbine wheel. In this construction, conventional mechanical attachment problems are eliminated by diffusion bonding high-fatigue-strength disks to creep-resistant airfoils that have properties tailored for their respective roles.

At the Detroit Diesel Allison (DDA) Division of General Motors Corporation, considerable attention has been focused on a concept for the manufacture of dual-property turbine wheels. In this concept, which involves solid-to-solid bonding, airfoil rings (either cooled or uncooled, cast or PM) and high-strength, near-net-shape PM disk details are produced in separate unrelated operations, following which the inside diameter (ID) of the rings and the outside diameter (OD) of the disks are ground to precision dimensions. The details are subsequently mated to form a near line-to-line butt-type joint configuration. Because a diffusion bond is the sought-after means of attachment, the interface between the airfoil ring and the PM disk must be sealed so that the airfoils and disks can be bonded by HIP techniques. The sealing step is accomplished by vacuum brazing with a high-temperature braze alloy. Following the braze alloy application, the system undergoes HIP processing during which the airfoil ring is pressed into intimate contact with the disk rim at high temperature, and diffusion bonding occurs. The resulting cost effective product offers the potential for improved temperature capability over integral wheel castings and is characterized by a high integrity metallurgical bond between disk and airfoil details that makes possible low rim/bore loading relative to mechanical attachment.

Since early "first generation" efforts, which culminated in component and engine demonstrations in uncooled Model 250-G20 gas generator hardware, the dual-property turbine wheel concept has been expanded. DDA is currently evaluating dual-property turbine wheel components in a number of "second generation" applications which include air-cooled axial as well as radial turbine designs. The following is an overview of both first and second generation dual-property efforts at DDA.

FIRST GENERATION COMPONENT DEVELOPMENT/EVALUATIONS

Initial efforts at DDA involved the fabrication of prototype and full-scale Allison Model 250 turbine components to investigate bonding techniques and evaluate joint strength potential. The alloys involved were primarily direct HIP-consolidated PA101 (IN 792) for the disk details and conventionally cast Mar-M246 for airfoil details. The compositions of these alloys are listed in Table 1.

TABLE I. ALLOY COMPOSITIONS.

	C	Cr	Mn	Al	Ti	Co	W	Hf	Zr	B	Si	Fe	Ni
PA101	0.15	12.6	2.0	3.5	4.0	9.0	4.0	1.0	0.02	0.025	---	4.0	BAL
Mar-M246	0.15	9.0	2.5	5.5	1.5	10.0	10.0	---	0.05	0.025	---	1.5	BAL
B/Si Mod Mar-M247	0.17	10.0	0.6	5.5	1.6	9.7	10.8	1.4	0.06	1.1	2.5	5.1	BAL

Axial Wheel Fabrication Techniques

Because of its convenient availability and its similarity to the size of wheel required for small, advanced-technology turbine engine designs, the solid-bladed Mar-M246 first-stage gas generator turbine wheel configuration for the Allison Model 250 turboshaft engine was selected as a study vehicle for axial wheel evaluations. Solid continuous airfoil rings were trepanned from the web area of available integral wheel castings and ID ground. PA 101 near-net-shape turbine disks HIP consolidated by metal can techniques were OD ground to provide an interference fit with the airfoil ring.

Typical machined airfoil ring and PA101 disk details prior to bonding are shown in Figure 1.

After machining, the details were vacuum outgassed at 1218°C (2225°F) for one hour to provide a clean surface for bonding. The outgassed airfoil ring and disk details were shrunk fit together by heating the airfoil ring to approximately 204°C (400°F) and slipping the hot ring over the cold rim of the disk. To braze seal, a boron-silicon modified Mar-M247 braze alloy powder with the composition shown in Table I was applied circumferentially to the front and rear faces of the assembly. Vacuum brazing was then conducted at 1218°C (2225°F) for 30 minutes, followed by 1093°C (2000°F) for 10 minutes for solidification. Subsequently, the temperature was increased to 1149°C (2100°F) for one hour to allow diffusion of the boron and silicon into the base metal to elevate the remelt temperature.

Fig. 1. Airfoil ring and PM disk details prior to braze sealing and HIP-Bonding.

Fig. 2. Macrostructure of HIP-Bond wheel with butt-type joint between cast airfoils and PM disk rim.

The braze-sealed assemblies were then HIP bonded for 3 hours at 1218°C (2225°F) and 103.4 MPa (15 ksi) and then heat treated to a simulated coating diffusion cycle of 1121°C (2050°F). A first-stage turbine wheel produced in this fashion is shown in Figure 2. Photomicrographs of the microstructural appearance of these joints (Figure 3) show that excellent metallurgical joints were produced in both the rim and web areas.

Typical tensile and stress rupture results for butt-type joint specimens machined from stylized wheels produced to HIP-Bond schedules are presented in Table 2. In all of the joint testing, specimen

Fig. 3. Microstructures of PA101/Mar-M246 butt-type diffusion bond joints developed in HIP-Bonded turbine components.

TABLE 2. REPRESENTATIVE MECHANICAL PROPERTY CAPABILITIES FOR DUAL-PROPERTY TURBINE WHEELS.

Specimen Type	TENSILE								STRESS RUPTURE			
	TEST TEMP °C	YIELD MPa	UTS MPa	0.2% YS (ksi)	UTS (ksi)	EL	BS	TEST TEMP °C	STRESS MPa	UTS (ksi)	HOURS TO FAILURE	EL
PA101/Mar-M246 JOINT	20	(70)	---	---	881.1 (127.8)	---	---	649 (1200)	758.3 (110)	---	977.2*	---
	649	(1200)	---	---	886.6 (128.6)	---	---	794 (1300)	654.9 (95)	---	---	---
	760	(1400)	---	---	---	---	---	760 (1400)	517.1 (75)	---	294.8	---
PARENT METAL PA101	20	(70)	945.2 (137.1)	1472.6 (213.1)	---	15.3	14.1	649 (1200)	861.8 (125)	---	98.4	5.3
	649	(1200)	896.9 (130.1)	1315.4 (190.8)	---	10.5	15.0	760 (1400)	586.0 (85)	---	89.6	10.0
	760	(1400)	875.5 (127.0)	1087.9 (157.8)	---	11.4	15.3	---	---	---	---	---
PARENT METAL Mar-M246 (CAST-TO-SIZE TEST BARS)	20	(70)	790.7 (114.7)	859.7 (123.8)	---	4.4	4.1	760 (1400)	723.9 (105)	---	49.0	6.6
	---	---	---	---	---	---	---	871 (1600)	413.6 (60)	---	78.7	17.0
	---	---	---	---	---	---	---	927 (1700)	268.9 (39)	---	151.6	25.3
	---	---	---	---	---	---	---	982 (1800)	220.6 (32)	---	40.1	28.0

*SPECIMEN DISCONTINUED

strengths were consistently at a level near that of the weakest material, indicating near 100% joint efficiency. Mechanical property data for parent metal PA101 and Mar-M247 processed to HIP-Bond cycles are also presented in Table 2. As indicated, an excellent level of strength capability was demonstrated for HIP-Bond processed turbine components.

Component Spin/Thermal Fatigue Testing

To verify system integrity under dynamic conditions, a fully machined dual-property turbine wheel (Figure 4) was balanced and proof spin tested for two minutes at ambient temperature to 64,000 rpm, which is 125% of Model 250 first-stage turbine speed. Fluorescent penetrant inspection after proof testing showed no evidence of joint distress. Consequently, a thermal fatigue rig test was conducted to evaluate the effects of high thermal strains across the joint area.

The thermal fatigue rig in this test was equipped with natural gas burners that impinged through a first-stage Model 250 engine turbine nozzle. The test wheel was instrumented with thermocouples and thermal paint for accurate measurement of temperature gradients. The wheel was mounted on a hollow drive shaft in back of the nozzle and rotated at 15 rpm to smooth out the burner patterns. Heating and cooling of the wheel was controlled by a timer which alternately cut the burner in and out at times which correlated to predetermined heat-up and cool-down airfoil/disk temperatures. The wheel was cooled by a compressed air blast. Typical cycle times were a 60-second heat-up and a 90-second cool-down. Respective peak airfoil and joint temperatures of 996°C (1825°F) and 760°C (1400°F) were achieved on heat-up; airfoil and joint temperatures on the order of 93°C (200°F) and 149°C (300°F) were observed during cool-down. In this fashion, 400 thermal fatigue cycles were run which, on the basis of previous studies, had been found to correlate well with the thermal conditions developed in the Model 250 engine.

At test completion, the joint area was totally intact and free of any distress. Because these test conditions have been known to create rim cracking in conventional Model 250 integral turbine wheels, the results were considered highly promising. After thermal fatigue testing, the wheel was again proof spin tested at 64,000 rpm (125%) for one minute, followed by 71,400 rpm (140%) for two minutes. Fluorescent penetrant inspection and blade tip measurements revealed no apparent change in the wheel structure or dimensional configuration.

Full-Scale Model 250 Wheel Fabrication

The promising material property data generated and the success of thermal cycling and overspeed testing prompted the start of manufacturing full-scale turbine wheels for engine testing. Emphasis in the manufacturing effort centered on a demonstration to show that individual or multiple airfoil segments could be bonded to the rim of a disk detail. The demonstration was of interest because the approach would allow the use of single-crystal or directionally solidified (DS) air-cooled airfoils which currently cannot be produced as integrally cast airfoil rings.

The individual Model 250 blade segments were obtained by trepanning the center of production-quality wheel castings to yield a ring of blades. This blade ring was then processed by electrical discharge machining (EDM) to separate it into blade pair segments. The segments were finish ground on the mating edges and the inner radius. In total, 19 airfoil segments containing a total of 38 airfoils were produced for each Mar-M246/PA101 HIP-Bond wheel fabricated.

After segmenting, the airfoils were positioned in a fixture (Figure 5) and laser tacked and brazed to form a ring.

Following ID grinding of the ring and OD grinding of the disk, shrink fitting, and vacuum braze sealing, the details were HIP bonded at 1218°C (2225°F) and 103.4 MPa (15 ksi) for 3 hours, heat treated, and ultrasonically inspected to verify bond line integrity. Several Model 250 turbine wheel assemblies were fabricated in this manner. The wheels were finish machined, inspected by FPI techniques, balanced, and successfully proof spin tested at 64,000 rpm (125% speed) for 2 minutes. After proof spin testing, one of the wheels was selected for engine testing.

Model 250 Engine Testing

Five hours of engine running time comprising 37 stop-start cycles were successfully completed. Each cycle in this test consisted of approximately 18% at idle and 32% at takeoff power; the balance of each cycle consisted of fan cooling in the shutdown condition to maximize thermal gradients. Turbine inlet temperature at takeoff power was 993°C (1820°F) and wheel speed was 51,500 rpm. Figure 6 shows the wheel after engine testing.

Although the duration of the engine test cycle selected for the uncooled wheel was limited, the cycle condition was in some respects

Fig. 4. Allison Model 250 prototype HIP-Bond turbine wheel in machined spin test configuration.

Fig. 5. Fixture used to fabricate airfoil rings from multiple airfoil segments.

substantially more severe than is expected to be encountered by an air-cooled dual-property turbine wheel in an advanced axial turbine engine design because of the significantly higher rim temperatures and corresponding thermal stresses inherent in an uncooled design. In particular, the peak joint temperature in the Model 250 engine was estimated to be on the order of 774°C (1425°F). In an advanced-technology air-cooled design, the joint in the rim would be operating at a peak temperature on the order of 592°C (1100°F) and, on startup and shutdown, the temperature gradients and resulting stresses would be far lower than in an uncooled Model 250 design.

In view of the high degree of integrity demonstrated by the engine test wheel and the high temperature/thermal stress environment encountered by both the joint and PA101 rim relative to an air-cooled design, the results of the test were felt to be highly successful.

SECOND GENERATION DUAL PROPERTY APPLICATIONS

The emphasis for developing dual-property technology into advanced small gas turbine wheel designs intensified with the promising component and engine results from work conducted with Model 250 gas generator components. As a result, several development programs were undertaken in a number of small turbine technology areas which offer the promise for significant performance/cost benefits.

Air-Cooled Axial Designs

Figure 7 is a photograph of an air-cooled, dual-property, first-stage turbine wheel for DDA's 800-shp class GMA500 turboshaft engine which is being developed as part of the Army's Advanced Technology Demonstrator Engine (ATDE) program. The impingement tubes inherent

Fig. 6. Allison Model 250 first-stage HIP-Bond turbine wheel after engine test.

Fig. 7. HIP-Bonded, air-cooled, first-stage turbine wheel for the GMA500 turboshaft engine.

with the cooling schemes in the first-stage wheel design in this engine are shown in Figure 8. Figure 9 shows the second-stage, air-cooled turbine wheel for the GMA500 engine. Featured on this wheel are DS airfoils which were produced by DDA's Exothermic Pack process. Currently undergoing extensive engine testing, GMA500 dual-property wheels offer a potential for cost effectiveness and performance not previously available in small turbine design.

Air-Cooled Radial Designs

Air-cooled radial turbine wheel designs have long been of interest because of their inherent superior performance relative to air-cooled axial designs. Specifically, a single air-cooled radial turbine design has been shown to be capable of duplicating the work of two air-cooled axial stages. As a result, an air-cooled radial turbine offers the potential for simplified design and associated reduced costs. However, the unavailability of a viable manufacturing technique for producing cost-effective air-cooled radial designs has limited the widespread implementation of this concept into turbine designs. Early attempts at casting full-scale, integrally bladed, air-cooled radial turbines were hampered by core support and wall thickness problems. The development of the solid-to-solid HIP-Bond technique for producing dual-property components has provided an attractive means for realizing these goals. An air-cooled radial turbine, shown schematically in Figure 10, has been designed for a 1260°C (2300°F) turbine inlet temperature; Figure 11 is a photograph of this rotor. As the airfoil shell is cast as a separate detail, cores can be printed out at the shell ID, providing a high degree of support. Consequently, complex integrally cast radial turbine airfoil shells can now be effectively produced for bonding to high-performance hubs. Under Army sponsorship, dual-property air-cooled rotors have been produced and tested with promising results in ambient temperature burst and elevated temperature cyclic spin (LCF) testing.

Fig. 8. X-ray image of impingement tubes contained in a GMA500 first-stage airfoil ring.

Fig. 9. GMA500 air-cooled second-stage turbine wheel featuring DS airfoils.

Fig. 10. Air-cooled, high-temperature, dual-property radial turbine rotor design with a 1260°C (2300°F) turbine inlet temperature capability.

Fig. 11. Full-scale, air-cooled radial turbine rotor.

Uncooled Axial Designs

Figure 12 is a photograph of a dual-property first-stage turbine wheel for the Model 250 turboshaft engine. This design features an integrally cast airfoil ring with a bond line inboard from the rim joint location that had been selected for the earlier segmented demonstration pieces. By locating the bond line inboard in this fashion, the joint metal temperatures are reduced to levels more consistent with the extended life requirements for man-rated applications. By

Fig. 12. Model 250 dual-property first-stage turbine wheel.

utilizing dual-property turbine wheel construction in this class of application, significantly improved hot section lives relative to integral wheel castings are projected. This is made possible by the superior LCF capabilities of the PM hub. By further modifying the wheel construction and substituting integrally cast airfoil rings with DS airfoils for conventionally cast airfoil rings, additional improvements in operating temperature/life are possible.

FUTURE TRENDS

The dual-property fabrication technique is beginning to be recognized as an attractive concept for achieving cost-effective durability/performance improvements in advanced turbine design. Although the greatest emphasis has been placed on gas generator components, which must operate under demanding temperature conditions, power turbine and compressor components can also benefit from the application of the dual-property concept. Specifically, in those cases where conventional attachment is employed, a strong potential for cost reduction exists because dual-property components constructed from integrally cast airfoil rings and near-net-shape disks preclude the need for expensive disk broaching and individual airfoil root grinding.

The application of the dual-property concept is not limited to superalloy components. The concept is currently being exploited for titanium centrifugal compressors where cost-effective net-shape cast airfoils are combined with the fatigue capabilities of wrought hubs. Overall, dual-property concepts are expected to play an increasingly important role in future gas turbine design. The work completed to date and that in progress will be important to this evolution.

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