THE DEVELOPMENT AND EVALUATION OF DIFFUSION-BONDED CLAD GAS TURBINE BUCKETS

A. M. Beltran and W. F. Schilling

General Electric Company

Processing studies related to the fabrication and diffusion-bonding of corrosion-resistant sheet alloys GE-2541 (Fe-base) and S-57 (Co-base) to Ni-base superalloy IN-738 are described. The results of extensive oxidation and hot-corrosion burner rig tests between 870 and 1038C indicate that pack aluminided S-57 is superior to GE-2541. Field testing of clad gas turbine buckets for 13,051 hours confirms the superiority of aluminided S-57, and demonstrates the viability of the clad composite system in corrosion service.

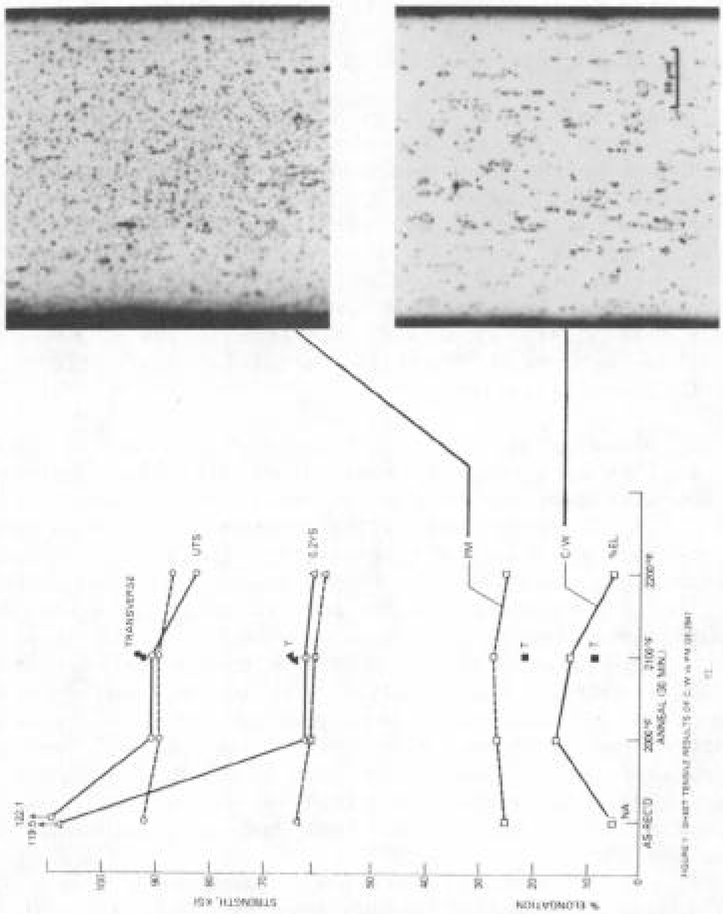
INTRODUCTION

The General Electric Company has been evaluating diffusion-bonded, corrosion-resistant sheet claddings since 1970 as a potential means of protecting industrial gas turbine buckets during extended service in corrosive petroleum or coal-fired environments. During this period sheet processing, clad forming, and diffusion-bonding methodologies have been developed, leading to the proof-testing of clad airfoils in operating turbines (1). This effort has been supported in the laboratory by extended small burner rig exposures in various environments over the critical temperature range of 593C (1100F) to 1038C (1900F) for periods up to 10,000 hours, and by extensive pre- and postexposure mechanical property tests of the clad composite system. A secondary goal has been the evaluation of metallurgical reactions between substrate and cladding and the resultant effect upon failure modes. A cladding thickness of 250μ was chosen at the outset to provide adequate life in order that surface and bondline reactions might be studied independently. This paper highlights the key results generated during this study.

PROCESS DEVELOPMENT

Sheet Fabricability - The principal cladding alloys of interest during this investigation have been GE-2541 (25 Cr-4Al-1Y-Fe Bal.) and S-57 (25Cr-3Al-10Ni-5Ta-0.2Y-Co Bal.; in weight percent). GE-2541 is a solid-solution ferritic stainless steel containing a dispersion of Y-Fe intermetallic precipitate, while Co-base alloy S-57 consists of an austenitic matrix containing β-CoAl and $Co_{17}Y_2$ particles. It was found that sheet fabricated from conventional cast and wrought ingot exhibited low ductility (less than 10% room temperature elongation) and poor cold-rolling response, which was related especially to Al and Y concentration and precipitate size and distribution. Since corrosion resistance is generally enhanced with higher Al and Cr levels, and Y is beneficial to oxide scale adherence, the tradeoff with sheet fabricability and formability is critical. Significant improvements have been achieved recently by starting with HIP (hot-isostatically pressed)-densified argon-atomized prealloyed prealloyed powder ingots. Tensile ductilities in excess of 20% have been produced due to the reduced size and improved distribution of precipitate (Figure 1), which permits maximization of the critical elements as needed.

Bucket Cladding Processes - The following key steps are involved in the fabrication of a clad airfoil: (i) surface preparation, (ii) clad forming, and (iii) HIP diffusion-bonding. Pre-HIP surface preparation of the cladding and substrate bonding surfaces involves grit-blasting or mechanical abrasion with Al_2O_3, ultrasonic cleaning to minimize grit retention, and vapor degreasing in hot trichlorethylene. Bondline cleanliness and, therefore, shear strength can be improved somewhat for certain alloy combinations, including S-57 bonded to IN-738, with the utilization of a closely controlled 12μ thick Ni electroplate at the interface. This inhibits the formation of a nearly-continuous bondline precipitate of TaC which apparently arises from Ta in the S-57 reacting with C available from the substrate. GE-2541 produces excellent bondline properties without plating, since preferential bondline precipitation is absent, and substantial cladding/substrate interdiffusion also occurs. In fact, remarkably high 870C (1600F) bondline tensile strength levels were achieved (200 MPa; 29 KSI) for butt-


TRANSVERSE
UTS
0.2YS
PM
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STRENGTH, KSI
% ELONGATION
AS REC'D
2000°F
2100°F
2200°F
ANNEAL (30 MIN)

Figure 1

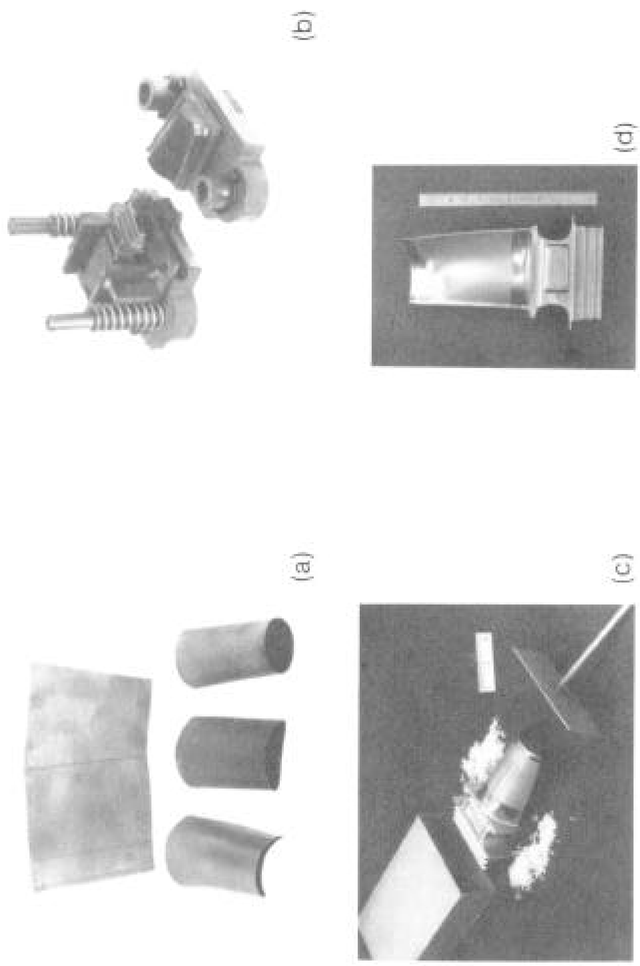
bonded composite bars containing a 250μ thick wafer of cladding. Reducing HIP temperature from 1150C (2100F) to 1093C (2000F), pressure from 103 MPa (15 KSI) to 6.9 MPa (1 KSI), and hold time from 1 to 1/2 hour, had minimal effect on joint strength, which indicates the lower processing limits that could be utilized to minimize cycle time.

Cold-forming of a sheet template into airfoil shape, performed in neoprene die blocks to aid uniform deformation and enhance leading and trailing-edge definition, requires a minimum of 5 to 8% sheet tensile ductility, since approximately 3% lineal stretch (in the rolling direction) is imparted during the forming operation (Figures 2a and 2b). Forming limit diagram (FLD) analyses using etched circle-grids has confirmed the relatively poor formability associated with this class of materials and the nature of localized strain concentrations for airfoil configurations.

Following attachment of the formed cladding to the airfoil by spot welding, solid-state diffusion-bonding is accomplished by one of the following techniques:

(i) Glass-HIP processing involves the total immersion of the bucket in soda-lime glass cullet in an outgassed, evacuated and sealed steel container (Figure 2c) (2). The glass becomes a low viscosity (less than 10^{-6} centipoise) isostatic pressure-transfer media when the argon pressurized autoclave cycle exceeds approximately 1000C (1832F). Molten glass must be excluded from the bondline by proper sealing of the exposed seams; a spot-welded stainless steel strip may be used for this purpose. While the success ratio of this technique is very high, the main disadvantage is the difficult task of removing solidified glass from the airfoil hollow and cooling holes.

(ii) Alternately, braze-HIP processing relies upon an initial controlled vacuum brazing cycle to seal the cladding/substrate seams (Figure 2d) (3). Transfer-tape of prealloyed, corrosion-resistant powder alloy (Ni-45Cr-10Si) is brazed in place at 1150C (2100F) for 10 minutes; this temperature slightly exceeds the braze alloy solidus temperature (1135C; 2075F). Since a vacuum exists between cladding and substrate, direct pressure transfer occurs in the autoclave, eliminating the need to contain the bucket. However, the HIP temperature must be controlled below the braze alloy remelt temperature. The advantages of this technique include the ability to



(a) (b) (c) (d)

Figure 2. Cladding Process. (a) Sheet template. (b) Cold-forming in neoprene die blocks. (c) Glass — HIP diffusion-bonding in an evacuated container. (d) As-brazed clad bucket prior to HIP — bonding.

leak-check the brazed cladding prior to the HIP cycle, and the elimination of post-HIP glass removal.

HOT-CORROSION EVALUATION

Laboratory Studies - In support of the actual turbine field testing of clad airfoils, extensive small burner rig tests have been conducted in facilities described previously (4). Accelerated gas turbine hot-corrosion exposures were simulated at 870C (1600F) and 980C (1800F) with doped diesel oil (1%S) containing 8 ppm Na in the combustion products. Normal oxidation exposures were evaluated at 980C (1800F) and 1038C (1900F) with undoped propane combustion.

Metallographic evaluation of maximum cladding penetration and general corrosion indicates that pack aluminided S-57 is superior to GE-2541 under all conditions of environment and temperature (Figure 3). It had been shown previously that GE-2541 has excellent oxidation and hot-corrosion resistance (4). After 5000 hours at 870C (1600F) in hot corrosion, GE-2541 exhibits moderate penetration in the form of internal sulfide and oxide particulates. Aluminided S-57, however, shows little indication of cladding penetration, although consumption of the added β-CoAl surface layer is almost complete. Hot-corrosion attack at 980C (1800F) is more pronounced for both cladding systems; GE-2541 suffers full penetration of 250μ thickness in about 2500 hours under these accelerated conditions. The β-CoAl surface layer on aluminided S-57 lasts approximately 3000 hours, while marked cladding penetration occurs after 4000 hours. The substantial gains in cladding life due to the β-CoAl surface layer on S-57 are even more pronounced following 4000 hours of oxidation at 1038C (1900F), where little change in cladding or β-CoAl have occurred. Conversely, significant internal oxidation occurs in GE-2541 after just 2000 hours, which is apparently related to the more rapid consumption of Al at the surface.

Substantial improvement has been generated in the life of GE-2541 cladding in the 980C (1800F) hot-corrosion and 1038C (1900F) oxidation exposures by providing an Al source at the bondline with the substrate. This is obtained by incorporating an inner layer of Al foil between the cladding and substrate. The HIP-bonding cycle is controlled to first apply pressure to the assembly;

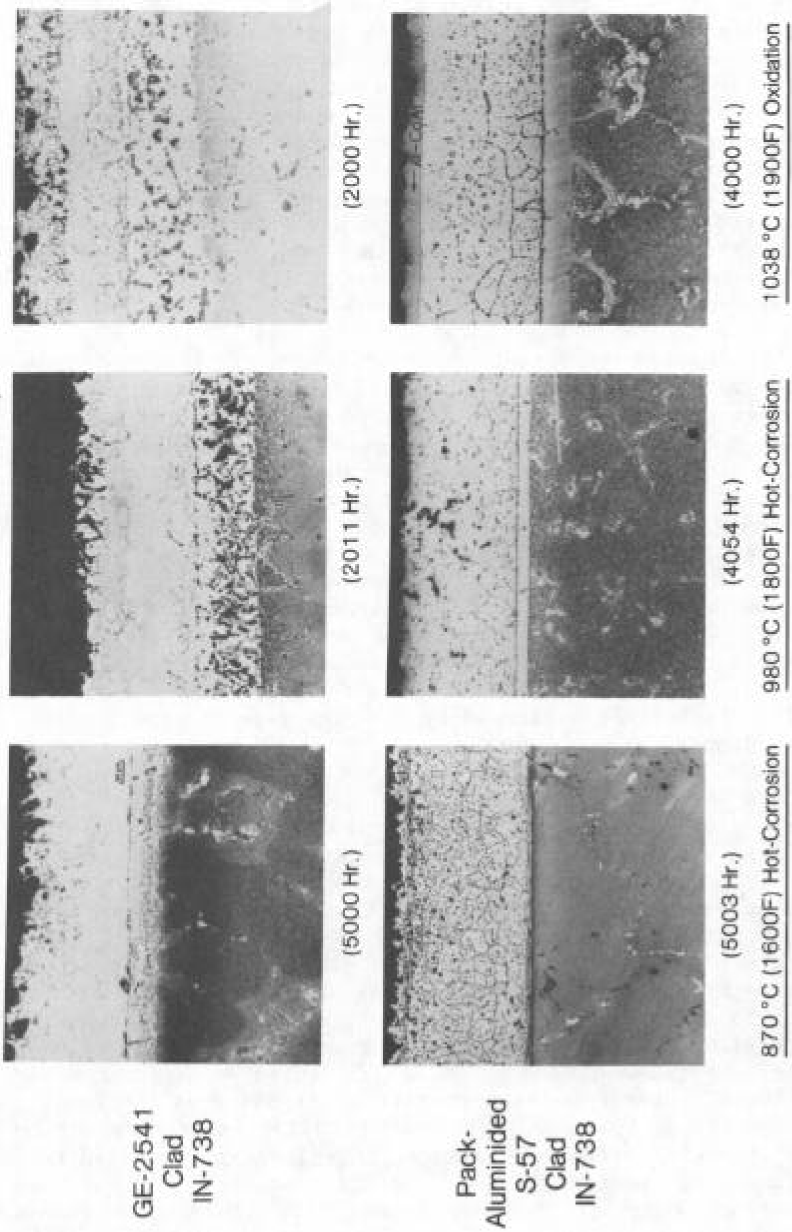
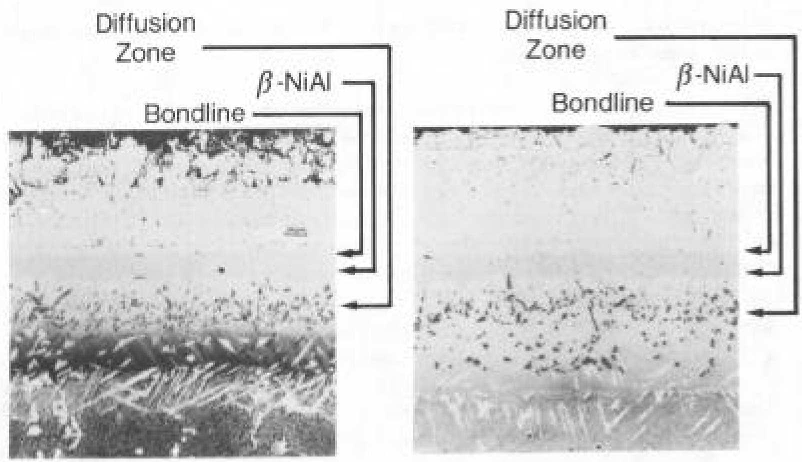


Figure 3. Burner Rig Exposures of Clad IN-738

temperature is then raised to melt the Al foil while it is constrained. Diffusion-bonding occurs simultaneous with the formation of a β-NiAl reaction zone at the bondline. Burner rig hot-corrosion tests at 980C (1800F) produced little cladding attack after 8300 hours, although internal oxide and sulfide particles were found to a depth of 125μ. Similarly, a 4000 hour oxidation exposure at 1038C (1900F) produced only 65μ of cladding penetration (Figure 4). Hence, a bondline Al source produces a factor of four gain in GE-2541 cladding life, and this composite compares very favorably with a surface aluminided S-57 CoCrAlY cladding system.

Another important observation from these studies is the significantly higher rate of Fe:Ni interdiffusion between GE-2541 and IN-738 compared to Co:Ni interdiffusion for S-57 clad IN-738, as indicated metallographically by the width of the γ'-denuded zone beneath the cladding:substrate bondline. Ni injection promotes the matrix transformation of body-centered-cubic (ferritic) GE-2541 to face-centered cubic austenite, while the counterflux of Fe into IN-738 gives rise to sigma-phase formation after just 2000 hours at 870C (1600F). Although Co is also regarded as a sigma-phase stabilizer, slower Co:Ni interdiffusion rates between S-57 and IN-738 apparently delay its formation, as sigma did not form after 5000 hours exposure. This is further evidenced by the slow rate of growth of the γ'-denuded zone (Figure 3).

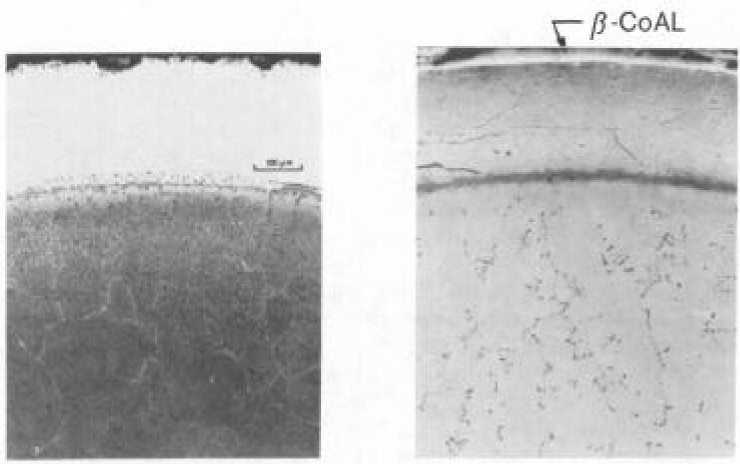
<u>Clad Bucket Evaluation</u> - Field test evaluation of these cladding systems have been carried out in "rainbow rotor" turbine exposures to obtain operating experience on various candidate protection schemes. A joint General Electric/American Arabian Oil Company study was recently conducted utilizing an MS-5002 gas turbine burning sour natural gas (>3% H_2S); airborne alkali is ingested at the site from desert sands containing up to 2% Na (5). A total of 13,051 fired hours of exposure were experienced over a total of 225 fired starts at an average load factor of 69%. As a reference, uncoated IN-738 suffered approximately 180μ of intergranular corrosion penetration at the leading edge of the 50% span location. Metallographic examination of the clad bucket airfoils at this location revealed less than 40μ penetration of GE-2541 accompanied by some surface roughening; the original 250μ cladding-thickness was virtually intact. The pack aluminided S-57 clad airfoil showed no measurable attack after this exposure



(8277 Hr)
980 °C (1800F) Hot Corrosion

(4000 Hr)
1038 °C (1900F) Oxidation

Figure 4. Effect of Al Source on GE-2541 Cladding Life



GE-2541

Aluminided S-57

Figure 5. Leading-Edge Microstructures of Clad IN-738 ARAMCO Buckets After 13051 Fired Hours

(Figure 5); only localized oxidation of the β-CoAl surface layer was experienced.

This turbine experience has demonstrated that diffusion-bonded sheet claddings are a viable means of protecting gas turbine buckets in corrosion service. Furthermore, the superior corrosion resistance of aluminided S-57 compared to GE-2541, identified in the accelerated laboratory burner rig tests, was confirmed by the turbine field test results. Finally, metallographic measurements of the bondline γ'-denuded zone for the GE-2541 clad ARAMCO bucket showed only marginal growth as a result of Fe:Ni interdiffusion. It must be concluded that metal temperatures at the 50% span location ranged from about 788C (1450F) to 843C (1550F), which is consistent with the operating load factor.

ACKNOWLEDGEMENT

The authors gratefully acknowledge the cooperation and support (in part) of the American Arabian Oil Company during this study.

REFERENCES

1. N. R. Lindblad, et al, "Gas Turbine Protection Developments", ASME Paper No. 79-GT-47, 12/78.

2. W. F. Schilling, A. M. Beltran, and G. E. Wasielewski, U.S. Patent No. 3,952,939, 4/76.

3. A. M. Beltran and R. J. Dybas, U.S. Patent No. 3,904,101 3,904,101, 9/75.

4. A. M. Beltran and W. F. Schilling, "The Diffusion-Bonding of Corrosion-Resistant Sheet Claddings to IN-738", Proc. Third Int. Sym. on Superalloys, Claitor's Publishing, Baton Rouge, 1976, p. 425.

5. W. F. Schilling, H. M. Fox, and A. M. Beltran, "Field Testing and Evaluation of Next Generation Industrial Gas Turbine Coatings", Conference on Advanced Materials for Alternate Fuel Capable, Directly-Fired Heat Engines, Castine, ME, 7/79.