AIRCRAFT GAS TURBINE BLADE AND VANE REPAIR

K.C. Antony and G.W. Goward

Turbine Components Corporation
Branford, Connecticut 06405

Abstract

The high replacement costs of aircraft gas turbine blades and vanes have created a fast-growing, highly-specialized segment of the aircraft repair industry. The economic rationale for repair in lieu of replacement is prima facie. The metallurgical rationale is less certain, but satisfactory flight performance over the past twenty-five years at least attests to the technical adequacy of blade and vane repairs. Blade repairs, other than re-coating, generally consist of weld overlays on low-stress blade tip or tip shroud locations. On average, high-pressure turbine blades undergo two repair cycles before replacement. Low-pressure turbine blades similarly require repair but are replaced less frequently. Dimensional restoration of a subtly distorted component to demanding original equipment standards is a real engineering challenge. Coating technology is an equally sophisticated aspect of blade repair. Vane repairs are more avant-garde ranging from platform dimensional restoration to complete airfoil replacement. Vane airfoil crack repair is commonplace and involves a multiplicity of metallurgical processes many of which are still maturing. The future of blade and vane repair, like the past, will be determined by replacement part pricing. The technical considerations will remain as they are but repair will probably become less labor-intensive as automation becomes more feasible.

Superalloys 1988
Edited by S. Reichman, D.N. Duhl,
G. Maurer, S. Antolovich and C. Lund
The Metallurgical Society, 1988

Introduction

Gas turbine blades experience dimensional and metallurgical degradation during engine operation. Dimensional degradation derives from wear, nicks, dents, hot corrosion and, in the case of coated blades, stripping and recoating as in repair. Metallurgical degradation derives from fatigue and high-temperature creep. Some degradation, depending on location and extent, is ammenable to "repair"; the definition of repair being rather broad. That is, only very rarely does a repair provide a part that is equivalent in all respects to a new part. This is not to say that the repair is not safe and cost effective. For example, dimensional restoration of a blade tip by welding provides a part which is functionally satisfactory even though the weld area does not have properties equivalent to the parent material.

Repair procedures and limits are established by the engine manufacturer and are interpreted and applied by the engine operator and/or repair facility. This paper will review some statistics relating the needs for repair or replacement, coating technology related to blade and vane repair, and the types of repairs that are commonly applied to contemporary hardware. Finally, some predictions on the future of repair technology will be attempted.

Some Statistics on Blade and Vane Repairs

Approximately twelve percent of the blades in a typical, moderately aged commercial engine are classified as non-repairable during routine overhaul. Typical blade rejection rates, by stage, are summarized in Table I.

Table I. Typical Blade Repair Rejection Rates

Stage	Rejection Rate
1	30%
2	7%
3	6%
4	3%

The average service lives of solid and air-cooled first-stage blades seem to correspond to three and four repair cycles respectively. Inspection criteria vary depending on blade configuration, but the major causes for retiring first-stage blades from service are generally related to cracks, dimensional discrepancies, hot corrosion, or creep as summarized in Table II.

Table II. Typical Causes for First-Stage Blade Rejection

Cause	Solid	Air-Cooled
1. Cracks	37%	71%
2. Dimensional	32%	20%
3. Hot Corrosion	13%	8%
4. Creep	18%	1%

Hot isostatic pressing (HIP) is being investigated as a means to reduce the number of blades that are being retired because of creep but it is doubtful that blade retirement rates will otherwise change significantly (1).

It is more difficult to ascertain the percentage of non-repairable vanes in a typical, moderately aged commercial engine inasmuch as many, otherwise non-repairable vanes are currently salvaged by airfoil replacement. Approximately forty-five percent of the high pressure turbine (HPT) vanes corresponding to the blades referred to in Table II require airfoil replacement

(2). The average service life of a HPT vane airfoil, if not the entire vane, is therefore only two repair cycles. Airfoil retirement causes vary; but approximately three quarters of the HPT vane airfoils are replaced because of dimensional discrepancies whereas only one-quarter are replaced because of excessive airfoil cracking. Replacement percentages in low pressure turbine (LPT) vanes are similarly difficult to ascertain since many LPT vanes are cast or assembled into multiple vane segments. One discrepant vane, in effect, necessitates replacement of four or more vanes thereby skewing replacement percentages. Dimensional discrepancies caused in many instances by multiple repair cycles, are the principle causes of LPT vane replacement.

Repair-Related Coating Technology

All HPT and some LPT blades and vanes are protectively coated to maintain airfoil geometry, with the intent that the coating endure at least until the parts must be otherwise repaired. Coatings are applied principally to protect against Types I and II hot corrosion (3) and simple oxidation. It is frequently stated that coatings also protect against particle erosion. What little data exist in the open literature indicates that the matter is quite complex and if coatings do provide some protection, the improvement is relatively small (4). There is some evidence that coatings improve the thermal fatigue resistance of equiaxed cast blades by minimizing crack initiation at grain boundaries (5). Conversely coatings generally degrade the thermal fatigue resistance of directionally solidified and single crystal castings (6). In these cases tradeoffs must be made between shortened lives due to thermal fatigue and extended lives afforded by coatings.

Each engine manufacturer develops and/or specifies the types of coatings used on blades and vanes in its engines. The most widely used coatings are the simple aluminides applied by pack cementation (7) or by gas phase aluminizing (8, 9). Aluminide coatings applied by gas phase processes are particularly useful for coating the interior surfaces of complex air-cooled HPT blades. Simple aluminide coatings are often modified with chromium and/or platinum applied in separate gas phase or electroplating processes to further enhance hot corrosion resistance.

At least one engine manufacturer specifies aluminide coatings formed by electrophoretic deposition and subsequent diffusion of aluminum alloy powders. Still another engine manufacturer specifies MCrAlY (where M represents nickel and/or cobalt) coatings applied by overlay processes. The simpler types of MCrAlY overlay coatings are applied by electron beam evaporation, whereas the more complex types, for example, those containing additions of silicon and hafnium, are currently applied exclusively by low pressure plasma spraying (10). Other methods in various stages of development include sputtering and suspension electroplating (11).

Considerable effort has been devoted over the past decade to adaptation of thermal barrier coatings to turbine airfoils. The most advanced of these in production consist of a low pressure plasma sprayed MCrAlY type bond coat followed by an air plasma sprayed partially (yttria) stabilized topcoat. The coating is so far used only on non-rotating airfoils. Zirconia coatings applied by electron beam evaporation show promise of superior thermal stress resistance compared to those applied by plasma spraying but are not yet at the production stage (12).

Masking to preclude deposition of coatings on mechanically critical areas of parts, for example, blade roots is an integral and usually complex part of all coating processes. High temperature diffusion processes usually require some type of slurry mask which acts as a barrier to, or getter of, the coatings species (13). Mechanical masks can sometimes be used for diffusion coating processes but may not always be completely efficient (9). Mechanical masks are satisfactory for low temperature coating processes, such as electrophoresis and high temperature overlay coating processes.

The repair of coated blades and vanes is generally preceded by localized or full removal of existing coatings. Some manufacturers require chemical cleaning with strong acid or alkali mixtures to remove field service debris and/or hot corrosion products prior to coating stripping. Others allow grit blasting to accomplish the same ends. Complex cooling passages in blades can accumulate dust or other debris in service and this may have to be removed with hot caustic at elevated pressure in an autoclave (14).

Physical methods, such as grit blasting or belt grinding can, for example, be used to locally remove coating prior to repair welding of unshrouded blades. Full removal of coatings is universally accomplished by selective dissolution of the coating phase(s) by various simple or complex mixtures of acids. Again, each engine manufacturer, and some repair houses have more or less independently developed their own acid formulations. Most procedures depend on selective attack of beta (NiAl or CoAl) phases. If the coatings are depleted of the beta phases, selective coating dissolution can become difficult or impossible and residual coatings must then be removed by physical means such as belt grinding. Great care must be exercised in the development and control of stripping solutions in order to avoid localized or general attack of the superalloy base. For example, dilute nitric acid is a commonly used, safe coating strippant. Contamination with a few percent of hydrochloric acid can, however, cause selective attack of the gamma prime (Ni_3Al) strengthening phase as illustrated in Figure 1 (15).

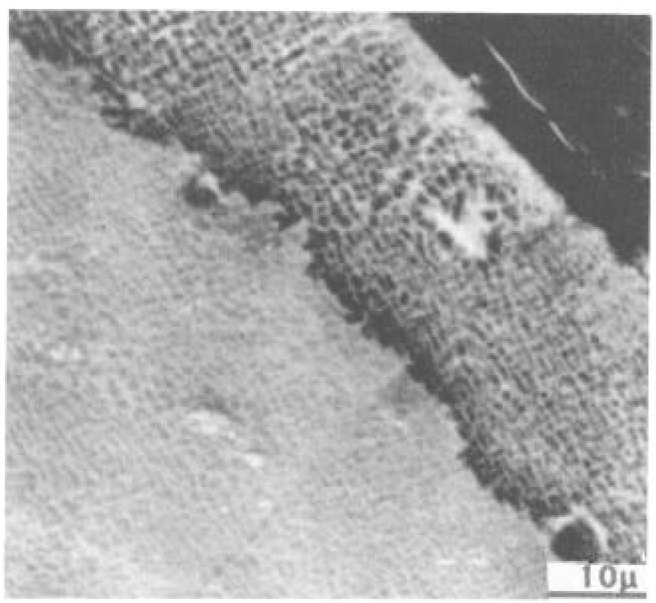

Figure 1. Gamma prime attack caused by coating stripping with nitric acid contaminated by chloride.

Inspection for completion removal of coating is usually accomplished by heat tinting at about 1000°F in air. Gold colors indicate residual coating while the fully stripped alloys are blue.

Since the diffusion aluminide coatings are formed, in part, by nickel (or cobalt) from the substrate alloys it follows that removal of the coatings will cause finite dimensional losses of the substrates. This usually amounts to 0.001 to 0.002 inches for commonly used coating thicknesses of about 0.003 inches.

To preclude the possibility of even minute amounts of attack on uncoated surfaces, such as blade roots and internal cooling passages, wax masking is usually employed. Coated cooling passages present special problems; because of the difficulty of inspecting for complete removal of coating, the passages are usually waxed to preclude any coating stripping.

Clearly gas turbine blade and vane repair involves the acquisition and implementation of a wide variety of coating technologies. Thus, access to coating technology and engine manufacturer coating approvals, in a very real sense, limit complete aircraft gas turbine airfoil repair to relatively few, technically sophisticated repair facilities.

Types of Blade Damage and Repairs

Blade repairs vary depending on blade configuration but are largely matters of restoring blade tips or tip shrouds to demanding dimensional criteria using weld overlay processes. Tip shroud repairs may also include hardfacing replacement and knife-edge seal restoration. Manual gas tungsten arc welding (GTAW) processes are most commonly used for blade repair, but plasma, laser, and electron-beam welding processes are finding increased usage as the trend to automation continues.

Blade repair is complicated by weld cracking problems inherent to blade alloys and by subtle dimensional changes which occur during engine service. Virtually all aircraft gas turbine blades are cast out of nickel-base superalloys with aluminum/titanium contents well above those empirically associated with moderately acceptable weldability, i.e. $Al + Ti/2 \leq 3\%$. Weld overlaying is not particularly difficult provided adequate precautions are taken; but some amount of microcracking is inevitable.

Weld filler alloys are usually selected to minimize microcracking but coating compatibility and strength should also be considered. Weld filler alloys containing even a small amount of aluminum are more compatible with diffused aluminide coatings than are weld filler alloys totally void of aluminum. Aluminum oxide and/or continuous alpha chromium (16) tend to form at the coating/substrate interface in the absence of aluminum in the weld repaired area. As illustrated in Figure 2, AMS 5837 (Inconel 625, $\sim$0.2% aluminum) weld overlays are more compatible with diffused aluminide coatings than are AMS 5679 (Fm 62, nil aluminum) weld overlays.

Further, weld overlay filler alloys generally derive from solid solution or gamma-prime lean nickel-base superalloys considerably lower in strength than the blade alloys they replace. It follows, therefore, that weld repairs are generally not made on highly stresses airfoil surfaces. Some small-engine manufacturing are however considering weld-overlay repairs over the upper two-thirds of the leading and trailing edges of the blade airfoils as well as the blade tips.

Types of Vane Damage and Repair

Some HPT vanes are cast out of nickel-base superalloys similar to those used for blade applications; but the majority of the HPT vanes currently circulating through overhaul facilities are cast out of cobalt-base superalloys. The cobalt-base superalloys, as a rule, are more amenable to repair than are the nickel-base superalloys.

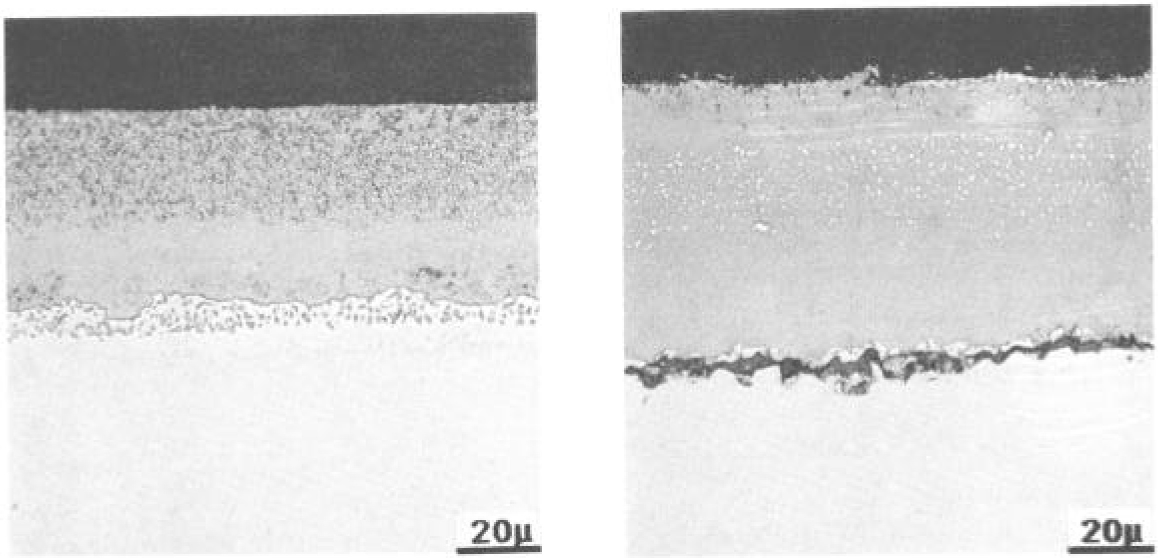

Figure 2. Comparison of compatibility of diffusion aluminide coating with weld filler materials. Left, diffusion coating on AMS 5837 (Inconel TM 625, ~0.2% aluminum). Right, same coating on AMS 5679 (Fm 62, nil aluminum).

HPT vanes encounter rather severe thermal gradients in engine service, distort, and frequently crack by thermal fatigue. HPT vane repair is largely a matter of straightening distorted airfoils in order to restore gas path flow area and re-joining airfoil cracks.

Straightening is accomplished by bending. A limited amount of bending can be accomplished at ambient temperature. However, straightening is best accomplished at elevated temperatures using hot dies, i.e., isothermal forging. Consideration of tensile ductility data suggests it is actually counterproductive to straighten heated nickel-base superalloys using ambient temperature dies or straightening tools. Straightening, if improperly accomplished, can, in and of itself cause airfoil cracking or result in subtle changes in gas path flow area due to relaxation at elevated temperature during subsequent repair operations or engine service.

Cracks in cobalt-base HPT vane airfoils, depending on location and severity, are usually repaired by manual GTAW using cobalt-base filler alloys. The metallurgical rationale for such weld repairs is prima-facie and substantiated by extensive laboratory testing, test stand validation, and field experience. Bonafide weld repairs are usually achieved in cobalt-base HPT vane components provided the crack surfaces are clean, the vane is fully annealed prior to weld repair, and reasonable care is taken while making weld repairs.

Cracks in nickel-base HPT vane airfoils are considerably more difficult to repair by GTAW. Microcracking is virtually certain in nickel-base superalloy crack weld repair; and, macrocracking is likely during post weld heat treatment. The consequences of such weld-induced defects on vane engine performance is uncertain; but it is a misnomer to refer to GTAW as a method of crack "repair" in nickel-base superalloy vanes.

The metallurgical problems associated with GTAW repairs have stimulated interest in braze welding as an alternate repair process for cracks in nickel-base superalloy HPT vane airfoils (17). Braze welding which, by definition, involves distribution of a high-temperature filler material by some mechanism other than capillary action seems well-suited to the repair of wide-gap (0.002 to 0.060 inches in width) cracks such as occur in HPT vane airfoils during engine service (18). However, the metallurgical rationale for braze welding is unclear and substantiating laboratory data are meager. Nevertheless, virtually every vane repair facility currently offers a proprietary three-initial acronym braze weld repair process for cracked HPT vanes. There is no question that cracks can be at least partially filled by braze welding and made acceptable to visual acceptance standards. However, true crack repair is another matter, requiring that the filler material wet and bond to all crack surfaces and approach vane base alloy mechanical/physical properties.

Complete oxide removal from all interior crack surfaces is essential to crack repair by braze welding. Those alloying elements that complicate crack repair by fusion welding in nickel-base superalloys also complicate crack repair by braze welding in that they contribute to the formation of extremely stable oxides that are difficult to reduce or otherwise remove in situ. Various fluoride-ion "cleaning" processes have been developed for the purpose of reducing or removing oxides that can form on nickel-base superalloy crack surfaces; but the efficacy of these processes remains uncertain (19, 20). The ability of these processes to reduce or remove oxides in deep, high-aspect-ratio cracks or as thick layers without detrimentally affecting other superalloy surfaces is suspect. Gamma prime solute depletion and spongy surfaces are natural consequences of fluoride ion treatment of unoxidized nickel-base superalloy surfaces. In addition intergranular attack is often a side-effect.

Braze welding filler materials, as used in vane crack repair, are generally mixtures of vane base alloy and high-temperature braze alloy powders. Typical base to braze alloy ratios range between 50-50 to 75-25. The braze alloys invariably contain boron and/or silicon as melting range depressants. In theory, interdiffusion between the base and braze alloys at temperatures above the solidus of the braze alloy dynamically increases the solidus temperature of the diffused filler material. In practice, the remelt or solidus temperature of weld brazing mixtures containing substantial amounts of boron seldom exceeds 1950°F.

In theory, interdiffusion retards flow without affecting wetting thereby accommodating much wider crack gaps than can be accommodated with braze alloys alone. In practice, flow is controlled by the base to braze alloy ratio and the braze welding temperature in relation to the liquidus of the diffused filler. It is extremely difficult to fill a wide-gap crack or crevice without leaving voids.

Published data concerning the mechanical properties of braze weldments are meager. High-temperature tensile and stress-rupture strengths of braze weldments approaching, and in some instances exceeding, corresponding base alloy strength levels have been measured (21). However, ductility is invariably impaired and thermal fatigue resistance is suspect. Braze welding, never-the-less, is "in vogue" as a method of repairing cracks in nickel-base superalloy HPT vane airfoils.

Thermal fatigue cracking is less frequent in LPT vanes but still occurs. Since virtually all LPT vanes are cast out of nickel-base superalloys, the problems associated with crack repair in nickel-base HPT vanes apply equally to LPT vanes; and complete airfoil replacement is not a repair option as it is with cobalt-base HPT vanes. LPT vanes are generally replaced for dimensional causes such as short chord, wall or airfoil thickness, etc. LPT vanes suffer dimensional degradation due to wear and corrosion. However, the collective effects of prior repairs such as blending and/or coating replacement eventually take their toll and can become the primary causes for LPT replacement. Repair cleaning operations such as grit blasting reduce airfoil thickness by approximately 0.00006 inches. However, chemical cleaning and/or chemical removal of diffused aluminide coatings reduce airfoil thickness by as much as 0.002 to 0.004 inches. Such thickness reductions, though seemingly small, can ultimately limit the useful life of a LPT vane or necessitate some form of dimensional restoration.

Undersized LPT vane platforms are dimensionally restored by weld overlay, thermal spray, or braze welding overlay processes depending on base alloy, location, service conditions, etc. LPT vane airfoil dimensions can be similarly restored. GTAW overlays are impractical for airfoil dimensional restoration because of distortion. However, low heat-input weld overlay processes, such as "Rapid-Arc", hold promise for LPT vane airfoil dimensional restoration applications but are limited to overlay materials that are available in continuous lengths of wire (22). Low pressure plasma spray, without alloy restrictions, holds even more promise for such applications. Weld braze overlays are being actively investigated for airfoil dimensional restoration purposes but are limited by base alloy embrittlement and coating compatibility considerations. The more avant-grade in LPT vane repair are evaluating methods of restoring airfoil dimensions while simultaneously changing gas path flow area to changing engine requirements (23). The "recast" process would seem to have the most potential in this regard although other processes/repair schemes are already being engine tested (24).

Coating Replacement

Subsequent to mechanical repair, coatings are replaced, usually in accord with the original requirements of engine manufacturers. In most cases, coating processing is identical to that used to coat new parts. In some cases, masking may be more complicated, if for example, parts were originally coated before machining to avoid masking costs which would be incurred, for example, in excluding coating from blade roots.

Recovery of alloy properties by heat treatment, if necessary, is accomplished in conjunction with or following the heat cycle of the coating process.

Future Trends

The majority of the processes used to repair aircraft gas turbine blades and vanes are labor intensive. Some processes such as brazing, coating, and heat treatment are batch processes and benefit from volume. However, even these processes require some amount of manual materials handling. There is, of course, considerable interest in automating blade and vane repair processes; but some processes such as crack weld repair must be addressed on an individual piece-to-piece basis. Weld overlay repair processes are, in theory, amenable to automation. However, weld overlay automation is proving difficult in practice due to dimensional inconsistencies intrinsic to engine-run components. Original equipment reference surfaces simply do not apply in repair and local component thickness or mass vary considerably on blades and vanes from the same engine. Automated weld overlay repair systems must be capable of adjusting the weld torch position over variable surfaces as well as adjusting the weld process heat input and deposition rate to accommodate a variable heat sink. The primary focus of automation in aircraft gas turbine blade and vane repair must be toward the development and implementation of adaptive control schemes that will permit automatic repair devices to alter their pre-programmed directions or torch conditions to suit the specific requirements of each individual blade or vane.

The future of blade and vane repair will be determined by replacement part pricing, "break-out" sales activity, and labor cost. The technical issues will probably remain as they are, but repair will become less labor-intensive as automation becomes more feasible.

References

1. J. Wortmann, "Improving Reliability and Lifetime of Rejuvenated Turbine Blades," Materials Science and Technology, 1 (1985), 644-650.

2. J. Riccitelli, private communication with authors, Turbine Components Corporation, Branford, CT.

3. G. W. Goward, "Low-Temperature Hot Corrosion: a Review of Causes and Coatings Therefor," Journal of Engineering for Gas Turbines and Power, 108 (1986), 421-425.

4. R. H. Barkalow, J. A. Goebel, and F. S. Pettit, "Erosion - Corrosion of Coatings and Superalloys in High Velocity Hot Gases," Erosion: Prevention and Useful Applications, ASTM STP 664, (American Society for Testing and Materials, 1979), 163-192.

5. M. Gell, G. R. Leverant, and C. H. Wells, "The Fatigue Strength of Nickel-Base Superalloys," Achievement of High Fatigue Resistance in Metals and Alloys, ASTM STP 467, (American Society for Testing and Materials, 1970), 113-153.

6. K. Schneider and H. W. Grünling, "Mechanical Aspects of High Temperature Coatings," Thin Solid Films, 107 (1983), 395-416.

7. G. W. Goward and L. W. Cannon, "Pack Cementation Coatings for Superalloys: a Review of History, Theory, and Practice," Journal of Engineering for Gas Turbines and Power, 110 (1988), 150-154.

8. R. S. Parzuchowski, "Gas Phase Deposition of Aluminum on Nickel Alloys," Thin Solid Films, 45 (1977), 349-355.

9. G. Gaujé and R. Morbioli, "Vapor Phase Aluminizing to Protect Turbine Airfoils," High Temperature Protective Coatings, ed. S. C. Singhal (Warrendale, PA: The Metallurgical Society of AIME, 1983), 13-26.

10. D. K. Gupta and D. S. Duvall, "A Silicon and Hafnium Modified Plasma Sprayed MCrAlY Coating for Single Crystal Superalloys," Superalloys 1984, ed. M. Gell et al. (Warrendale, PA: The Metallurgical Society of AIME, 1984), 711-720.

11. J. E. Restall, "Development of Coatings for the Protection of Gas Turbine Blades Against High Temperature Oxidation and Corrosion," ibid., 721-730.

12. R. Shankar, "Electron Beam Physical Vapor Deposition Development of Zirconia Coatings" (Paper presented at Coatings for Advanced Heat Engines Conference, U. S. Department of Energy, Castine, Maine, July 27-30, 1987).

13. A. L. Baldi, "Diffusion Treatment of Metal," U.S. Patent 3,958,047 (1976).

14. E. A. Ault and C. E. Bevan," Cleaning Process for Internal Passages of Superalloy Airfoils," U.S. Patent 4,439,241,(1984).

15. G. W. Goward, "Effects of Superalloy and Coating Structures on Hot Corrosion," J. Vac. Sci. Technol., A4 (1986), 2905-2906.

16. G. W. Goward and D. H. Boone, "Mechanisms of Formation of Diffusion Aluminide Coatings on Nickel-Base Superalloys," Oxid. of Metals, 3 (1971), 475-495.

17. J. W. Lee, J. H. McMurray, and J. A. Miller, "Development of a New Brazing Technique for Repair of Turbine Engine Components," Welding Journal, 64 (1985), 18-21.

18. Metals Handbook. Ninth Edition, (American Society for Metals, 1983) Glossary 3.

19. D. L. Keller, D. L. Resor, "Superalloy Article Cleaning and Repair Method," U.S. Patent 4,098,540, (1978).

20. J. W. Chasteen, "Method for Cleaning Metal Parts," U.S. Patent 4,405,379, (1983).

21. N. Czech, W. Esser, and R. Wolters, "Hot Corrosion and Air Creep Rupture Properties of Superalloy Weldings and Brazings," (Final Report, Cost 50-111 Dig. 1983).

22. E. Craig, "A Unique Mode of GMAW Transfer," Welding Journal, 66 (1987), 51-55.

23. P. J. Draghi, J. P. Arrigoni, "Turbine Vane Nozzle Reclassification," U.S. Patent 4,726,101, (1988).

24. S. J. Cretella, M. Bernardo, and R. T. DeMusis, "Refurbished Turbine Vanes and Method of Refurbishment Thereof," U.S. Patent 4,028,787, (1977).