Development of Inconel* Alloy MA 6000 Turbine Blades For Advanced Gas Turbine Engine Designs

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Abstract

This paper deals with Allison's work with the MA 6000 alloy aimed at near-net-shape forgings and thermal protection coatings for uncooled turbine blade applications. The work described is presented from the user's viewpoint and summarizes the ongoing efforts of a team that included leaders in oxide dispersion strengthening (ODS) alloy production and the forging of these alloys into near-net-shape airfoil configurations.

Results that were achieved in this program to date include the attainment of conventional forging schedules at both Textron Excello and Doncasters Monk Bridge for producing a near-net-shape shrouded second stage T406 turbine blade configuration. In addition, Doncasters was able to demonstrate their ability to EDM machine their forgings to required airfoil dimensions. The Excello and Doncasters stress rupture results were both competitive with single crystals in the high temperature/low stress regime, with the Doncasters blades showing the best performance. Also, results of oxidation testing performed at 2150°F on a new duplex coating system were very promising. The data showed that the new coating system was superior to that of contemporary coating systems and that the MA 6000 coating interface was free of porosity after 400 hours of exposure.

Overall, it was shown that near-net-shape forging to produce complicated MA 6000 turbine airfoils has the potential for significantly improved temperature capabilities relative to the CMSX-3 single crystal alloy in selected high taper ratio low stress turbine blade designs. For certain applications and configurations, the reduced input stock and attendant cost savings inherent with the conventional forging process appeared to justify this approach. For other applications that are less complicated from a configuration viewpoint the machining of the airfoils from extruded and hot rolled product may represent the best approach.

* Inconel is a registered trademark of the Inco family of companies.

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Introduction

MA 6000 is an austenitic Ni, 15 Cr, 2.0 Mo, 2.0 Ta, 2.5 Ti, 4.5 Al, 4.0 W, 0.01B, 0.15Zr, 1.1 Y_2O_3 alloy that is produced by mechanical alloying techniques. The alloy is unique in that it combines gamma prime age hardening with Y_2O_3 dispersion strengthening providing it with a combination of intermediate and high temperature strength characteristics for turbine blading applications; it is generally produced as bar product and is used in the directionally recrystallized form.

The road to a major commitment in U.S. gas turbines has been relatively slow for MA 6000. This has in large part been due to competitive pressures from directionally solidified (DS) and single crystal (SC) castings and the relatively low intermediate temperature properties of MA 6000.

However, MA 6000's potential for superior high temperature capability at moderate stress levels continues to make it an attractive candidate for selected modern high taper ratio low stress designs where the alloy's dispersion strengthening mechanism can be used to advantage. Specifically, as is shown in Figure 1, the MA 6000 alloy has the potential to offer an approximate 125°F temperature advantage over a contemporary single crystal alloy such as CMSX-3 at a 15 ksi stress level. When this advantage is translated into either an elimination or a reduction in the amount of cooling air required for a turbine blade design, the resulting fuel savings can be significant.

During the early 1980s, the Garrett Turbine Engine Company, under NASA MATE (Materials For Advanced Turbine Engines) sponsorship, undertook a program to develop MA 6000 processing schedules for an uncooled HP turbine blade in the TFE 731 engine[1]. This effort, involved a dedicated activity to tailor a new blade design to the alloy's unique balance of moderate intermediate temperature capability and excellent high temperature properties. This work focused on a fabrication sequence for the new blade design that involved extrusion followed by hot rolling and directional recrystallization to develop barstock with the desired high aspect ratio (10:1 and greater) grain structure. The final blade configuration was then produced by a combination of airfoil electro chemical machining (ECM) and blade root grinding.

This program was very successful technically, however, because of its focus on a relatively simple unshrouded blade configuration and the design's relatively moderate blade operating temperature requirement, the program did not address two important issues. In particular, near-net-shape processing that could lead to improved materials utilization and subsequently reduced acquisition costs was not pursued. Also, the issue of Kirkendal porosity at coating/substrate interfaces following extended exposures in the 2100°F range remained as an impediment to the realization of maximum metal temperature operating capability. In the final analyses, the excellent Garrett work with MA 6000 firmly established the technical feasibility of utilizing MA 6000 in tailored engine designs. However, because of cost and maturity factors relative to DS and SC castings, the effort failed to transition to production implementation in their small commercial engine designs.

In recognition of the potential associated with the use of ODS blade alloys in large engine designs NASA funded, in the mid 1980s, a second, although, limited effort to dimension the capabilities of MA 6000 in a larger turbine blade configuration[2]. Emphasized for the first time was conventional forging activity aimed at reducing processing costs through improved materials utilization. The results of this effort, which was performed by Textron Excello, were encouraging in that the material was shown to be workable under carefully controlled conventional forging techniques. However, the limited scope of this program precluded a full scale optimization of the required thermo mechanical processes (TMP) and as a consequence work on the alloy by gas turbine manufacturers in the U.S. ceased.

This was the case in the U.S. until 1983 when Allison turned again to the potential that MA 6000 might have for utilization in several new turboprop engine programs that stood to benefit from the availability of a blade alloy with improved temperature capabilities relative to contemporary single crystal alloys. Of particular interest were T406 first- and second-stage turbine blade designs as shown in Figure 2. In the case of first-stage blade design, which is unshrouded and air cooled, it was desired to demonstrate that forged MA 6000 properties could be developed such that the cooled blade could be redesigned to be run uncooled. In the case of the uncooled second-stage shrouded blades, it was desired to demonstrate that cost advantages relative to cast single crystal designs could be realized with near-net-shape forging techniques. Consequently with a combination of U.S. Air Force and company support, a team effort was launched to develop the required process technologies. The vehicle for the work was a low stress, high taper ratio shrouded design for the second-stage T406 turbine blade. Included in the program were forging, machining and blade characterization efforts. Also included was coating development aimed at coating systems that would be diffusionally stable at temperatures to 2150°F. Team members included the following:

- o Inco Alloys International (IAI)-Hereford, England and Huntington, West Virginia - Extruded and Hot Rolled MA 6000 Bar Supply
- o Textron, Excello-Euclid, Ohio - Forging/Machining Optimization
- o Doncasters Monk Bridge, Limited-Leeds, England - Forging/Machining Optimization
- o Boone and Associates-Walnut Creek, California - Coating Consultants

Following is an overview of the work performed by the team and the status of the effort as it relates to Allison Gas Turbine engine design.

<u>Textron Excello Forging Development</u>

MA 6000 is forged from barstock which is in the fine equiaxed grain structure condition. Unless properly insulated the alloy can be prone to brittle fracture during conventional forging due to die chilling. In order

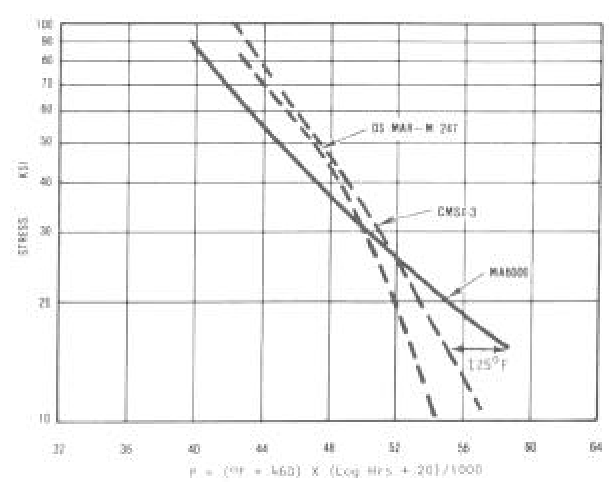

Figure 1. Stress-rupture data for MA 6000, SC CMSX-3, and DS Mar-M247, longitudinal orientation.

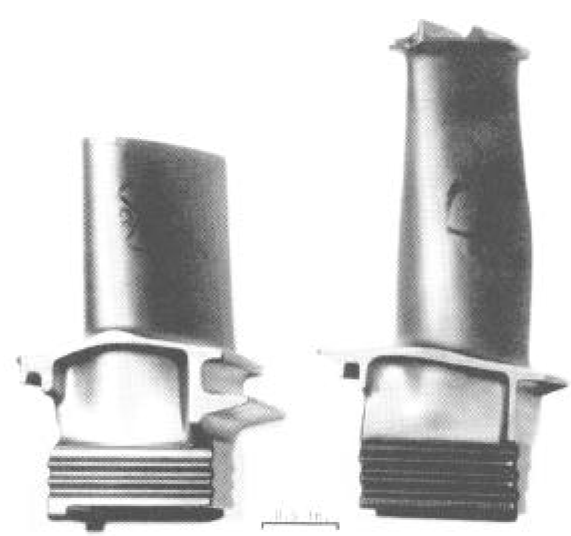

Figure 2. T406 first and second stage turbine blades.

to overcome die chilling problems, the Excello approach was to perform conventional mechanical press forging with the mild steel can left intact from the extrusion process.

The forging approach initially selected was based on a two step process involving preform and finish forge operations. Forge tool development involved an iterative approach to develop the finish forge blade design requirements. Forged blades representative of the last forging iteration were then to be directionally recrystallized, heat treated, and tested for mechanical properties.

To develop an optimum material input condition for the forgings, three approaches were pursued simultaneously as follows:

(1) Direct powder extrusion to a required one inch square cross section.
(2) Double extrusion which included an oversize extrusion followed by a second extrusion to the require cross section.
(3) Oversize extrusion followed by hot rolling to the required cross section.

The forging response of MA 6000 processed through the three approaches was more or less the same in that the material forged satisfactorily during the preform step. However, cracking was developed for each during the finish step due to die design difficulties.

The preliminary DR trials were conducted by IAI on preform as well as finish forgings. The results for preform forgings indicated that a complete recrystallization was achieved, however DR response for finish forging was only marginal. Further, the most favorable DR response was obtained with the Approach 3 material. Because the one-hit forgings (preforms) consistently exhibited a positive, coarser columnar grain structural response, a new set of dies was designed and built specifically for a one step, oversize forging approach. The new design was also aimed at minimizing metal flow patterns which could lead to cracking. Forgings representative of the new design were crack free, Figure 3, and exhibited a DR structure comparable to that observed previously with preform forgings.

Consequently, additional forgings, were made in order to generate tensile and creep/stress rupture data and to establish property performance levels for the MA 6000 forgings. They were directionally recrystallized at 2300°F, solution heat treated at 2250°F for 1/2 hour, exposed to a simulated coating diffusion cycle at 1975°F for 4 hours and then aged at 1550°F for 4 hours and 1400°F for 16 hours. This heat treatment was selected from an independent study on coating heat treatment compatibility.

Mechanical property evaluations included tensile and creep/stress rupture tests on specimens machined from airfoil sections of the forgings. Analysis of the tensile data over a range of temperatures from room temperature to 2150°F indicated little scatter in the properties and when compared with properties obtained in the Garrett NASA-MATE program, it was seen that the forged MA 6000 demonstrated tensile strength levels which were similar to those of the extruded and hot rolled material.

Stress rupture testing on small sub sized specimens (0.070 in. diameter) machined from airfoil stacking axes was conducted at temperatures ranging from 1400°F to 2150°F. The analysis of the test results indicated that, strength levels generally failed to match the MA 6000 performance demonstrated in the earlier Garrett NASA-MATE program. Figure 4 illustrates forged MA 6000 properties compared with MA 6000 properties obtained from large diameter test bars (0.250 in.) in the Garrett NASA-MATE program. Also shown are CMSX-3 single crystal properties for both large diameter and thin

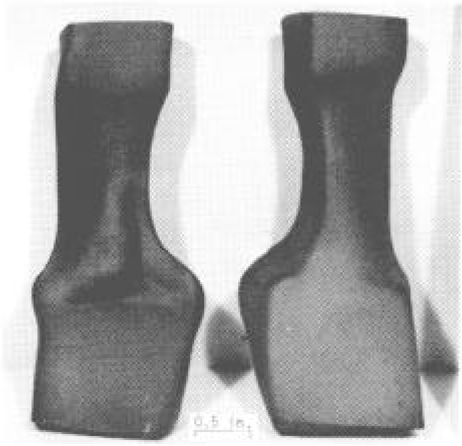

Figure 3. Second stage MA 6000 T406 forgings produced by Textron Excello.

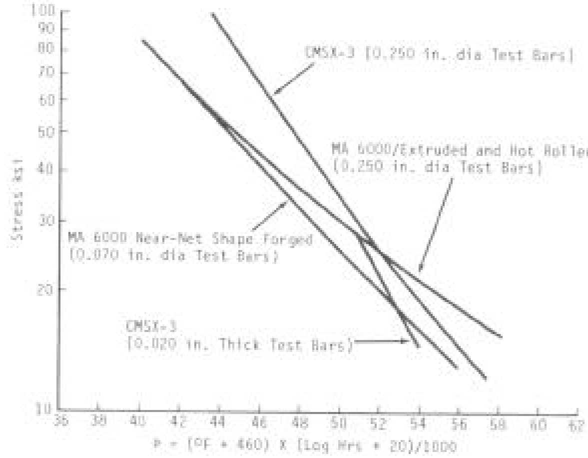

Figure 4. Textron Excello forged MA 6000 stress rupture properties compared to Garrett-NASA MATE ex truded and rolled MA 6000 bar and CMSX-3 single crystal test results.

wall (0.020 in.) test specimens. As shown, the small 0.070 in. diameter test bars machined from forged MA 6000 demonstrated that stress rupture strengths at the lowest test temperatures and the highest stress levels were similar to the strength behavior of the extruded material. However, as temperatures increased and stress levels decreased the forged MA 6000 properties degraded possibly as a consequence of environmental effects(3). In addition, the forged MA 6000 results showed considerable scatter. By comparison to thin wall CMSX-3 data at 20 ksi stress levels and higher the MA 6000 results were generally lower. Below 20 ksi the MA 6000 results were competitive. Metallographic evaluations of several longitudinal sections indicated several microstructural deficiencies: (a) non-uniformity in grain aspect ratio within the airfoil regions as well as in shroud and root sections, (b) sporadic equiaxed grain structure throughout the blade, and (c) absence of a consistent coarse and high aspect ratio grain structure. These microstructural deficiencies may explain the scatter in the rupture strengths.

Doncasters Forging Development

Doncasters' MA 6000 near-net forging development effort was also aimed at the second-stage T406 turbine blade configuration. In this effort, Doncasters developed a two-step conventional forging route to produce crack-free near-net shape T406 blades with a high aspect ratio directionally recrystallized structure. The approach pursued involved the use of a screw press and a proprietary thermal barrier to minimize die chill. In this work, the general impact of forging and DR parameters on blade structures was identified. These experiments proved that similar recrystallized morphologies, in terms of grain size and aspect ratio, could be realized by either tailoring forging parameters for a fixed DR condition or independently selecting optimum DR parameters for a fixed forging practice. A wide degree of control over structures, therefore, was shown to exist by the variation of chosen parameters.

Subsequent efforts were aimed at improving the degree of structural control by "fine-tuning" the processing conditions as well as measuring creep rupture strength at elevated temperatures. This was followed by the forging of second-stage T406 turbine blades and EDM machining trials to produce airfoils for component testing. The blades from this forging campaign were extensively examined for shape control to ensure that finished blades of the correct size and tolerance could be produced. Following minor die modifications, additional blades were forged, heat treated and EDM machined and polished to create finished airfoils and platforms. Most of these were destructively examined to ensure that potentially deleterious effects, such as recast layer, were eliminated. A final forging run was then completed from which blades with finished airfoils and platforms were made. Figure 5 illustrates two typical forgings before and after machining of the airfoil surfaces. Dimensional inspection indicated that most blades had sufficient material in the root and shroud areas from which finished dimensions could be machined. Some, however, were slightly short of material in non-critical areas indicating that further die modifications would be desirable.

At Allison, metallographic evaluation of several directionally recrystallized and heat treated longitudinal sections showed that a desired coarse and high aspect ratio grain structure had been achieved in most of the airfoil cross sections. However, after careful review it was noted that there was a microstructural deficiency observed near the leading edge. These areas appeared not to have received the same TMP as the rest of the airfoil cross-section, possibly as a consequence of die chill developed during the forging operation. Stress rupture test results for specimens machined from airfoil stacking axes at temperatures ranging from 1400°F to 2150°F were then compared with 0.020 in. thin wall CMSX-3 single crystal alloy properties. With the exception of specimens that were machined from the leading edge area and which showed significantly reduced strength levels, the small 0.070 in. diameter test bars machined from the forged MA 6000 blades demonstrated stress rupture strength levels that were on the order of 50°F improved over thin section CMSX-3 properties at a 20 ksi stress level and 100°F at a 15 ksi stress level. A comparison of Excello and Doncasters thin section MA 6000 results to thin section CMSX-3 single crystal data is presented in Figure 6. Shown is the superiority of the Doncasters forgings over the Excello forgings. It is not clear as to the explanation for the different performance levels. However, several variables, ranging from starting input stock to DR heat treat practice could be significant factors.

The grain quality problems encountered at the leading edge of the Doncasters blades will require additional work, however, this is not expected to pose a significant roadblock to achieving the desired high aspect grain quality throughout the airfoil.

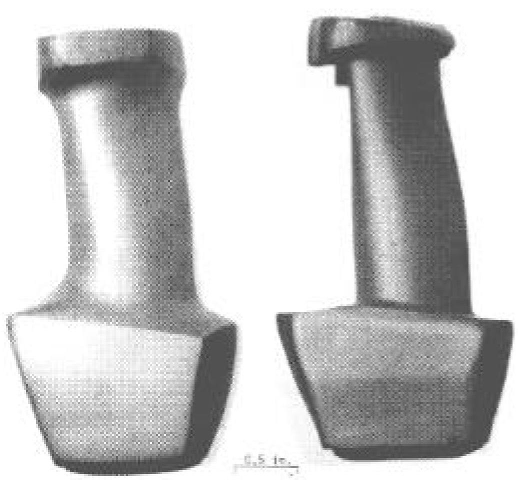

Figure 5. Typical Doncasters T406 second-stage turbine blade forgings before and after airfoil machining.

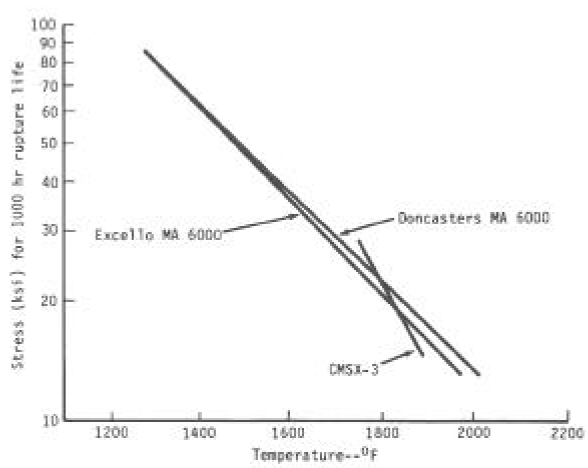

Figure 6. Thin section stress rupture capability for MA 6000 and CMSX-3.

In order to circumvent the grain quality problem at the leading edge, Doncasters has recently introduced a modified conventional forging procedure. This technique uses a multi-stage preform preparation cycle based on extrusion, prior to the standard finish forging operation. The preform contains a more uniform distribution of work, particularly in the airfoil section and is designed to eliminate the fine grained structure. Projected advantages for this approach include better overall structural control and reproducibility.

Trials are in progress to establish the correct working parameters to achieve coarse-grained structures in directionally recrystallized blades and improve the uniformity of structure across the airfoil. Additional blades are now being forged to verify and quantify the structural improvements in terms of stress rupture properties.

Coating Development

It has been shown in work conducted at Allison that the MCrAlY class of overlay coatings can provide excellent environmental protection on the MA 6000 alloy at temperatures up to and beyond those developed during second stage T406 blade operation. By contrast, the aluminide class of coating has much less temperature capability on MA 6000 and performs poorly under 1950°F test conditions due to the formation of Kirkendall porosity that occurs at the coating/substrate interface following extended exposure. The Kirkendall porosity is felt to develop as a consequence of outward diffusion of aluminum and chromium during the oxidation process, leaving behind vacancies or pores that ultimately lead to coating spallation and failure. As an example, Figure 7, shows Kirkendall porosity in an aluminide coated MA 6000 test specimen following 1000 cycles of oxidation testing between 1950°F and 600°F. Figure 8 shows a relatively porosity free MCrAlY coated MA 6000 test specimen following 1000 cycles to the same temperature and conditions as the aluminide.

Overall, conventional MCrAlY overlay coatings on MA 6000 have been determined to perform well in assorted hot corrosion tests to 1650°F and oxidation/thermal fatigue tests to 1950°F.

However, in order to utilize coatings on MA 6000 beyond 1950°F for extended periods of time, it was determined that it would be necessary to overcome diffusional stability problems that develop between the overlay

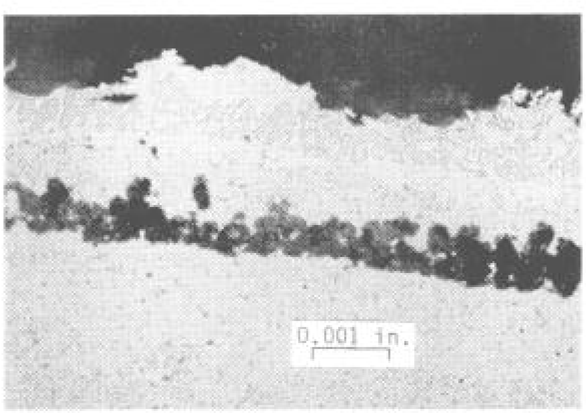

Figure 7. Microstructure of aluminide coating on MA 6000 after 1000 cycles, 1950°F/1 hr. - 600°F/10 min.

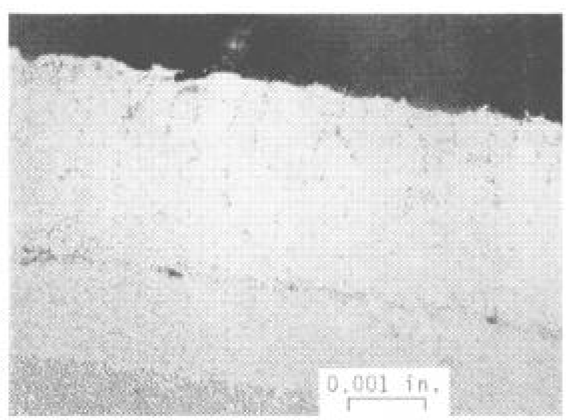

Figure 8. Microstructure of MCrAlY coating on MA 6000 after 1000 cycles, 1950°F/1 hr - 600°F/ 10 min.

coating and the MA 6000 substrate. Figure 9 shows an example of porosity developed on a MCrAlY/MA 6000 specimen following 400 hours of exposure at 2150°F. Diffusional stability of the coating with the substrate was felt to be particularly important for first-stage T406 blade applications as, in order to benefit from the full temperature potential of the alloy in advanced designs, a capability for using the alloy to metal temperatures in the 2150°F range was required. Consequently, an initiative was undertaken to develop a coating system with diffusional stability to 2150°F.

In this effort, a systematic screening approach was devised to evaluate a number of different coating systems. Included were aluminides, platinum aluminides and overlays. None, however, provided the diffusional stability sought for the MA 6000 alloy. Following a review of this work, it was conjectured that the presence of Kirkendall porosity could be eliminated by the application of a compositionally compatible interlayer to the MA 6000 over which a second high aluminum composition would be applied. The concept was to decrease the chemistry gradients between the outer coating and the substrate. In subsequent experimentation, the apparent validity of this concept was verified by extended static testing at 2150°F. Shown in Figure 10 is a MA 6000 specimen both with and without the interlayer but with an aluminide top coat following 400 hours exposure. Significantly, the duplex coating is free of porosity but the single layer coating is heavily decorated with pores.

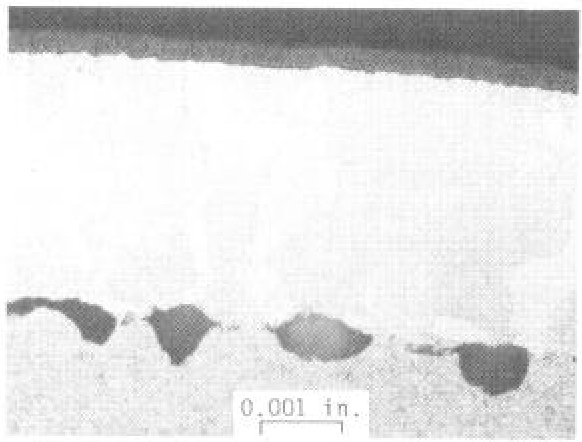

Figure 9. Photomicrographs of MCrAlY coated MA 6000 after 400 hours at 2150°F exposure.

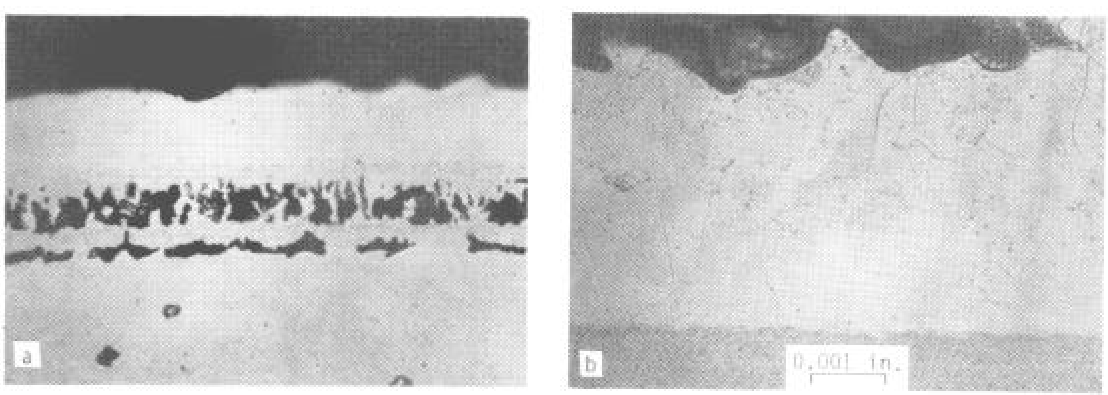

Figure 10. Photomicrographs of coatings on MA 6000 after 400 hours at 2150°F. (a) aluminide without interlayer and, (b) aluminide with interlayer.

Although more testing and evaluation of this new coating system is required, the results are felt to be very promising and offer the potential for fully exploiting the temperature capability of the MA 6000 in low stress/high temperature blading applications.

Concluding Remarks

Significant progress continues to be made in the development of MA 6000 for turbine blading applications. In particular, near-net-shape forging approaches have been identified that provide the potential for minimizing the amount of input stock and complimentary blade machining techniques have been demonstrated. Also, significant progress has been made on the problems of coating/substrate diffusional stability and as a consequence, the future appears promising for the protection of the alloy from oxidation attack in the 2100°F regime.

Although grain quality consistency issues have not been completely resolved, MA 6000 stress rupture results were developed that showed temperature capabilities in the 20 ksi and lower stress regime that ranged from competitive to superior relative to contemporary single crystal alloys. Therefore, for shrouded turbine blade designs of the type represented by the second-stage T406 turbine blade, the potential appears to exist for utilizing MA 6000 as a direct replacement for the single crystal CMSX-3 alloy. With forging mult weight on the order of 0.5 pounds, a materials utilization factor in the 3 to 4 range is projected for the near-net-shape forging. (The materials utilization factor is defined as input weight divided by finish machined weight). If the shrouded blades were to be machined from a solid piece of bar stock, a much larger forging mult would be required owing to the severe twist inherent in this design resulting in a materials utilization factor on the order of 20.0. As a consequence, the near-net-forging approach for this design saves approximately two pounds of the relatively expensive MA 6000 alloy. Even when finish machining costs are added to the cost of this configuration, the near-net-shape MA 6000 forging offers the potential for being cost competitive with cast single crystals.

In the case of the unshrouded first-stage T406 blade, the inherently simpler first-stage configuration lends itself far more readily to either forging or direct machining from extruded and hot rolled bar stock with a projected materials utilization factor of less than 10 for direct machining. With its inherently superior temperature capability at low stress levels and a suitable protective coating for high operating temperatures, the potential appears to exist for substituting an uncooled MA 6000 blade design for a cooled CMSX-3 blade design. Significantly, this would afford the opportunity for eliminating the need for cooling air with attendent fuel savings benefits. It would also provide the opportunity for reduced acquisition costs as an unshrouded uncooled MA 6000 turbine blade is projected as being lower cost than a cooled single crystal design.

It is anticipated that future work in both the shape processing and coating area should provide improved capabilities and lead to cost effective MA 6000 products that can be used in tailored turbine blade designs. These products will have the potential for being used at single crystal operating temperatures and beyond. However, to achieve eventual implementation into U.S. designs, MA 6000 products will need to demonstrate clear cut advantages over single crystals that have become firmly established in a number of U.S. applications. Further, they will need to demonstrate that process control is in place and that quality levels are reproducible and consistent with application requirements.

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