Task 8.4 - High Temperature Turbine Disk Development

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1.0 INTRODUCTION

Increasing turbine disk rim temperatures above current allowables would permit blade attachments to run hotter, requiring less cooling flow, resulting in greater turbine cycle efficiencies. Boosting rim temperature above current levels will, however, require materials with better creep and stress rupture properties in both the blade attachments and disk posts. The entire turbine rotor could conceivably be made from a cast nickel-base superalloy which has the required rupture strength for the rim. Unfortunately, cast superalloys typically have insufficient low cycle fatigue (LCF) strength for the bore region of most 100,000 hour life turbine designs.

The goal of Task 8.4 is to demonstrate a bonding technique to produce a dual-alloy turbine disk concept which will satisfy the diverse property requirements of the rim and hub areas of the disk. The program examines methods of attaching a cast superalloy rim with sufficient rupture strength to a fine grain hub material with the required LCF properties. The goals of the program were established in the context of a preliminary turbine design by Solar Turbines, Incorporated designated ATS 5. The initial target for the ATS 5 application was to allow rim operating temperatures in the 1350-1400°F range. The life goal of the Dual-Alloy Disk was envisioned to maintain Solar's standard turbine disk philosophy of 100,000 hours.

The rim temperature goals of the Dual-Alloy Disk Program for ATS 5 coincide with a regime where superalloys often exhibit a trough in rupture and tensile ductilities. It has been observed that reduced ductility can be accompanied by a tendency for notch sensitivity in rupture (Ref. 1) and an adverse interaction between creep and fatigue when both deformation modes are operative, i.e., creep-fatigue interaction (Ref. 2). To address these issues, Task 8.4 also examines advanced stress analysis and life prediction techniques for high temperature materials, and Non-Destruction Inspection (NDI) techniques to find cracks in the structure as a result of cyclic operation, should they occur. Thus, Task 8.4 attempted to take a holistic approach to introduce the Dual-Alloy Disk concept by considering three interrelated areas:

1. Dual-Alloy Bonding Demonstration: Three bonding techniques were studied to produce the bi-material structure. This effort is summarized in Section 3.0 and is based extensively on collaborative work with Howmet Corporation through subcontract HD9501525, documented in Howmet final report HC93113C.
2. Stress Analysis & Life Prediction Methods. The goal was to develop finite element analysis and Life Prediction techniques which accurately account for material deformation and failure modes in the presence of mechanical notches. This effort was directed primarily toward analysis of the cast rim material and is summarized in Section 4.0 based on a subcontract with Southwest Research Institute, Materials and Structures Division Report 06-7436.
3. Non-Destructive Inspection (NDI) Development. Task 8.4 explored NDI techniques aimed at characterizing initial flaws in the disk structure and to monitor potential growth of cracks during cyclic operation. This work is summarized in Section 5.0 and is based on work by Southwest Research Institute, Nondestructive Evaluation Science and Technology Division Report 17-7440.

It was recognized from the outset that the rapidly paced performance period allowed for these three tasks (10 months for SwRI, 16 months for Howmet) would constitute only an initial phase in what was anticipated to be a more extensive investigation. In particular, the first two tasks were very

challenging, relatively high risk – high payoff goals. The philosophy was to evaluate the potential of these technologies in this brief initial phase, and determine if follow-on and scale-up efforts were appropriate.

2.0 TURBINE DISK DESIGN FACTORS

As discussed in section 1.0 a key goal of turbine design is to reduce the cooling air supply at the disk rim area. The reduction in cooling air usage will improve thermodynamic cycle efficiency. The ultimate goal is to fully eliminate the use of cooling air at the disk rim thus gaining the added cost benefit of eliminating the required air delivery apparatus. Studies have shown that an approximate 1.0% increase in cycle efficiency may be attainable. This task is not without increased durability risks particularly in the disk rim turbine blade attachment area.

Solar's typical turbine application uses 800-900°F cooling air to reduce the turbine blade attachment temperature to a level that is safe from stress rupture failure. In addition, fatigue strength is also considered but is generally a secondary consideration given the low cyclic requirements of Solar's industrial engines. Using Waspaloy as the standard turbine disk material, maximum attachment design temperatures of 1100°F are achievable for 100,000 hour and 5,000 start cycle designs. Eliminating or greatly reducing cooling air would push the blade attachment temperature toward the 1350-1400°F range. There is no possibility to operate conventional wrought nickel disk alloys like Waspaloy at these temperatures. Therefore, the desire is to move to a high strength cast alloy such as Mar-M-247LC which demonstrates superior rupture strength and adequate fatigue capability, for the rim/attachment area. Combining this with a high strength wrought alloy hub having excellent cyclic fatigue properties, would provide the optimum combination.

The design and life prediction practices used currently with wrought materials will need to be modified in order to fully take advantage of the high temperature capability of a cast disk rim, and the bond line interface properties will represent additional challenges in stress analysis and life predictions. Issues of creep-fatigue interaction, limited ductility, and notch sensitivity will mandate a more detailed design analysis. From a mechanical design standpoint the task of incorporating the cast disk technology into a turbine engine is fairly straight forward. From one viewpoint it actually will simplify the design by eliminating the cooling air delivery system. Life prediction and durability concerns are limiting the application of this technology. Therefore, research and development of the dual alloy wheel is essential to ensure a solid understanding of this technology.

3.0 DUAL-ALLOY BONDING DEMONSTRATION

Howmet Corporation was selected as the subcontractor for investigating bonding methods in demonstrating the Dual-Alloy Disk concept. The Howmet Technology Center has valuable background in the bonding of cast superalloy materials for multi wall blades and other superalloy structures. Solar and Howmet collaborated on all phases of the Program Plan, materials selection and process development. Early discussions with Howmet were to propose a cast rim with a hub section produced by Vacuum Plasma Structural Deposition (VPSD). This concept was subsequently abandoned because of size limitations (diameter) of the VPSD process, and the solid-to-solid concepts described in Section 3.2 have been pursued.

3.1 SELECTION OF MATERIALS

3.1.1 Rim Material

Alloy Mar M 247LC was selected for the rim material of the Dual-Alloy disk. Mar M 247LC is one of the strongest equiaxed polycrystal alloys commercially available (Ref. 3), and is an alloy which both Solar and Howmet have experience in blade and nozzle applications. The chemistry of Mar-M-247LC is in Table 1.

Table 1. Nominal Chemical Composition (wt %) of Mar-M-247LC

Cr	Co	W	Mo	Ta	Al	Ti	Hf	B	Zr	C	Ni
8.3	10	10	0.7	3.0	5.5	1.0	1.5	0.01	0.05	0.15	Bal

The Mar M 247LC rim geometry was produced using Howmet's Spraycast process since it had the potential for being a lower cost alternative to investment casting, and also because the product could be obtained for the program quickly. Spraycast is a modified version of the OSPREY process in which vacuum melted material is argon gas atomized and spray formed in a one-step conversion directly into a ring shape (Ref. 4). In addition to the Dual-Alloy application, spray casting technology has spin-off potential in the manufacture of other gas turbine ring shaped components since it can provide one or more of the following:

- Parts which cost less than those made from ring forgings.
- Parts from "unforgeable" alloys.
- Use of alloys providing creep strength not obtainable in forged alloys.

3.1.2 Hub Material

The hub material selected for the Dual-Alloy Disk Program is Udimet 720, a high strength nickel base superalloy available in wrought, forged and powder forms. In a fine grain-size condition Udimet 720 exhibits exceptional yield strength and LCF properties and is used extensively in aircraft and helicopter turbine rotors. The high strength is due in part to a relatively high gamma-prime volume fraction of approximately 40% (Ref. 5). The chemistry of Udimet 720 is shown in Table 2.

Table 2. Nominal Chemical Composition (wt %) of Udimet 720

Cr	Co	Mo	W	Ti	Al	C	B	Zr	Ni
18.0	14.7	3.0	1.2	5.0	2.5	.015	.015	.030	Bal

Powder versions of Udimet 720 have demonstrated excellent forgeability and provide a unique balance of creep strength and LCF properties after super-solvus heat treatment (Ref. 6). The powder form of Udimet 720 was specified for this program because of its flexibility in processing and also because it was available in the time-frame of the program.

3.2 PROCESSING

Three processes were evaluated to demonstrate joining the Mar M 247 rim to the Udimet 720 hub. They were; (1) Diffusion bonding by Hot Isostatic Pressing (HIPing); (2) HIPing with surfaces 'activated' by boron deposits (boronizing); (3) Shear Forging. The first two were performed by Howmet, and Shear Forging by Ladish Company. In addition to studying bonding techniques, the program plan included an extensive evaluation of machining and surface cleaning methods, along with documenting bond surface profile/geometry.

3.3 EXECUTIVE SUMMARY: BONDING DEMONSTRATION

The following is a summary of conclusions which incorporates, and expands upon, the findings in Howmet's Final Report No. HC93113C. Examination of the anticipated impact of the bonding demonstration phase on the ATS 5 turbine design and other potential technology spinoffs from the program, along with recommendations for future work, are discussed in Section 6.0.

- The process with the best overall bond quality in producing the prototype bi-metal disk structure was solid-to-solid HIP bonding, and was therefore selected for the balance of the program. Further, this process was estimated to be the lowest cost of the three processes evaluated.
 - Improved mechanical properties of solid-to-solid bonded Spraycast-X Mar-M-247LC was achieved with a 2165°F/25 ksi/4hour HIP over a 2050°F HIP cycle.
 - Both base metal and bond line failures were observed in tensile and creep-rupture tests of specimens machined from prototype rotors. Although bond line failures are undesirable, the specimens displayed strengths well beyond yield with relatively high ductility (strain to failure).
 - Tensile properties of the solid-to-solid bonded material were higher than conventionally cast Mar-M-247LC.
- A modified solid-to-solid HIP process using boron activated surfaces showed the second best bond quality within the program. Boronizing has promise as a back-up should difficulties be experienced during scale-up of the (preferred) straight HIP bonding approach.

- Ladish shear forge bonding subscale trials of the Spraycast-X Mar-M-247LC rim and P/M U720 hub were unsuccessful.
- A suitable machining method for producing the solid-to-solid HIP and boronized bonding surfaces was defined using a relatively low cost single-point machining method.
- Spraycast-X Mar-M-247LC rim:
 - Microstructural examination of the Spraycast-X Mar-M-247LC showed a generally fine grain, nondendritic structure relative to conventionally cast product.
 - Typical grain size was ASTM 6.5 to 7, with grains as large as ASTM 1.0 to 2.0. The variation in grain size was observed through the thickness from I.D. to O.D.
 - Stress rupture properties of the Spraycast-X Mar-M-247LC were lower than conventionally cast materials due to the fine grain size, and did not meet the ATS 5 program rupture strength goal for allowing 1350-1400°F rim operating temperature.
 - The attempt to produce a uniformly coarse grain Spraycast-X Mar-M- 247LC product (for improved rupture strength) was unsuccessful, although the effort was too brief to optimize the process and was considered secondary to the bonding demonstration.
 - A complete porosity closure in the Spraycast-X material was attained with a 2165 F/25 ksi/4 hr HIP. Evidence of thermally induced porosity (TIP) was observed after 2280 F solutioning. TIP is typical of argon atomized materials.
 - An ultrasonic inspection technique was developed by QMI, Inc. for inspecting the bondline. The method successfully found an area of debond in one of the prototype disks, which was traced to a rupture in the HIP can during processing.

4.0 STRESS ANALYSIS AND LIFE PREDICTION

The intent of the ATS 5 design is to improve efficiencies by increasing firing temperatures and reducing disk cooling in order to minimizing parasitic losses. Stress analysis of the Dual-Alloy Rotor in this design represents a significant challenge since it falls outside of Solar's experience base. It was therefore decided early in the Program to collaborate with Southwest Research Institute (SwRI) to develop the required stress analysis and life prediction tools based on their expertise in the field. A contract was awarded for SwRI to tailor existing codes and constitutive models, developed under EPRI, Nuclear and Aerospace Industry sponsorship, to the specific design aspects of the ATS 5 rotor.

The SwRI Program was directed primarily at analysis of the blade attachment region of the disk rim, although it was anticipated the tools developed would be applicable to a broad range of high temperature components, thus having substantial spin-off potential. The program consists of 6 interrelated tasks aimed at analyzing the deformation modes in the area of mechanical notches, and to apply creep-fatigue damage models calibrated to the disk rim material, Spraycast Mar M 247. Based on several early creep-rupture tests of the Spraycast Mar M 247 by Solar and Howmet, it became clear the fine grain size product would likely not meet the initial 1350 - 1400°F/100,000 hour life goal. After analysis of the available data it was concluded the program goal should be reduced to 1280°F/100,000 hours assuming a net section stress of 45 ksi, and a stress concentration factor of 3.5 in the blade attachment slot.

4.1 NON-LINEAR STRESS ANALYSIS

The stress analysis techniques presently used by Solar Turbines, Incorporated typically are based on linear-elastic approaches to determine stress and strain ranges for estimating the fatigue component of damage, and creep rupture concepts (Larson-Miller Parameter) for determining the creep damage component. In some instances, the Neuber approximation is used to convert elastically calculated strain ranges into elastic-plastic strain ranges.

A goal within Task 8.4 was to investigate the applicability of available unified constitutive models for analyzing non-linear time-dependent deformation of high temperature materials. This type of analysis is considered critical for designing components such as the Dual-Alloy Disk which could potentially have stress concentrated regions (blade slot) experiencing cyclic plastic strains superimposed on long-term steady state creep deformations. SwRI personnel have substantial experience in the application of a elastic-viscoplastic constitutive model, known as the Bodner-Partom model, suitable for this type of analysis.

The constitutive model is referred to as "unified" because all aspects of inelastic deformation, including plasticity under monotonic and cyclic loading, creep, and stress relaxation, are represented by a single inelastic strain rate term. The framework of the equations are based on the Bailey-Orowan theory which theorizes inelastic deformation to occur as a result of competing processes; the difference between a hardening process and a thermal recovery process (Ref. 7). An attractive feature of the Bodner-Partom model is its accurate physical basis which takes into account the deformation mode of metals by dislocations motion. The approach thus provides a unique tie between the mechanics aspects of the problem with the required metallurgical aspects. The model has in past studies demonstrated excellent predictions and correlations for both isothermal and nonisothermal deformations using arbitrary cyclic and steady state loading histories in conventionally cast Mar-M-247 superalloy (Ref. 8).

An additional Program task was to determine if the Bodner-Partom constitutive model could be incorporated into ANSYS as a user-developed subroutine. The Bodner-Partom model was originally incorporated by NASA and SwRI into MARC finite-element computer code and has demonstrated the capability to predict structural response in complex multi-axial stress states in hot section components (Ref 7). Since Solar primarily uses ANSYS for stress analysis, SwRI agreed to evaluate the viscoplastic subroutine USERVP within ANSYS for potential future use on high temperature components.

4.2 CREEP-FATIGUE LIFE PREDICTION

In the past, it has been adequate to analyze the life of high temperature components using methods which calculate creep life and Low Cycle Fatigue life independently in predicting service hours. However, as temperatures increase metals can show some form of time-dependant behavior which results in a reduced fatigue life, exhibiting an interaction between creep and fatigue mechanisms (Ref. 9). When both deformation modes are present, the combined creep-fatigue conditions can be more damaging in terms of service life than either mode alone. Studies of creep-fatigue interaction at elevated temperature have made progress and some of the results have been reflected in structural design codes. For example, the ASME Boiler & Pressure Vessel Code Case N-47 incorporates a linear damage summation method for examining creep-fatigue effects (Ref. 10).

Solar Turbines, Incorporated typically has not analyzed components in terms of creep-fatigue interaction. With the aggressive temperature and stress goals of the Dual-Alloy Disk design for ATS 5, significant creep and LCF damage at the roots of the fir tree attachments could be anticipated. Therefore, it was concluded that enhanced life prediction techniques should be investigated. SwRI was selected for this effort based on their past experience in performing creep-fatigue damage evaluations of steam and gas turbine components. It was anticipated that the investigation would certainly be complemented by their work in the area of non-linear stress analyses (Section 4.1) as well.

The SwRI Work Statement included a critical literature review to assess the availability of material data and creep-fatigue damage models applicable to the turbine disk rim material. SwRI would generate a limited data set for the Spraycast Mar-M-247LC, then based on the literature review and available test results recommend a damage criterion to be applied to the component. The data set was limited because of the very short 10 month duration of the contract. It was assumed from the outset that a thorough evaluation of life prediction techniques would require additional time for complete material testing. If the results of the abbreviated first Phase were promising, then follow-on tasks could be considered in the future, including a task for validating the life prediction model using cyclic-creep testing of notched specimens.

4.3 RESULTS OF STRESS ANALYSIS AND LIFE PREDICTION

Detailed results of the overall non-linear stress analysis and creep-fatigue life prediction tasks are presented in SwRI Final Report # 06-7436. Included in the report are the Spraycast Mar-M-247 uniaxial tensile and cyclic stress-strain response tests from which the material constants for the Bodner-Partom constitutive model were determined, plus the creep and low cycle fatigue tests needed for the life prediction task. Summary conclusions of this effort are presented in Section 4.4.

4.4 EXECUTIVE SUMMARY: STRESS ANALYSIS AND LIFE PREDICTION

The following is a summary of conclusions which incorporates, and expands upon, the SwRI findings. Examination of the anticipated impact of the stress analysis and life prediction techniques on the ATS 5 and other turbine design, and recommendations for future work, are discussed in Section 6.0.

- Non-Linear Stress Analysis
 - A non-linear time-dependant stress analysis is required to capture the deformation modes and potential failure mechanisms of the Dual-Alloy Disk blade attachment. Linear-elastic techniques currently used would not accurately predict the material response in this temperature/stress regime.
 - The Bodner-Partom constitutive model successfully described the non-linear time-dependent deformation behavior of the Spraycast Mar-M-247LC material.
 - The Bodner-Partom model can be incorporated into the ANSYS finite element stress analysis code. The model was originally incorporated into MARC code, however with some modification could be adapted to ANSYS.
- Spraycast Mar-M-247LC Test Results & Observations
 - At the operating conditions of 1280°F, net section stress of 45 ksi, and a stress concentration factor of 3.6, the material exhibited notch sensitive behavior in creep rupture tests.
 - The Spraycast Mar-M-247LC exhibited a pronounced ductility trough at around 1475°F with measured elongations at failure of 2-4%. The low ductility would contribute to the notch sensitivity of the alloy.
- Creep-Fatigue Life Prediction
 - Results of a critical literature review, and analysis of the limited data set produced in the program suggests that a simple linear damage summation be used for evaluating creep-fatigue damage.
 - Using the linear damage summation approach at the 1280°F/45 ksi attachment operating conditions with a 20 hour dwell period at maximum stress, a minimum life time of 180,000 hours was calculated, despite the notch sensitive behavior exhibited by the alloy.
 - It appears the 1280°F modified operating target for the Spraycast Mar-M-247LC could be reevaluated upward in light of the 180,000 hour calculated life versus the 100,000 hour goal. This should only be considered after completing the testing begun in this initial phase, and after a thorough validation of the life prediction model with appropriate cyclic rupture testing.

- In the future, assuming a more extensive database can be completed for the candidate rim alloy, the ductility exhaustion method should be considered as a creep-fatigue damage criterion.

5.0 NON-DESTRUCTIVE INSPECTION DEVELOPMENT

The aggressive operating goals of new turbine hot section components, such as the ATS 5 Dual-Alloy Disk, require Non-Destructive Inspection (NDI) techniques to monitor the condition of the structure in terms of potential cracking in service. In addition, NDI techniques could be used to assess the initial flaw size in a given structure for use in fracture mechanics design calculations. NDI can be used as part of an integrated design/materials behavior philosophy, including validation of the stress analysis and life prediction methodologies discussed in Section 3.0 and 4.0. NDI can also provide enhanced safety due to improved understanding of a components capabilities and condition, particularly when pursuing higher temperatures and higher stresses in future designs.

The goal within Task 8.4 was to develop a NDI method for the ATS 5 Dual-Alloy Disk attachment slot since this is a critical region where cyclic plastic deformation and potential cracking could occur. The ATS 5 preliminary design specifies an axial slot configuration, a geometry which does not lend itself to visual examination or fluorescent penetrant inspection to find structural cracking. The geometry requires a non-visual inspection technique because of the long axial length of the slot which blocks viewing of the subject surfaces. It was concluded that eddy current or ultrasonic inspection techniques could provide the necessary access and sensitivity for detecting relatively small cracks in the blade attachment slots. Eddy current was identified as the leading candidate based on developments in the steam turbine and aero turbine industries.

5.1 NDI PROGRAM PLAN

The Non-Destructive Evaluation Science and Technology Laboratory at Southwest Research Institute was selected for a relatively small contract to develop the Eddy Current Inspection technique. SwRI has a strong capability in this field, and has demonstrated the eddy current method on turbine disks in steam turbine applications. The SwRI Work Statement included the design and fabrication of a unique, very compact eddy current probe and scanning fixture with the appropriate geometry to inspect the slot. The initial probe was designed for demonstrating the method using Solar's Centaur Gas Turbine disk since the geometry is similar to the slot envisioned on the ATS 5 disk. The Centaur disk was selected because of its design and because of the availability of disks with significant service hours as candidates for inspection. In addition, the program was to fabricate a set of calibration standards using electro-discharge machining (EDM). A complete inspection technique was to be developed and documented in a procedure specific to the slot application.

5.2 EXECUTIVE SUMMARY: NDI DEVELOPMENT

The following is a summary of conclusions which incorporates, and expands upon, the findings in SwRI Final Report #17-7440. Examination of the anticipated impact of the Eddy Current techniques on the ATS 5 and other turbine designs, and recommendations for future work, are discussed in Section 6.0.

- A probe, fixture, calibration standards and inspection procedure were successfully developed for demonstrating eddy current inspection of the turbine disk slot geometry.
- The minimum detectable flaw size was determined to be 0.010 inch deep by 0.020 inch long. This size flaw, if found in a ATS 5 turbine disk slot, may provide a basis for retirement of a disk from service prior to potential failure in the field.

- It was determined that a flaw of detectable size could be found if it is at least 0.040 inch from the end of an attachment slot.
- Two turbine disks were randomly selected from the turbine overhaul cycle for an initial demonstration. The disks received two eddy current inspections, one prior to grit-blast cleaning of the slots and one after cleaning. Prior to cleaning one of the disks had numerous reportable indications when inspected. However, after cleaning the indications were no longer detectable. Surface condition is a very important variable and a suitable cleaning procedure prior to eddy current inspection will be required.

6.0 DISCUSSION/RECOMMENDATIONS

A fundamental conclusion of Task 8.4 is that the concept of a Dual-Alloy Rotor for application in industrial gas turbines appears to be technically feasible, and a bonding method has been demonstrated for producing the bi-metal structure. The concept is considered relatively high risk, but if successfully scaled-up the payoff in terms of turbine performance and design flexibility would be of significant value. For example, the Dual-Alloy approach could make possible an uncooled second stage rotor with component lives of 100,000 hours, a design which could not be achieved with single alloy monolithic disks. Task 8.4 has proved to be a strong first step toward this goal, and the results thus far indicate that further study of the concept is warranted.

It is clear that a philosophy which uses an integrated approach including non-linear stress analysis, life prediction, NDI, and material characterization is required for designing the complex Dual-Alloy Disk. The condensation of these methods into a design philosophy is a secondary benefit of Task 8.4 which can be applied to other critical high temperature components. Several spin-offs of the techniques studied in this program have been identified and are being pursued.

The bonding development effort in Task 8.4 resulted in down selecting the solid-to-solid HIP process based on overall joint quality and anticipated cost. Issues with bond line ductility were uncovered, and a path for optimizing the HIP cycle and diffusion heat treatment for improved properties was identified. In summary, the ductility results are very encouraging and indicate value in pursuing further optimization of the bond line. The foundations of a follow-on effort are being established and it is recommended that the program be evaluated in Solar's ATS Phase 3 Program. The effort will have the goal of producing bondline properties which meet the requirements of Solar's current ATS-S design.

Based on results from the Task 8.4, it appears that future use of Spraycast Mar-M-247LC would require optimization of the processing and heat treatment to improve ductility and to avoid notch sensitivity in rupture. Despite the notch sensitive behavior, the life prediction effort calculated a life of 180,000 hours, and suggesting the possibility of temperatures above 1280°F. However, it is unlikely that notch sensitive material would be readily accepted by the design and materials community for long term service. With additional process refinement, Spraycast Mar-M-247LC still has potential as a disk rim material. Equally interesting is the possible spin-off applications of Spraycast materials to other components requiring very high temperature properties in a ring shaped component. A recommended alternative approach is the application of "conventionally" cast or Grainex investment cast Mar-M-247LC to produce a rim with uniform coarse grain size for improved creep strength relative to the fine grain size Spraycast Mar-M-247LC. The same bonding technique developed in Task 8.4 would be applicable to the alternative Mar-M-247 cast rims. Several preliminary notch rupture tests of Grainex cast material are presently in test to compare rupture strength and determine if the material is notch sensitive.

The Eddy Current Inspection technique developed in Task 8.4 shows promise for application in a Dual-Alloy Disk concept as well as in existing "standard" industrial turbine products. The method could provide an efficient component monitoring system, and a way of validating the life prediction techniques discussed previously. To complete the effort begun in Task 8.4 it is recommended that additional Centaur turbine disks with high operational hours be obtained for inspection as a follow-on in Solar's ATS Phase 3. Cracks which are found in the experiment will be sectioned open in the laboratory for dimensional analysis and to provide further calibration of the non-destructive inspection technique.

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