Thermographic evaluation of coating thickness in superalloy turbine parts

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ABSTRACT

The current operational environment imposed on power generation gas turbines require physical/chemical protection from oxidation and hot corrosion. The advanced technology which has been incorporated in these units to improve the overall efficiency of power generation has resulted in increased temperature and structural loads on all hot section materials and components. To achieve the mechanical properties demanded by these modern designs, steps had to be taken to improve the superalloys (complex nickel and cobalt-based alloys), but resulted in sacrifices in the oxidation and corrosion resistance of these materials.

As a result of many years of research and development for government and aerospace applications, two basic coatings for modern superalloys have emerged, diffusion and overlay. Both depend on the sacrificial oxidation of aluminum or natural protective properties of chromium in the coating to provide a spall-resistant, protective alumina coating or chromium zone to prevent or strongly inhibit further attack. Current advanced thermographic techniques have been applied to these coatings with good results.

The basic technology for using thermographic techniques for thickness determination evolved out of research conducted by the author in support of Department of Defense and NASA programs dating back to 1986 and earlier.[4]

This paper presents the data to support the premise that based on the physical/metallurgical make up of both diffusion and overlay coatings, the thickness and/or percent of active material remaining are measurable and quantifiable utilizing thermographic techniques.

Keywords: Combustion Turbine, oxidation protection coating, thermographic evaluation, thickness evaluation, % aluminum remaining, % chromium remaining.

1. INTRODUCTION

The evolution of large land based gas turbine units from 1967 to present has brought with it structural and materials demands new to the electrical power generation industry. The combined cycle unit's efficiency has risen from 43% to 58%. The main reason for this improved efficiency has been the result of turbine inlet temperatures increasing from 1650^{o}F to 2600^{o}F. To provide a design that can operate in this type of an environment

requires the latest innovations in basic materials, aerodynamic, active cooling, and mechanical designs. Many of the technologies required to make the present designs work have been adapted from the aircraft jet engine industry.[1 and 2]

2. BACKGROUND

Few, if any, of the current hot section components would meet their designed life expectancy without some form of oxidation, corrosion or thermal resistance coating. Present coatings are divided into two basic types, diffusion and overlay.

Diffusion coatings: In the diffusion coating application process, aluminum is made to react at the surface of the substrate, forming a layer of monoaluminide. For coatings applied over nickel-base superalloys, nickel aluminide is the resulting species. This type of coating is modified to some extent by the elements contained in the substrate as the diffusion reaction proceeds, and is usually further modified by other metallic elements intentionally added during the coating process to improve coating and/or system performance for specific expected service conditions.

Overlay coatings: This group of coatings does not rely on reaction with the substrate for their formation, although some moderate interdiffusion usually occurs during service. Coatings of this type are generally called MCrAlY coatings and essentially comprise a monoaluminide component contained in a more ductile matrix of a solid solution. In the case of the coating like PWA-286, it is a NiCrAlY (nickel-chromium-aluminum-yttrium). The supply of aluminum for formation of protective alumina scales comes largely from the dispersed monoaluminide phase during the useful life of such coatings.

With reference to **figure 7**, the as coated condition depiction on the left side shows the beta phase aluminide with a small interdiffusion zone between the aluminide and base material. The right side of this figure depicts the condition, which exists after 2 or 3 thousand thermal cycles at 1800°F to 1850 °F. The outer Al2O3 protective oxide layer spalls off during service and aluminum from the coating will diffuse out to reform the protective layer. At the same time, aluminum will also diffuse into the substrate causing the interdiffusion zone to increase in thickness. The coating is only functional when enough aluminum, approximately 3% to 5% is present to reform the outer protective oxide layer.

By optimizing the coating thickness and avoiding thermal cyclic-induced stresses, longer lifetimes can be achieved and the time between overhauls can be extended. Coatings for superalloys, whether diffusion or overlay types, are typically applied with thickness of 2 to 6 mils. It should be noted that protective life increases in proportion to thickness. During overhaul, turbine blades and vanes that have not exceeded creep limits and are not otherwise severely eroded or damaged can be refurbished for reuse. The ability to identify the remaining coating thickness at some intermediate inspection operation would allow for maximize operation time while limiting risk of failure due to coating depletion.

One additional benefit of being able to identify the remaining coating thickness is during the remanufacture or refurbishment operation. Some of these recoating processes require that all of the old coating be removed. For the most part, this is a machining operation and if the exact coating thickness is not known the tendency is to machine more material off and this could remove critical base material. There is little margin to spare; therefore the end result can be an out-of-spec scrap part.

Based on the physical/metallurgical make up of the protective coating systems and the superalloy substrate materials, coating thickness variations can be measured using thermographic techniques. The thermal diffusivity of the coating and the superalloy materials are different by a sufficient margin to allow thickness determination. This difference can be used to establish a time dependent thermal decay function, which then can be used to generate a calibratable thickness output. In addition, the depletion of aluminum within a given coating thickness will also modify the diffusion rate and therefore is quantifiable as % aluminum or chromium remaining.

The basic technology for using thermographic techniques for thickness determination evolved out of research conducted by the author in support of Department of Defense and NASA research. Extensive effort has been expended on software code, modeling and technique development to understand heat flow and diffusion in various materials. As an example, the US Navy identified a need to evaluation millions of spot welds on installed stainless steel structures to establish acceptance for intended use. A thermographic technique was developed that could meet the evaluation requirements for these spot welds. The thickness of the spot weld was a major item in the go, no go, acceptance requirements.[3]

NASA requested assistance in evaluation of grease film thickness of the "Clevis" joint on the solid rocket boosters used on the space shuttle. The thermographic technique developed could detect variations of 0.0001 inches and lent itself to computer interpretation for evaluation of large areas.[4]

3. RESULTS OF INITIAL TESTING

To establish the feasibility of using thermographic techniques for evaluation of power generation gas turbine hot section protective coatings, the author conducted a series of tests in 1999 and 2000.

The choice of hardware used for these initial thermographic evaluations was somewhat limited due to the short lead-time imposed by the thermographic test equipment availability. Two of the turbine blades available were selected for extensive thermographic evaluation. A small section from each blade tip was removed for chemical and metallurgical testing and identification. Both blades were made out of IN738 material; however, there was a different coating system on each blade.

Blade #1 was determined to have a NiCrAlY oxidation-reduction coating, possibly PWA-286. Blade #2 has a thin NiCrAlY bond coat with a TBC on top. The Alstom Power Corp. of Chattanooga, TN, supplied several samples of a chromized material. This material is similar to the protective coating used on the ABB GT-24 and GT-26, 5th row blades and the GE 7/9FA 3rd row blades.[2] These samples were supplied in two basic configurations: 1-1/2 inch tubing and small flattened tube sections. The tube samples were provided in five (5) thicknesses ranging from 5-8, 9-12, 14-16 to 18-21 mils. Although this group of blades and samples covered only a small part of the base materials and coating systems presently in use, it did give a look at detecting aluminum and chromium in various thicknesses over different base materials.

The technical evaluation of chromizing zone inspection using advanced thermographic techniques was divided into two (2) major areas, theoretical and experimental. The theoretical approach included reviews and documentation of the physical and metallurgical make up of the chromium-enriched layer and several of the possible base material compositions. This review included, but was not limited to, steady state and dynamic heat flow calculations with consideration given to a variation of compositions and chromizing layer thickness. Of the three (3) mechanisms by which the transfer of thermal energy in solids may be explained, only two (2) apply to metals – free electron mechanism and lattice vibrations, only the primary method, free electrons were considered for this investigation.

Thermal diffusivity was determined to be the major quantifiable physical property. Diffusivity by definition is a measure of the rate of change in temperature of a solid under a given set of conditions.[5] It was determined that based on the physical/metallurgical make up of the chromium-enriched zone, thickness variations of this zone should be measurable. The thermal diffusivity for chromium and the base material, although similar, are different. As an example, a given radiant heat flux to a surface with a .006 inch thick chromizing zone and one with a .007 inch thick zone will have a different surface temperature at any given time from the application of a uniform heat flux providing all other factors remain the same. A large number (in excess of 50) of combinations of thickness of chromizing zone, % chromium, chromium carbide zone and base material make up were evaluated to determine the affect of each likely variable on the diffusivity of the material. It was determined that small differences in diffusivity

could be used to establish a time dependent thermal decay function, which then could be used to generate a calibratable thickness output.

4. EXPERIMENTAL PROCEDURE

Based on positive results from the theoretical evaluation, a group of physical tests were conducted to validate the predicted thickness values productions. These tests were designed to provide data for refinement of the technique so that final system and hardware requirements could be established. The first thermographic evaluations were conducted on three small samples supplied by Alstom Power, Inc. with chromized zones of .008, .013 and .020 inch thickness. (**figure 1**, Thermographic Decay Curve Microbolometer IR test) (**figure 2**, Thermographic Decay Curve Quantum Well IR test)

The thermographic testing of the three-chromized samples was conducted as follows:

Each sample was evaluated using established metallurgical techniques to verify and document the chromized zone thickness and condition.

Based on the metallurgical evaluation and the samples physical appearance, a previous developed testing protocol was applied to each sample to establish the emissivity of the chromized surface. Additionally, tests were conducted to establish the most efficient wavelength to use for radiant heating the samples for the thermographic testing.

Due to the somewhat reflective condition of the chromized surface, additional tests were conducted on each sample to establish the reflected flux conditions so that reflected energy from any source would not cause misleading or erroneous test results. For each data run, a room temperature (starting) image of each sample was established and recorded.

The optimized heat source was used to provide a uniform radiant flux to the three (3) samples. (Note that six (6) different heat sources were evaluated. Each with different wave length and power densities.)

Data from the IR camera (radiometer) was collected for approximately 30 seconds for each sample, test condition and combination. A decay function was established for the radiant existence for each test.

To fully understand the variability in the surface conditions on each sample, the tests were rerun with five (5) different radiometers covering different portions of the infrared spectrum.

The data generated by these tests provided the information required to establish the optimized heating method, image timing and data used to generate the thermographic decay curves presented in **figures 1 and 2.** Both images were establish a single image in 0.016 second. The radiometer used for Figure 1 has a Microbolometer photo detector operating in the 7.5 to 13 micron spectral range and has thermal sensitivity of 0.08^{o}C. The radiometer used for **figure 2** has a Quantum Well photodetector operating in the 8 to 9 micron spectral range and has thermal sensitivity of less than 0.02^{o}C. Both of these radiometers provide 14-bit radiometric IR digital image data. Both sets of data were generated under the same environmental, heat input, image timing and data storage conditions. The major difference between the two data sets is the "window" to be used to establish the chromize zone thickness; which is better defined by the Quantum Well (from Image 41 to 49 and from 47 to 54 for the Microbolometer). This is not to say that the Microbolometer unit could not be successfully used, only that it would take more image processing and enhancement than would be required by the Quantum Well.

A complete review of all tests and theoretical data was conducted to finalize the testing protocol for the second set of chromized samples. Alstom Power Metallurgical Services Laboratory fabricated a set of five (5) steel tubes with chromized zones ranging from 0, 5-8, 9-12, 14-16 and 18-21 mils thick. Each tube was tested as a single test subject and in groups of two, three, four and all five. An example of a single tube run is depicted in **figure 3**. (Chromized tube 5-8 mils) It was determined that the rate of diffusion was repeatable on any given sample to within less than 1% during a series of 25 test runs.

In order to establish a baseline condition for image processing and enhancement, each of these single-tube tests were run with the sample tube starting at room temperature (68^o – 69^{o}F). As depicted by examples in **figures 4 and 5**, the tubes were run in two (2), three (3) and four (4) under varying imaging and heating conditions. With reference to **figure 5**, it can be clearly seen that the four different chromizing zones have a distinct thermal decay curve which lends itself to image enhancement techniques that could be analyzed for thickness determination.

The same type data generated from thermographic evaluation of two (2) turbine blades, but in a different format, is presented in **figure 6**. The effect of the thermal barrier coating (TBC) can clearly be seen in the data from turbine blade #1. As stated for the chromized samples evaluation, the data of interest is from peak or max temperature out for 1/6 seconds or so. The slope of the curve and inflection points are important keys. The effects of the physical presence of the TBC on the thermographic response requires additional image processing and adjustment of heating techniques.

Test on all of these samples was rerun several times with good repeatability. The measured valve was within .001 inch of actual for the 150 + tests conducted.

With reference to **figure 8** (basic heat flow conditions during thermographic test sequence), the physics of heat flow are well understood and are straight forward; however, when Active Heating thermographic methods are used, the response of the area under test is more complex and is time dependent. The scale of the time dependence will vary depending on the thermal properties of the materials, the thickness of each layer and the overall thermal properties of the substrate. Response times may vary from a few milliseconds to one or two seconds. The surface of the material under test "E" is heated with a small amount of radiant heat "A." It is important to provide a radiant flux of the proper wavelength and intensity to establish a small heat flow into the surface "E". The infrared imaging/sensing device then records the radiant exitance "D" from the surface. (This is the total radiant flux per unit area leaving the surface "D.") As the heat is conducted/defused into surface area "E" and on into the base material "C," the aluminide or chromized zone will conduct heat at a different rate depending on many factors, but primarily on the aluminum or chromium content and thickness.

5. CONCLUSION

Based on tests described in this paper and the previous work in thickness determination, it is concluded that thermographic techniques can be applied to most material and coating systems to provide a fast, accurate and repeatable thickness measurement technique.

6. REFERENCES

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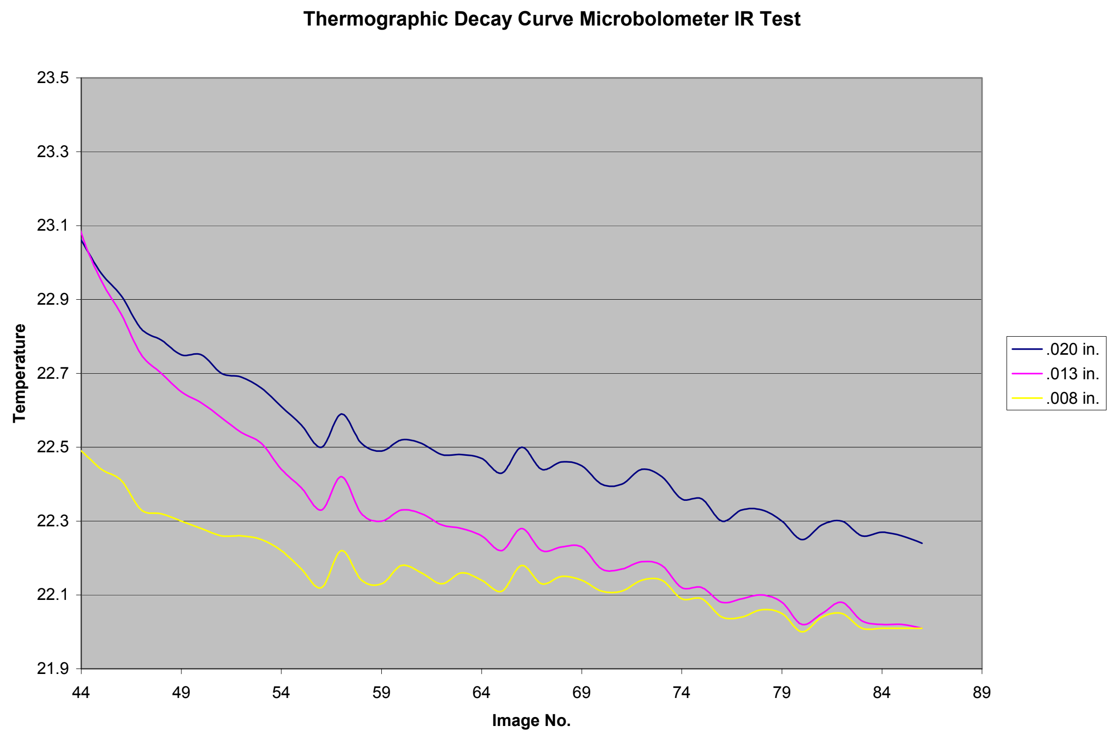


Figure 1. Thermographic Decay Curve Microbolometer IR Test

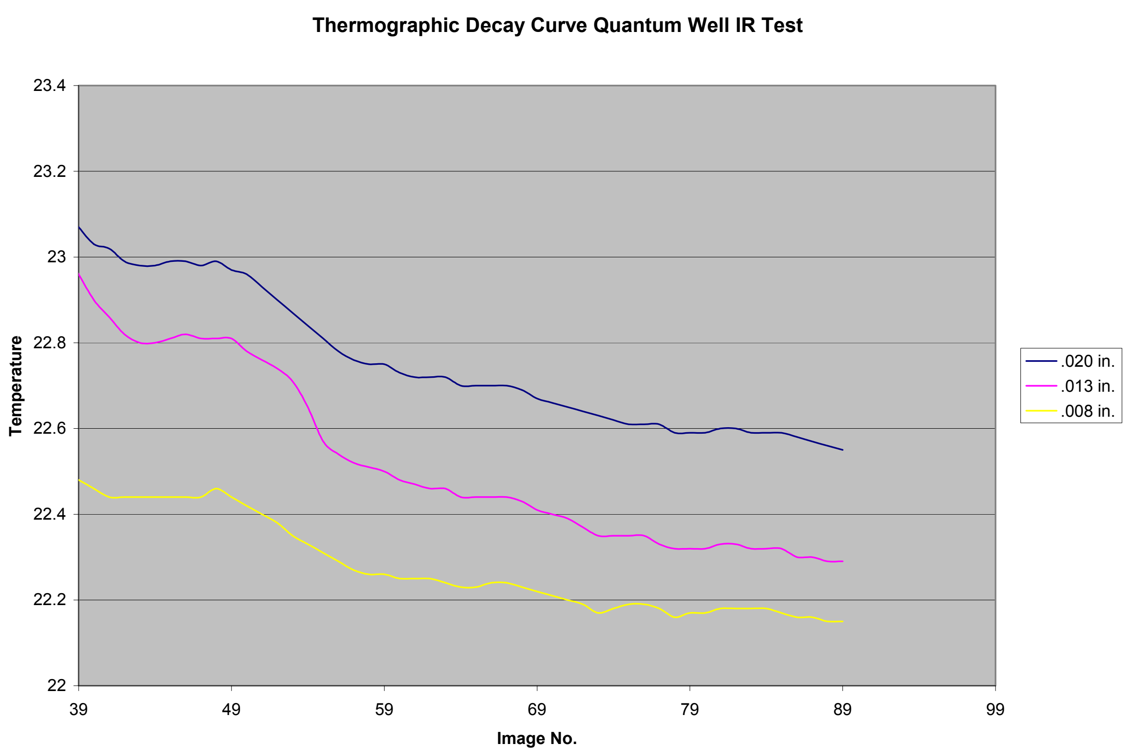


Figure 2. Thermographic Decay Curve Quantum Well IR Test

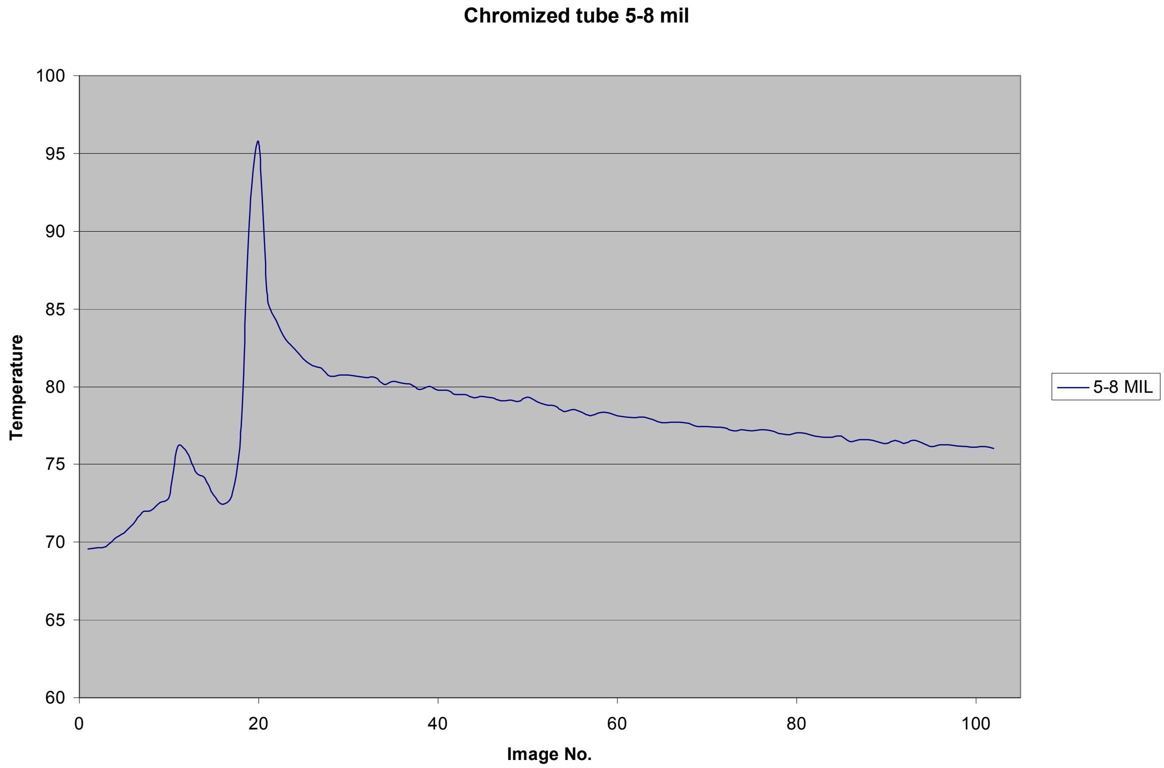


Figure 3. Chromized tube IR Test 5-8 mil thickness

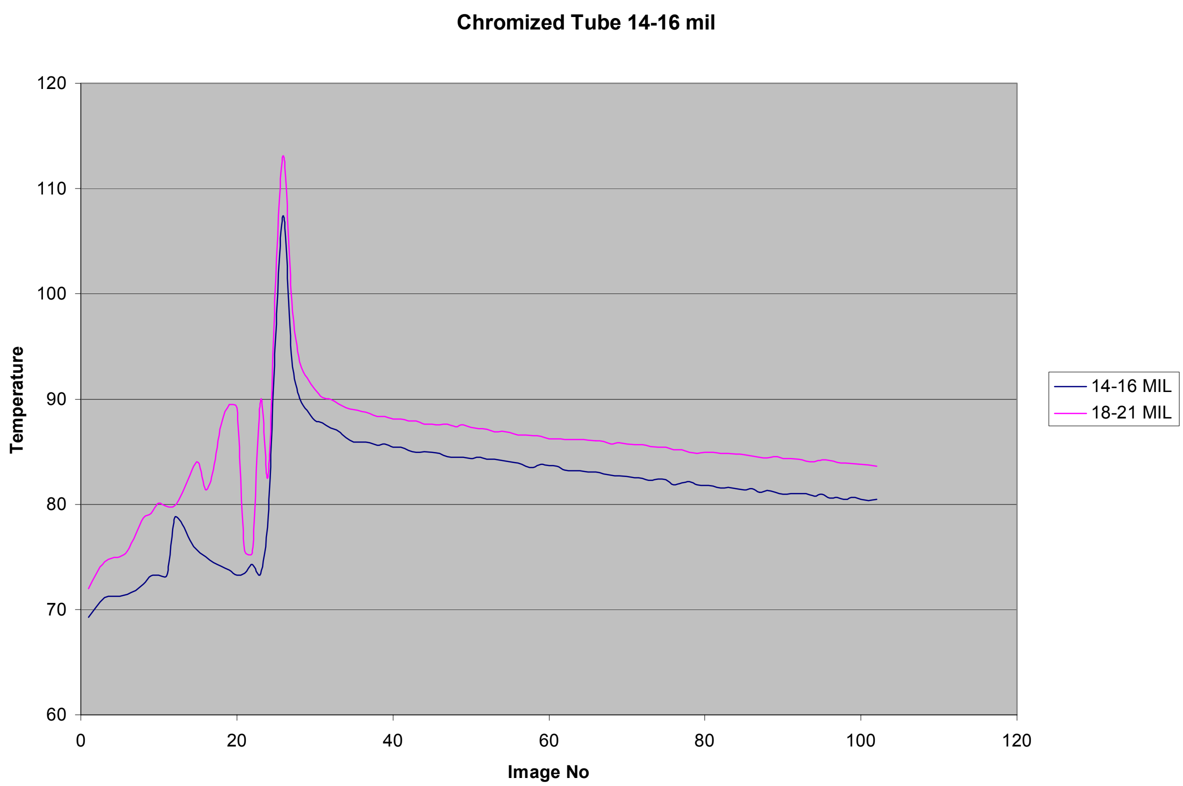


Figure 4 Chromized Tube IR Test 14-16 mil thickness

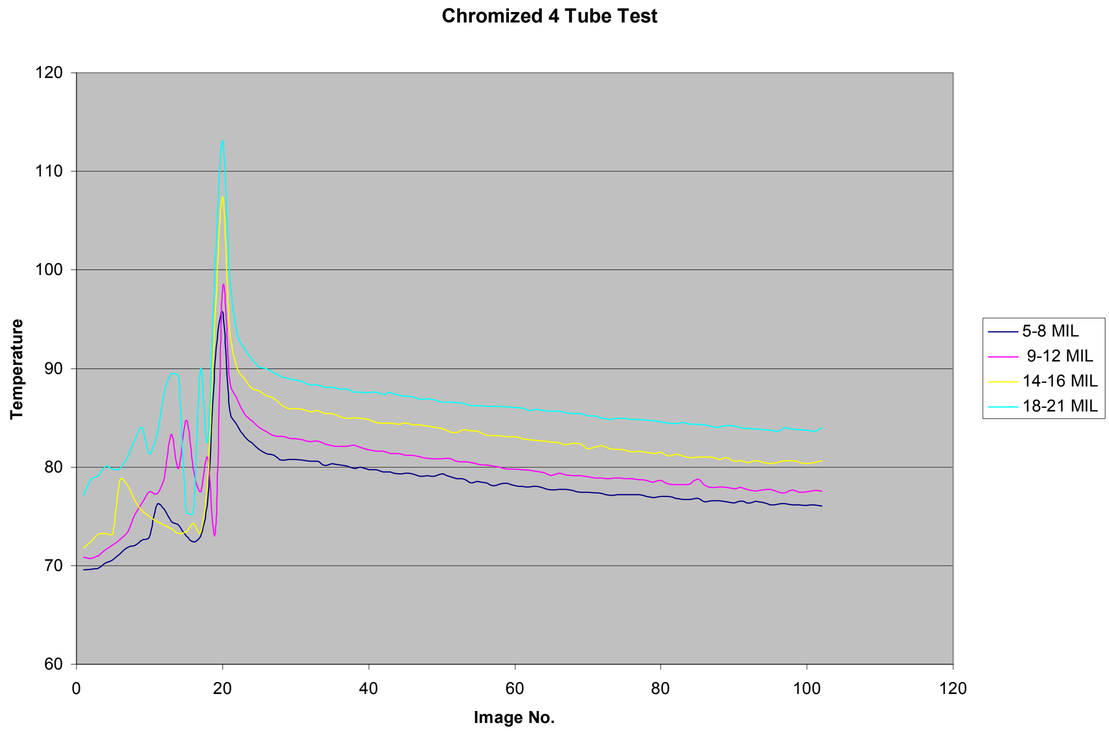


Figure 5. Chromized Tube IR Test 5-8,9-12,14-16,and 18-21 mil thickness

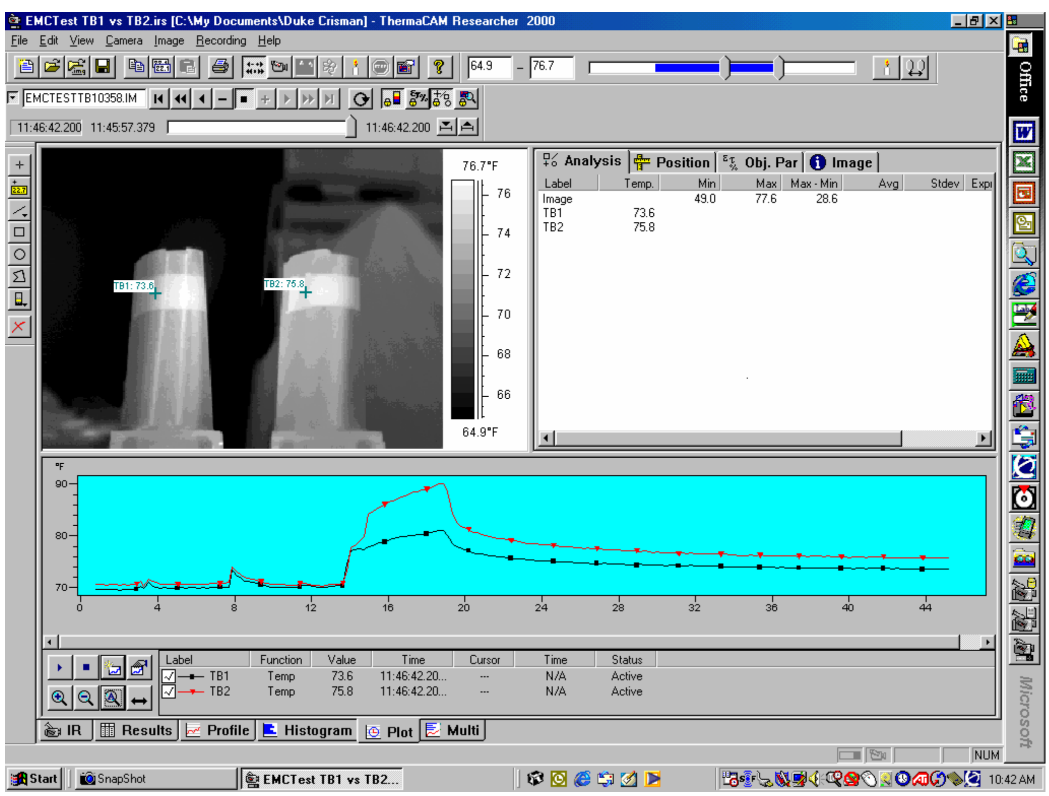
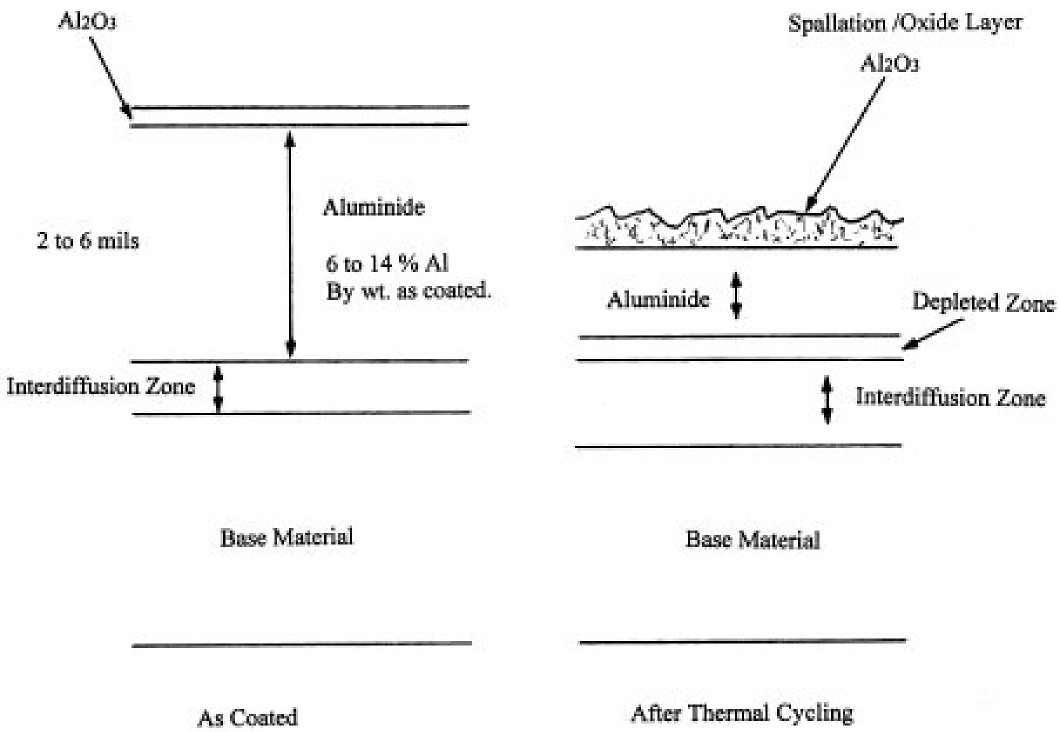
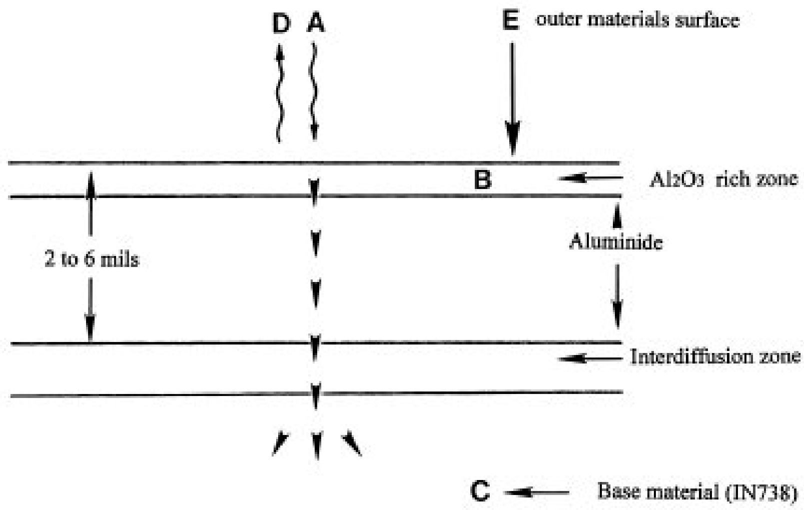


Figure 6. Turbine Blade IR Test



Tipical NiCrAlY overlay coating – As coated vs. after thermal cycled.

Figure 7. Typical NiCrAlY overlay coating—as-coated (left) vs. after thermal cycled (right)



Basic heat flow conditions during thermographic test sequence.

1. The surface of material "E" is heated with a small amount of radiant heat "A".

2. Radiant heat "A" is removed.

3. Infrared image/sensing device records radiant exitance from surface (this is the total radiant flux per unit area leaving the surface "D")

4. Heat is conducted/defused into surface area "E" and into the base material "C". The aluminide zone will conduct heat at a different rate depending on aluminum content and thickness.

Figure 8. Basic heat flow conditions during thermographic test sequence