A Detailed Analysis of Mechanical Behavior of Aircraft Gas Turbine Materials

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Abstract- In this paper we conducted a detailed analysis over mechanical behavior of the materials used in aircraft gas turbines. Gas turbine materials damage leads to decrease the overall combustion efficiency of the combustion chamber as well as performance of the aircraft gas turbine engines. In order to minimize the efficiency loss and to improve the performance of the combustion chamber, we need to replace the combustor materials which must overcomes the factors such corrosion, erosion and other surface degradation due to the presence of carbides and other factors due to the application of high temperature. Materials at elevated temperature may affect the properties of combustor materials so that they may subject to thermo - mechanical fatigue, creep – fatigue and other micro structural deformation. We performed a detailed analysis over structural behavior of existing materials to optimize the thermo – mechanical properties in order to improve the aerodynamic characteristics of combustion gases and improve safe-life of the combustor materials.

Keywords – High temperature materials, surface degradation, combustion chamber, material optimization, thermal properties and micro structural deformation.

I. INTRODUCTION

The main component of aircraft gas turbine is combustion chamber where the compressed air mixed with fuel. From the compressor high pressurized air is let into the combustor, where it is mixed with the fuel droplets by using injector. In combustion chamber, spark plug is used to ignite the fuel-air mixture to produce the bang. This combustion process leads to elevated temperature that is up to 2000^0c. Since high temperature is produced, affects the property of the combustor materials. The temperature at which metals in this part of the engine start to melt is 1300^0C. We need to select materials that have corrosion resistance and that do not lose phase stability & strength at elevated temperatures. Combustion process should be continued for long duration (i.e. 5 to 7 hours). So some methods are adapted such as advanced cooling technique. Aircraft gas turbines face the problems associated with operating over a wide range of inlet pressure and temperature within the flight envelope of Mach number and altitude. A typical subsonic airliner will operate at a cruise altitude of 11000 m, where the ambient pressure and temperature for LS.A. Conditions are 0·2270 bar and 216·8 K, compared with the sea level values of 1·013 bar and 288·15 K. Thus the combustor has to operate with a greatly reduced air density and mass flow at altitude, while using approximately the same fuel/air ratio as at sea level to maintain an appropriate value of turbine inlet temperature. Atmospheric conditions will change quite rapidly during climb and descent, and the combustor must deal with a continuously varying fuel flow without allowing the engine to flame-out or exceed temperature limits; high performance fighters

II.REQUIRMENTS OF AIRCRAFT GAS TURBINE MATERIALS

Gas turbine coatings are designed mainly to protect the structural material against corrosion, oxidation, erosion and high temperatures. Therefore their microstructure is optimized towards these tasks. Important properties of the gas turbine components, such as mechanical strength and integrity, are normally given by the bulk properties of the structural material. In the context of future gas turbine components designed for increased efficiency and durability, there is strong need to further improve and understand the intrinsic mechanical properties and degradation mechanisms of gas turbine coatings. Extensive research are being directed towards mechanism-based life-prediction modeling of coating systems, which requires input data in the form of coating properties. Degradation mechanisms of coatings are, however, very complex since many elements are usually involved and their interaction effects at high temperature involve a complex loading scenario. After long time high temperature exposure of corrosive and erosive environment and interdiffusion with the substrate material, both the microstructure and the physical/mechanical properties of the coatings change. Thus, to gain better knowledge of the mechanical behavior and failure mechanisms of coatings, there exists a further need to evaluate property changes with service time and temperature. The combustion process takes place for long duration so that the combustor materials are able to withstand high temperature for long duration without losing its phase stability and mechanical property like strength, corrosion resistance apart from thermal coatings and same time materials should able to radiate heat energy to outside through convective heat transfer so that its micro structure should not vary with respect to temperature at elevated conditions and different operating conditions.

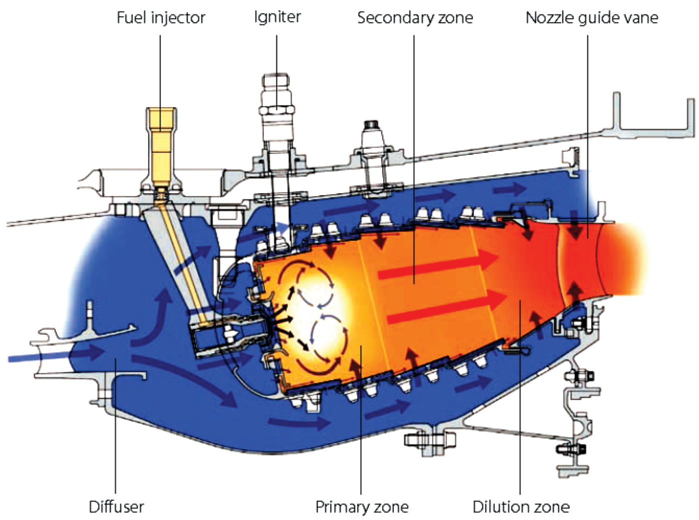

Figure 1.fuel is burned in the combustion chamber at temperatures of over 2000°c, about half the temperature of the sun.

A. FACTORS AFFECTING GAS TURBINE MATERIALS

The principal deterioration mechanisms in high temperature plant are creep damage, micro structural degradation, high temperature fatigue, creep-fatigue, embrittlement, carburization, hydrogen damage, graphitization, thermal shock, erosion, liquid metal embrittlement, and high temperature corrosion of various types. Additionally, stress corrosion cracking and aqueous corrosion may be problems although these damage mechanisms are not generally expected in high temperature components: however they may occur when components are cooled down and liquid is still present within or in contact with them. The temperature of the gases after combustion must be comparatively low to suit the highly stressed turbine materials. Development of improved materials and methods of blade cooling, however, has enabled permissible combustor outlet temperatures to raise from about 1100 K to as much as 1850 K for aircraft applications.

- The formation of carbon deposits ('coking') must be avoided, particularly the hard brittle variety. Small particles carried into the turbine in the high velocity gas stream can erode the blades and block cooling air passages.
- Creep: It involves time-dependent deformation and high temperature creep cracking generally develops in an intercrystalline manner in components of engineering importance that fail over an extended time. These include boiler super heater and other components operating at high temperature, petrochemical furnace and reactor vessel components and gas turbine blades. At higher temperatures, as can occur with local overheating, deformation may be localized, with large plastic strains and local wall thinning.
- High temperature fatigue and thermal fatigue: Fatigue, involving repeated stressing, can lead to failure at high temperature as it does at low temperature. In components operating at high temperature it often arises through temperature changes that can lead to cyclic thermal stresses. This can lead to thermal fatigue cracking. The cracking tends to develop in areas of high constraint, and the detailed mechanism may be one of local creep deformation.
- Microstructural degradation is a damage mechanism that can lead to failure by some other process such as creep, fatigue or more rapid fracture. It is important that it is recognized as a mechanism of damage as it can result in a significant loss in strength in a material. It is appropriate to discuss this following directly upon the discussion of creep damage, because the two mechanisms are closely bound together and, indeed,

are difficult to separate. It has already been noted that Cr-Mo steels that are liable to fail by creep in a short time may display spheroidization of the carbides but little, if any, void formation. The formation of voids appears, in many cases, to be a very local phenomenon occurring very close to the time of fracture.

- Creep-fatigue interaction is a complex process of damage involving creep deformation and cyclic stress and the predominant damage mode can range from primarily fatigue crack growth at higher frequencies and lower temperatures to primarily creep damage where hold times are long and temperature is at the high end of the scale.
- Embrittlement from precipitation can arise in a number of different ways. For example, sigma phase formation in austenitic stainless steels maintained at high temperature or cycled through the critical temperature range (approximately 565 to 980 °C) causes loss of ductility and embrittlement. Ferrite stainless steels may be subject to an embrittlement phenomenon when held at or cooled over the temperature range 550 to 400 °C. If the temperature conditions are considered likely to lead to such effects, metallographic checks are advisable after extended exposure prior to an unexpected rupture developing. In addition to the embrittlement of ferrite steels exposed to high temperature during service, and of austenitic stainless steels through the formation of sigma phase, carburization can produce brittle material when a component is exposed to a carburizing atmosphere for extended time at high temperature.
- Hydrogen damage, arising particularly in petrochemical plant, can occur in carbon steels through diffusion of atomic hydrogen into the metal, where it combines with the carbon in the Fe_3C to form methane and to eliminate the pearlite constituent. carbon steel from a catalytic cracking unit. Carbide from the original pearlite has been converted to methane, producing voids. In fact, recrystallization of the ferrite was observed around some of the voids, produced by the combination of deformation under pressure of the methane and the elevated temperature. The steel had been subjected to a temperature during service that was higher than appropriate for the grade of steel employed.
- Hydrogen-assisted cracking is a potential problem in petroleum reactor pressure vessels in hydrogen service, and the concern is that such sub-critical cracks do not reach a critical size for failure. Relations are available to estimate crack growth rates, and the important matter is the ability to detect and measure accurately the depth of such cracks lying beneath stainless steel cladding so that accurate predictions can be made.
- Erosion can occur in high temperature components when there are particles present in flowing gases. This is a not uncommon situation in coal-fired power plants in which erosion by fly-ash can lead to tube thinning and failure in economizers and reheaters, and soot blower erosion can produce thinning in super heaters and reheaters in those tubes that are in the paths of the blowers. The solution to fly ash erosion depends in part on improving boiler flue gas distribution and cutting down on local excessively high gas velocities. The control of soot blower erosion depends on many factors including excessive blowing pressure, poor maintenance and the provision of effective tube protection where required.
- Minimization of corrosion in alloys for high temperature applications depends on the formation of a protective oxide scale. Alternatively, for alloys with very high strength properties at high temperature, a protective coating may need to be applied. The oxides that are generally used to provide protective layers are Cr_2O_3 and Al_2O_3. Corrosion protection usually breaks down through mechanical failure of the protective layer involving spalling of the oxide as a result of thermal cycling or from erosion or impact.
- High temperature corrosion can also occur by carburization or sulphidation. Sulphidation can be a serious problem in nickel-based super alloys and austenitic stainless steels, with sulphides forming on grain boundaries and then being progressively oxidized, with the sulphides moving ahead along the grain boundaries, so causing embrittlement in the alloy.

III. GAS TURBINE MATERIALS

The combustor experiences the highest gas temperatures in a gas turbine and is subject to a combination of creep, pressure loading, high cycle and thermal fatigue. The materials used presently are generally wrought, sheet formed nickel-based super alloys. These provide good thermo mechanical fatigue, creep and oxidation resistance for static parts and are formable to fairly complex shapes such as combustor barrels and transition ducts. Equally of importance is their weldability, enabling design flexibility and the potential for successive repair and overhaul operations, which is crucial to reducing life cycle costs. The high thermal loadings imposed often mean that large portions of the combustor hardware need to be protected using thermal barrier coatings. The current thermal barrier coatings technology for metallic combustor applications is based exclusively on multi-layered systems comprising of a MCrAlY bondcoat and a ceramic topcoat applied using plasma spray deposition techniques. Application of this technology generally aims to limit peak metal temperatures to 900 to 950°C. Future developments are aimed at applying thicker coatings to enable higher flame temperatures and/or reduce metal temperatures further. Other programmes are aimed at increasing the phase stability and resistance to sintering of the ceramic topcoat at temperatures above 1250°C and to the inclusion of diagnostic sensor layers within the coating that enable the plant and component condition to be actively monitored [3]. Due to the requirements to meet all problems faced during high temperature conditions, it is strongly recommends that super alloys will be better solution and suitable for long duration operation of the combustion process and it is very essential for the combustor materials to withstand high temperature to have extraordinary mechanical properties like corrosion resistance, light weight, durability, resistance against the surface degradation and all essential characteristics to meet high temperature application under different operating conditions of a aircraft such ground operation, climbing, high altitude operation and adverse weather conditions. So super alloys will cover all demands made by combustion process. Future combustor designs are aimed at replacement of conventional wrought nickel-based products with:

• More capable Ni-based alloys.
• Oxide dispersion strengthened metallic systems
• Ceramic matrix composites

A. SUPER ALLOYS

Superalloys are heat-resisting alloys based on nickel, nickel-iron, or cobalt that exhibit a combination of mechanical strength and resistance to surface degradation. Superalloys are primarily used in gas turbines, coal conversion plants, and chemical process industries, and for other specialized applications requiring heat and/or corrosion resistance. A noteworthy feature of nickel-base alloys is their use in load-bearing applications at temperatures in excess of 80% of their incipient melting temperatures, a fraction that is higher than for any other class of engineering alloys.

B. NICKEL BASE SUPERALLOYS:

Nickel-base super alloys are the most complex, the most widely used for the hottest parts, and, too many metallurgists, the most interesting of all super alloys. They currently constitute over 50% of the weight of advanced aircraft engines.

The principal characteristics of nickel as an alloy base are the high phase stability of the face-centered cubic (FCC) nickel matrix and the capability to be strengthened by a variety of direct and indirect means. Further, the surface stability of nickel is readily improved by alloying with chromium and/or aluminum.

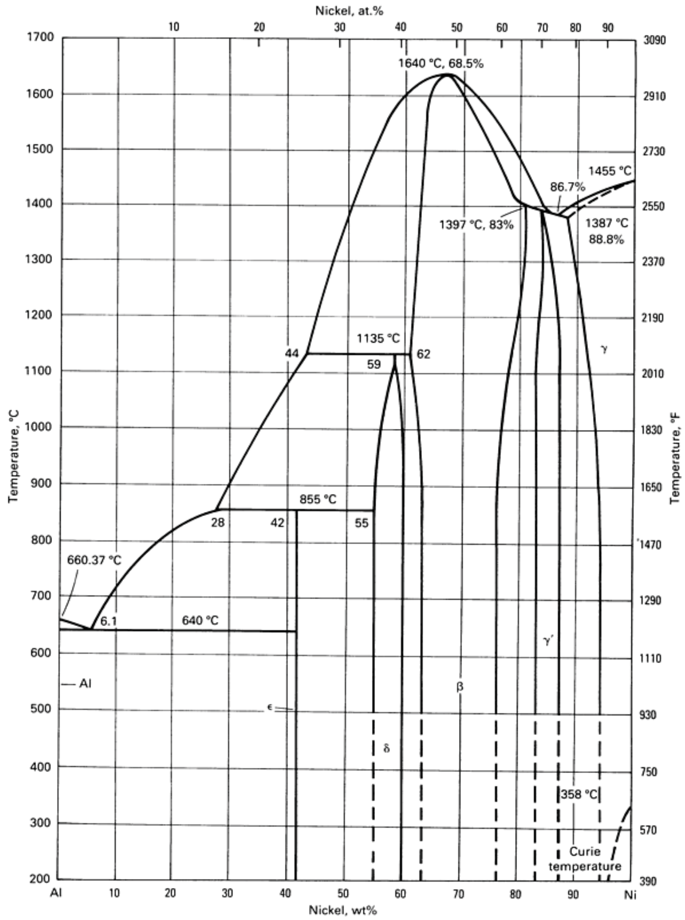

Figure 2. Nickel property changes with respect to temperature.

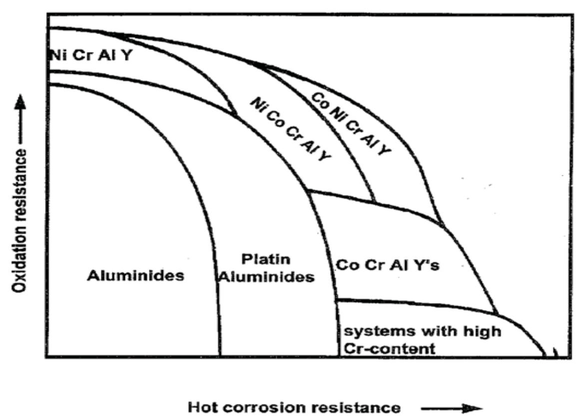

Figure. 3 Oxidation and corrosion resistance of different types of coatings

IV. FATIGUE BEHAVIOR OF NICKEL BASED SUPER ALLOYS

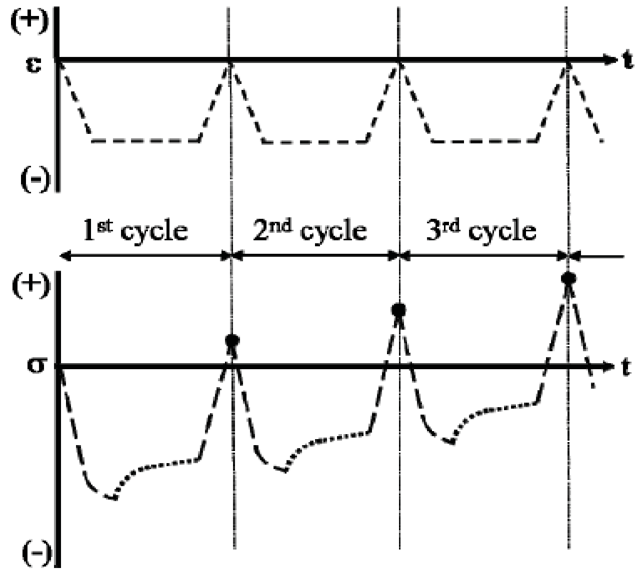

Figure. 4. Schematic of applied strain during cyclic loading with compression hold time and the resulting stress response evolution with time

Nickel based super alloys have been used historically in the aerospace industry for turbine airfoil applications. The alloys are useful at high temperatures because of their creep resistance, along with hot corrosion and oxidation resistance [1,2]. Until recently, creep has been the limiting factor for turbine airfoils, and thus creep mechanisms have been the subject of numerous studies [1-6]. Early generation alloying of monocrystalline alloys was developed to improve creep resistance by adding slower diffusing elements, such as rhenium and ruthenium. Rhenium additions improve creep rupture life and oxidation resistance [7,8], while ruthenium decreases overall density compared to rhenium, stabilizes the microstructure, and increases oxidation resistance [8,9]. Additionally, creep resistance increases with a decreasing number of grain boundaries, and therefore the invention of the monocrystalline blade increased creep resistance. Coincidentally, fatigue resistance has tended to increase with improvements in creep resistance. However, more recently fatigue failures have been experienced. Consequently, fatigue mechanisms have become of interest. It is known that engine efficiency increases with increasing temperature, and therefore the need for alloys that can withstand higher temperatures is necessary. Past engine designs have been limited by the melting temperature of the blade material, and ceramic systems are not feasible due to fracture issues. The introduction of cooling channels has caused local stresses, especially within the thin regions between the channels, and temperature gradients across the blade to increase. In these HPT components, experience and experimental studies have shown that fatigue can be a life-limiting factor. The changing limitation from creep to fatigue has highlighted the need for a comprehensive study of fatigue deformation mechanisms, as well as creep-fatigue mechanisms, since the engine operates at high temperature where creep occurs

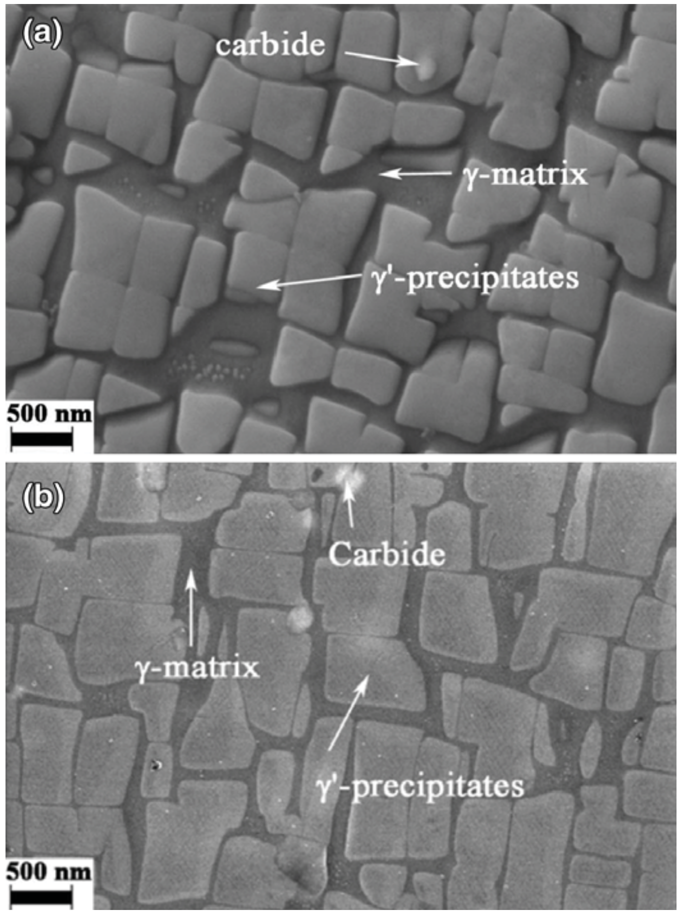

Figure. 5. Microstructure of IN 713 produced by MIM in the ‘‘as sintered’’ state, (b) microstructure of MAR-M247 produced by MIM in the ‘‘as sintered’’ state.

Between the coating and the substrate a gradient of physical and mechanical properties exists, which causes differences in physical and mechanical behavior. If the gradient is too large, incompatibility may cause coating failure and accelerated oxidation or corrosion of the substrate material. The most relevant coating properties are: Young’s modulus, the thermal expansion coefficient, the thermal conductivity, the fracture strain, the yield strength, the fracture toughness, the ductile-to-brittle transition temperature, and creep behavior [22]. The stresses and strains that would exceed a critical limit are induced either by mechanical loads, oxide growth or thermal loads. One of the most important properties of a gas turbine coating is its ductility or its resistance to cracking by thermally and mechanically induced stresses. Many coatings for service at high temperatures have a brittle microstructure up to relatively high temperatures, especially when Al is used as an oxide-forming element, since it is mostly deposited in the intermetallics NiAl phase. It is typical for diffusion aluminide coatings that they have a ductile-to-brittle transition temperature (DBTT) around 700- 900oC [23-28], which means that during start-up and shut down operations the coating is loaded in the brittle regime where cracks can propagate. Fig. 4 gives the ductile-to-brittle transition for different types of diffusion coatings. The rapid increase in ductility above DBTT is typical for many intermetallics [29-30], but the exact mechanism behind this has not yet been fully understood. The brittle nature of NiAl at low temperatures is because it has only three independent slip systems, which restricts crack-free plastic deformation. It has also low grain-boundary cohesive strength and the typical fracture mode is intergranular [31].

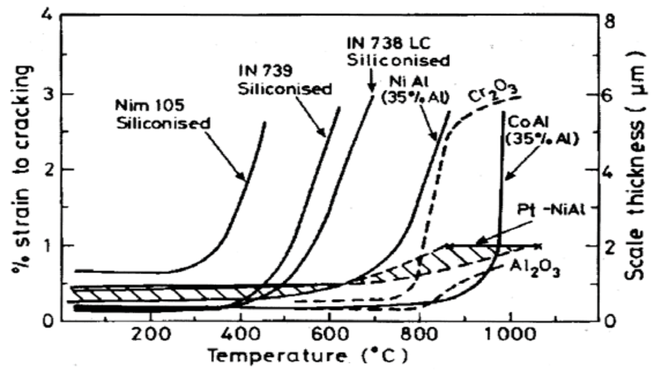

Figure 6. Ductile-to-brittle transition temperatures for diffusion coatings

C. ADVANCED COMBUSTION CHAMBER MATERIALS ANSD COATINGS

The combustion system is a multiple-chamber assembly composed of three basic parts: the fuel injection system, the cylindrical combustion liner and the transition piece. Driven by the ever-increasing firing temperatures of the gas turbines and the need for improved emissions control, significant development efforts are being made to advance the combustion hardware of heavy-duty gas turbines. What were originally simple parts in early gas turbines are now highly complex pieces of hardware with sophisticated materials and processing requirements. The primary basis for the material changes that have occurred has been increased high temperature creep rupture strength. These material changes had to be done while maintaining satisfactory oxidation/corrosion resistance. An indication of the strength improvement is shown in *Figure 21*, which compares the creep rupture strength of the three material classes now in use. Nimonic 263, the most recently introduced alloy, is some 250°F/140°C stronger than the original AISI 309 stainless steel. Hastelloy-X, which was used in the 1960s through the early 1980s, is intermediate in strength between the two.

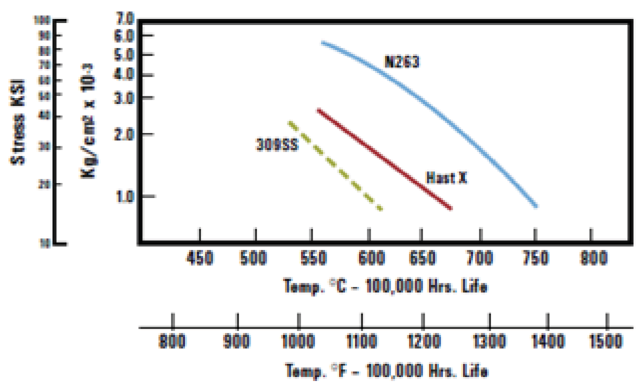

Figure. 7 Rupture comparison, N-263Vs Hallestoy- X Vs 309SS

Two major changes have occurred since the original AISI 309 stainless louver cooled liners: the adoption of Hastelloy X/RA333 in the 1960s, and the adoption of the slot-cooled liner in the early 1970s. This slot-cooled design offers considerably more liner cooling effectiveness, and, from a materials standpoint, presents a new area of processing challenges. Fabrication is primarily by a combination of brazing and welding. Earlier liners, on the other hand, were made using a welded construction with mechanically formed louvers. As firing temperatures increased in the newer gas turbine models, HS-188 has recently been employed in the latter section of some combustion liners for improved creep rupture strength. In addition to the base material changes, the use of a thermal barrier coating (TBC) on combustion liners of advanced and uprated machines has been incorporated. TBCs consist of two different materials applied to the hot side of the component: a bond coat applied to the surface of the part, and an insulating oxide.

Characteristics of Thermal barrier coatings:

- 15—25 Mil (380—640 Micron) Thickness
- Insulating — Porous

- Plasma Sprayed in Air
- Two Layers
  ----Bond Coat — NiCrAlY

  ----Top Coat — YTTRIA Stabilized Zirconia

Advantages

• Reduced Metal Temperature of Cooled Components

• 8—16°F (4—9°C) Reduction Per Mil (25.4 Micron) of Coating

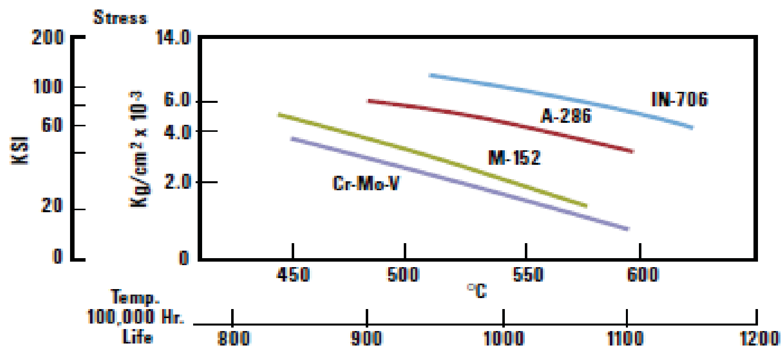

Figure. 8. Stress rupture comparison

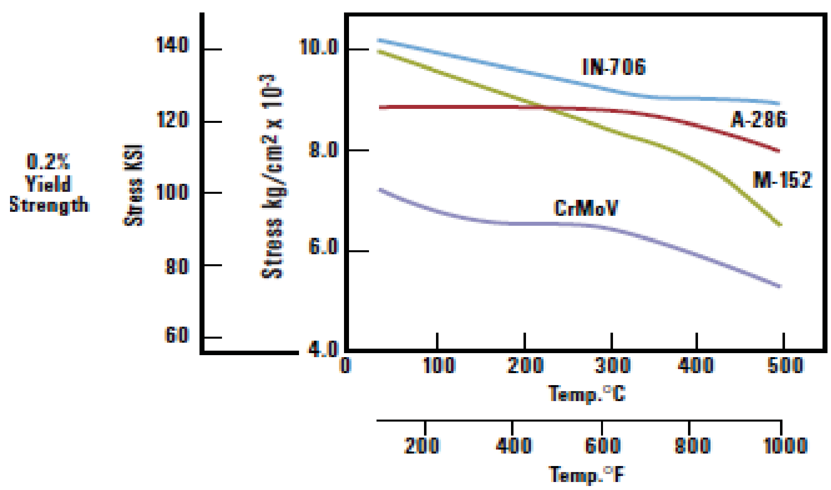

Figure 9. Tensile yield strength comparison

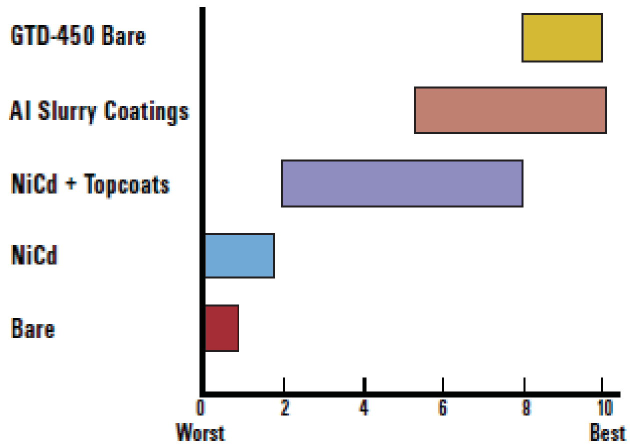

Figure 10. Acidic laboratory tests

D. FUTURE MATERIALS:

Advances in ductile iron have been made in laboratory trial castings that will enable this material to be extended to higher temperature applications. These trial heats have shown the capability to extend the useful temperature of this material by 100°F/56°C. This development program is now in the Rainbow field trial phase and will most likely find application in advanced and uprated GE gas turbines. In future gas turbine combustor must be made of materials which can able to withstand high temperature so that it should have more durability, high thermal resistance property, high phase stability along with resistance against surface degradation due oxidation process due to high temperature, corrosion due to the presence of chemicals such as hydrocarbons and other chemicals which is present in the fuel then materials should withstand high temperature and it should not lose its strength under all operating conditions of aircraft.

IV.CONCLUSION

Combustion chamber materials must withstand high temperature and maintain its phase stability and it should not lose its mechanical strength so combustion chamber materials should made up of super alloys which should meet combustion chamber requirements and it should not easily corrode by carbon particles. Combustor materials must have high durable and resistance against high temperature attack like creep, embrittlement, corrosion, micro-structural degradation and so on in order to meet future demands. So super alloys which mainly consists of nickel, iron and other elements like magnesium which promote resistance against high temperature attack so replacement of combustor materials by using suitable super alloys will provide effective efficiency and duration also will increase so that aircraft power plant will become a more reliable one and periodical maintenance too important for effective propulsion system.

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