

Recent Advances in Energy Materials for Hot Sections of Modern Gas-Turbine Engines

Zainul Huda

Abstract—This presentation reviews recent advances in superalloys and thermal barrier coating (TBC) for application in hot sections of energy-efficient gas-turbine engines. It has been reviewed that in the modern combined-cycle gas turbines (CCGT) applying single-crystal energy materials (SC superalloys) and thermal barrier coatings (TBC), and – in one design – closed-loop steam cooling, thermal efficiency can reach more than 60%. These technological advancements contribute to profitable and clean power generation with reduced emission. Alternatively, the use of advanced superalloys (e.g. GTD-111 superalloy, Allvac 718Plus superalloy) and advanced thermal barrier coatings (TBC) in modern gas-turbines has been shown to yield higher energy-efficiency in power generation.

Keywords—Energy materials, gas turbine engines, superalloy, thermal barrier coating

I. INTRODUCTION

MODERN gas turbine engines require a significant increase of gas inlet temperatures in order to achieve maximum efficiency. This results in an increased service temperature and consequently in enhanced high temperature corrosion attack of the blade materials. The blades in modern aero, marine and industrial gas turbines are manufactured exclusively from nickel based super alloys and operate under the most arduous conditions of temperature and stress of any component in the engine [1] and [2]. The nickel-base superalloys possess excellent high-temperature creep resistance, thermal stability, good tensile strength, long fatigue life, microstructural stability at high temperature, as well as good resistances to oxidation and corrosion. For these reasons, they are used in the manufacturing of gas turbine hot components [1], [3], [4], and [5].

The application of thermal barrier coating (TBCs) on gas turbines components provides a potential opportunity of increasing the operating temperature and further enhances the life of components [6] and [7]. The TBCs can be used at tolerable metal temperature at constant cooling levels and the efficiency of cooling leads to lower metal operating temperatures with extended life-times [8].

II. RECENT ADVANCES IN SUPERALLOYS

A superalloy is an alloy developed for elevated temperature service where severe mechanical stressing is encountered and where high surface stability is frequently required.

Superalloys are usually based on nickel, cobalt, or iron with several alloying additions, including aluminum, titanium, and chromium as the principal alloying elements [9]. A number of superalloys have been developed in recent years; however notable advanced superalloys for application in hot-sections of energy-efficient gas-turbine engines include GTD-111 superalloy and Allvac 718Plus superalloy.

A. The GTD-111 superalloy.

The GTD-111 superalloy is employed in manufacturing of the first stage blades of high power gas turbines. The chemical composition of GTD-111 superalloy is presented in Table 1 [10]; which shows a high aluminum and titanium contents to ensure precipitation of high volume-fraction of the γ' particles in the microstructure for good creep strength.

TABLE I
COMPOSITIONS OF GTD-111 AND ALLVAC® 718 PLUS SUPERALLOYS
[10] AND [11]

| Element | GTD-111 superalloy | Allvac718 Plus |
|---------|--------------------|----------------|
| Cr | 13.5 wt% | 17.9 wt% |
| Co | 9.5 wt% | 9.0 wt% |
| Ti | 4.75 wt% | 0.74 wt% |
| W | 3.8 wt% | 1.04 wt% |
| Al | 3.3 wt% | 1.5 wt% |
| Ta | 2.7 wt% | --- |
| Mo | 1.53 wt% | 2.68 wt% |
| Fe | 0.23 wt% | 9.3 wt% |
| C | 0.09 wt% | 0.02 wt% |
| B | 0.01 wt% | 0.003 wt% |
| Nb | --- | 5.51 wt% |
| Nickel | balance | balance |

The GTD-111 superalloy has a multiphase structure consisting of γ matrix, γ' precipitate, carbide, γ - γ' eutectic, and a small amount of deleterious phases such as: δ , η , σ and Laves [12] and [13]. Figure 1 shows the as-standard heat-treated microstructure of GTD-111. The alloy obtains its high-temperature strength mainly through γ' precipitates that are present with >60% volume fraction [14]. The primary γ' particles have a cubic shape with 0.8 μm average edge. The fine spherical γ' particles precipitated during an aging treatment have an average diameter of $\approx 0.1 \mu\text{m}$. The serrated grain boundaries increase creep life and creep plasticity.

Zainul Huda, *Ph.D* is Professor in Materials Engineering, Department of Mechanical Engineering at King Saud University, P.O. Box 800, Riyadh 11421, Saudi Arabia (email: drzainulhuda@hotmail.com).

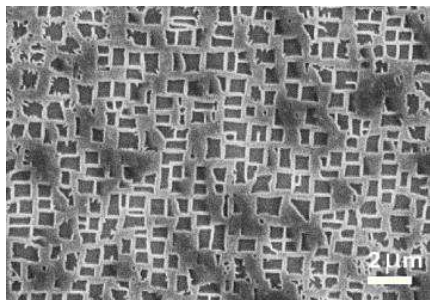


Fig. 1 SEM micrograph showing primary γ' in as heat treated GTD-111 superalloy [14]

B. The Allvac[®] 718 Plus[™] superalloy

Recently, a new 718Plus nickel-base superalloy has been developed for application in energy-efficient gas-turbine engines; thereby allowing to increase turbine inlet temperature to a considerable degree for high power output. The Allvac[®] 718Plus[™] is a novel nickel-based superalloy, which has been designed for heavy-duty applications in aerospace turbines [11].

The Allvac[®] 718Plus[™] alloy contains nanometer-sized spherical γ' phase precipitates ($\text{Ni}_3(\text{Al,Ti})$) and plate-shaped δ phase precipitates (Ni_3Nb) of micrometer size. The chemical composition of the Allvac[®] 718Plus[™] superalloy is shown in Table I; which shows higher chromium (Cr) and molybdenum (Mo) as compared to the GTD superalloy. An exceptional feature in the composition of the Allvac[®] 718Plus[™] alloy is its good niobium content (which is absent in the GTD alloy). The high niobium content restricts the coarsening of the γ' particles in the microstructure of the superalloy thereby ensuring long-time creep resistance so as to allow operation the GT engine at high temperature for longer periods of time [1] and [4].

Figure 2 shows transmission electron micrograph of superalloy: Allvac[®] 718Plus[™] after aging at 1148 K for 7800 s, showing spherical precipitates of γ' phase in the γ matrix. The aging heat treatments of the superalloy lead to a significant increase of hardness, which is due to precipitation of intermetallic phases [11].

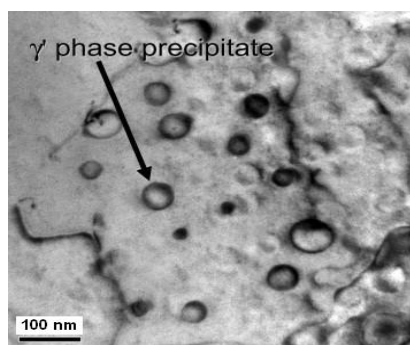


Fig. 2 TEM image of superalloy ATI Allvac[®] 718Plus[™] after aging at 1148K for 7800 s [11]

III. THERMAL BARRIER COATINGS (TBC)

A. TBC and Coating Technologies

A thermal barrier coating (TBC) is a multi-layer coating system that consists of an insulating ceramic outer layer (top coat) and a metallic inner layer (bond coat) between the ceramic and the substrate. The function of the ceramic topcoat is to insulate the metallic substrate from high surface temperature; thereby lowering the components temperature and reducing the oxidation and hot corrosion of bond coatings, while simultaneously reducing cyclic thermal strains [7]. Recently, Kitazawa and co-workers (2010) have reported that a temperature gradient of 150 oC can be achieved by using a ceramic TBC ($\text{Y}_2\text{O}_3\text{-ZrO}_2$ top-coat) on superalloy components [15]. In most cases, the top coat and bond coats are applied by plasma spraying; however, sputtering and EBPVD (electron beam physical vapor deposition) are also used. The commonly used method of thermal spraying of TBCs on developed metal surfaces involves a metallic bond-coating either by cold spraying (CS) or by low-pressure plasma spraying (LPPS) followed by deposition of a ceramic top-coat by either air plasma spraying (APS) or electron beam physical vapor deposition (EB-PVD).

The following techniques have been developed in recent years: (a) electron beam physical vapor deposition (EBPVD), and (b) electrophoretic deposition (EPD). These techniques are discussed in the following sub-sections.

B. Electron Beam Physical Vapor Deposition (EBPVD)

The EB-PVD thermal-barrier coatings (TBCs) consist of thin ceramic layers of low thermal conductivity-typically, partially stabilized zirconia (PSZ) – that are applied on airfoil surfaces that have a metallic corrosion-resistant coating [16]. During EB-PVD, a high-energy EB melts and evaporates a ceramic-source ingot in a vacuum chamber. The ingot is not the only ceramic source; there are also possibilities to deposit ceramics with powder. Preheated substrates are positioned in the vapor cloud above where the vapor is deposited on substrates at deposition rates of 0.1 – 0.25 mm/s [17]. Typical columnar microstructures and aerodynamically smooth surfaces are obtained without the need for final polishing or conditioning of cooling holes. Due to the columnar microstructure, the lifetime of the TBC is prolonged and the damage tolerance improved. The application of the TBCs increases the engine performance by either increasing the gas-turbine inlet temperature or reducing the required cooling-air flow [18].

C. Electrophoretic Deposition (EPD)

An alternative, relatively inexpensive way to apply an oxide thermal barrier coating (TBC) is by electrophoretic deposition (EPD). Figure 3 illustrates a typical coating system in a high-pressure turbine blade [19].

In recent years, electrophoretic deposition (EPD) technique has been widely used for TBC [20], [21], [22], and [23]. For EPD, a suspension is prepared from particles of the desired material in a dispersing liquid. The suspension can be stabilized by electrical charge on the surface of the particles due to the acid or alkaline nature of the suspension or by charges due to adsorption of a surfactant. Steric hindrance can

be used as well, but the particles do need a surface charge for the process to work [24]. When an electrical field is applied over the suspension the charged particles move towards the oppositely charged electrode where they form deposit. Upon drying and heat treatment (sintering) this is the product, either freestanding or on a substrate.

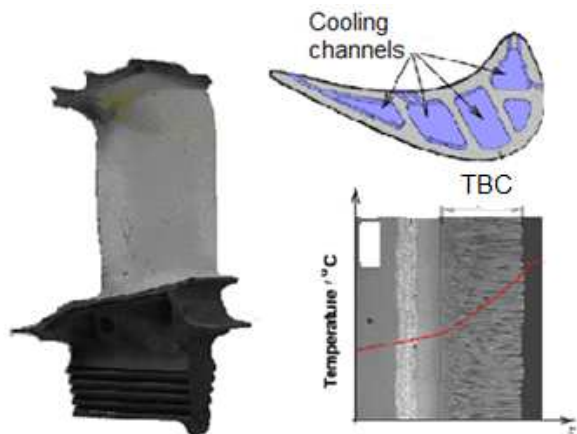


Fig. 3 Illustration of a typical coating system in a high-pressure turbine blade. Clockwise, a TBC coated high-pressure turbine blade, view from top showing the cooling systems; and schematic profile temperature, note the drop of temperature close to the blade surface due to the presence of a thin cooling air film [20]

IV. CONCLUSIONS

The techniques to enhance energy efficiency through advanced materials and coatings in the hot sections of modern gas-turbine engines have been highlighted. It has been reviewed that use of recently developed nickel-based superalloys (e.g. single crystal, GTD-111, 718Plus superalloy, etc) (with controlled microstructural control) in the hot sections of GT engines of a modern power plant provide considerable economic leverage. Additionally, thermal barrier coatings (TBC) techniques (particularly, EB-PVD and EPD) have been shown to have significantly improved energy efficiency of the modern gas-turbine plants.

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