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An alternative coating material for gas turbine blade for aerospace applications

Yajnesh M Poojari, Koustubh S Annigeri, Nilesh Bandekar, Kiran U Annigeri, Vinayak badiger, Arun Patil*, Santosh Billur and Basavaraj B Kotturshettar

School of Mechanical Engineering, KLE Technological University, Hubballi, India

E-mail: *patilarun7@gmail.com

Abstract. Gas turbine needs to withstand high temperature, stresses and fatigue loads they are exposed to, while still being affordable and maintaining a long-life span. This paper presents an alternative material for Thermal Barrier Coating (TBC) of the gas turbine blade. The paper also summarizes the basic properties of nickel superalloys that are used as a base material for the blades. The simulation study is conducted on the CAD model with and without coating in ANSYS.

1. Introduction

Gas turbines work at very high-temperature ranges of about 1200°-1500°, to withstand these high temperatures, it is necessary to insulate the components thermally. Thermal barrier coatings are used for this purpose. Thermal Barrier Coatings (TBCs) allow the parent material to operate cooler. They perform the important function of insulating components, such as gas turbine, aero-engine parts, operating at elevated temperatures (e.g. turbine blades, combustor cans, ducting and nozzle guide vanes). TBCs are characterized by very low thermal conductivity [1,2].

TBCs consists of typically four layers:

1. The metal substrate: Ni or Co base alloy.
2. Metallic bond coat: NiCrAlY or NiCoCrAlY.
3. Thermally grown oxide (TGO)
4. Ceramic topcoat.

At peak operating temperatures bond coat, the bond-coat temperature in turbine typically exceeds 700°, resulting in bond-coat oxidation and the inevitable formation of the third layer that is the thermally grown oxide (1 to 10mm thickness) between the bond-coat and ceramic top-coat.

Yttria stabilized zirconia is used as a ceramic topcoat. Pure zirconia undergoes phase transformations at different temperature ranges:

1. Monoclinic (1173°)



2. Tetragonal (2370°)
3. Cubic (2690°)
4. Melt (2700°)

Zirconia can be stabilized by the host of different oxides. Empirically Y_2O_3 found to be the most efficient stabilizer. Y_2O_3 stabilizes the zirconia in the tetragonal phase which is more desirable for TBC applications [3,4].

The present topcoat of the turbine can withstand a temperature of about 1200°. Above which it fails due to thermal fatigue. This paper emphasizes on researching an alternate material for TBC so that it can withstand even higher temperatures than 1200° which in-turn increases the efficiency of the Turbine engine.

2. Methodology

The work started with the literature survey, we looked for different implemented solutions for the gas turbine blade to withstand the high working temperature of the engine. After understating the limitations of the available solutions, we started our work. The complete workflow is shown in Figure 1.

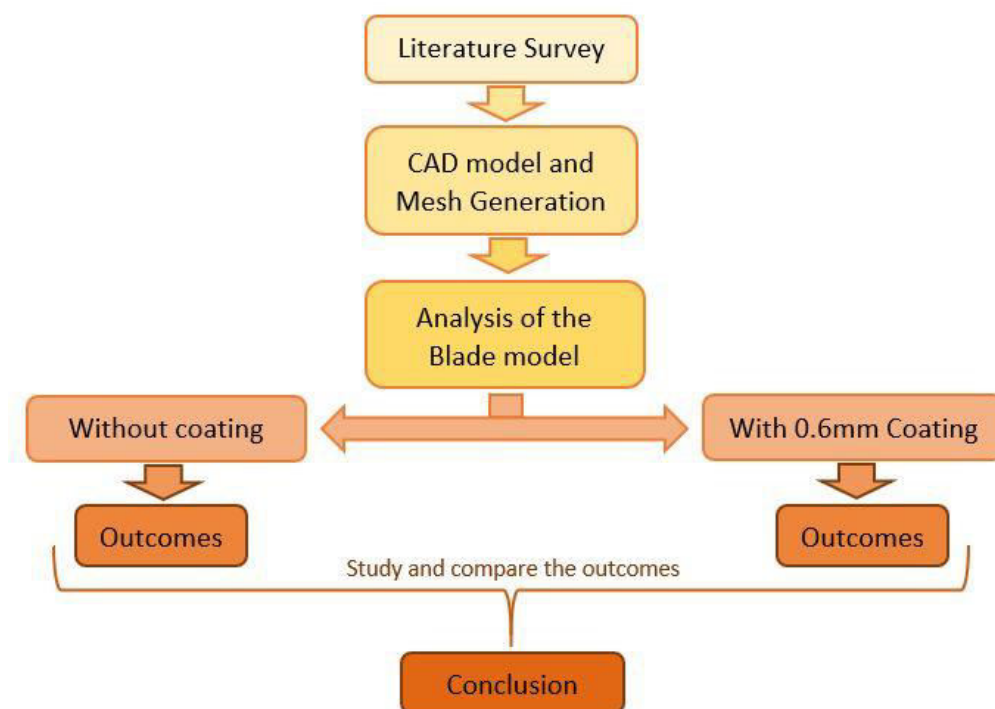


Figure 1: Work flow chart

The Simulation study was carried out for the blade, started with importing the CAD model and conducting the geometry cleanup. We carried out a basic study of the blade by conducting Static structural analysis and also steady-state thermal analysis was carried out for Advanced study of the blade. The complete workflow for the simulation study is shown in Figure 2.

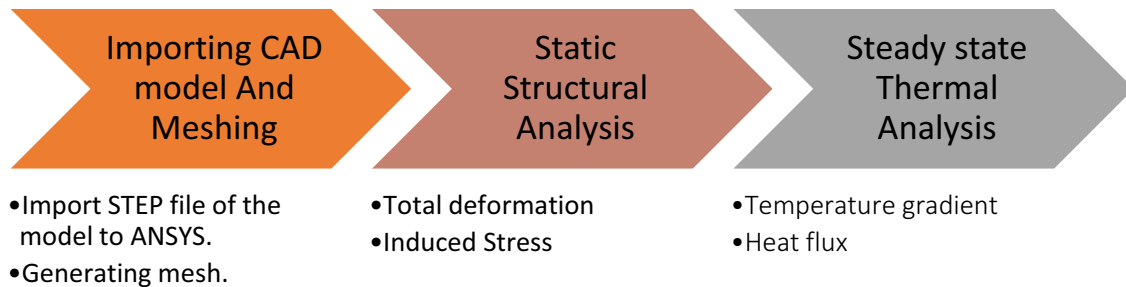


Figure 2. Flow chart of Simulation study

3. Prerequisites for the Simulation study

3.1 CAD model:

The CAD model of the Gas turbine blade shown in Figure 3 was taken from the GRABCAD [5]. The further model was converted into STEP neutral format to import it into ANSYS WORKBENCH 19.2 version. After importing the model, it was edited in Design Modeler to perform geometry cleanup.

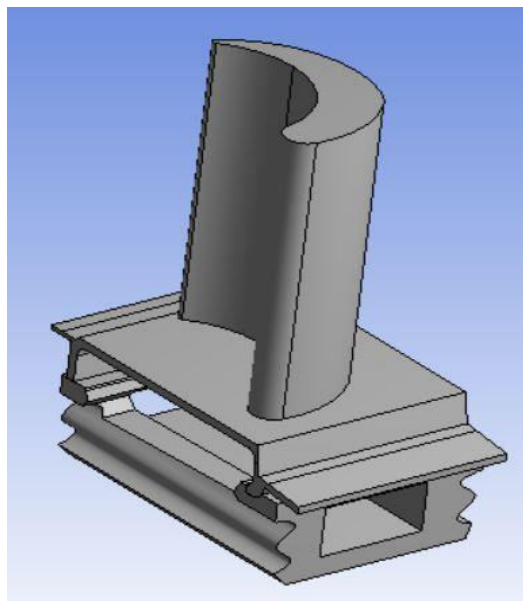


Figure 3: CAD model of the turbine blade

3.2 Mesh generation:

Mesh generation was done in using the default auto mesh option in ANSYS mechanical. The global element size was varied from 0.6mm to 22mm based on the complexity of the model and the thickness of the coating. Figure 4 and 5 show the completely meshed blade model with and with and without topcoat respectively.

The analysis results were validated for h-type (element size) and p-type (element order) methods [6,7]. The symmetric nature of the deformation plot depicts the corrective measures of loads and boundary conditions [8,9]. The maximum principal stress plot results seem to be accurate based on the convergence theory and compatibility equation which is decided based on the number of iterations carried out for each of the case [10,11].

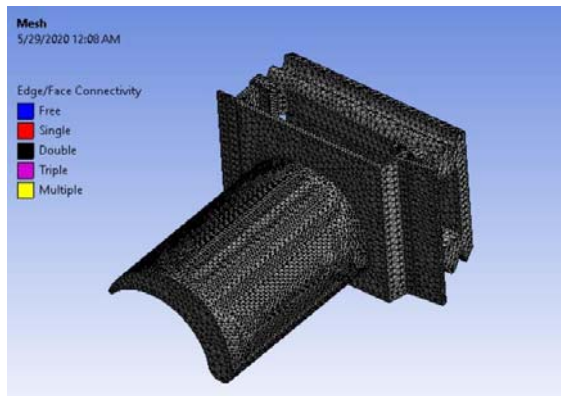


Figure 4: Mesh generation for the blade without Coating.

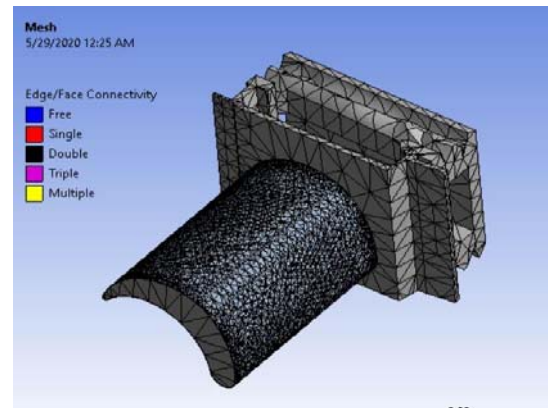


Figure 5: Mesh generation for the blade with 0.6mm Coating.

3.3 Loads and boundary conditions:

For the analysis model loads are the mechanical forces and thermal loading that act on the blade underuse and boundary conditions are the environmental factors that influence the behavior of the blade underuse.

3.3.1 Loads and boundary conditions static structural analysis:

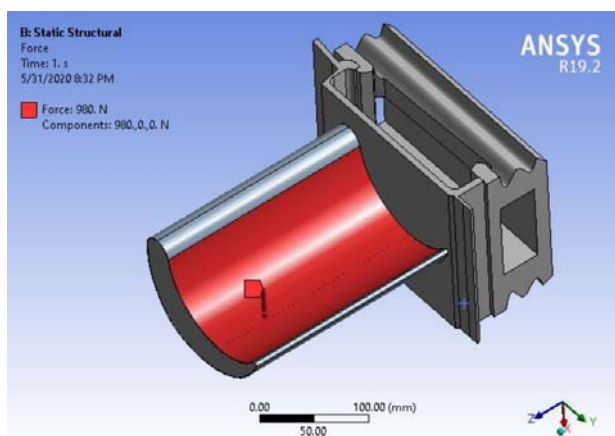


Figure 6: Force of 980N acting on the blade

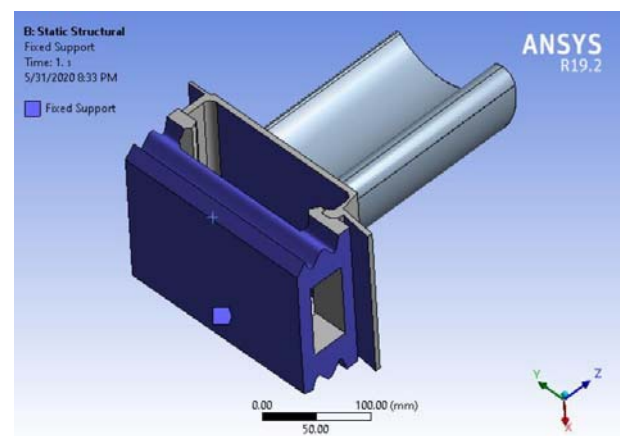


Figure 7: Fixed Support

The rotor in the turbine consists of the shaft and the wheel. The turbine wheel is a dynamically balanced unit. The turbine wheel is referred to as turbine disc without blades. When the blades are installed, then the disc is called the turbine wheel. The blades are mounted on the disc through grooves or the notches that are made on the disc to seat the blade. Once the blade fits into the groove lock tabs or rivets are used

to retain the position of the blade on the disc [12]. With this knowledge, we have assigned fixed support boundary condition to the fir-tree design on the blade at its end, as shown in Figure 7. The assembly rotates at very high speed, this imposes a very high load on the blades up to 980N [12] as shown in Figure 6.

3.3.2 Loads and boundary conditions static structural analysis:

As a result of the fuel combustion in the engine, the working temperature of these engines is very high. Most of the components of the engine are exposed to extreme temperature. Among which the turbine blades are the one which is always exposed to the maximum working temperature of the engine. As the hot exhaust gases directly pass through these blades. In most of the gas turbines, the current working temperature is 1200° [2]. Hence, we applied the Forced convection to the upper and lower surfaces of the blade as shown in Figure 8.

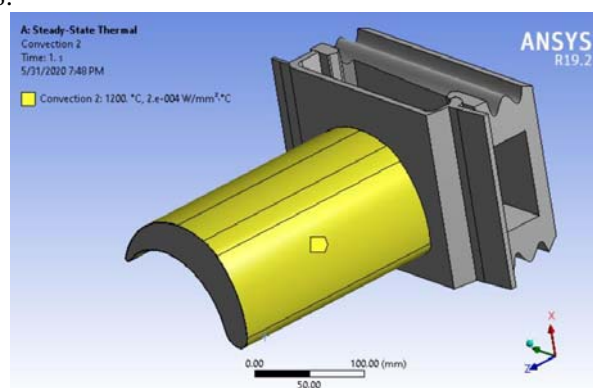


Figure 8: convection on the blade surface due to hot air stream at 1200°

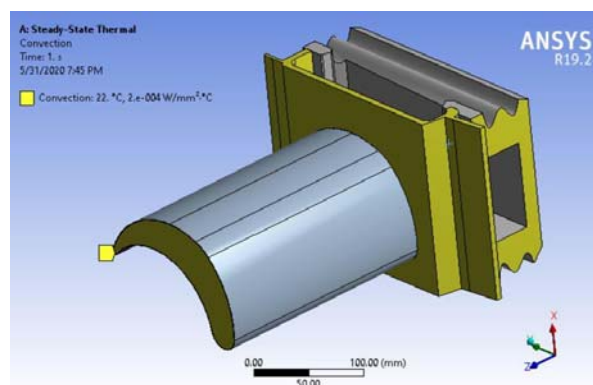


Figure 9: convection on the other regions of the blade exposed to ambient air

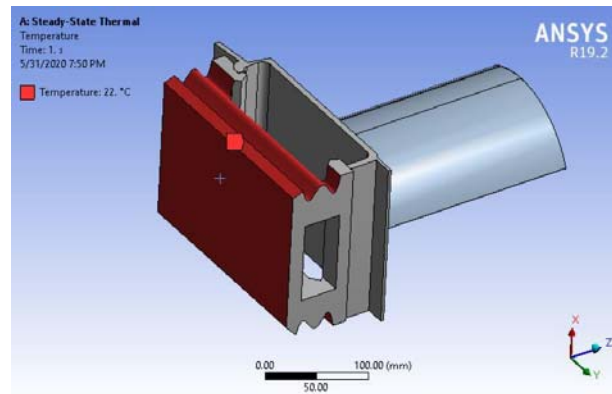


Figure 10: conduction on the blade due to contact

Even the disc rim temperature is very high and well above the temperature of the inner portions of the disc. As a result of this thermal stresses are generated in addition to rotational stress. To reduce this thermal stress, cool ambient air is passed on to the face of the disc which will help in lowering the temperature of the disc rim [2]. So, we have applied free convection to the region of the blade close to the disc rim as shown in Figure 9. In addition to this, the disc rim also absorbs heat from the blade by conduction as shown in Figure 10.

4. Simulation Study

4.1 Analysis of the blade without Thermal barrier coating:

We analyzed the blade model without any coating. The turbine blade is made up of Ni-based superalloy Inconel 625 [3], whose properties are mentioned below in Table 1. We conducted the static structural analysis for a basic study of the design. The result of the static structural analysis i.e. Total deformation and Equivalent strength were noted down. We also carried out steady-state thermal analysis and outcomes were noted down for further reference.

Table 1: Ni-based super alloy properties

Material	Nickel-based superalloy Inconel 625
Composition	Mn Max 0.5 Mo 8 - 10 Nb 3.15 - 4.15 Ni Min 58
Melting point	1280-1350 ⁰ C
Thermal conductivity	21.3 W/m-K
Density	8.44 g/cc
Young's Modulus	180 GPa
Tensile strength	830 MPa
Yield strength	415 MPa

4.1.1 Static structural analysis:

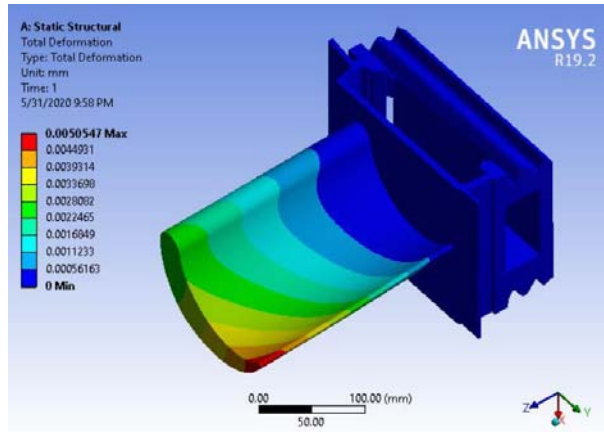


Figure 11: Total deformation

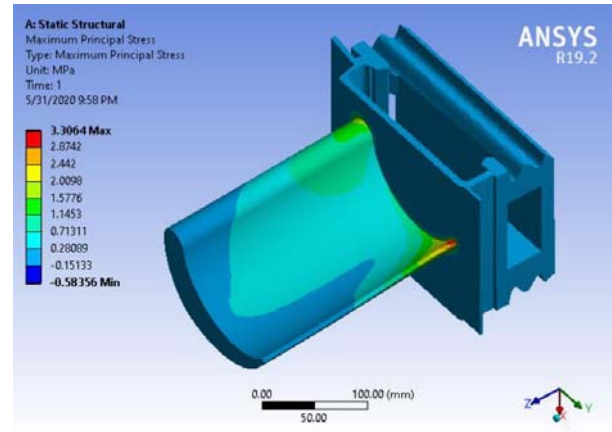


Figure 12: Maximum principal stress

The static structural analysis resulted in the total deformation and the maximum principal stress for the model, the maximum stress generated in the model was 3.306 MPa shown in Figure 12 and maximum deformation of the model was 0.005 mm, which is comparatively very small. In Figure 11, We can observe that maximum deformation was near the trailing edge of the blade tip, this is due to its thin cross-section at the trailing edge.

4.1.2 Steady-state thermal Analysis:

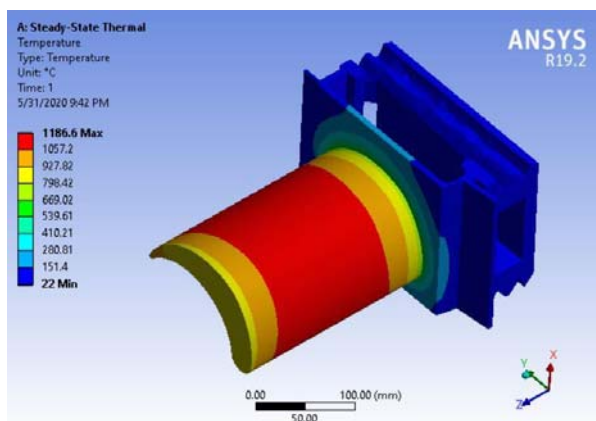


Figure 13: Temperature gradient

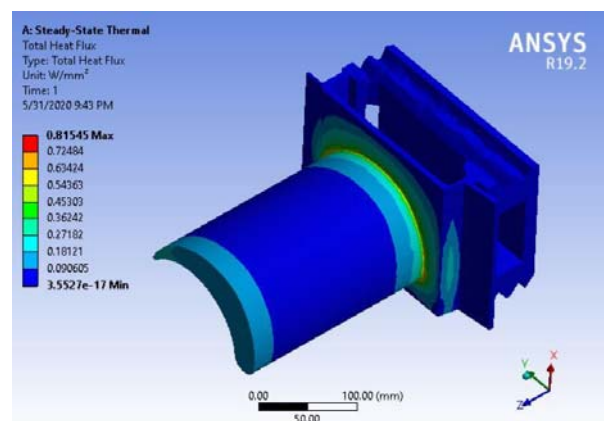


Figure 14: Total heat flux

The steady-state thermal analysis resulted in the temperature gradient across the model and the heat flux. In figure 13, we can observe that maximum temperature i.e. 1186.6° is at the upper and lower surface of the blade as the hot stream of air passes through the surface. And this temperature is very close to the melting temperature of the blade material i.e. Ni-based alloy, so to avoid melting of the blade due to continuous exposure to high-temperature proper coating is essential for the blade. The proper coating for

the blade will increase the life of the blade as it will prohibit the blade exposing to the higher temperature. Figure 14 shows the heat flux variation across the model.

4.2 Analysis of Gas turbine blade with Thermal barrier coating:

The material for the coating of the blade should be carefully chosen, along with having lower Thermal conductivity it should also have lower density. If the material is too heavy it will increase the power requirement of the gas turbine engine to run, which will indirectly reduce the efficiency of the engine.

We considered three ceramic material for coating of the gas turbine blade they are (A)Titanium Carbide, (B) Tantalum Carbide, (C) Zirconium Carbide. These materials were selected because of their lower density, lower thermal conductivity and higher melting temperature. We have conducted Static structural analysis and steady-state thermal analysis considering 0.6mm coating thickness separately and noted the outcomes [13]. Table 2 contains all the properties of these three ceramic materials required for simulation.

Table 2: Properties of the Ceramic material

Material property	Titanium carbide (TiC)	Tantalum Carbide (TaC)	Zirconium Carbide (ZrC)
Density g/cc	4.94	14.3	6.56
Youngs Modulus GPa	451	722	406
Poissons Ratio	0.19	0.24	0.19
Ultimate Strength MPa	114	291	110
Melting temperature °C	3065	3965	3532
Thermal Conductivity W/m-K	41.84	21	20.5

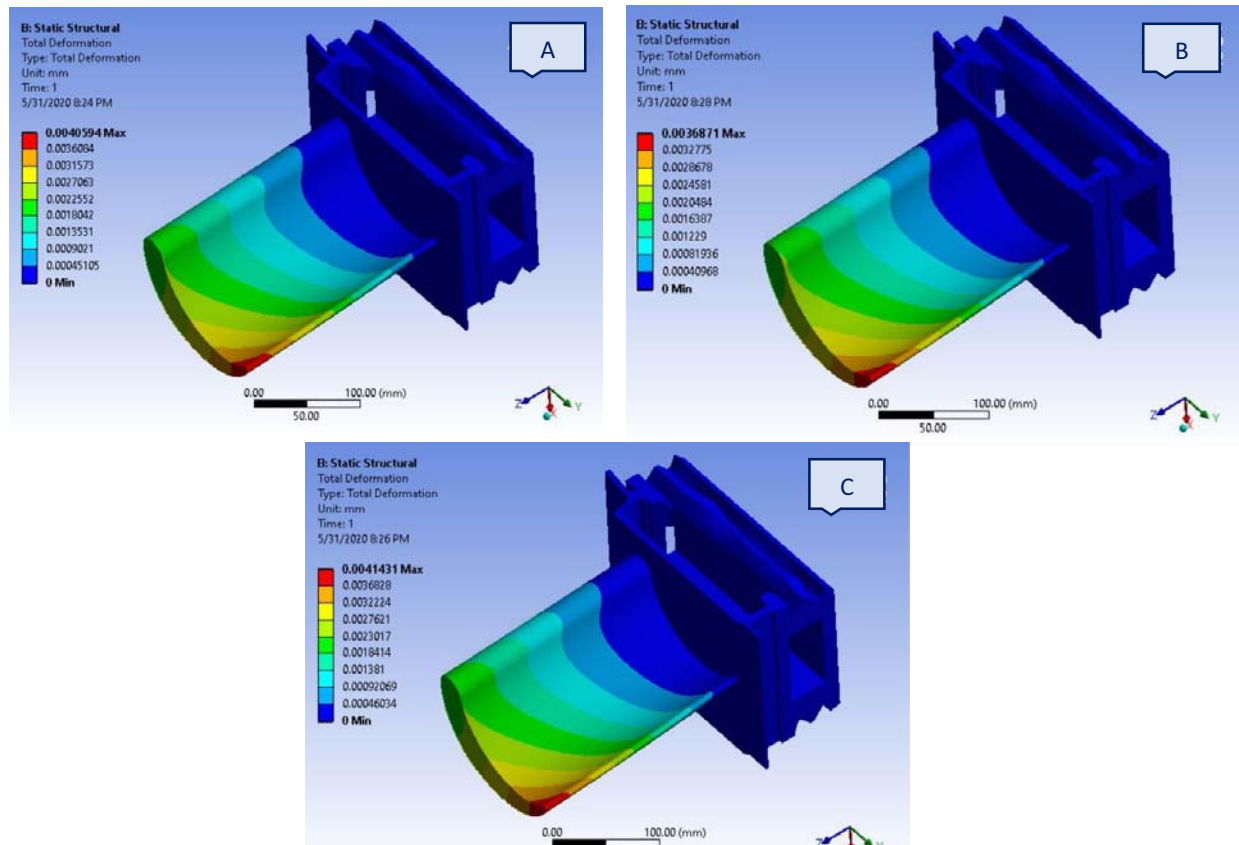


Figure 15: Total deformation: (A) Titanium Carbide, (B) Tantalum carbide, (C) Zirconium Carbide.

4.2.1 Static structural analysis:

The total deformation[14,15,16] for the blade model with Zirconium carbide coating was higher (i.e. 0.004143mm) when compared to Titanium carbide and Tantalum carbide shown in Figure 15.

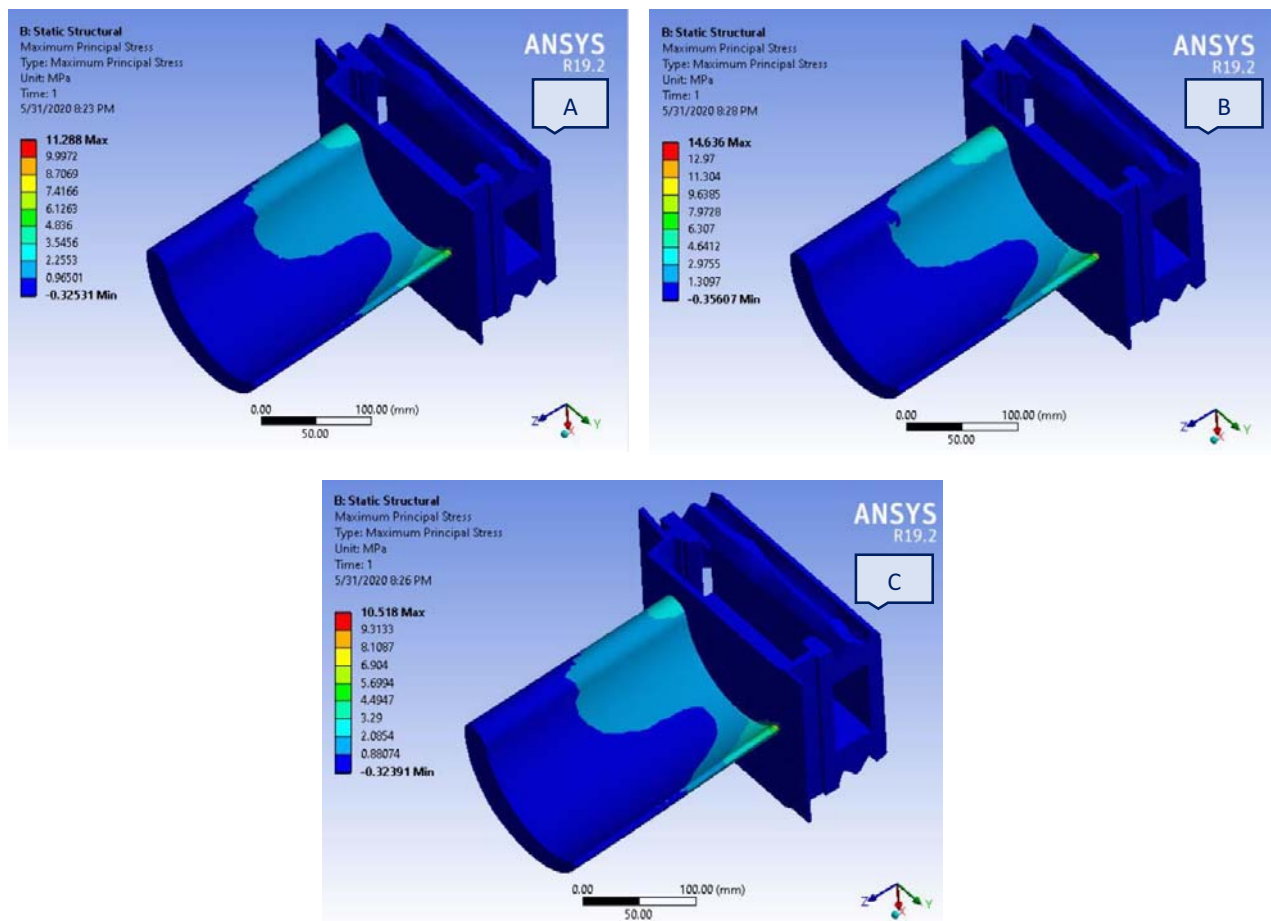
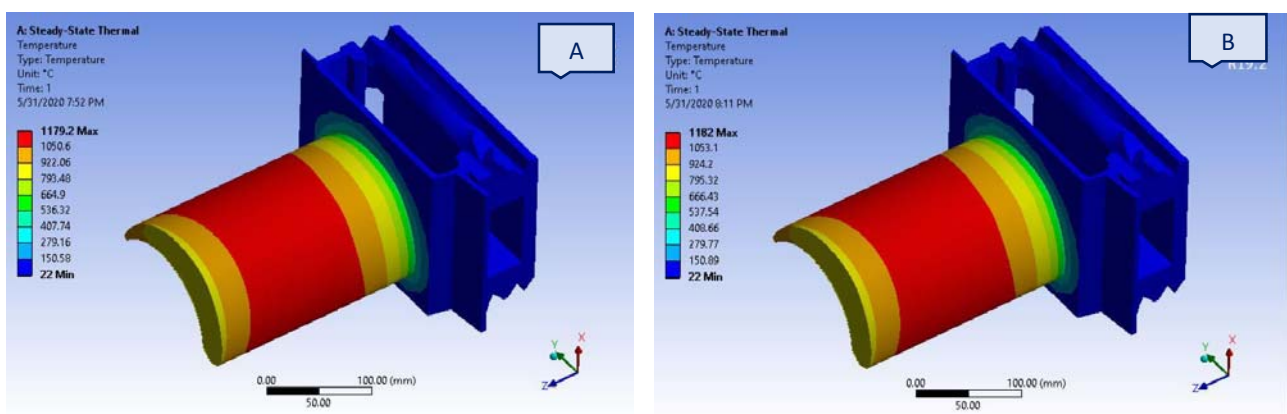


Figure 16: Maximum Principal stress: (A) Titanium Carbide, (B) Tantalum carbide, (C) Zirconium Carbide.

As the material was brittle in nature, we calculated maximum principal stress[17,18,19] for all three cases and found that blade model with Zirconium carbide coating has least induced stress compared to other two blade models shown in Figure 16.

4.2.2 Steady-state thermal Analysis:



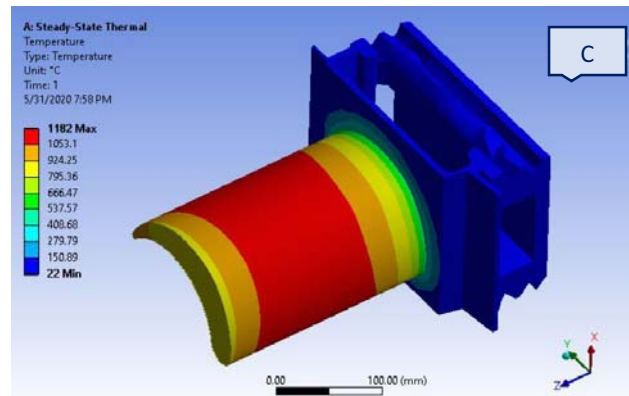


Figure 17: Temperature: (A) Titanium Carbide, (B) Tantalum carbide, (C) Zirconium Carbide.

The steady-state thermal analysis resulted in the temperature contour which helped us in knowing the temperature variation for the blade model. From the temperature contour shown in Figure 17, we can observe that for all three model's maximum temperature is attained at the ceramic coated region.

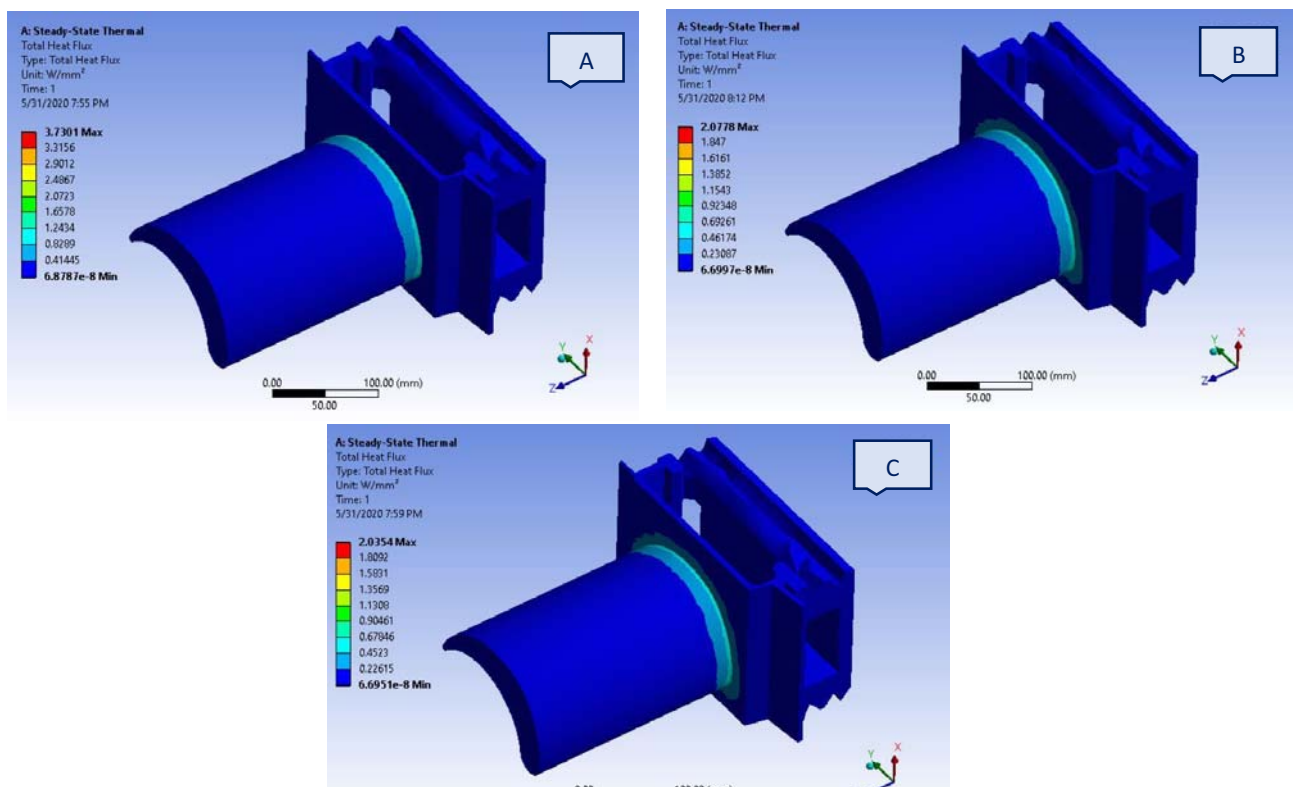


Figure 18: Heat Flux: (A) Titanium Carbide, (B) Tantalum carbide, (C) Zirconium Carbide.

From the steady-state thermal analysis, heat flux variations across the blade shown in Figure 18 was extracted for all three blade models and the model with Zirconium carbide has the list least value of maximum heat flux followed by the blade model with Tantalum carbide and Titanium carbide. The comparative study of these materials have yielded a good correlation with analytical aspects[

5. Conclusion:

From the Simulation study of the blade model without thermal barrier coating, it is clear that the coating is essential for the gas turbine blade to work efficiently under high temperature. We have carried out an analysis of the blade model with a different coating material.

From the static structural analysis, we find that blade coated with Zirconium carbide has lesser induced maximum stress value (i.e. 10.518MPa) compared to the other two coating materials. So, it is clear that Zirconium carbide can withstand a higher load compared to the other two materials.

From the steady-state thermal analysis, we find that the maximum heat flux value (i.e. 2.035 W/mm²) for the blade model with Zirconium carbide coating is less compared to the other two models.

The coating material along with adding strength and thermal resistance to the blade, it should be very light in weight so that the power requirement for the turbine engine should not increase much. So, Zirconium carbide is one of the low-density Ceramic material (i.e. density = 6.56 g/cc) its best suite alternative for coating of the gas turbine blade.

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