

T.R.
GEBZE TECHNICAL UNIVERSITY
ENERGY TECHNOLOGIES

**ANALYTICAL AND NUMERICAL COMPARISON OF
COOLING AIR NEEDS OF HIGH PRESSURE TURBINE SHROUDS
WITH TWO DIFFERENT MATERIALS: N22 SiC/SiC CMC AND
IN738LC**

HAMZA FARUK AKKURT
**A THESIS SUBMITTED FOR THE DEGREE OF MASTER OF
SCIENCE**
ENERGY DEPARTMENT

GEBZE
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SUMMARY

In this study, two high-pressure turbine shrouds designed from SiC/SiC CMC and IN738LC nickel-based super-alloy are compared in terms of their cooling air needs. The geometric designs of the shrouds are the same, and the only difference is the materials. During this comparison, two different temperatures are established at which the two materials can operate safely under the determined environmental conditions, taking into account their high-temperature limits. The required cooling air mass flows which keep parts at predetermined temperatures are calculated by 1D heat transfer analysis in the same cycle parameters. The effects of differences in the cooling air mass flow on engine performance are discussed. Finite element thermal analysis are performed with the results obtained from the 1D heat transfer analysis, and the part temperatures are obtained. The stresses of the parts under these temperatures are calculated by finite element structural analysis, and compared with the material strength limits.

Key Words: High-pressure turbine shroud, silicon carbide, super-alloy, ceramic matrix composite.

ÖZET

Bu çalışmada, SiC/SiC Seramik Matris Kompozit ve IN738LC nikel bazlı süperalaşım malzemedan tasarlanan iki yüksek basınç türbini kanatçık kılıfı soğutma havası ihtiyaçları açısından karşılaştırılmıştır. Kılıfların geometrik tasarımları aynı olup tek fark malzemeleridir. Karşılaştırmada, iki malzemenin belirlenen çevre koşullarında sıcaklık dayanım limitleri göz önünde bulundurularak, güvenli şekilde çalışabilecekleri iki farklı sıcaklık belirlenmiştir. Parçaları belirlenen sıcaklıklarda tutulabilmesi için gerekli soğutma havası debisi aynı çevrim parametrelerinde 1-boyutlu ısı transferi analiziyle hesaplanmıştır. Soğutma havası debisi ihtiyacındaki azalmanın motor performansına etkileri tartışılmıştır. 1-boyutlu ısı transferi analizinden elde edilen sonuçlarla sonlu elemanlar termal analizi yapılarak parça sıcaklıkları elde edilmiştir. Parçaların bu sıcaklıklar altındaki gerilmeleri sonlu elemanlar yapısal analizleriyle bulunmuş ve bulunan gerilmelerle malzeme dayanım limitleri karşılaştırılmıştır.

Anahtar Kelimeler: Yüksek basınç türbini, kanatçık kılıfı, silisyum karbür, süperalaşım, seramik matris kompozit.

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LIST OF ABBREVIATIONS AND ACRONYMS

<u>Abbreviations and Acronyms</u>	<u>Explanations</u>
SiC	: Silicon carbide
SiN	: Silicon nitride
CVI	: Chemical vapor infiltration
HPT	: High pressure turbine
CMC	: Ceramic matrix composite
LC	: Low carbon
GE	: General Electric
SNECMA	: Société nationale d'études et de construction de moteurs d'aviation
C/C	: Carbon/carbon
NASA	: National Aeronautics and Space Administration
BN	: Boron nitride
E	: Elastic modulus
G	: Shear modulus
ν	: Poisson ratio
HTC	: Heat transfer coefficient
TBC	: Thermal barrier coating
T ₃	: Cooling air temperature
T ₄	: Turbine inlet temperature
T ₄₁	: Shroud flowpath leading edge temperature
T ₄₂	: Shroud flowpath trailing edge temperature
C _p	: Specific heat capacity
W ₂	: Total engine mass flow
HT	: Heat transfer
FE	: Finite element
SFC	: Specific fuel consumption

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1 INTRODUCTION

1.1 Hot Section Gas Turbine Materials

In early examples of gas turbines, engine efficiencies were much lower than today's engines, and efficiencies did not exceed 30%. As a result of the studies to increase the engine performance and efficiency, it was concluded that turbine inlet gas temperature and thus the operating temperatures in the hot section should be increased. However, components had to withstand the hotter operating conditions. Therefore, relatively cold air taken from the compressor was used to cool the hot section components in order to prevent failures caused by the temperature increase. In addition to cooling technologies, nickel and cobalt-based alloys with improved temperature resistance were developed in the 1950s.

Nickel-based alloys show high strength properties in the range of 700-1000 °C, while cobalt-based alloys can work at slightly higher temperature levels, such as 1050 °C. Thus, nickel-based alloys are used in turbine discs and blades, while cobalt-based alloys are used in nozzle guide vanes operating at higher temperatures.

In the 1960s, in addition to material development studies, powder metallurgy and new material production techniques were developed such as hot isostatic pressing and directional solidification [1].

In the early 1970s, single-crystal castings were developed to increase the melting/maximum operating temperature and creep strength of turbine blades. In the late 1970s, they started to be used in hot section components of commercial engines, especially in turbine blades and nozzle guide vanes [2]. Figure 1-1 shows turbine blades which are manufactured by conventional casting, directional solidification, and single crystal casting.

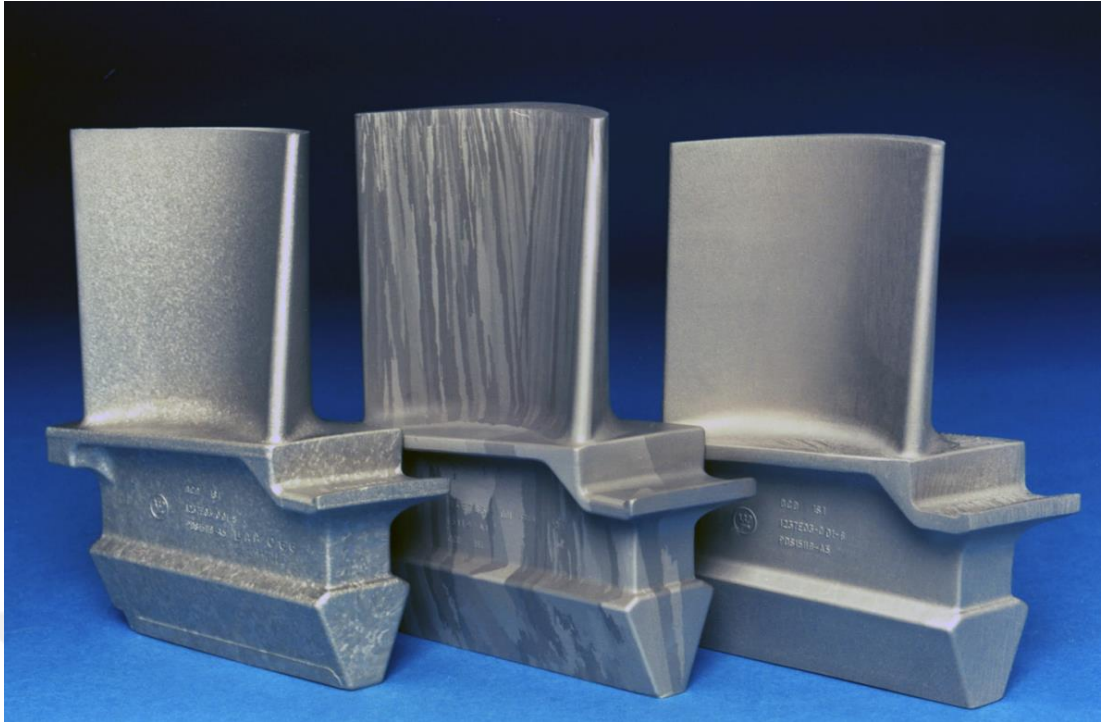


Figure 1-1: Small crystal grains, directionally solidified, single crystal blades from left to right [2].

In the later processes, researches on materials tended towards monolithic ceramics such as silicon carbide (SiC) and silicon nitride (SiN) due to their lower density and better thermal properties than metals. However, the failure of parts produced of monolithic ceramics in impact tests was a major concern preventing their use as a common engineering material. Another problem was the oxidation of silicon carbide and silicon nitride when exposed to moisture. Although the initial tests of monolithic ceramics showed that they were insufficient for gas turbine applications, their performance in short-term operation under high temperature indicated that they may be suitable when further studies are conducted and technologies developed.

In 1977, ceramic silicon carbide matrices reinforced with carbon fibers began to be produced using chemical vapor infiltration (CVI) technique. Tests on this material showed that the matrix structure is not as brittle as the monolithic structure and the material toughness is much higher. Thereupon, General Electric Company (GE) began to develop and produce its own ceramics of higher quality [1]. Figure 1-2 shows the ceramic-based shrouds used in one of GE's latest commercial engines, LEAP.



Figure 1-2: SiC/SiC Shrouds of LEAP Engine.

1.2 Ceramic Matrix Composites

In gas turbine engine applications, the material allowable temperature limits of metal-based materials, including super-alloys, are reached or even exceeded. In order to increase the durability and service life of parts in hot regions, e.g. high pressure turbines, alternative materials such as ceramics are needed. When the material properties of advanced ceramics are considered, they possess low density, high strength, high hardness, high temperature capability, high elastic modulus, as well as very good chemical and environmental stability. However, the absence of energy-dissipating mechanisms in monolithic ceramics makes them brittle, causes catastrophic failures, and prevents ceramics from being used as structural components. In order to improve the fracture toughness of ceramics, the incorporation form of reinforcements with ceramic particles, platelets, whiskers, chopped or continuous fibers in a ceramic matrix are produced, which is ceramic matrix composite (CMC). Thus, CMCs are the combination of increased fracture toughness and excellent thermo-mechanical properties of ceramics. The properly designed fiber-matrix

structure ensures that the possible cracks are directed and stopped, so that early failure of components are prevented [3].

Some of the usage areas of composites are listed below:

- Aerospace and military applications
- Advanced aero-jet engines
- Stationary gas turbines (marine and electrical power generation)
- Nuclear fusion reactors
- Automotive industry
- Brake kits (Figure 1-3)
- Heat exchangers
- Bearings in missiles
- Machinery wear parts, cutting and forming tools
- Valve seals, high precision ball bearing, and plungers



Figure 1-3: Carbon ceramic brake kit.

1.3 IN738LC, SiC/SiC and N22

IN738 is one of the commonly used nickel-based super-alloys. In 1969, it was developed and patented by Inconel Corporation [4]. This super-alloy was designed for industrial gas turbines used in power generation, not aircraft gas turbines operating under high corrosion, oxidation and stress environments [5]. It was developed to

combine the strength of IN713 and the oxidation/corrosion resistance of Udimet500 [6]. IN738LC (low carbon), on the other hand, is an improved version of IN738's high temperature resistance, and corrosion resistance, by finely balancing its critical elements [7]. Chemical composition of IN738LC is shown in Table 1.1.

Table 1.1: IN738LC chemical composition (wt. %).

Elements	Range	Nominal Composition
Ni	Balance	Balance (61)
Ti	3.20-3.70	3.4
Nb	0.6-1.1	3.4
Ta	1.5-2	1.75
C	0.09-0.13	0.11
Co	3-9	8.5
Cr	15.7-16.3	16
W	2.4-2.8	2.6
Mo	1.5-2	1.75
B	0.007-0.012	0.01
Zr	0.03-0.08	0.05
Al	3.20-3.70	3.4

In most IN738LC applications, allowable temperature limits are exceeded, if additional cooling is not applied. Metal temperature should not exceed 950°C for the safe usage of IN738LC shrouds. Considering the flow path temperatures reach 1400°C in the area where the shrouds are located, the part must be coated with thermal barrier coatings, and cooled in order to lower the metal temperature.

Ceramic matrix composites are composed of brittle fibers and brittle matrix structure. However, the combination of these two brittle structures creates composites with high damage tolerance. Composites can be produced by different production techniques. Figure 1-4 shows standard manufacturing processes to produce CMC systems followed by NASA. In their fabrication, liquid or gaseous precursors can be used. CVI SiC/SiC is obtained by combining SiC-based matrix reinforced by SiC-based fibers together in Chemical Vapour Infiltration (CVI). Basically, the deposited SiC-based matrix from gaseous reactants is settled on a heated substrate of SiC-based fibrous preform. Although the CVI technique has been researched since the 1960s, it has increased its importance in the commercial field with the commercialization of this technique by SNECMA.

The weak oxidation resistance of CVI C/C composites causes the development of CVI SiC/SiC composites. C/C composites have lower oxidation resistance when compared to SiC/SiC composites.

CVI SiC matrix has the following advantages compared to metals.

- High strength at higher temperatures
- Lower weight due to lower density
- Good oxidation resistance.

CVI SiC/SiC composites also offer solutions to the following problems of monolithic ceramics:

- Toughness
- Thermal shock resistance
- Damage tolerance
- Reliability.

Different factors such as strength between fiber-matrix, type of SiC fiber and matrix used, fiber orientation, etc. affect the mechanical and thermo-physical properties of the composite [3].

N22 is a type of CVI SiC/SiC composite developed by NASA. It is labeled by the prefix N for NASA and 22 for its upper temperature capability in degrees Fahrenheit divided by 100. The N22 was developed in 1997. Dow Corning was the only company that had been manufacturing small diameter Sylramic SiC fiber types with satisfactory high temperature resistance that were commercially available then. Nippon Carbon was also the only manufacturer for carbon-rich Hi-Nicalon SiC fibers. Hi-Nicalon fibers and composites using Hi-Nicalon fiber have lower thermal conductivity, thermal stability, creep resistance and resistance to environmental endurance compared to Sylramic fiber. This is because Hi-Nicalon fibers have low processing temperatures and their surfaces are rich in carbon. For this reason, Sylramic SiC fibers were preferred for the N22 system. Silicon added BN (Boron Nitride) produced with CVI was preferred for the interfacial coating architecture in the N22 system, because BN has higher oxidation resistance than conventional carbon-based coatings, and good compatibility around the fibers for matrix crack deflection [8]. Microstructure of N22 can be seen in Figure 1-5.

Within the scope of this study, the material data of the N22 system is used to represent SiC/SiC CMC materials.

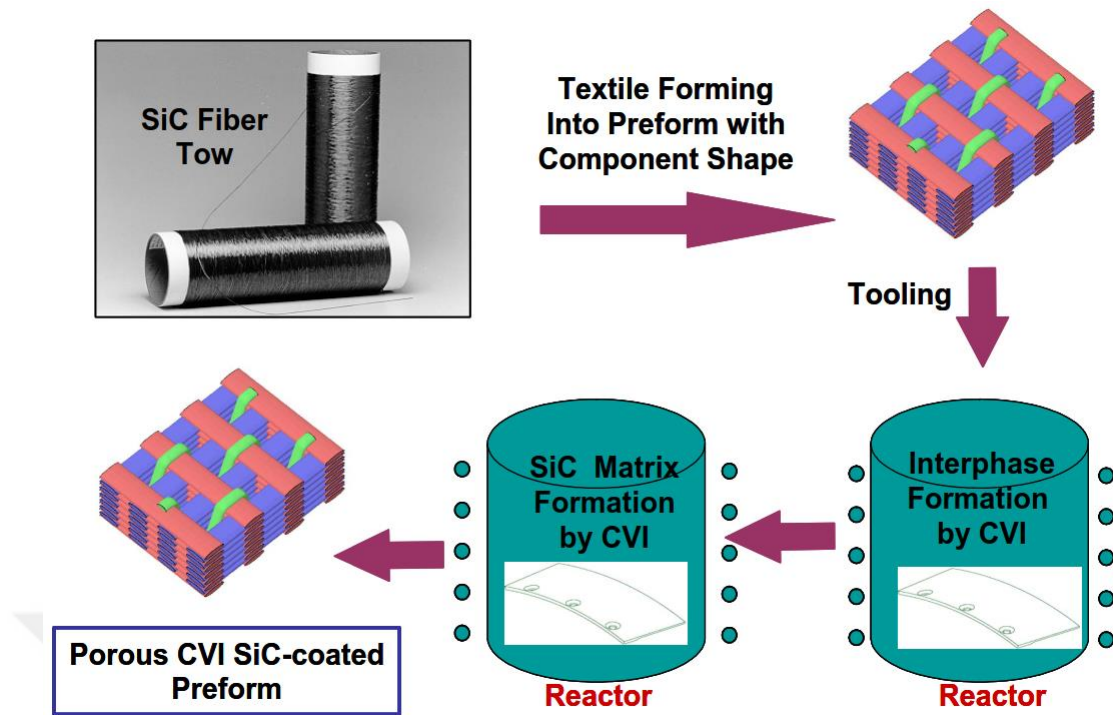


Figure 1-4: NASA CMC systems standard manufacturing road map [8].

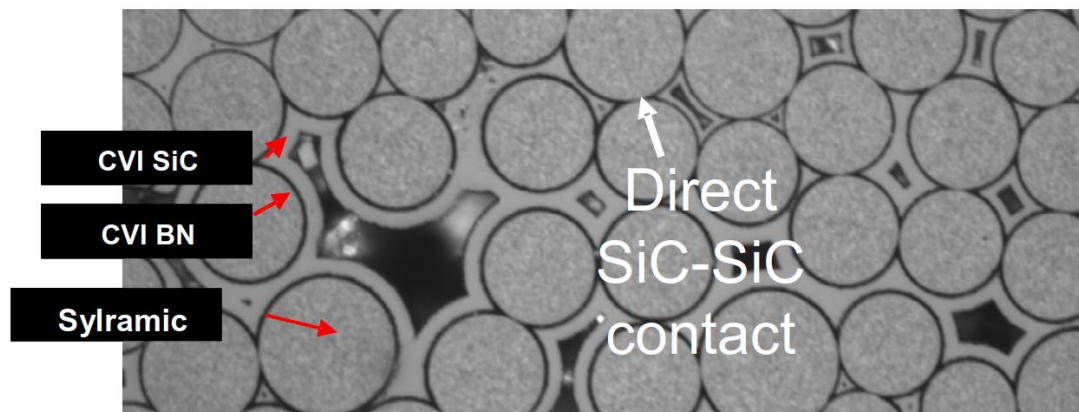


Figure 1-5: N22 microstructure [8].

1.4 Properties of the Materials Used

The material properties used in all analyses within the scope of this study are summarized in the tables below. Since IN738LC is a material that has been widely used for many years, it is possible to access the properties of this material both in the open literature and in the database of aerospace companies using this material. On the other hand, N22 is comparatively a much newer material and is still not widely used

in industry, so it is difficult to reach material properties compared to IN738LC. Since N22 is a material developed by NASA, material properties can be obtained only from documents published by NASA and from reports of side studies performed with N22. Material data in Table 1.2, Table 1.3 and Table 1.4 are obtained from Reference 8 and 9.

Table 1.2: Physical properties of N22 and IN738LC.

		N22	IN738LC	
Upper Use Temperature	°C	1204	950	
Density	g/cm ³	2.85	8.192	
			@ 20°C	@ 950°C
Thermal Expansion Coefficient	strain/°C		1.33E-05	1.58E-05
Thermal Linear Expansion	%	$T [2.62 \times 10^{-4}] + T^2 [2.314 \times 10^{-7}] - T^3 [0.518 \times 10^{-10}]$ (T = °C)		
Thermal Conductivity	W/m.°C	See Figure 1-6	9	27.4

Table 1.3: Elastic properties of N22 and IN738LC.

			N22		IN738LC	
			@ 20°C	@ 1204°C	@ 20°C	@ 950°C
Elastic Modulus	E _z , E _y	GPa	269.46	246.57	196	146
	E _x	GPa	213.75	200.64		
Shear Modulus	G _{zy}	GPa	92.39	86.6	76	56
	G _{zx} , G _{yx}	GPa	90.12	84.67		
Poisson Ratio	v _{zy}		0.14	0.144	0.283	0.311
	v _{zx} , v _{yx}		0.195	0.193		

Table 1.4: Mechanical properties of N22 and IN738LC.

		N22		IN738LC	
		@ 20°C	@ 1204°C	@ 20°C	@ 950°C
Proportional Limit Stress	MPa	180	170	705	270
Ultimate Tensile Strength	MPa	400	320	770	360

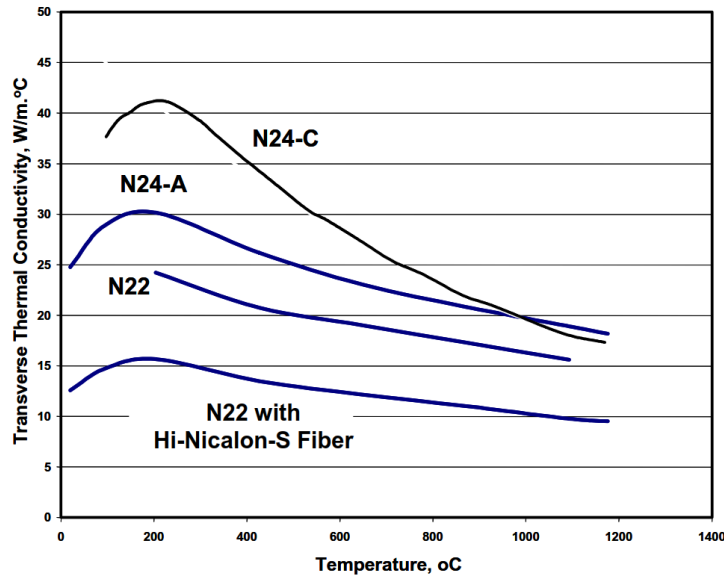


Figure 1-6: Transverse thermal conductivity for N22.

IN718 (forging) is used for parts such as turbine case and c-clip other than shroud. Data for this material can also be obtained from open literature and company sources. Table 1.5 shows the material properties of IN718 forging used.

Table 1.5: Material properties of IN718 forging.

		@ 20°C	@ 750°C
Thermal Expansion Coefficient	strain/°C	1.28E-05	1.61E-05
Thermal Conductivity	W/m.°C	11.2	24.1
Elastic Modulus	GPa	204	157
Shear Modulus	GPa	78	61
Poisson Ratio		0.3	0.3
Proportional Limit Stress	MPa	940	547
Ultimate Tensile Strength	MPa	1240	686
Density	g/cm ³	8.24	

1.5 High Pressure Turbine Shrouds

Shroud is a key component in High Pressure Turbine (HPT) stator system. As shown in Figure 1-7, shrouds are located over the rotor blades in HPT module, and as represented in Figure 1-8, HPT is located just after combustion chamber. They create sealing surface over the rotor blades, and serve as the final orifice in the stator outer cooling system. Shrouds are one of the hottest parts in gas turbine engines. Therefore, high temperature durable materials are used in shroud designs.

Shrouds are designed as segmented to accommodate thermal variation between inner and outer surfaces. The selection of number of segments is critical since segment count affects thermal distortion and stresses in circumferential direction. Additionally, shrouds must be provided with sufficient cold slash face clearance to assure that they will not structurally influence the diameter or roundness of the stator by arc-binding.

As with all cooled turbine components, cooling air usage is strictly controlled in order to minimize the engine performance penalty. Reducing the cooling air requirement of the parts also reduces the negative effect on engine performance. Therefore, the development and use of materials with better resistance at high temperatures is very important in shroud designs for increasing the performance and efficiency of next generation engines.

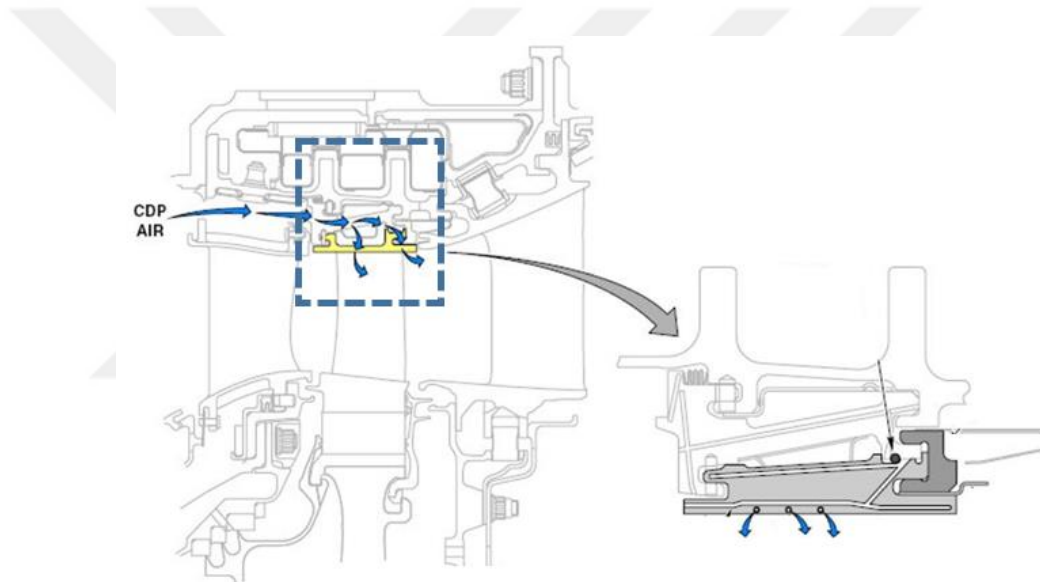


Figure 1-7: High pressure turbine shroud on CFM56 engine.

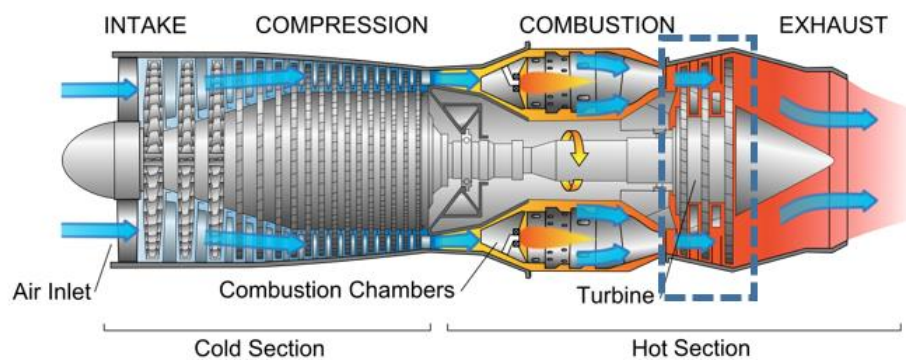


Figure 1-8: An example of gas turbine engine section.

2 METHOD AND GEOMETRY

2.1 Method of the Study

Shroud is a flow path component and it is constantly exposed to hot air in the flow path. When the flow path temperatures rise above the allowable temperature limit of the shroud material, part cooling needs to be considered. Since shroud is constantly exposed to hot flow path air on its inner surface, it needs to be cooled down by the cooling air on its outer surface. The cooling air mass flow rate determines the equilibrium temperature of the part. As the amount of cooling air increases, the maximum and average temperatures of the part decrease. On the other hand, since cooling the part more than the material needs affects the engine performance negatively, the equilibrium temperature should be kept close to the material limits.

As represented in Figure 2-1, while the cooling air cools shroud from the outer diameter surface, the hot gas heats the part from the inner diameter surface. The method followed during the calculation of the cooling air is described in the Figure 2-2. In addition, Figure 2-2 explains step by step the method followed throughout the whole study.

In order to define the cooling air need, first, hot gas side heat transfer coefficient (HTC) is calculated. The hot HTC is the same for both IN738LC and N22. Second, required cooling air HTC is calculated to keep the material temperatures under the material limits. Last, required cooling flow is calculated to provide the required cooling air HTC.

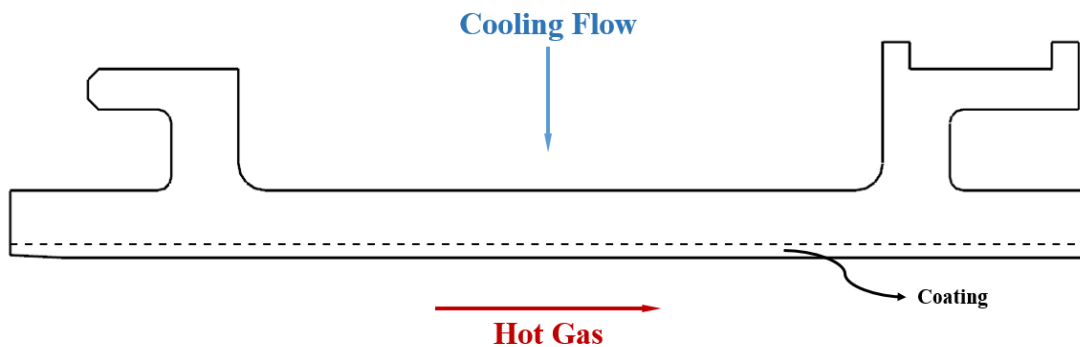


Figure 2-1: Schematic representation of cooling and heating of shroud.

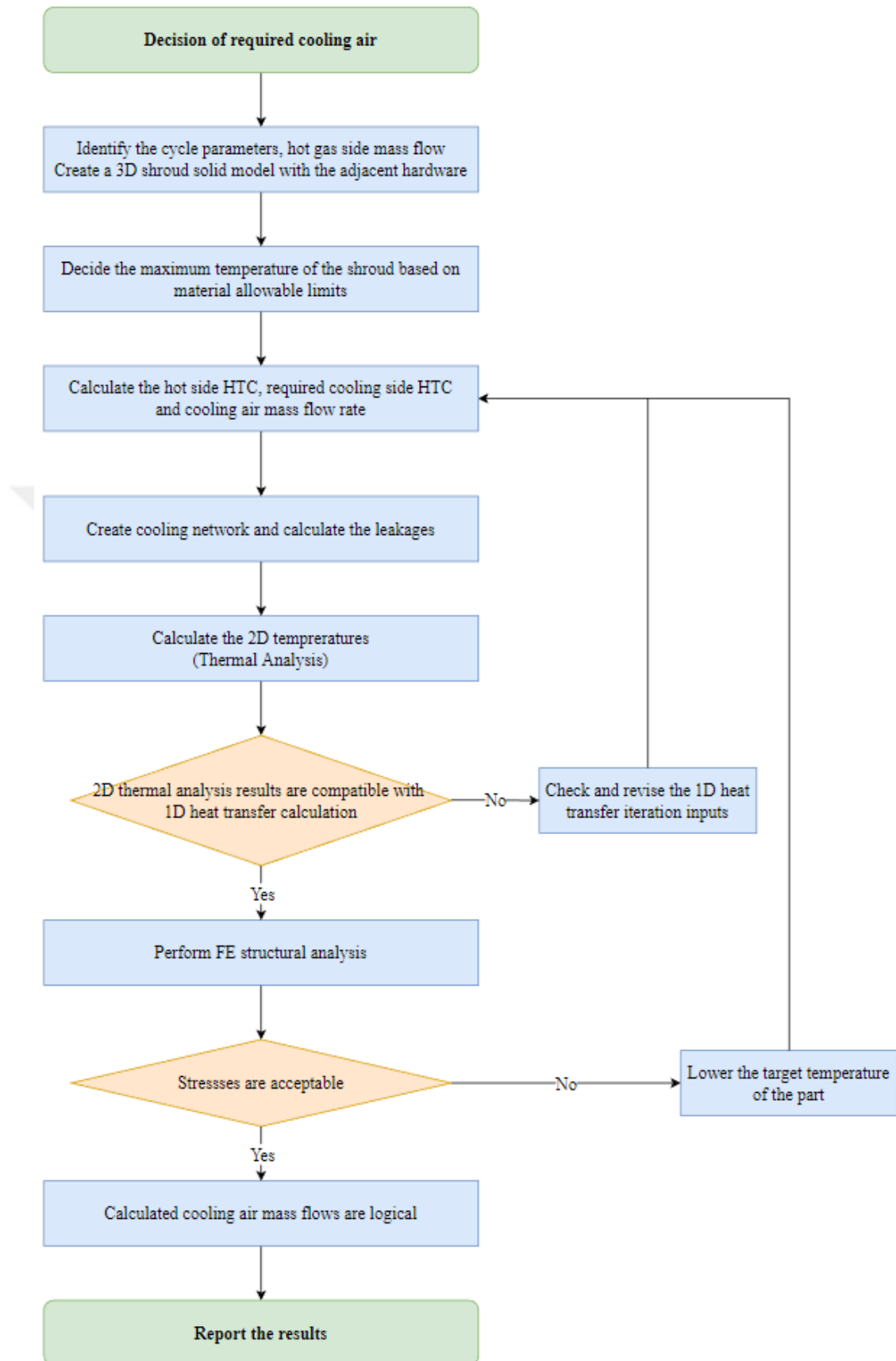


Figure 2-2: Flowchart of the method followed during the calculation of the cooling air.

2.2 3D Geometry Development

The shroud geometric design begins by deciding the number of segments. The most important parameter when determining the number of segments is to use a high segment count to withstand the stresses that would result from the radial thermal gradients. On the other hand, the minimum possible number of segments should be used, as using too many segments causes undesirable cooling air leakages.

Considering these design practices, an 18° shroud geometry is modeled, simulating the use of 20 segments in one turbine stage as shown in Figure 2.1. Siemens NX 12.0 is used as the 3D modelling tool.

Since the purpose of the study is back to back comparison using two different materials on the same shroud geometry, feature details (anti-rotation slots, casting cooling bumps, conduction reduced pads, etc.) are not modelled for simplification purposes.

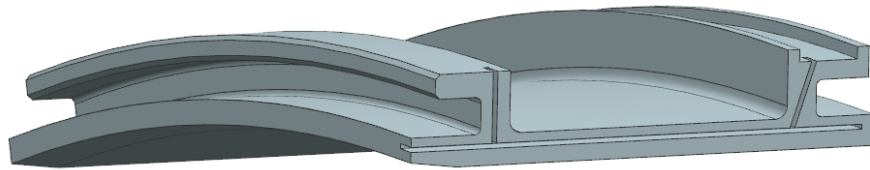


Figure 2-3: 3D isometric view of shroud model.

360° turbine case, holding the shroud in position, and impingement plate are modelled as 20° , as shown in Figure 2.2. C-clip segment is modelled as 18° in order to make the tangential lengths of c-clip and shroud equal. The spline seals, which are placed between the shroud segments for sealing purposes, are modelled as 3 pieces.

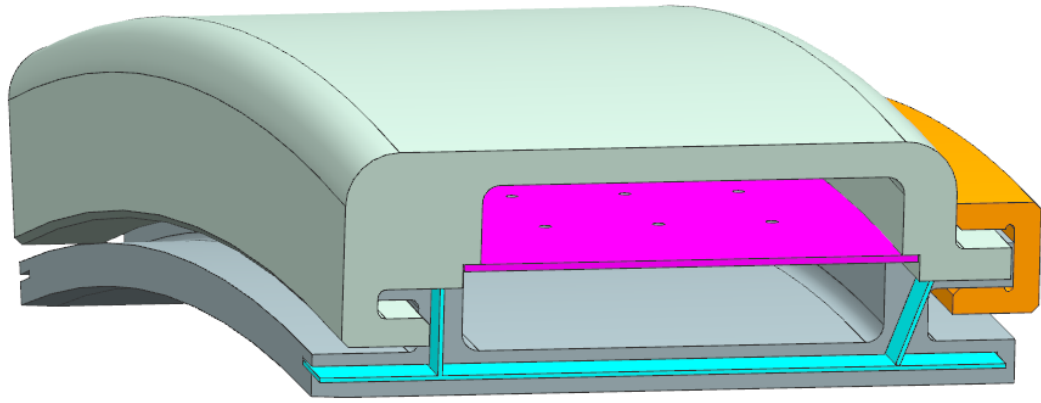


Figure 2-4: 3D isometric view of modelled shroud assembly.

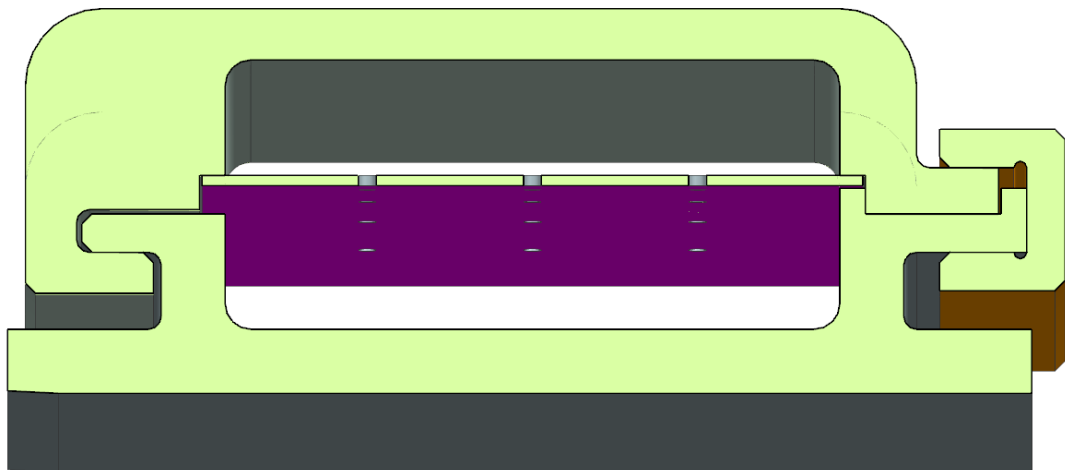


Figure 2-5: Section view shroud assembly.

3 NUMERICAL CALCULATIONS

3.1 1D Heat Transfer Calculation

As a SiC/SiC CMC material, N22 system material properties are used [8], [9]. Maximum allowable metal temperatures are defined as 950 °C for IN738LC, and 1204 °C for SiC/SiC (N22).

There is a high risk when designing a part at the material allowable temperature limit. Component temperatures in the working envelope of the engine may reach the temperature resistance limits of the material or even exceed it for a short time. However, under continuous operating conditions, it is necessary to stay below these limits in order to ensure the required component life is met. For this reason, in 1D heat transfer analysis, the required cooling air is calculated by aiming to stay 15-20% below the material allowable temperature limits. As a result, the heat transfer coefficient and cooling air mass flow that will give the maximum metal temperatures of 850 °C for IN738LC and 1000 °C for N22 are calculated.

Same leakage pads and the gaps are used for both IN738LC and SiC/SiC shrouds. The same impingement plate and hole orientation are used. Same bond coat and thermal barrier coating (TBC) thicknesses are included in the calculations for both parts. The cycle parameters used are shown on Table 3.1.

Table 3.1: Cycle parameters used.

Cooling Air Temperature	T_3	790	K
Turbine Inlet Temperature	T_4	1781	K
Shroud Flow Path Leading Edge Temperature	T_{41}	1612	K
Shroud Flow Path Trailing Edge Temperature	T_{42}	1476	K

While performing 1D heat transfer analysis, the following steps are performed respectively:

- A 1D iterative heat transfer calculator using resistance method is created.
- In the resistance method, constant thickness material (N22 and IN738LC), bond coat and TBC are used. Convective heat transfer coefficients are calculated on the two sides of the system. One side is cooled using

impingement of pressurized air and the other side is exposed to the hot flow path gases.

- Cold side heat transfer coefficient is calculated using the impingement correlation by Florschuetz et. al for a fixed array of holes [10]. Once the array is fixed, the cooling air amount is the only variable to adjust the required HTC values. The convective heat transfer coefficient is calculated by Nusselt number equation (1). The length L is the geometrical length of the geometry under consideration which is the impingement hole diameter. The heat transfer coefficient is represented by h , and k is the thermal conductivity of cooling air. Nusselt number is calculated by equation (2).

$$Nu = h \frac{L}{k} \quad (1)$$

$$Nu = A Re_j^m \{1 - B[(z/d)(G_c/G_j)]^n\} Pr^{1/3} \quad (2)$$

Where A, B are the coefficients, and m, n are the exponents depending on the geometric parameters.

$$A, m, B, \text{ and } n = C(x_n/d)^{n_x}(y_n/d)^{n_y}(z/d)^{n_z}. \quad (3)$$

Table 3.2 gives the constants used to find A, m, B and n.

Table 3.2: Constants for use in Florschuetz correlation equation.

	Inline Pattern				Staggered Pattern			
	C	n_x	n_y	n_z	C	n_x	n_y	n_z
A	1.18	-0.944	-0.642	0.169	1.87	-0.771	-0.999	-0.257
m	0.612	0.059	0.032	-0.022	0.571	0.028	0.092	0.039
B	0.437	-0.095	-0.219	0.275	1.03	-0.243	-0.307	0.059
n	0.092	-0.005	0.599	1.04	0.442	0.098	-0.003	0.304

Figure 3-1 represents an impingement plate geometry and shows the dimensional features used in equations.

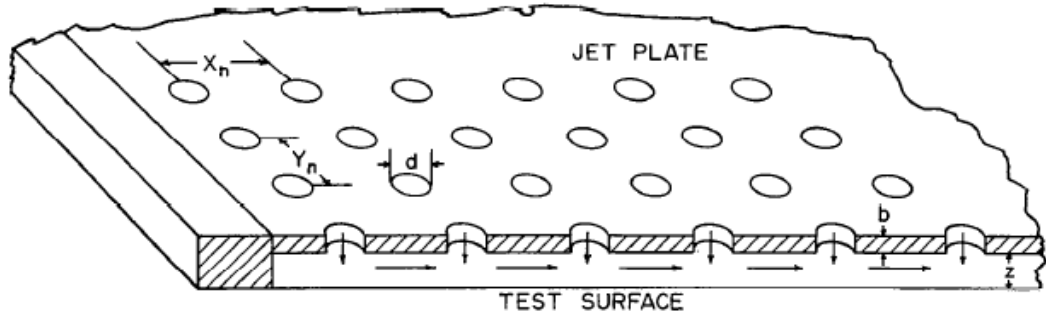


Figure 3-1: Basic impingement plate geometry and nomenclature.

- Hot side heat transfer coefficient is calculated using the correlation by Stepka et. al [11]. Correlation by Stepka et. al (4) is:

$$Nu_g = h_g C / K_g = 0.052 Re_g^{0.8} (1 - 2\delta)^{0.8} \quad (4)$$

Hot gas side heat transfer coefficient (h_g) is calculated by using tip clearance to blade span ratio (δ), Reynolds number at the blade tip inlet (Re_g) evaluated at Mach number 0.8, thermal conductivity of gas (K) near the shroud surface and characteristic dimension of blade chord (C). $Re_g = 2.9 \times 10^5$, $C = 0.025\text{m}$, $\delta = 0.015$ and $K = 0.077$. Resulting $h_g = 3500 \text{ W/m}^2\text{K}$.

- In order to calculate the heat transfer resistance values for material, bond coat and TBC thicknesses are determined. Knowing the shroud segment count, the total areas on the cold and hot side are also calculated. Finally, the convective heat transfer resistances on the both sides are also calculated. Thermal conductivity values are taken from open literature and updated on each iteration depending on the average temperatures of material, bond coat and TBC. Composite system of resistance method is represented in Figure 3-2. The heat transfer rate in the resistance method (5) is expressed as:

$$q_r = \frac{T_{\infty,1} - T_{\infty,4}}{\frac{1}{2\pi r_1 L h_1} + \frac{\ln(r_2/r_1)}{2\pi k_A L} + \frac{\ln(r_3/r_2)}{2\pi k_B L} + \frac{\ln(r_4/r_3)}{2\pi k_C L} + \frac{1}{2\pi r_4 L h_4}} \quad (5)$$

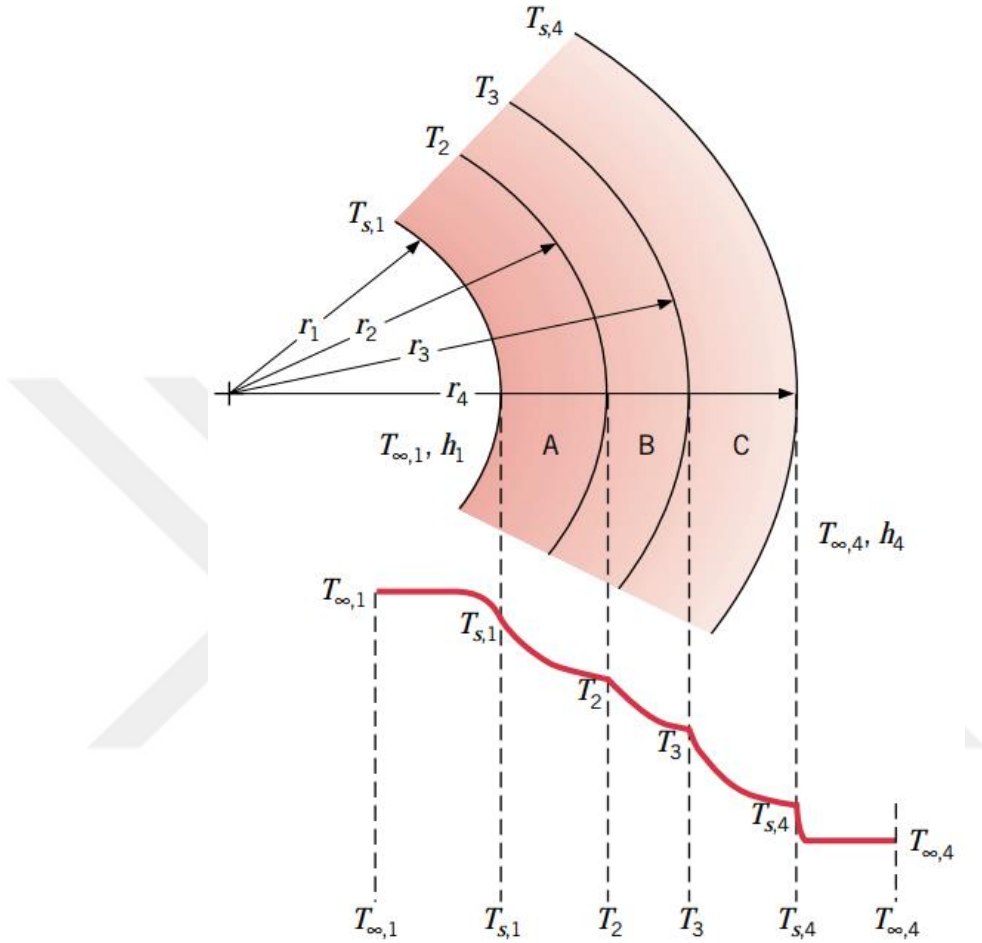


Figure 3-2: Temperature distribution for a composite wall.

Thermal conductivities of each material are evaluated iteratively, as a function of average metal temperature. Coolant and hot gas temperatures were cycle parameters, heat transfer coefficients of coolant and flowpath side are calculated using Florschuetz and Stepka correlations, respectively. Characteristic lengths taken as axial lengths of TBC, bond and metal (or CMC). Total resistance (6) can be found via;

$$q_r = \frac{T_{\infty,1} - T_{\infty,4}}{R_{tot}} = UA(T_{\infty,1} - T_{\infty,4}) \quad (6)$$

Each material's resistance can be found using (7);

$$q_r = \frac{2\pi Lk(T_{s,1} - T_{s,2})}{\ln(r_2/r_1)} \quad (7)$$

- Provided information is enough to compute the temperature distribution of the system in 1D. It is now possible to find the minimum impingement HTC that is going to keep the material temperatures below the limit. Once the limiting impingement HTC is calculated, it is possible to go back and find the corresponding amount of impingement air.

Same methodology is applied for both N22 and IN738LC shrouds. As expected, IN738LC has much higher minimum impingement HTC and air requirement as its limiting temperature is lower and thermal conductivity is higher. For comparison purposes, both materials are taken into limiting high temperature case and minimum air they require for cooling purposes are calculated.

The air flow rates calculated in the cooling network are one of the most important inputs for FE thermal analysis of the part.

3.2 Thrust and Specific Fuel Consumption Calculations

In gas turbine engines, thrust force is generally calculated by the equation (8) shown below:

$$T = \dot{m}_{core}((1 + f)V_{exit} - V_{inlet}) + A_{exit}(P_{exit} - P_{ambient}) \quad (8)$$

Where,

P : Pressure

V : Velocity

A : Area

f : Fuel/air ratio

$\dot{m}$: Mass flow rate = mass/time

While calculating the thrust force, cooling air mass flow affects engine parameters such as turbine efficiency, turbine outlet temperature and pressure. In order to simplify the scope of this study, it is assumed that all engine parameters remain constant except for the cooling air mass flow.

V_{inlet} can be assumed as zero. In this case, the only parameter affecting the thrust force is the amount of cooling air goes to the turbine without burning in the combustion chamber. The general thrust equation (9) becomes:

$$T = (\dot{m}_{total}(1 + f) - f \cdot \dot{m}_{cooling})V_{exit} + A_{exit}(P_{exit} - P_{ambient}) \quad (9)$$

$\dot{m}_{total}$ represents the total air entering the engine. W_2 term is used for $\dot{m}_{total}$ in other parts of the study. $\dot{m}_{cooling}$ is used as $W_2\%$.

Specific fuel consumption is the ratio of the fuel mass flow of an engine to its output thrust. It calculates by the equation x.

$$SFC = \frac{\dot{m}_f}{T} \quad (10)$$

$\dot{m}_f$ can be defined as f times $\dot{m}_{core}$. So the equation can be written as below.

$$SFC = \frac{f \cdot \dot{m}_{core}}{T} \quad (11)$$

$\dot{m}_{core}$ is obtained by subtracting $\dot{m}_{cooling}$ from $\dot{m}_{total}$.

$$SFC = \frac{f \cdot (\dot{m}_{total} - \dot{m}_{cooling})}{T} \quad (12)$$

As can be clearly seen from this form of the equation, the increase in cooling flow has a direct effect on SFC.

4 ANALYTICAL CALCULATIONS

4.1 Finite Element Thermal Analysis

In order to determine the 2D thermal distribution and predict metal temperatures, a finite element solver code called SC03 is used. As a first step, the NX geometry is imported into SC03. While preparing the 2D thermal model, some details in the 3D geometric model are deleted, and the model is simplified. For instance, spline seals are physically removed from model, and the relevant mass flow rate is implemented instead.

Mesh generation is carried out as presented in Figure 4-2. Tri6 element type which is an adaptive 6 node element triangular mesh is used. All settings are shared in Figure 4-1. Max node number is adjusted to 5e5.

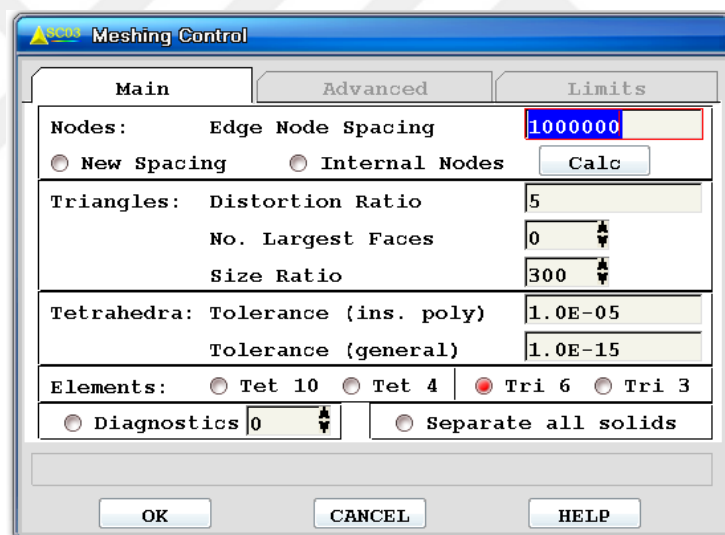


Figure 4-1: 2D thermal model meshing settings.

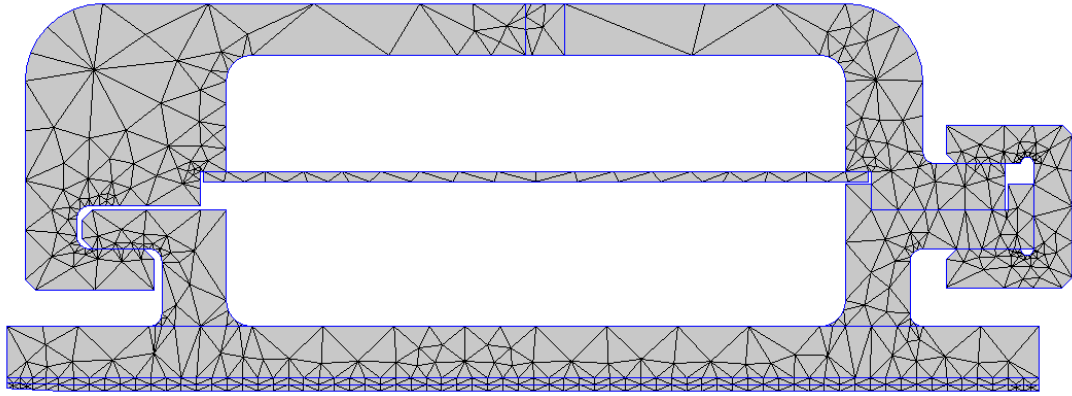


Figure 4-2: FE thermal model mesh.

The material properties for both IN738LC shroud and N22 shroud as well as turbine case and c-clip hardware are defined into the program used. Also material data cards are created to calculate thermo-physical properties properly.

All mass flow distributions are defined as input and user variables to code.

SCO3 is a heat conduction solver and uses specialized boundary conditions as stream, prescribed temperature, void, thermal contacts and duct. They are defined to the model. The explanations of these boundary conditions are summarized below according to their functions on the model.

- Stream: Represents a given mass flow of air over the metal surface and calculates heat transfer coefficient if the stream direction is exact such as orifice flow.
- Prescribed temperature: Used for locations with known temperatures. CS3, CS4, CS5 and CS6 are the prescribed boundary conditions in Figure 4-3.
- Void: Used to calculate HTC and air temperature when the air mostly static. It is used for natural convection zones such as post-impingement area and segment end gaps.
- Thermal contact: Used to represent conduction level between parts. If the parts have perfect face to face contact, it ensures complete convey of heat.
- Duct: Special cases of streams. It is used to calculate HTC for two faces which can transfer energy to the each other across the gap between them.

The boundary conditions used in the model can be seen in the Figure 4-3.

The analysis is performed as steady state for both IN738LC and N22 shrouds.

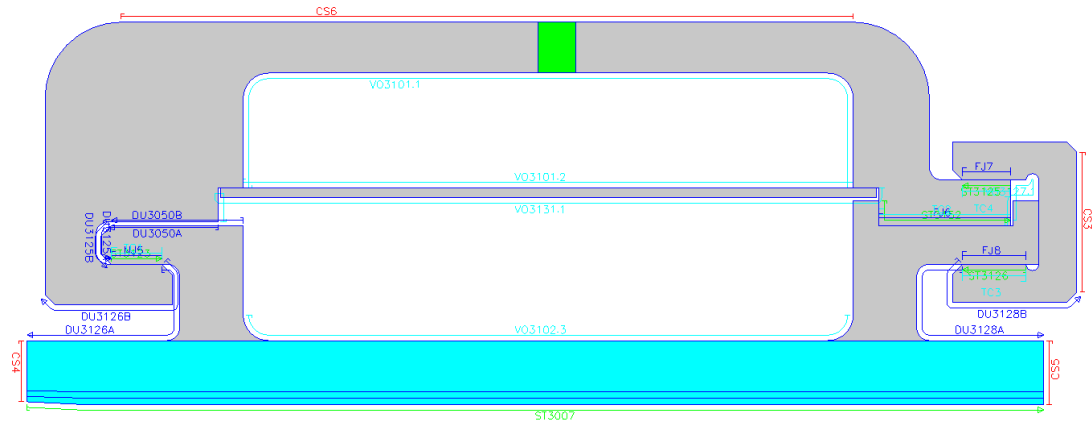


Figure 4-3: Boundary conditions of heat transfer model.

4.2 Finite Element Structural Analysis

Hypermesh is used for meshing the whole geometry, and Ansys v18.1 is used for solution and post processing. The procedure explained below is done for both IN738LC shroud and N22 shroud. The difference between two models are temperature, pressure and shroud material properties.

4.2.1 Finite Element Mesh and Model Setup

All dimensions in the geometry are modelled as nominal. Sector cross section is meshed using 2D 4-noded elements and then swept in circumferential direction to obtain 3D mesh. 8-noded brick elements are used (SOLID 45). All 90° fillets in shroud are captured with 9 elements. 5 elements are used at 90° fillets of the rest of the parts to reduce the node count as the parts are not of interest for this study. Total element count is 159,069 including contact and target elements, and 148,573 for solid elements. Total node count is 176,029. Mesh details are shown in Figure 4-4 and Figure 4-5. There are no error elements in the model as shown in Figure 4-6.

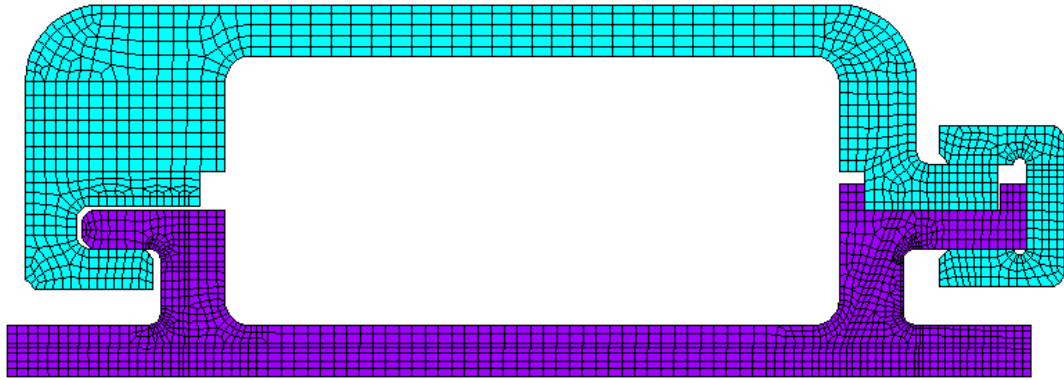


Figure 4-4: 2D cross-section mesh details.

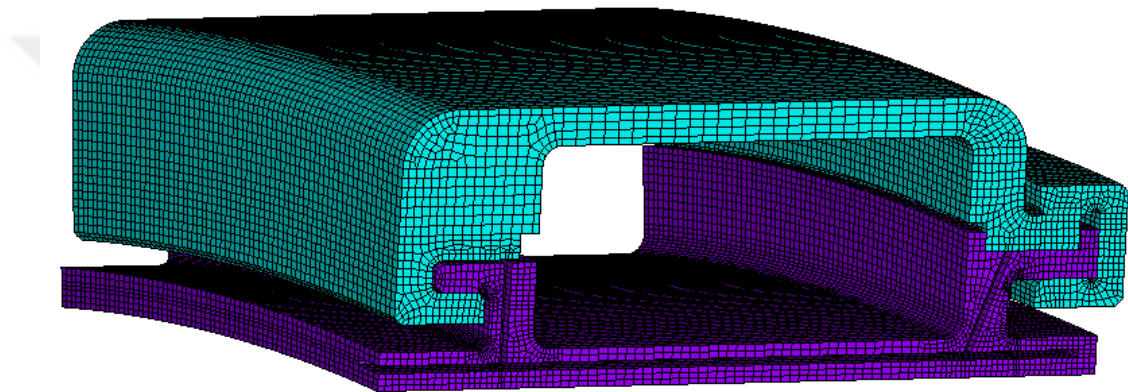


Figure 4-5: 3D isometric view of model mesh.

SUMMARIZE SHAPE TESTING FOR ALL SELECTED ELEMENTS

<<<<<< SHAPE TESTING SUMMARY >>>>>> <<<<<< FOR ALL SELECTED ELEMENTS >>>>>>				
! Element count 148573 SOLID45 !				
Test	Number tested	Warning count	Error count	Warn+Err %
Aspect Ratio	148573	0	0	0.00 %
Parallel Deviation	148573	332	0	0.22 %
Maximum Angle	148573	0	0	0.00 %
Jacobian Ratio	148573	0	0	0.00 %
Warping Factor	148573	0	0	0.00 %
Any	148573	332	0	0.22 %

Figure 4-6: Warning and error element summary.

Surface to surface contact elements are used (CONTA174, TARGE170) to simulate contact between mating parts as shown in Figure 4-7 and Figure 4-8. 0.03 mm interference between c-clip and shroud is not explicitly modeled in the geometry.

Interference is applied at contact settings using CNOF and final gap/interference values are confirmed using CNCHECK.

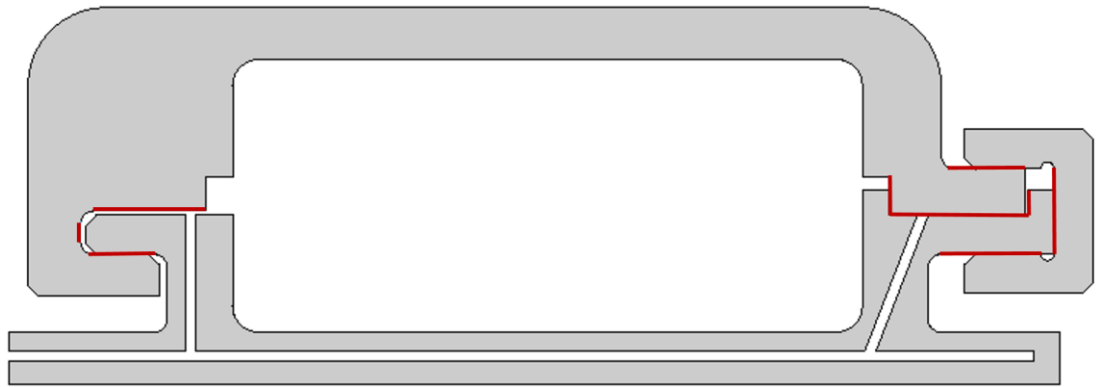


Figure 4-7: Representation of contact elements in cross-section.

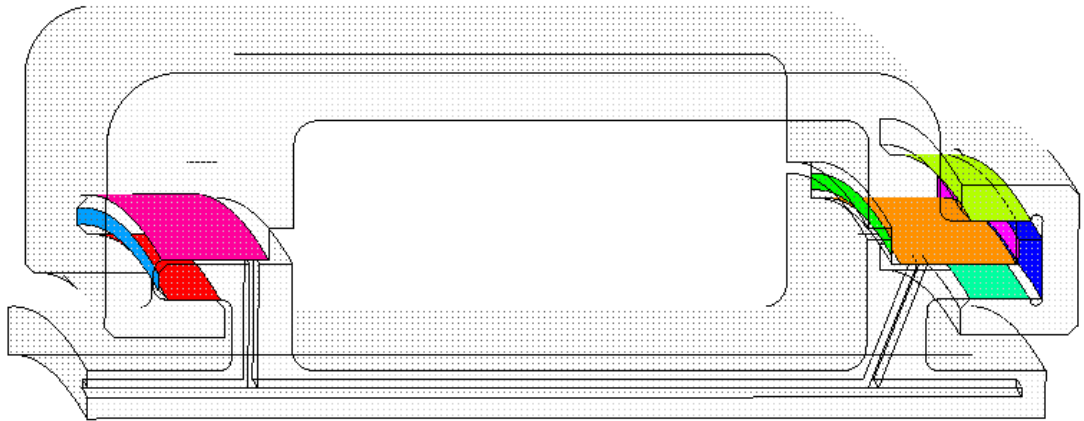


Figure 4-8: Contact elements used.

Sector size for the stress model is 10° . Reflective symmetry boundary conditions are applied on both sides of the turbine case symmetry planes to simulate 360° part. For shroud and c-clip, reflective symmetry is applied on one end (mid plane of 20° sector) to simulate 20° segmented parts. Reflective symmetry is given by rotating the nodes at symmetry planes to cylindrical coordinate system and applying zero displacement in circumferential direction. Model is held axially at one node on turbine case for stability. All boundary condition details can be seen in Figure 4-9 and Figure 4-10.

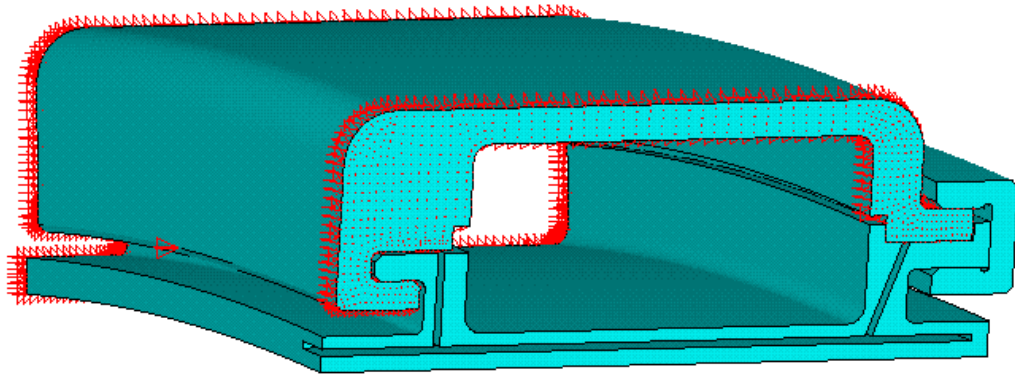


Figure 4-9: FE structural analysis model boundary conditions (cross-section front view).

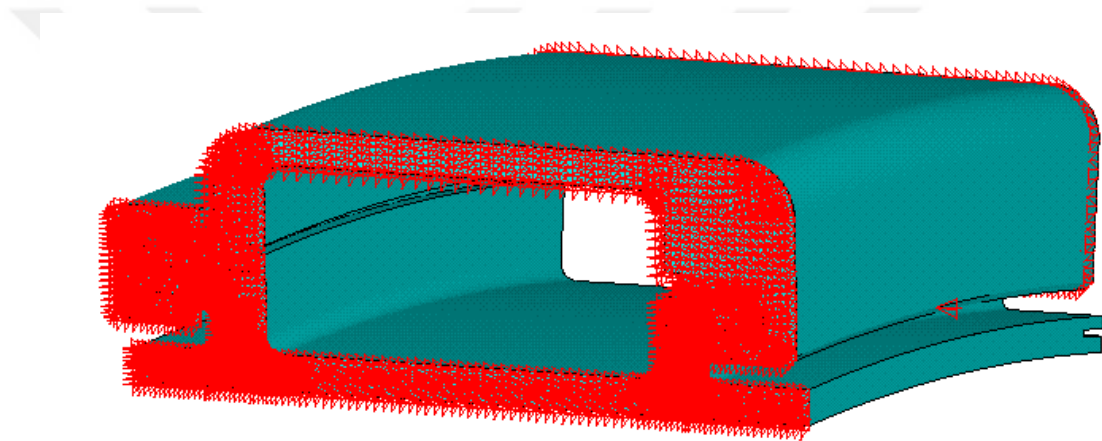


Figure 4-10: FE structural analysis model boundary conditions (cross-section back view).

4.2.2 Temperature/Pressure Mapping

Since thermal model is 2D, 3D mesh is collapsed in circumferential direction to project all nodes to a 2D plane. Thermal 2D mesh and collapsed stress model mesh did not overlap. Stress model mesh is positioned to overlap the HT model mesh for mapping purposes. Stress model nodes and locations are extracted. Then, thermal model RTH file is read in Ansys. Temperatures are mapped using sub modeling /interpolate body forces option in Ansys for both IN738LC and N22 conditions.

Pressure is obtained as cavity pressures from thermal model and applied manually as nodal pressures to both models.

4.2.3 Material Definition

N22 fiber orientation is assumed to be parallel to engine axis. Material is defined as orthotropic per data in Section 1.4. For IN738LC condition, material is defined as isotropic.

4.2.4 Analysis Assumptions and Run Parameters

Assembly and operation time points are considered for the run. Friction is assumed as 0.2. Reference temperature is 20 °C. Large deflection and stress stiffening options are turned on. Force convergence value is determined as 1 N for assembly and 10 N for operation time point. For assembly load step, number of substeps is given as 1 for initial start, 50 for maximum and 1 for minimum. For operation load step, number of substeps is given as 10 for initial start, 500 for maximum, and 5 for minimum. Convergence is achieved within given targets for both load cases and models (IN738LC shroud & N22 shroud).

5 RESULTS

5.1 1D Heat Transfer Results

Table 5.1 shows cooling flow calculation results. Required cooling flow HTC is 3300 W/m²K for IN738LC, and 800 W/m²K for N22. Based on this results, required cooling mass flow is 2.4 W₂% for IN738LC, and 0.5 W₂% for N22 accordingly. This results show that IN738LC needs 4.8 times cooling air than N22.

Table 5.1: Cooling flow calculation results.

			IN738LC	N22
Maximum Allowable Metal Temperature	T _{metal}	K	1250	1477
Cooling Air Temperature	T _{cooling}	K	790	
Hot Gas Air Temperature	T _{gas}	K	1612	
Hot Gas Side HTC	h _{gas}	W/m ² K	3500	
Cooling Side HTC	h _{cooling}	W/m ² K	3300	800
Required Cooling Mass Flow	G _j	W ₂ %	2.4	0.5

After required cooling flows are calculated, flow networks are created for both materials. Perfect gas (constant C_p), and adiabatic flow assumptions are made. Impingement plate leakages are ignored. Whole cooling air is accepted as impinged to shroud surface. Spline seals use a commonly used effective gap. Shroud end gaps are assumed as 0.5 mm in the tangential direction. Secondary air system design details are shown in Figure 5-1.

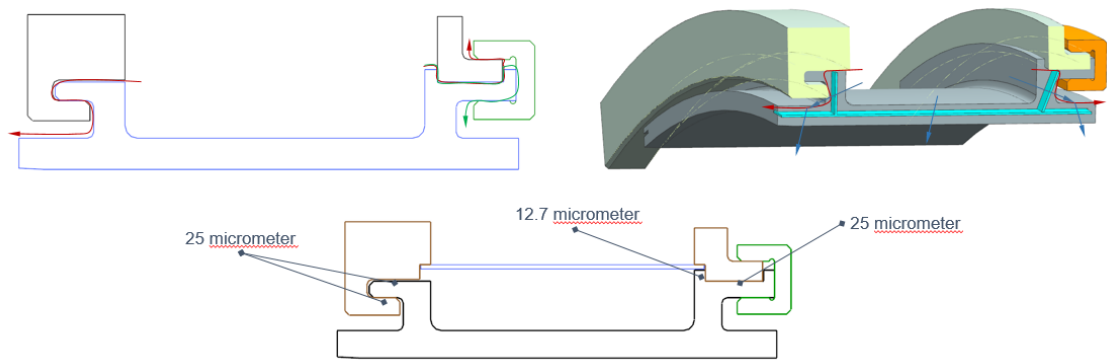


Figure 5-1: Secondary air system design details.

The cooling air extracted from the compressor cool the shrouds passes through the leakage interfaces of the part and mixes into the flow path. It is very important to identify these leakage interfaces and the amount of air that will pass through these paths because the air continues to cool the parts in the areas it passes through. Flow network results are shared in Figure 5-2 and Figure 5-3. All results are shown in $W_2\%$.

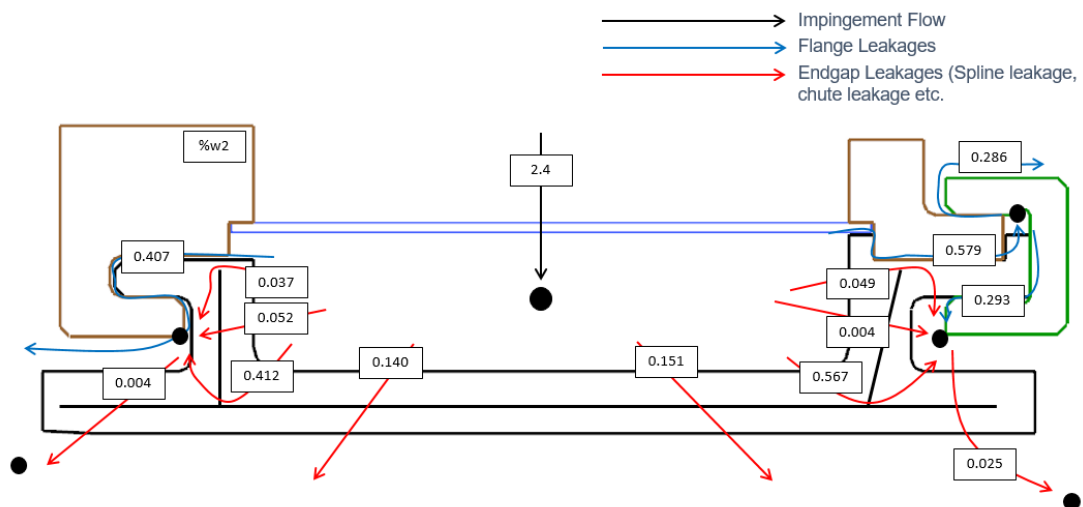


Figure 5-2: IN738LC cooling flow network.

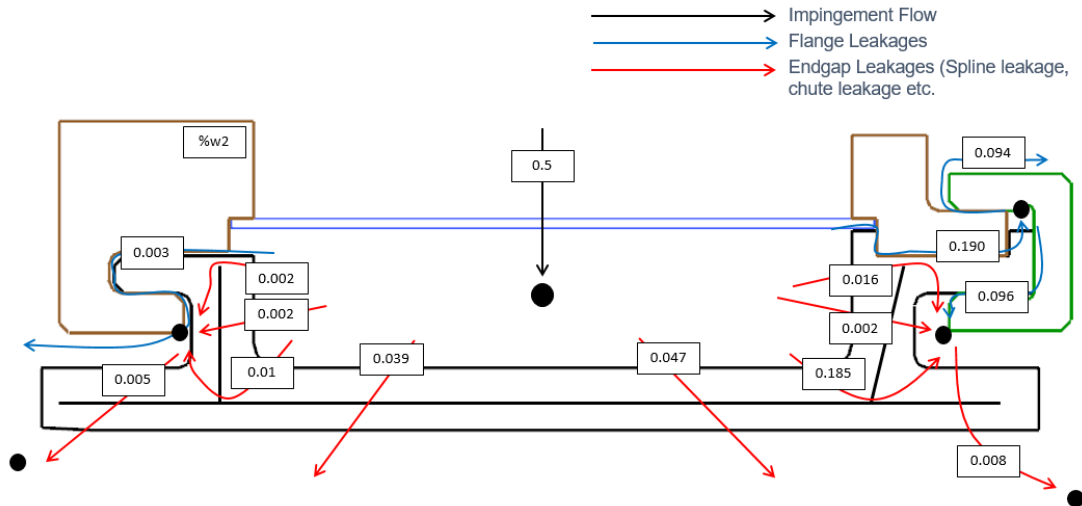


Figure 5-3: N22 cooling flow network.

5.2 Heat Transfer Analysis Results

Heat transfer analysis results for IN738LC and N22 shrouds are shared respectively. Two different figures are added for both materials. In first figures, there are thermal barrier coatings. Since the structural analysis models do not include the coating, it is also necessary to show images of the deleted versions of the coatings.

Figure 5-4 shows the temperatures of the IN738LC shroud and other parts. The unit of temperature in the images is kelvin. In case the thermal barrier coating is also shown, the highest temperature seen in the system is 1301 K (1029 °C) and it is seen on the thermal barrier coating.

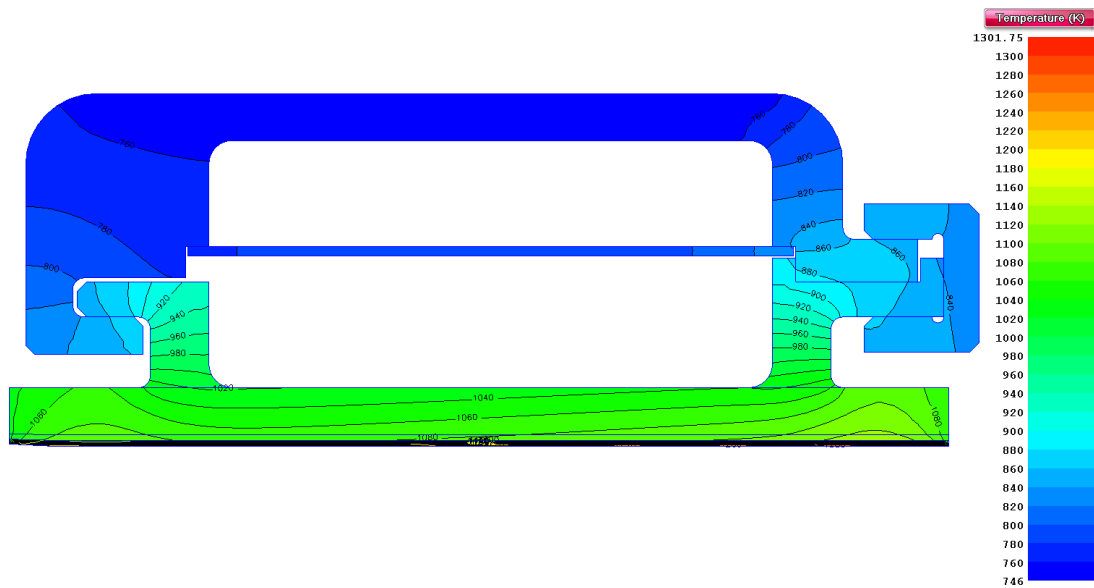


Figure 5-4: Metal temperatures of IN738LC shroud assembly (TBC is shown).

In Figure 5-5, unlike Figure 5-4, only metal temperatures are shown by removing the thermal barrier coating temperatures. The hottest part in assembly is the shroud and its flow-path temperatures reach 1124 K (850 °C).

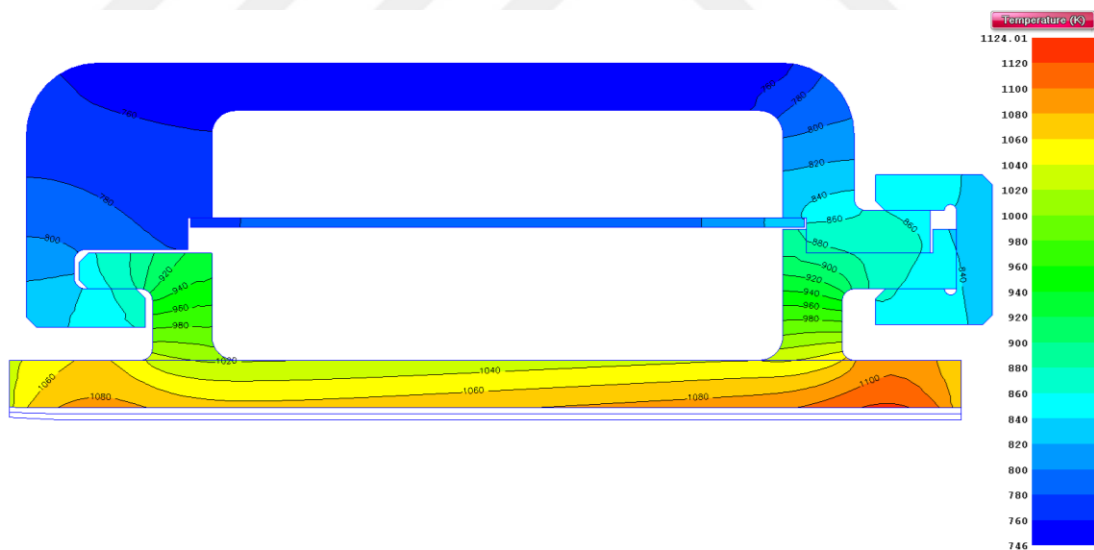


Figure 5-5: Metal temperatures of IN738LC shroud assembly (TBC is removed).

The method followed in IN738LC is used to display N22 heat transfer results. The temperatures of the thermal barrier coating are also included in the temperatures seen in Figure 5-6. Figure 5-7 shows the remaining metal temperatures when the thermal barrier coating temperatures are not shown.

Figure 5-6 illustrates the temperature of N22 shroud. In the design with N22, the highest temperatures are seen on the thermal barrier coating, as expected, and the maximum temperature is 1345 K (1072 °C).

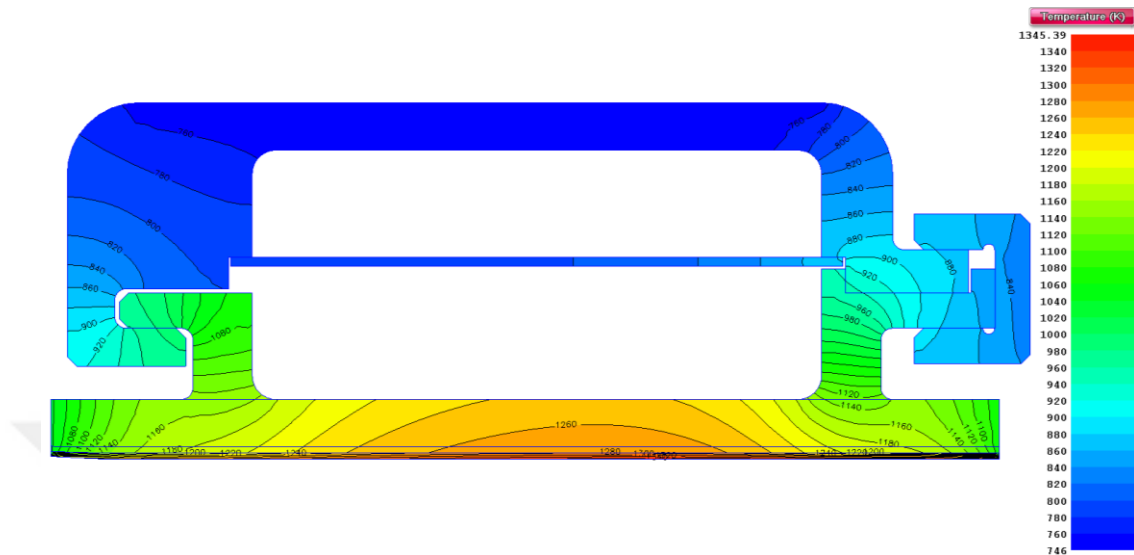


Figure 5-6: Metal temperatures of N22 shroud assembly (TBC is shown).

When TBC is removed from display, the remaining maximum temperature is 1273 K (1000 °C) and is seen in the middle region of the N22 shroud flow path (see Figure 5-7).

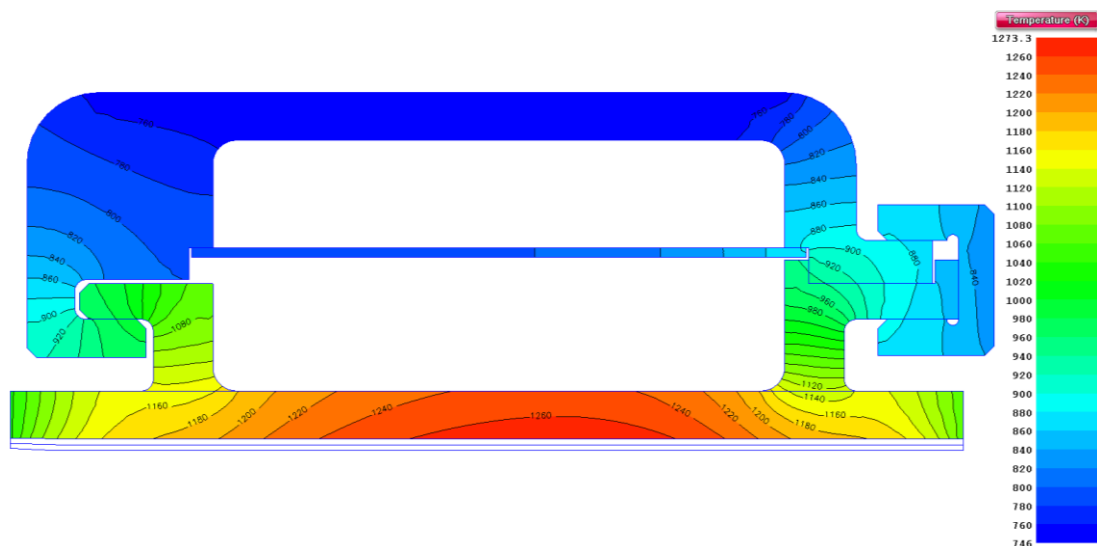


Figure 5-7: Metal temperatures of N22 shroud assembly (TBC is removed).

Thermal barrier coatings are removed and only metal temperatures are used, while heat transfer results are transmitted as an input to structural analysis.

5.3 Finite Element Structural Analysis Results

Finite element analysis results can be grouped under two main categories. The first of these is the preload condition, where the parts are assembled but the temperature and pressure loads are not loaded. The preload condition represents the assembly condition on the engine. The second one is the operating condition where pressure and temperatures are loaded on the preload. Since the stress values observed on the sheaths are much higher than the preload condition, the operation condition is the main condition commented on the strength of the parts. Results are also shown separately for both IN738LC and N22.

5.3.1 IN738LC Preload Condition

As shown on Figure 5-8, in the assembly where IN738LC shroud is used, the highest stresses are seen in c-clip. This is because the c-clip is interference fit into turbine case and shroud structures. As a result, c-clip deforms elastically and becomes the region of highest stress in the preload condition. Although c-clip strength is not within the scope of this study, the values seen are well below the yield strength of IN718 forging material, which is 940 MPa.

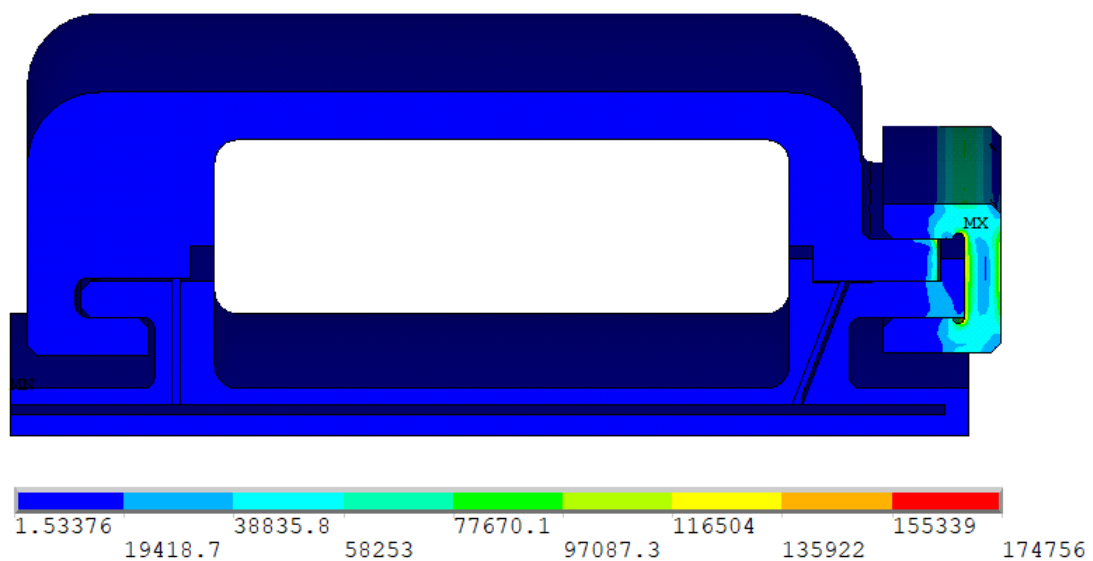


Figure 5-8: Equivalent stresses of IN738LC shroud assembly during preload.

As represented in Figure 5-9, when the shroud is separated from the other parts in the assembly and examined alone, it is seen that the highest equivalent stress on the part is 36.8 MPa on the shroud aft rail. The stresses in this region are mainly due to c-clip interference fit. All the stress values seen on the shroud are well below the 705 MPa yield strength of IN738LC at room temperature.

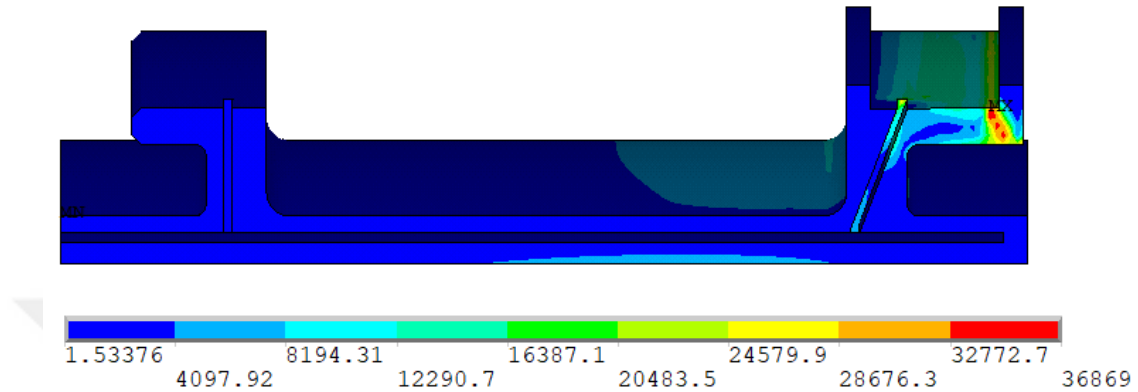


Figure 5-9: Shroud only equivalent stresses of IN738LC during preload.

5.3.2 N22 Preload Condition

As seen in the Figure 5-10, the highest equivalent stresses are also seen in the c-clip, similar to the IN783LC shroud assembly, in the assembly where N22 shroud is used. This is because, again, the c-clip is an interference fit.

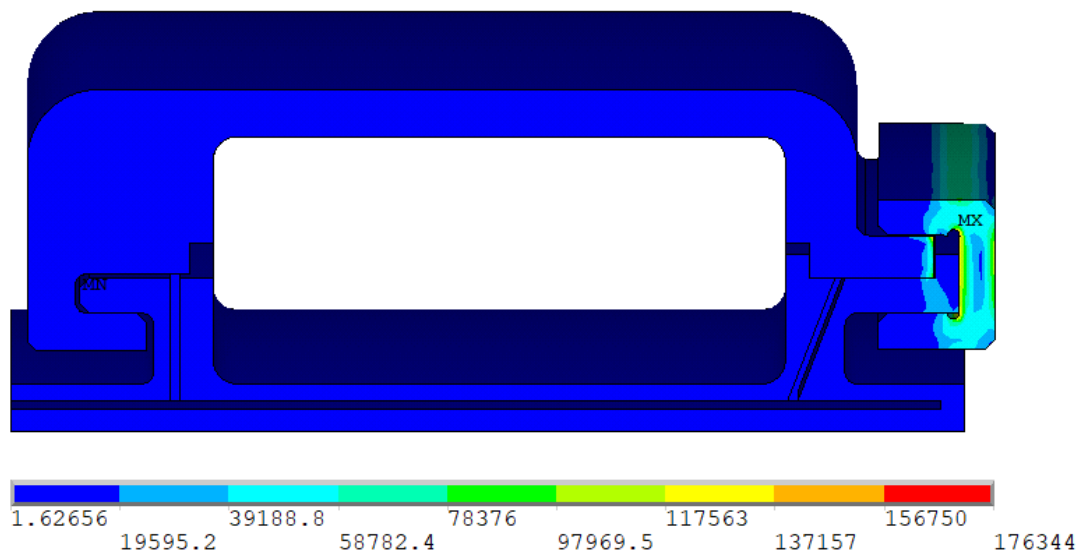


Figure 5-10: Equivalent stresses of N22 shroud assembly during preload.

Considering the 180 MPa proportional limit stress value of N22 at room temperatures, these stresses illustrated in Figure 5-11 will not cause a problem in terms of part strength.

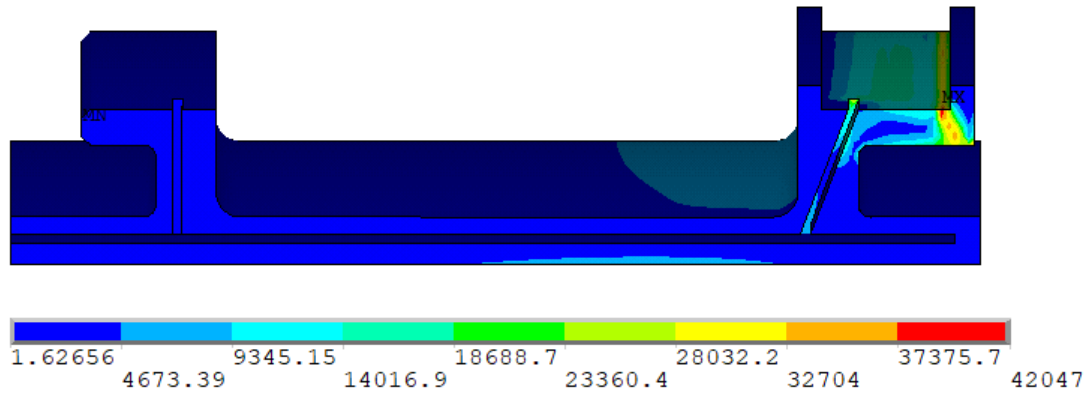


Figure 5-11: Shroud only equivalent stresses of N22 during preload.

5.3.3 IN738LC Operation Condition

When the whole assembly is considered under operation condition, the highest stresses are again on the c-clip. Stress plots become meaningless for other parts because c-clip stresses are quite dominant compared to other parts. For this reason, it is decided to show the equivalent strains when all parts are shown together.

Showing the strain values is also a good way to check if the boundary conditions are working correctly. The areas where the minimum strains are seen in Figure 5-12 are the locations where the model is held axially. Since the axial strain contribution is very close to zero in these regions, the strain seen are only in the radial and circumferential directions. The further away from the axial boundary condition in the axial direction, the contribution of axial strain contribution increases towards the aft of the shroud and the c-clip. For this reason, the highest total strains are seen at the end of the c-clip, which is the farthest point where the model is held in the axial direction. Radial strain in the shroud represent the chording deflection, while circumferential values indicate the hot gap closure between shroud segments.

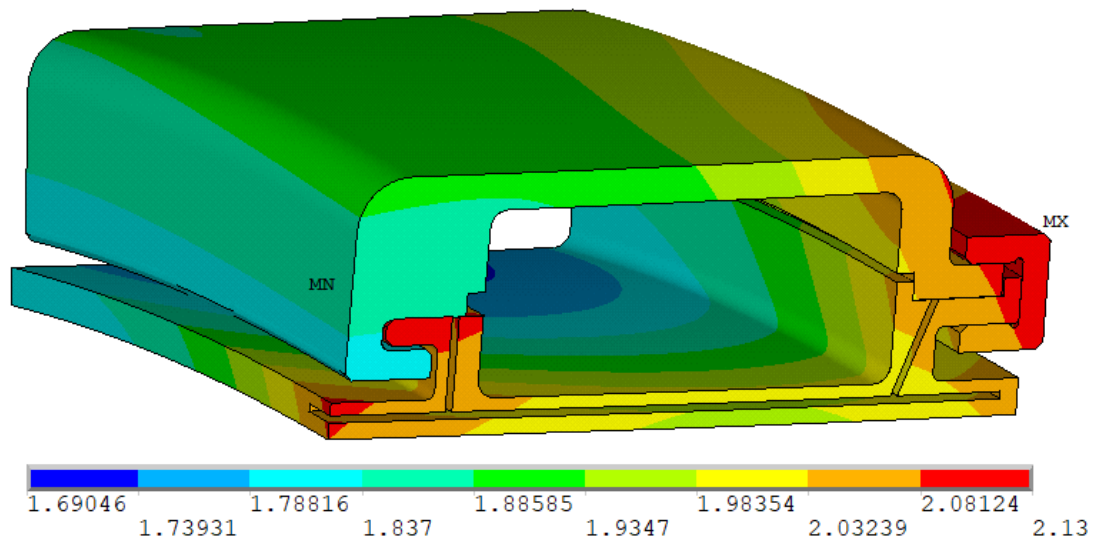


Figure 5-12: Equivalent strains of IN738LC shroud assembly during operation.

When only the IN738LC shroud is shown, it is seen that in Figure 5-13, the highest stresses on the part are at the intersection of the aft rail and spline seal slots. The reason for the highest stresses in this region is due to the interference fit loads during assembly. As temperature of the part increase, these stresses coming from the assembly also raises.

Except for stresses from preload, the stresses are thermal stresses and are caused by the temperature gradients between a higher temperature radially inner shroud surface and a lower temperature, air cooled shroud outer surface. This thermal gradient also cause the shroud segment to chord (straightening). As a result of chording, the shroud segment ends in the circumferential direction expand radially outward relative to the middle of the part. However, c-clip interference fit works in a way that prevents chording. In addition, after the radial gap between turbine case and shroud in the front of the part is closed, the chording is completely limited by the 360° case. Limiting the chording increases the stresses on shroud.

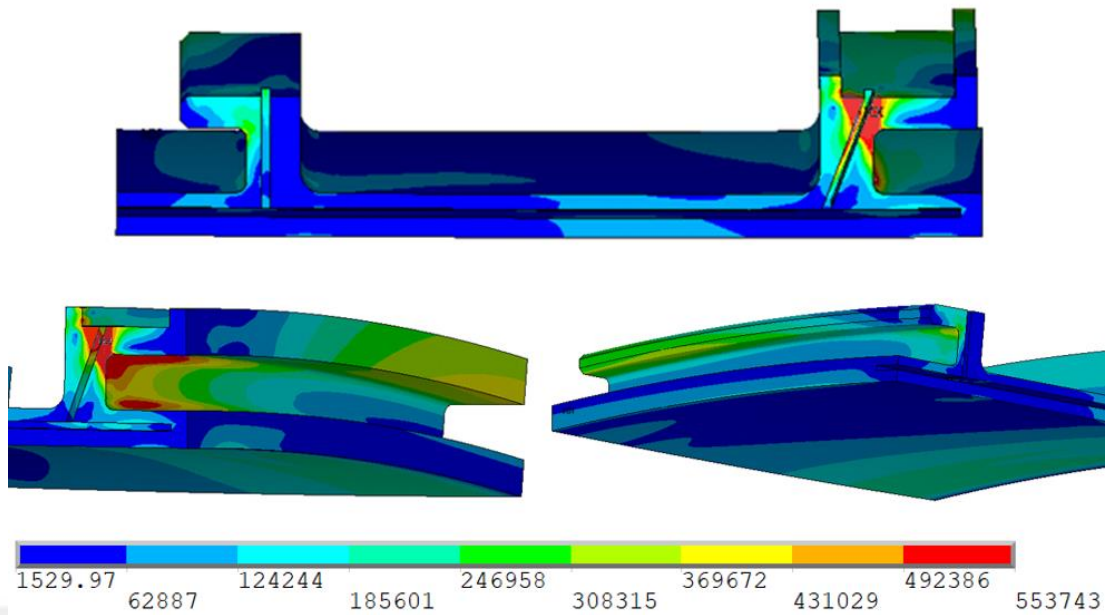


Figure 5-13: Shroud only equivalent stresses of IN738LC during operation.

As a result, the highest equivalent stresses observed on the shroud are 554 MPa. Considering that the temperatures in the maximum stress region are around 650 degrees, these stresses are well below the yield strength of the material at this temperature, 640 MPa. In the light of these results, no problem is foreseen in the strength of the part.

5.3.4 N22 Operation Condition

The behavior of the N22 shroud assembly is also very similar to the IN738LC shroud assembly. For the same reason, equivalent strains are shown instead of equivalent stresses as the assembly. The maximum and minimum strain points are very close to the IN738LC assembly as illustrated in Figure 5-14. The result values are also very similar to each other. The reason for the difference in turbine case is that turbine case temperatures also change as a result of N22 shroud operating hotter than IN738LC shroud. The variation on the shroud are due to the differences in both the IN738LC-N22 shroud temperatures and the thermal expansion coefficients between the two materials. When the behavior of the whole system is evaluated, no abnormality is observed.

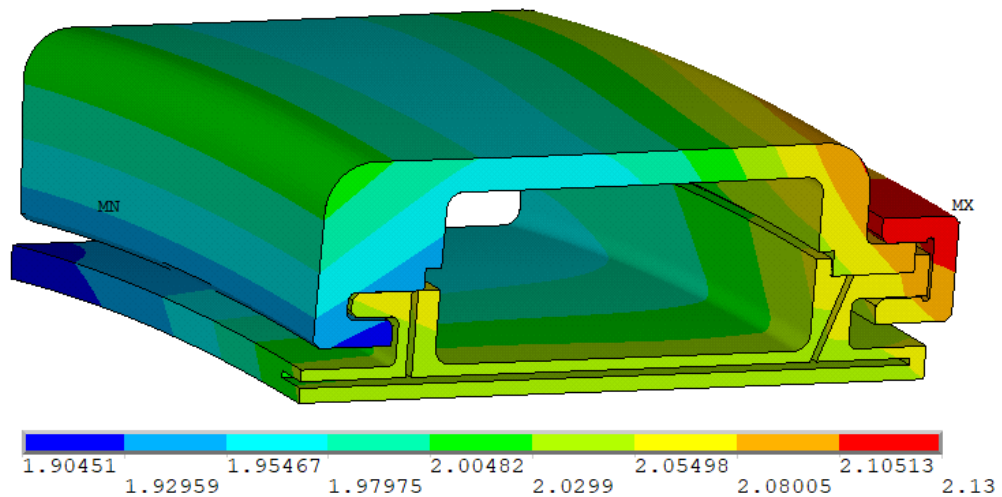


Figure 5-14: Equivalent strains of N22 shroud assembly during operation.

In the N22 shroud only results, the region of highest stress is very similar to the IN738LC shroud (see Figure 5-15). This is because changing the properties of the shroud material does not seriously affect the overall behavior of the system. Although the part temperatures increased, the stress values on the shroud decreased. Low thermal expansion characteristics and high average conductivity limit stress-loading phenomena on the part. As a result of all these, the highest equivalent stress value observed on the N22 shroud is monitored as 158.5 MPa. This value is even below 170 MPa, which is the proportional limit stress value at 1204 °C. There is no question foreseen in terms of the strength of the part.

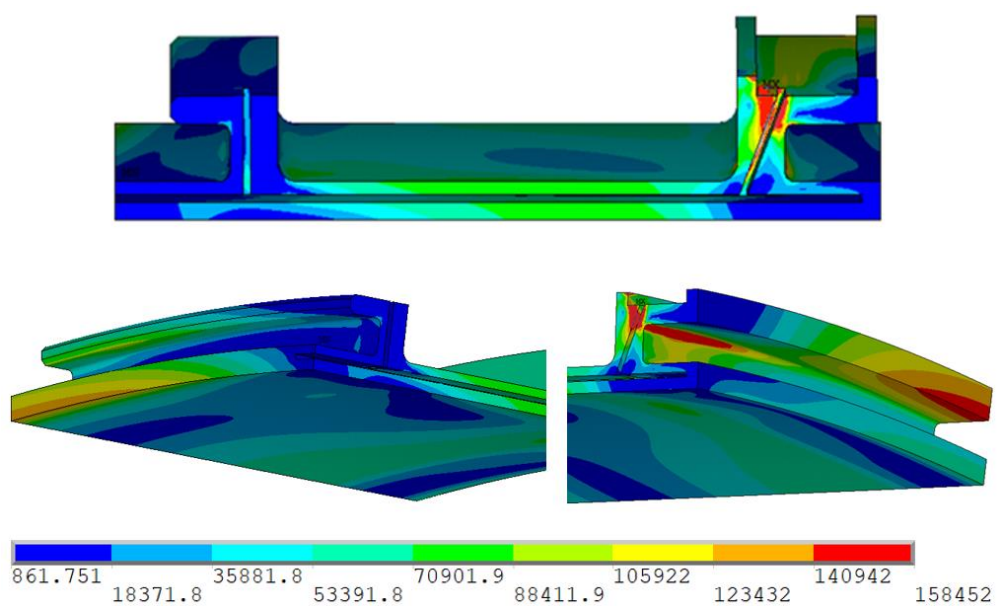


Figure 5-15: Shroud only equivalent stresses of N22 during operation.

6 CONCLUSION AND DISCUSSION

Part temperatures are calculated with the cooling air mass flow rates calculated in the 1-dimensional heat transfer analyses. Structural analysis are performed using these temperatures and the stresses on the parts are determined. Considering that the stresses are well below the material yield, it can be said that the strength problem is not foreseen. Based on these results, it can be accepted that the initially defined cooling air mass flow rates are reasonable and consistent values. As shown in Table 5.1, IN738LC needs 4.8 times more cooling air than N22. Using N22 instead of IN738LC for only first stage shroud material in the engine and designing the part accordingly reduces W_2 usage in cooling air by approximately 1.9%. By the approach described in Section 3.2, cooling air need decrease provides a 0.06% increase in thrust while reducing specific fuel consumption by 2%. This study shows the positive effects of using N22 instead of IN738LC as shroud material on engine performance in a sample engine operating with the same cycle parameters.

REFERENCES

- [1] Andrew S. Bakir, (2015), "Review on Gas Turbine Hot Section Materials and Technology Developments", American Institute of Aeronautics and Astronautics.
- [2] Xu, Li & Bo, Sun & Hongde, You & Lei, Wang. (2015). Evolution of Rolls-royce Air-cooled Turbine Blades and Feature Analysis. *Procedia Engineering*. 99. 1482-1491. 10.1016/j.proeng.2014.12.689.
- [3] Bansal, N. P. (2005). *Handbook of ceramic composites*. Boston: Kluwer Academic Publishers.
- [4] B. C.G. and J. Galka, "Cast Nickel-Base Alloy". United States Patent 3.459.545, 5 August 1969.
- [5] P. Schilke, "Advanced Gas Turbine Materials and Coatings," General Electric Company, New York, 2004.
- [6] A. Thakur, "Microstructural Responses of a Nickel Base Cast IN-738 Superalloy to a Variety of Pre-weld Heat-treatments (Master's Thesis)," Universtiy of Manitoba, pp. 4,13-14, 1198.
- [7] M. Boyce, *Gas Turbine Engineering Handbook*, Woburn: Gulf Professional Publishing, 2006, pp. 5-6.
- [8] DiCarlo, J. A., Yun, H.-M., Morscher, G. N., & Bhatt, R. T. "SiC/sic composites for 1200°C and above." *Handbook of Ceramic Composites*, (2004), 77–98.
- [9] Gowayed, Yasser & Ojard, G. & Miller, R. & Santhosh, Unni & Ahmad, Jowairiyya & John, R.. (2007). *Mechanical Properties of MI SiC/SiC Composites and Their Constituents* (Preprint). 22.
- [10] Florschuetz, L. W. et al. "Jet array impingement with crossflow-correlation of streamwise resolved flow and heat transfer distributions." (1981).
- [11] Yeh, Fredrick C. and Francis S. Stepka. "Review and status of heat-transfer technology for internal passages of air-cooled turbine blades." (1984).

BIOGRAPHY

Hamza Faruk Akkurt started his professional career as a product development engineer. Then he joined aviation industry.

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