ASEN 5063 Aircraft Propulsion Final Report

2015

Materials for Aircraft Engines

TAKEHIRO OKURA

Contents

1. Overview

In 1939, the world's first jet plane flew in the sky in Germany. A jet engine in this jet plane was designed by Dr. Ernst Heinkel, a German aircraft designer. The basic configuration of jet engines has not changed up until now, and the engine is composed of an air intake, a compressor or a fan, a combustor or a combustion chamber, a turbine and an exhaust nozzle. (*Figure 1*) Thereafter, aerodynamic design technology for a compressor and a turbine, cooling technology for turbine blades, and advances in material technology have significantly improved jet engine performance. (*Figure 2*)

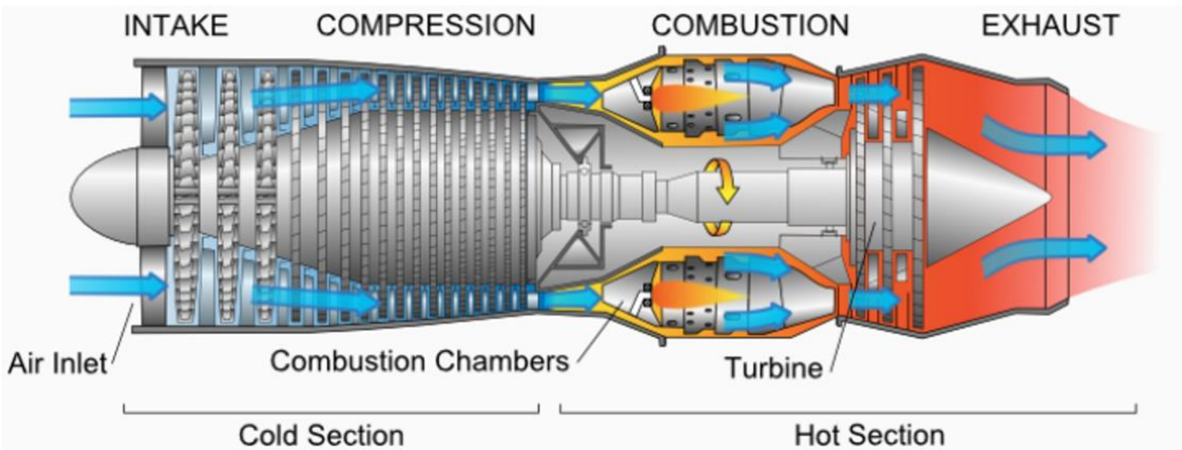


Figure 1. Basic configuration of a jet engine

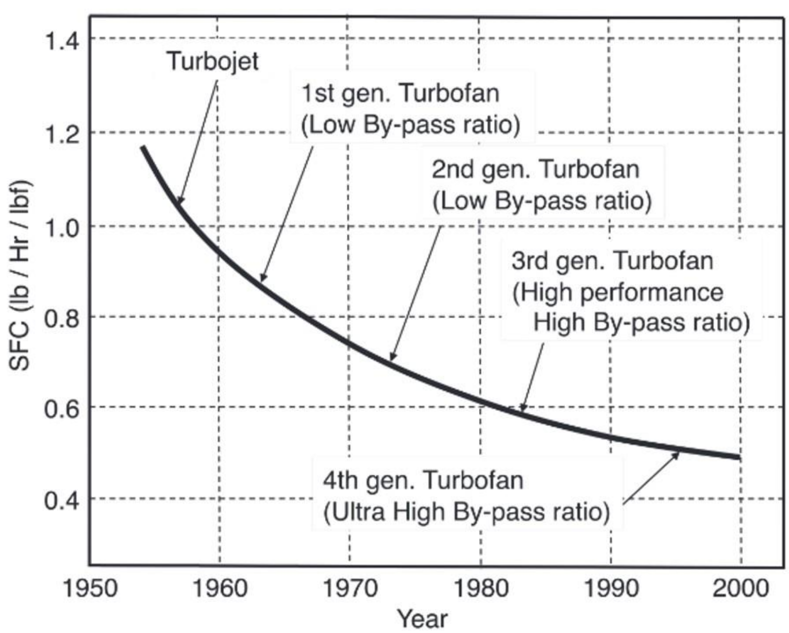


Figure 2. Improvement of specific fuel consumption

In recent years, civil aircraft engines are expected to have a further improvement in specific fuel consumption (SFC) in terms of economy. Because further weight reduction and higher efficiency of the engine can lead to improvement of SFC, the development of structural materials in particular heat-resistant alloys in hot sections is an essential task in addition to advances in design and manufacturing technology. These materials will be chosen based on material properties such as the low density, high strength, workability, and heat-resistant property. This paper describes the latest developments of materials for aircraft engines, mainly for the General Electric engines. In addition, compositions of materials used in each engine section are summed up in the Appendix.

2. <u>Fan Section</u>

The Fan section is responsible for taking air into the engine. Even though the heat restriction is not strict, the fan should be made of light and high-specific-strength materials due to strong centrifugal forces. It is also important to have high stiffness so that it can prevent torsional distortion. In recent years, in order to obtain high propulsion efficiency, the fan has become bigger to have high bypass ratio, and the fan weight has become heavier. Therefore, the GEnx engines utilize composite materials and latest aerodynamic design technology for reducing the weight.

2.1. Fan Blade

Titanium, aluminum and stainless steel have been used in the fan blades, and titanium is often used because of its high strength to weight ratio, corrosion resistance, and creep resistance. For the GEnx engines, the fan blades are composed of Carbon Fiber Reinforced Plastic composite (CFRP) blades and titanium leading edge (Ti-6Al-4V alloys), which was introduced in the GE90 engine, for improving the impact damage resistance in case of bird strikes. (*Figure 3 and 4*)

Figure 3. Fan blade in the GE90

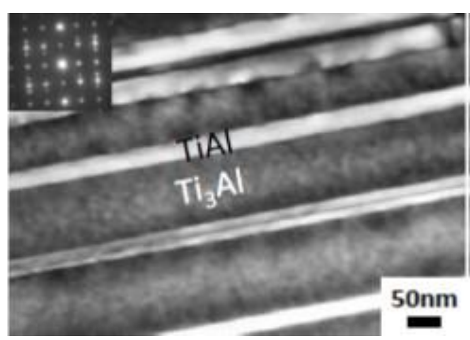


Figure 4. Microstructure of Ti-6Al-4V alloys

As shown in Figure 4, $TiAl$ and Ti_3Al phases in Ti-6Al-4V alloys constitute a lamellar structure. In terms of mechanical properties, a lamellar structure shows more resistance against creep and fatigue crack growth and higher toughness. Especially, Ti-6Al-4V alloys show high-temperature strength below approximately $800°C$.

As a supplement, the forward-swept wing type is adopted as a result of the latest three dimensional aerodynamic design technology. This improves the aerodynamic performance and also is able to reduce the number of fan blades from 22 to 18, which reduces weight and the number of parts. (*Figure 5*)

2.2. Fan Case

The fan case is the heaviest part in the engine; therefore, in general, relatively light materials such as titanium, Aluminum, and CFRP are used for the fan case. For the GEnx engines CFRP is adopted as in Figure 5. This composite case is composed of composite materials which is laminated fiber fabrics having a specific gravity of about half of the metal case, which realizes weight reduction and at the same time satisfies safety requirements of the containment property in case the fan blade is off. In addition, this CFRP case shows high durability against damage, fatigue, and corrosion.

Figure 5. Composite Technology advancement in the GE engines

3. <u>Compressor Section</u>

The Compressor section is responsible for compressing air which is taken into the engine by the fan. Due to compressing air, the temperature in the section begin to rise; therefore, materials having high-temperature strength are used such as Fe-, Ni-, and Ti-based alloys. For the GEnx engines, they have high compression ratios by using two compressor sections, a seven stage low-pressure compressor and a ten stage high-pressure compressor. Also, the low-pressure compressor spins counter-clock wise, and the high-pressure compressor spins clockwise, which realizes improvement of fuel efficiency.

The low-pressure compressor blades and several high-pressure compressor blades are made of Ti-6Al-4V alloys which are also used for the fan blade, and the rest of high-pressure compressor blades are made of Ni-based superalloys such as Hastelloy X. In recent years, Ti-based alloys have become to be used for the high-pressure compressor section in order to reduce weight, and for the same purpose Ti-based alloys such as Ti-6242 (Ti-6Al-2Sn-4Zr-2Mo) is used in the middle section exposed to high temperature.

4. <u>Combustor Section</u>

The Combustor section, after the compressor section, is responsible for mixing the compressed air with fuel and igniting the mixture of air and fuel. This provides a high temperature and high energy airflow generating the power to propel an aircraft. The temperature in combustor can reach to approximately $1000°C$, so this section needs to be made of heat-resistant alloys such as Co- and Ni-based superalloys. (*Table 1*) To improve mechanical properties of the superalloys, several additives will be selected such as Aluminum (Al) and Titanium (Ti) for strength, Chromium (Cr) for corrosion resistance, and Molybdenum (Mo), Tungsten (W) and Rhenium (Re) for increasing high-temperature strength. The microstructure of Ni-based superalloys is introduced in Section 5.

Table 1. Combustor materials

Grade	Chemical composition	Remarks
Hastelloy X	Ni22Cr1.5Co1.9Fe0.7W9Mo0.07C0.005B	Nickel-base superalloy
Nimonic 263	Ni20Cr20Co0.4Fe6Mo2.1Ti0.4Al0.06C	Nickel-base superalloy
HA188	Co22Cr22Ni1.5Fe14W0.05C0.01B	Cobalt-base superalloy
617	54Ni22Cr12.5Co8.5Mo1.2Al	Nickel-base superalloy
230	55Ni22Cr5Co3Fe14W2Mo0.35Al0.10C0.015B	Nickel-base superalloy; values for Co, Fe and B are upper limits.

5. **Turbine Section**

5.1. Turbine Blade

The Turbine section is responsible for generating the power to rotate other parts; the fan, compressor and combustor. The rotation of the turbine blades is generated by the combustion air and is transmitted to the rotation of the shaft which goes through four sections introduced so far and therefore rotates in a wide operating temperature range. In the engine, the turbine section is exposed to the harshest environment in terms of temperature and pressure. (*Figure 6*) Therefore, the materials of turbine section need to satisfy many requirements such as high creep strength, high temperature fatigue strength, and high temperature corrosion resistance. The turbine materials in high pressure and temperature section are generally Ni-based superalloys because of their high creep strength, while the materials in low pressure and temperature section can be stainless steels, Co-, and Ni-based superalloys. Since the turbine blade temperature exceed $1200°C$ and can reach to $1500°C$ in the latest engines, cooling passages design, zirconia (ZrO_2) for thermal barrier coating, and Ni-Co-Cr-Al-Y alloys for high temperature corrosion resistance can be used in order to improve turbine blade performance. (*Figure 7*)

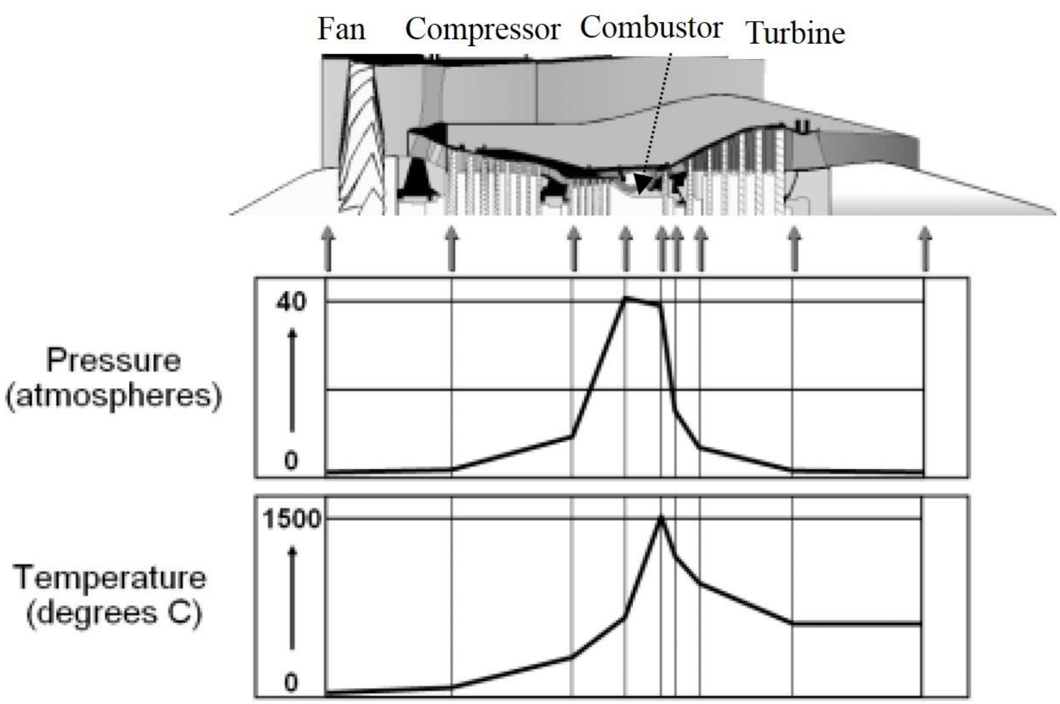
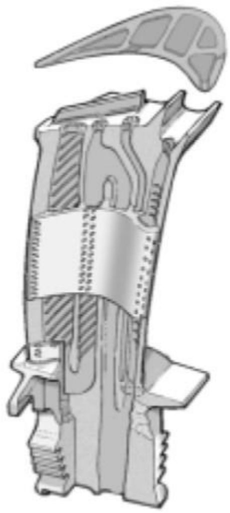


Figure 6. Temperature and pressure at which each part of the engine is exposed



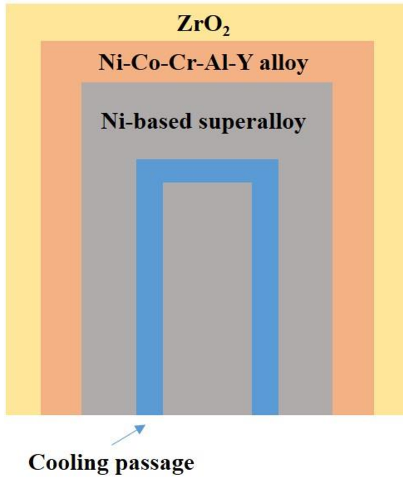


Figure 7. Design for turbine blade cooling passages (Left) and Rough design of thermal barrier coating (Right)

For the GEnx-1B, the turbine section has seven low-pressure stages and two high-pressure stages. The latter two low-pressure stages (sixth and seventh) are made of TiAl alloys in order to reduce weight, and the rest of low-pressure stages and high-pressure stages are made of Ni-based superalloys such as Rene' N5 manufactured by GE. *Table 2* shows the nominal compositions (wt%) of common Ni-based superalloys.

Table 2. Nominal composition, wt% of Ni-based superalloys

Name	Ni	Co	Cr	Mo	W	Al	Ti	Ta	Re	Ru	Density [kg/dm^3]
PWA1480	Bal.	5	10	-	4	5	1.5	12	-	-	8.70
Rene' N4	Bal.	8	9	2	6	3.7	4.2	4	-	-	8.56
CMSX-2	Bal.	4.6	8	0.6	8	5.6	1	9	-	-	8.56
TMS-6	Bal.	-	9.2	-	8.7	5.3	-	10.4	-	-	8.90
PWA1484	Bal.	10	5	2	6	5.6	-	3	-	-	8.95
Rene' N5	Bal.	8	7	2	5	6.2	-	3	-	-	8.63
CMSX-4	Bal.	9	6.5	0.6	6	5.6	1	3	-	-	8.70
TMS-82+	Bal.	7.8	4.9	1.9	8.7	5.3	0.5	2.4	-	-	8.93
Rene' N6	Bal.	12.5	4.2	1.4	6	5.75	-	5.4	-	-	8.98
CMSX-10	Bal.	3	2	0.4	5	5.7	0.2	6	-	-	9.05
TMS-75	Bal.	12	3	2	6	6	-	5	-	-	8.89
PWA1497 / MX-4	Bal.	16.5	2.0	2.0	6.0	5.55	-	5.95	3.0	9.20	9.20
TMS-138	Bal.	5.8	3.2	2.9	5.9	5.8	-	5.0	2.0	8.95	8.95
TMS-138A	Bal.	5.8	3.2	2.9	5.6	5.7	-	5.8	3.6	9.01	9.01
TMS-162	Bal.	5.8	3.0	3.9	5.8	5.8	-	4.9	6.0	9.04	9.04
TMS-196	Bal.	5.6	4.6	2.4	5.0	5.6	-	6.4	5.0	9.01	9.01

5.2. Ni-based superalloys

There has been a great attention for the combined cycle system to improve power generation. The improvement of the system is known to lead to high fuel efficiency and also to decreasing the carbon emission. For the improvement, the gas turbine entry temperature (TET) should be increased by developing superalloys which show their great heat-resistant properties. The common superalloys for the gas turbine inlet would be Co- and Ni-based superalloys. Co-based superalloys used to be main materials of the gas turbine blade. However, after the development of Ni-based superalloys, the Co-based turbine blades were replaced with Ni-based turbine blades. There are several reasons for the replacement. Firstly, in terms of Clarke number, which shows the content of the chemical elements (weight percentage, wt%) in the surface of the earth, the content of Nickel element is more than that of Cobalt elements; namely, the rarity of Nickel is respectively low. Second reason is Nickel crystal structure, which is that the face centered cubic (FCC) structure, atoms located at each cube corner and the centers of each cube face. In the FCC structure, the atoms are packed closer than the body centered cubic (BCC) structure; the atomic packing factor of FCC is 0.74 compared with that of BCC 0.68. The slip of FCC structure occurs on {111} planes along <110> direction and has twelve slip systems and five active slip systems. This system performs moderate strength and ductility. Lastly, the outstanding mechanical properties (high strength, long fatigue life with good resistance oxidation and corrosion at high temperature) of Ni-based superalloys are the main reason to apply them to the engine turbine blades. The properties are related to their microstructures of Ni (γ) and Ni_3Al (γ'). (*Figure 8*) As shown in the right hand side of the Figure 8, Ni-based superalloys are fabricated in the wide range of Ni amount. Even though special methods is necessary to fabricate the single crystal, this applicable wide range allows manufacturers to arrange the composition of Ni-based superalloys. As shown in the left hand side of the Figure 8, Ni (γ) is the continuous matrix usually containing a high percentage of solid-solution elements such as Chromium, Molybdenum, and Tungsten; on the other hand, Ni_3Al (γ') is the primary precipitation strengthening phase. The value of the lattice match is known to affect mechanical properties, and the lattice parameters of Ni (γ) and Ni_3Al (γ') are nicely very close (approximately 0~1%). Also, the volume fraction and size of Ni_3Al (γ') phase are factors contributing to high mechanical properties of Ni-based superalloys. For example, compared to

Boeing 777 and 747, Boeing 777 changes the volume fraction of Ni_3Al (γ') phase from 65% in Boeing 747 to 70% in order to get less deformation in high temperature.

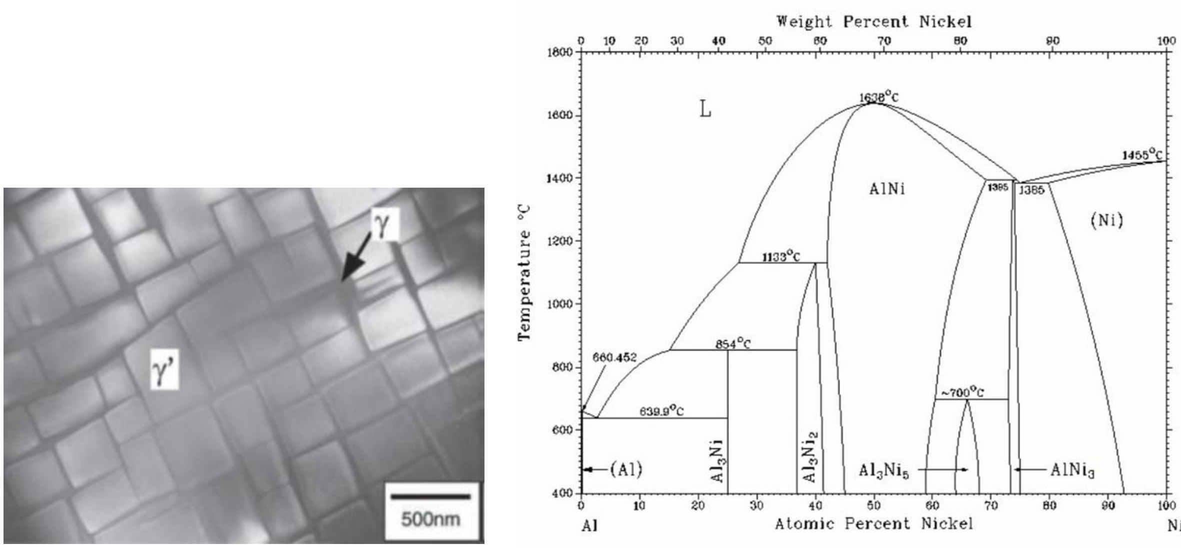


Figure 8. Microstructure of Ni_3Al-Ni (Left) and Ni-Al phase diagram (Right)

6. <u>Shaft</u>

As discussed in the previous section, the engine shaft rotation is driven by the turbine, and the shaft goes through the entire engine and transmits the power from the turbine to other sections; the fan, compressor, and combustor sections. In the long run, heat resistance, high temperature strength, high fatigue strength, and toughness are required material properties in order to withstand the high-speed rotation under low and high temperature environment. Therefore, steels with high cleanliness and without segregation are used to ensure high reliability such as stainless steels, Ti-6Al-4V alloys, Fe-, and Ni-based superalloys. The common materials would be Cr-Mo-V steels, Inco-718, and Maraging steels (GE1014). The Maraging steel is a very strong steel containing 18-25% of Ni and has high fatigue strength (~2200Mpa or more) and high toughness due to its high cleanliness, and therefore the Maraging steels have been adopted in the TRENT1000, GE90-115B, and GEnx engines. (*Figure 9*)

Figure 9. Mid Fan Shaft (Left) and low-pressure turbine shaft (Right) in the GE1014 engine

7. Conclusion

This paper introduces the latest developments of materials for aircraft engines, mainly for the General Electric engines. (*Figure 10*) The development of aircraft materials is still in the middle, but many organizations and universities have studied and gradually improved the material performance. These effort will enable aviation industries to save fuel cost and perform more safety flight. As shown in Figure 11, the recent engines such as GEnx engines tend to apply Titanium and composite so that the weight of engines can be reduced, which leads to improve the fuel efficiency. Especially, composite study has been actively done, and it is said that most of engine pars will be made of composites in the future. Thus, further development and saving cost can be expected.

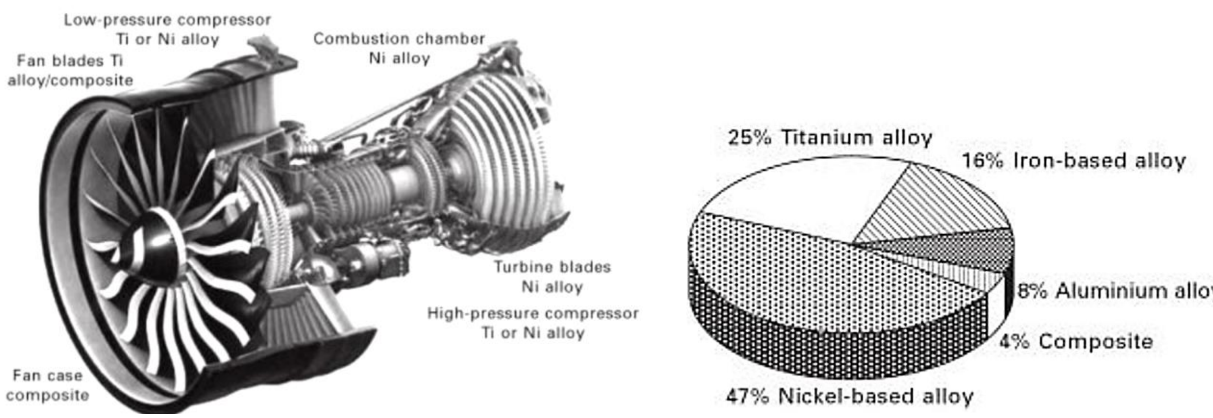


Figure 10. Cross-section of the GEnx engine for Boeing 787 (Left) and Material distribution in the General electric engine (CF6) for Boeing 787 (Right)

8. Appendix - compositions of materials-

Common compositions of materials used in each engine section are summed up.

Table 3. **Combustion chamber alloys and their composition**

ALLOY	Ni	Cr	Co	Mo	W	Al	Ti	Fe	C	
Hastelloy X	Bal.	22.	1.5	9.0	0.6			18.5	0.07	Si 0.4 Mn 0.6
Nimonic C263	Bal.	20.	20.0	5.9		0.45	2.15	0.7	0.06	Si 0.25 Mn 0.4
Nimonic PK33	Bal.	18.	14.0	7.0		2.1	2.2		0.05	
Inconel 617	Bal.	22.	12.5	9.0		1.0			0.07	
Haynes 188	22.0	22.	Bal.		14.0				0.1	La 0.05
Nimonic 86	Bal.	25.		10.0					0.05	Mg0.015 Ce0.03

Table 4. **Nozzle guide vane alloys and their composition**

ALLOY	Ni	Cr	Co	W	Ta	Nb	A1	Ti	Fe	C	B	Zr
X 40	20.0	25.0	Bal.	8.0		1.0			1.0	0.5	0.01	
X 45	10.0	25.0	Bal.	8.0					1.0	0.25	0.01	
MAR M 509	10.0	23.5	Bal.	7.0	3.5			0.2	1.0	0.6	0.01	0.5
FSX 414	10.0	29.0	Bal.	7.5					1.0	0.25	0.01	
ECY 768	10.0	23.5	Bal.	7.0	3.5		0.15	0.2	1.0	0.60	0.01	0.05
IN 939	Bal.	22.4	19.0	2.0	1.4	1.0	1.9	3.8		0.15	0.01	0.1
GTD 222	Bal.	22.5	19.0	2.0	1.0	0.8	1.20	2.3		0.1	0.01	

Table 5. **Blade wrought alloys and their composition**

ALLOY	Ni	Cr	Co	Mo	W	Nb	A1	Ti	Fe	C	B	Zr
INCONEL-X750	Bal.	15.5				1.0	0.7	2.5	7.0	0.04		
NIMONIC 105	Bal.	15.0	20.0	5.0			1.2	4.7		0.13	0.006	0.1
UDIMET 500	Bal.	18.0	18.5	4.0			2.9	2.9		0.08	0.006	0.05
INCONEL 700	Bal.	15.0	17.0	5.0			4.0	3.5		0.06	0.03	
NIMONIC 115	Bal.	14.5	13.0	3.0			5.0	3.8		0.15	0.016	0.04
UDIMET 520	Bal.	19.0	12.0	6.0	1.0		2.0	3.0		0.05	0.005	
UDIMET 710	Bal.	18.0	15.0	3.0	1.5		2.5	5.0		0.07	0.02	
UDIMET 720	Bal.	17.9	14.7	3.0	1.3		2.5	5.0		0.03	0.033	0.03

Table 6. **Blade/nozzle guide vane cast alloys and their composition**

ALLOY	Ni	Cr	Co	Mo	W	Ta	Al	Ti	C	B	Zr	
UDIMET 500	Bal.	18.0	19.0	4.2			3.0	3.0	0.07	.007	0.05	
INCONEL 713 LC	Bal.	12.0		4.5			5.9	0.6	0.05	0.01	0.1	Nb 2.0
RENÈ 77	Bal.	14.6	15.0	4.2			4.3	3.3	0.07	.016	0.04	
IN 100	Bal.	10.0	15.0	3.0			5.5	4.7	0.18	.014	0.06	V 1.0
RENÈ 80 (80H)	Bal.	14.0	9.5	4.0	4.0		3.0	5.0	0.17	.015	0.03	(Hf0.8)
MAR-M-246	Bal.	9.0	10.0	2.5	10.0	1.5	5.5	1.5	0.14	.015	0.05	
IN 738 LC	Bal.	16.0	8.5	1.70	2.6	1.70	3.4	3.4	0.10	0.01	0.05	Nb 0.9
MAR-M-247	Bal.	8.3	10.0	0.7	10.0	3.0	5.5	1.0	0.14	.015	0.05	Hf 1.5
MAR-M-002	Bal.	9.0	10.0		10.0	2.5	5.5	1.5	0.14	.015	0.05	Hf 1.5
RENÈ 125	Bal.	8.5	10.0	2.0	8.0	3.8	4.8	2.5	0.11	.015	0.05	
GTD 111	Bal.	14.0	9.5	1.5	3.8	2.8	3.0	4.9	0.10	0.01		

Table 7. **Blade single crystal alloys and their composition**

ALLOY	Ni	Cr	Co	Mo	W	Ta	Nb	Al	Ti	Hf	Re	V
PWA 1480	Bal.	10.0	5.0		4.0	12.0		5.0	1.5			
RENÈ N4	Bal.	9.0	8.0	2.0	6.0	4.0	0.5	3.7	4.2			
SRR 99	Bal.	8.0	5.0		10.0	3.0	0.7	5.5	2.2			
RR 2000	Bal.	10.0	15.0	3.0				5.5	4.0			1.0
AM1	Bal.	7.0	8.0	2.0	5.0	8.0	1.0	5.0	1.8			
CMSX-2 (-3)	Bal.	8.0	5.0	0.6	8.0	6.0		5.6	1.0	(0.1)		
CMSX-6	Bal.	10.0	5.0	3.0		2.0		4.8	4.7	0.1		
PWA 1484	Bal.	5.0	10.0	2.0	6.0	8.7		5.6		0.1	3.0	
CMSX-4	Bal.	6.4	9.6	0.6	6.4	6.5		5.6	1.0	0.1	3.0	
RENÈ N5	Bal.											
SC 16	Bal.	16.0	5.0	3.0		3.5		3.5	3.5			

9. References

ANIMAGRAFFS. Inside a Jet Engine. [Online]

Available at http://animagraffs.com/inside-a-jet-engine/

M. Hetmanczyk, L. Swadzba, B. Mendala. (2007) Advanced Materials and prospective coating in aero-engines application. *Jornal of Achievements in Materials and Manufacturing Engineering*, 24, Issue 1.

K.Harris, G.L. Erickson, S.L. Sikkenga, W.D. Brentnall, J.M. Aurrecoechea, K.G. Kubarych. (1992) Development of the Rhenium containing superalloys CMSX-4 & CM 186 LC for single crystal blade and directionally solidified vane. *The Minerals, Metals & Materials Society*, 297-306.

Daniel G. Backman, James C. Williams. (1992) Advanced Materials for Aircraft Engine Applications. *JSTOR*, 255, 1082-1087.

.Nageswara Rao Muktinutalapati. (2011) Materials for Gas Turbines –An Overview. *VIT University, India.*

E. Campo – Fiat Avio S.p.A., Torino, V. Lupinc. (1933) High Temperature Structural Materials For Gas Turbines. *Metallurgical Science and Technology*, 11, 31-47.

INSG Secretariat briefing paper. (2013) Nickel-based superalloys. *INSG Insight*, 20, 1-9.

L. Backerud, B. Carlsson, R. Oskarsson, M. Mikus. (1974) A study of the Nickel-rich and Cobalt-rich Corner of the System Ni-Ti-C and Co-Ti-C. *SCANDINAVIAN JOURNAL OF METALLURGY*, 3, 225-235.

Saeed Farokhi. (2014). Aircraft Propulsion, Second Edition. *WILLY*, ISBN: 9781118806777.

Adrian P. Mouritz. (2012). Introduction to Aerospace Materials. *AIAA Education, Woodhead Publishing*, ISBN: 978-1-85573-946-8.