Material Selection for a Jet Engine Turbine Blade

Structures and Properties of Materials

MANE 2220U

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I. INTRODUCTION

The turbine blade is a critical component of a gas turbine engine. Without turbine blades, a gas turbine engine would not be able to function properly. As the name suggests, the turbine blade is a blade for the turbine. The turbine is responsible for converting the energy stored in the hot gases resulting from the combustion process into mechanical energy. Specifically, the combustion gasses flow into the turbine which is composed of turbine blades attached to a shaft. As the hot gases are directed against these turbine blades, they impart their kinetic energy into the blades causing them to spin rapidly. This is needed to power the compressor of a gas turbine engine as the compressor is also attached to the same shaft as the turbine. As such, the turbine blades typically must operate in high-temperature and high-pressure environments [1].

II. PROPERTIES OF THE COMPONENT

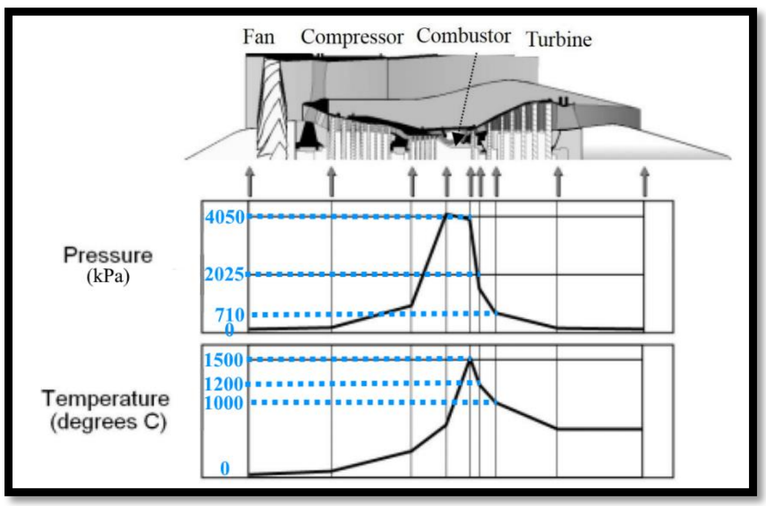

Figure 1: Temperature and Pressure Values Along Different Areas of a Gas Jet Engine [2]

Turbine blades are exposed to extreme pressures and temperatures as seen in Figure 1. The temperature that the turbine blades are exposed to varies with their proximity to the combustion chamber. The conditions near the combustion chamber are much harsher than the conditions further down the turbine, as seen in Figure 1. As such, the material further down the turbine doesn’t necessarily need to be the same material as the one at the entry the turbine. The material further down the turbine can afford to be a less heat resistant.

The blades closest to the combustion chamber will be subject to temperatures reaching up to 1500 ℃ while the blades around the midpoint of the turbine will be subject to temperatures reaching up to around 1200 ℃. The blades near the end of the turbine will be subject to temperatures up to around 1000 ℃. For simplicity, different sections of the turbine will be divided up according to their proximity to the combustion chamber:

- Stage 1: Entry section of the turbine reaching temperatures up to 1500 ℃
- Stage 2: Midpoint section of the turbine reaching temperatures up to 1200 ℃
- Stage 3: Exit section of the turbine reaching temperatures up to 1000 ℃

This high operating temperature means that the material strength is reduced as strength generally decreases with increasing temperatures. As such, failure due to creep and fatigue is a concern [3]. The creep-rupture life of a material would be a good measurement of its performance. However, turbine blades typically utilize a cooling system which allows for an airflow with a temperature of around 650 ℃ into the turbine blades. This is relatively cool when compared to the combustion chamber airflow temperature, which has temperatures up to 1500 ℃ [4]. Typically, the cooling system will cool the material to eight-tenths of its melting temperature [5]. This cooling system means that a material with a lower melting and thus operating temperature can be used. Additionally, a ceramic coating is typically applied to turbine blades which allow for at least a 170 ℃ greater operating temperature [4]. For the purposes of this report, a material with a melting temperature around 1330 ℃ should be sufficient for Stage 1 since the maximum temperature that the turbine blades will be exposed to is 1500 ℃. With the addition of a ceramic coating, the turbine blade will only need to withstand up to 1330 ℃ and with the help of the cooling system, the blade will be cooled to a temperature of 1064 ℃ which will give a safety margin of error if the temperature fluctuates. Using this same methodology for Stage 2 and 3, a material with a melting point of 1030 and 830 ℃ will be needed, respectively.

Turbine blades are also subjected to high pressures with the same general relationship to proximity to the combustion chamber that the turbine blades have with temperature. The blades closest to the combustion chamber will subject to a pressure reaching up to around 4050 kPa while the blades around the midpoint of the turbine will be subject to pressures reaching up to 2025 kPa. The intensity of the pressure falls off significantly for the blades near the end of the turbine, with pressures only reaching up to around 710 kPa.

The turbine blades also experience a tremendous amount of centrifugal force due to the high rotation speed of the turbine, reaching up to several tons, and this is typically done at very high temperatures [4]. The turbine blade should also possess a balance of strength and ductility to withstand cyclic loading and prevent premature cracking [6]. The turbine blade should also be corrosion resistant because the hot gases typically contain elements that can react with the blade surface, creating a corrosive environment. This corrosive environment is fueled even more by the fact that the turbine operates at very high temperatures, facilitating chemical corrosion reactions [4].

Single crystal alloys are also desirable because they don't have grain boundaries which eliminates the defects and impurities which occur at the boundaries [3]. This is desirable because having a single-crystal structure enhances the mechanical properties of a material and increases its resistance to high temperature environments [5].

III. MATERIAL SELECTION

Typically, nickel-based superalloys are used for gas turbine blades. Nickel-based superalloys generally have the best performance at high temperature. With this in mind, four viable materials for manufacturing the turbine blade were selected. These materials were chosen to be:

1. René N5
2. CMSX-4
3. PWA 1484
4. Inconel 718

René N5

René N5 is a Ni-based single crystal superalloy which is typically used for gas turbine blades. It has a melting point between 1322-1385 °C which makes it a prime candidate for a Stage 1 material [7]. René N5 also has a good creep rupture life of around 200 hours at 982 °C and 207 MPa [8] . Additionally, René N5 offers good corrosion thermal corrosion resistance [8]. René N5 has also been tested in a 1450 °C-class gas turbine as a part of the "Advanced Turbine System" project [9]. As shown in Figure 2, René N5 has a great ductility at temperatures over 900 °C. In Figure 4, the Yield Strength of René N5 in MPa can be seen to be around 300 MPa at 1100 °C.

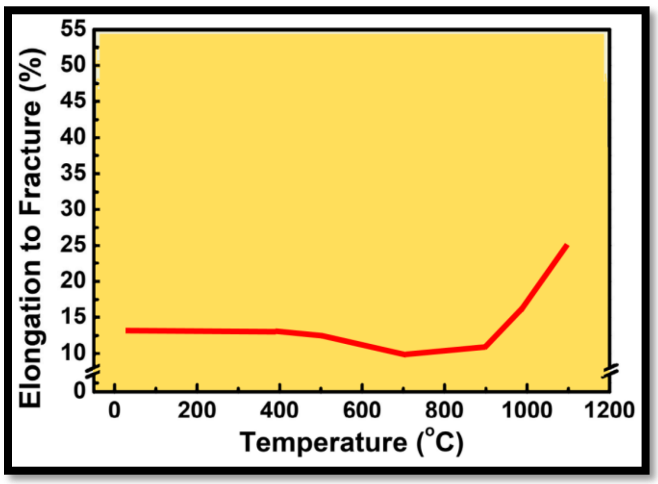

Figure 2: Graph of René N5 Elongation to Fracture Percentage with Respect to Temperature [10]

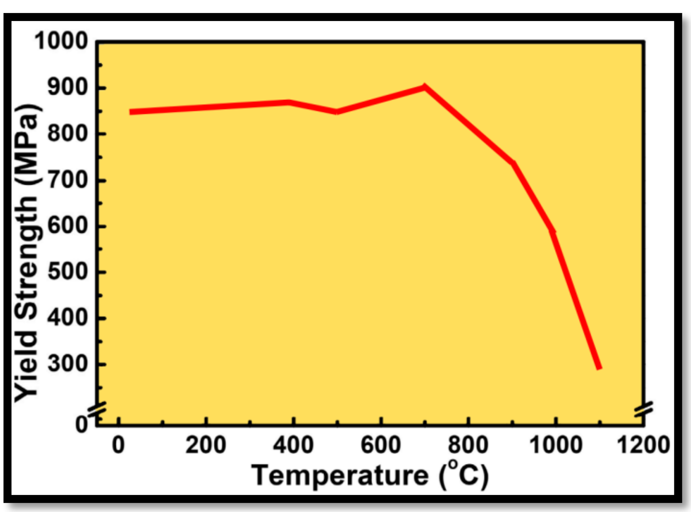

Figure 3: Graph of René N5 Yield Strength with Respect to Temperature [10]

CMSX-4

CMSX-4 is also a Ni-based single crystal superalloy. It is commonly used in the aerospace industry for turbine blades in the hot sections of gas turbines [11] . The melting point of CMSX-4 is between 1330 °C and 1396 °C [11]. This melting point makes CMSX-4 another candidate for a Stage 1 material. CMSX-4 has a creep rupture life of around 231 hours at 980 °C and 250 MPa [12]. Additionally, CMSX-4 offers excellent corrosion resistance at high temperatures [13]. As shown in Figure 4, CMSX-4 also has a great ductility at temperatures over 900 °C. In Figure 5, the Yield Strength of CMSX-4 in MPa can be seen to be around 350 MPa at 1100 °C.

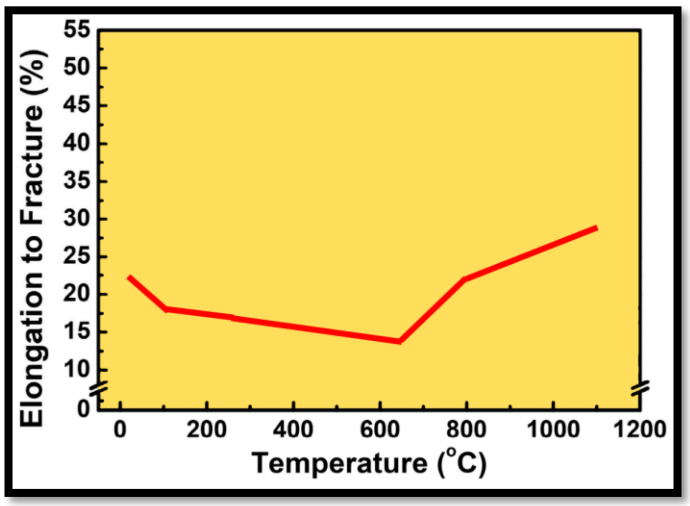

Figure 4: Graph of CMSX-4 Elongation to Fracture Percentage with Respect to Temperature [10]

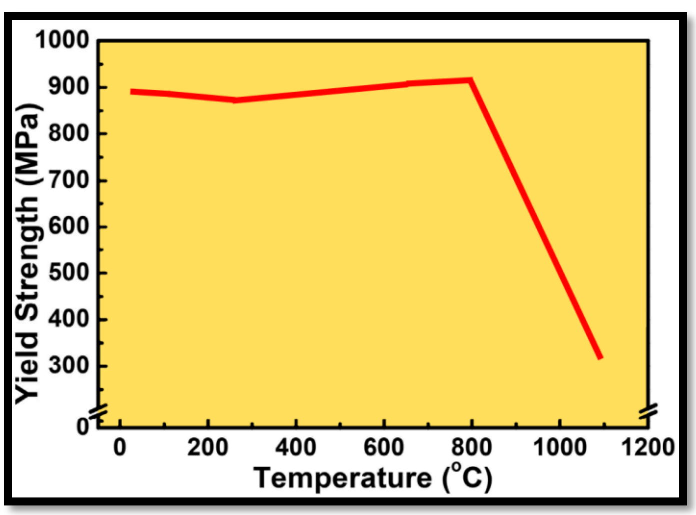

Figure 5: Graph of CMSX-4 Yield Strength with Respect to Temperature [10]

PWA1484

PWA1484 is yet another Ni-based single crystal superalloy. The melting point of PWA1484 is between 1340 and 1404 °C [14]. This melting point makes PWA1484 a good candidate for a Stage 1 material as well. PWA1484 has a creep rupture life of 350 hours at 982 °C and 248 MPa. In addition, PWA1484 also has excellent oxidation and corrosion resistance [15]. As shown in Figure 6, PWA1484 has a great ductility at temperatures over 900 °C. In Figure 7, the Yield Strength of PWA1484 in MPa can be seen to be around 430 MPa at 1100 °C.

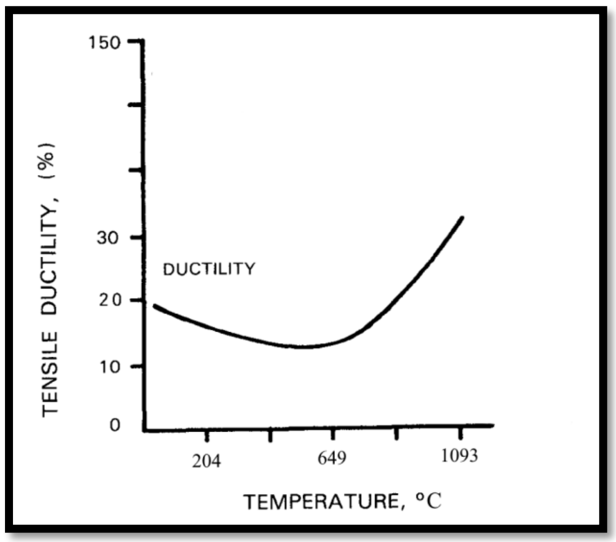

Figure 6: Tensile Ductility Percent of PWA1484 with Respect to Temperature [15]

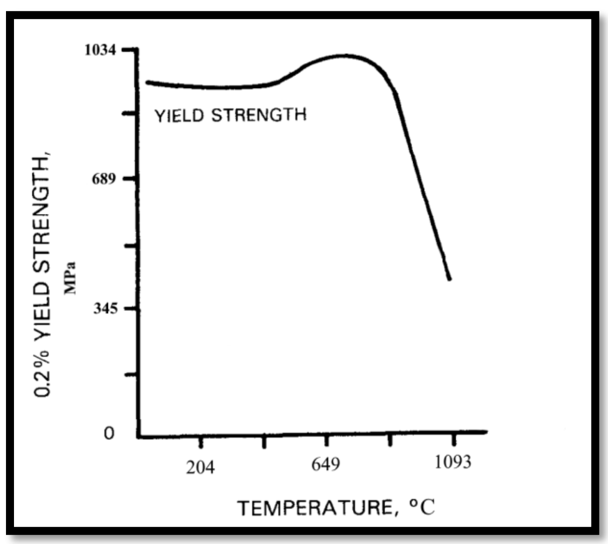

Figure 7: 0.2% Offset Yield Strength of PWA1484 with Respect to Temperature [15]

Inconel 718

Inconel 718 is also a Ni-based single crystal superalloy. From Figure 8, Inconel 718 has a liquidus and solidus temperature of approximately 1310 °C and 1240 °C, respectively.

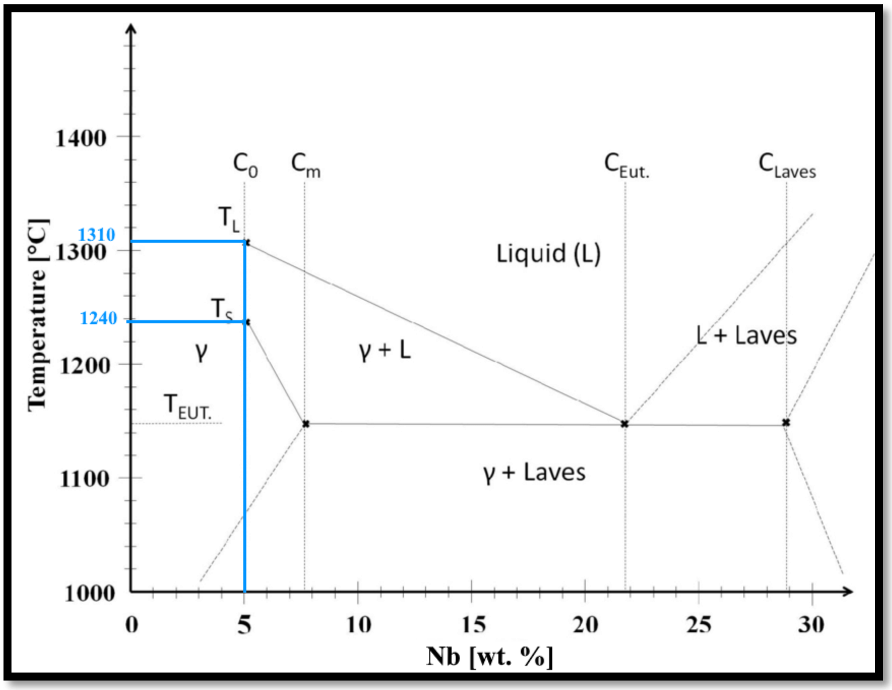

Figure 8: Pseudo-Binary Phase Diagram for Inconel 718 [16]

This gives Inconel 718 a melting point of 1240-1310 °C which doesn't meet the requirement of a 1330 °C melting temperature for a Stage 1 material. Instead, Inconel 718 would be an excellent contender for a Stage 2 or 3 material because it has a melting temperature greater than 1030 and 830 °C, which is needed for Stage 2 and 3 materials. Inconel 718 would be more suited for a Stage 3 material because it still has excellent yield strengths at temperatures lower than 900 °C. In addition to this, Inconel 718 has excellent creep-rupture life of 1000 hours at 649 °C and 593 MPa [17]. As with most Ni-based superalloys, Inconel 718 also has great corrosion resistance at high temperatures [18].

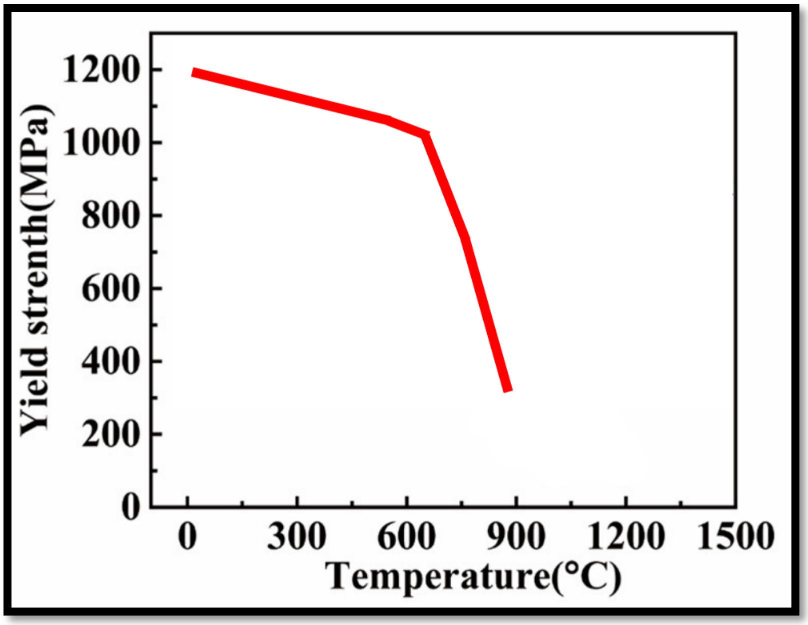

Figure 9: Yield Strength of Inconel 718 with Respect to Temperature [19]

IV. Summary and Conclusion

Finding an appropriate material for a jet engine turbine blade was a challenging task that required careful examination of various properties of materials to ensure they met requirements. Different areas of the turbine were divided up into sections according to their proximity to the combustion chamber. Through predictions of the performance of ceramic coatings and cooling systems, different melting temperatures for each stage were calculated. They were as follows:

- Stage 1: Melting Temperature > 1330 °C
- Stage 2: Melting Temperature > 1030 °C
- Stage 3: Melting Temperature > 830 °C

In addition to the melting temperature requirements, the following mechanical properties were needed at high temperatures:

1. Good corrosion resistance
2. High yield strength
3. High ductility
4. Long creep-rupture lives

The materials discussed in the Material Selection section that met these requirements were all single crystal Ni-based superalloys. These alloys were René N5, CMSX-4, PWA1484, and Inconel 718. René N5, CMSX-4, and PWA1484 shared very similar properties and all of them could be used for Stage 1, Stage 2, or Stage 3 turbine blades. Inconel 718's melting point was too low to be used for Stage 1. For Stage 2, Inconel 718 could possibly be used but it would perform better as a Stage 3 turbine blade material as Inconel 718 had a high creep rupture life at lower temperatures.

This report can be enhanced in the future if turbine entry temperatures of a specific engine could be found, as well as the type of ceramic coating that would be used along with the cooling system. Accurate calculations of the temperature that the turbine blade would be cooled to at different sections of the turbine would help to narrow down the possible materials that can be used.

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