Thermo-mechanical simulation of steam turbine blade with spark plasma sintering fabricated Inconel 738LC superalloy properties

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Abstract

The exponential increase in the demand for energy has placed tremendous pressure on the power generation companies and the components used for the power supply. The efficiency of such supply is dependent on the operating parameters of the plants but at the expense of the useful life of the components. Turbine blade is one of the components that contribute immensely to such efficiency and it should be made of high-strength material with an exceptional ability to withstand the harsh operation environment. The properties of spark plasma sintering technique produced Inconel 738 low carbon (IN738LC) superalloy was used in finite element analysis software, Abaqus CAE/2017 to simulate the thermo-mechanical behaviour of steam turbine blade. The maximum thermo-mechanical stress and strain were developed on the root of the turbine blade (along the tailing edge) and the value of the maximum stress developed is far below the yield stress of the superalloy. Hence, spark plasma sintered Inconel 738LC is suitable for turbine blade production as such blade will survive several thermo-mechanical stress and strain cycles prior to failure.

1. Introduction

The exponential growth in human population and industries has placed profuse demands on the power generation companies to provide substantial energy for the growing population. This imply that there is a need for energy capacity expansion and an urgent call to maximize the available power generation plants for better energy output such that minimal break down of the plant’s component is recorded. This rising demand for energy has prompt modern turbine engines to operate under extreme conditions with the sole aim of exceeding the manufacturer’s recommended conservations, but still maintaining the necessary safety requirements [1].

In order to increase the performance of the turbine, the operating temperature must be raised, thus, making the blade to operate in a harsh environment. Turbine blade are vital components that makes up the turbine assembly of a gas or steam turbine engine and it helps to convert the kinetic energy of the steam or burning gases into mechanical energy [2]. The efficiency of the turbine is conditioned by the vanes of the turbine blades, and the leading edge of the blade is a site where severe thermal damage is experienced [2-5]. In operation, the blades are subjected to stresses due to numerous factors such as very high temperature of steam or gases, centrifugal force creep, thermal gradients developed due to start up and shutdown, vibration...
fatigue, stresses induced due to complexity in geometry and hot corrosion [2]. Hence, superalloys are used to fabricate turbine blades due to their excellent mechanical properties and good structural stability at high temperature environment [6]. Superalloys differ in their percentage composition and their phases differ with respect to the alloying elements present.

For Inconel 738 low carbon (IN738LC), the secondary intermetallic gamma prime prime (γ''-Nb, Mo,) phase and carbon may sometimes be absent [7]. The principal phases often found in this type of alloy are gamma matrix phase (γ-Ni), precipitate intermetallic gamma prime phase (γ'-Ni₃(Al, Ti)) and some hard-solids solution strengthening phases [7, 8]. These are phases are responsible for the excellent creep and thermal properties exhibited by this alloy at high temperature environments [9, 10]. Also, the presence of chromium improves the corrosion resistance properties of the alloy.

In this paper, the thermo-mechanical behaviour of 60 MW low pressure spark plasma sintered (SPS) Inconel 738LC produced steam turbine blade in operation was determined using finite element analysis (FEA) software, Abaqus CAE/2017.

2. Material Properties

The tables below show the dimensions and material properties of Inconel 738LC used.

Table 1: Weight percentage of IN738LC constituent elements

| Material | Ni  | Cr  | Co  | Ti  | Al  | W  | Ta  |
|----------|-----|-----|-----|-----|-----|----|-----|
| Percentage (%) | 64.58 | 16  | 8.3 | 3.4 | 3.4 | 2.6 | 1.72 |

Table 2: Dimensions of the blade

| Airfoil (m) | Root (m) | Leading Edge (m) | Trailing Edge (m) | Chord Length (m) | Pitch (°) |
|-------------|----------|------------------|-------------------|------------------|----------|
| 0.2         | 0.05     | 0.0092           | 0.00245           | 0.05             | 14.2     |

Table 3: Modulus of elasticity of Inconel 738LC as a function of temperature

| Elasticity (GPa) | Poisson Ratio | Temperature (°C) |
|------------------|---------------|------------------|
| 200.638          | 0.28          | 24               |
| 195.120          | 0.27          | 93               |
| 190.295          | 0.27          | 204              |
| 184.780          | 0.28          | 315              |
| 179.264          | 0.28          | 426              |
| 175.127          | 0.30          | 538              |
| 167.543          | 0.30          | 649              |

Table 4: Specific heat capacity and thermal conductivity of inconel 738LC

| Temperature (°C) | Specific Heat Capacity (J/KgK) | Thermal Conductivity (W/mK) |
|------------------|-------------------------------|----------------------------|
| 100              | 460.548                       | 30.243                     |
| 200              | 502.416                       | 30.726                     |
| 300              | 523.35                        | 30.033                     |
| 400              | 544.284                       | 32.924                     |
| 500              | 565.218                       | 34.734                     |
| 600              | 586.152                       | 37.061                     |
Table 5: Thermal expansion of inconel 738LC

| Temperature (°C) | Thermal Expansion (10^-6 K^-1) |
|-----------------|-------------------------------|
| 93              | 6.45                          |
| 204             | 6.75                          |
| 315             | 7.15                          |
| 426             | 7.55                          |
| 538             | 7.75                          |
| 694             | 8.05                          |

3. Analysis Methodology

A sequentially coupled procedure was used for the thermo-mechanical simulation in Abaqus CAE/2017 FEA software. The analysis was carried out on a scaled down, 60 MW low pressure turbine blade model shown in figure 1(a). The procedure involves the development of a scaled down turbine blade model which is a representative of a blisk. The material composition of the SPS fabricated Inconel 738LC turbine blade and its dimensions are shown in table 1 and 2 respectively while the material properties are shown in tables (3-5). These material properties are added to the appropriate material properties section of Abaqus CAE/2017. The creation of section and assignment of the relevant section to part was also done, after which a dependent instant was created before assigning the section to a part as shown in figure 1(b).

The blade was subjected to 550 °C sink temperature which represents the typical operating temperature of a steam power plant and the assumed film coefficient (convective heat transfer coefficient) at the operating temperature is 10 000 W/(m²K) [11]. Also, a sink temperature of 25 °C with an assumed film coefficient of 18 W/(m²K) [11] representing the convective heat transfer coefficient of air was applied to the blade. This represent the initial condition of the blade prior to operation. For the heat transfer analysis, a 10-node quadratic heat transfer tetrahedron (DC3D10) element type was used while for the thermo-mechanical analysis, a 10-node quadratic tetrahedron (C3D10) element type was used. Text element shape with global seed size of 0.8 mm was used for the analysis as shown in figure 1(c). The temperature distribution profile from the output data base (ODB) file in the heat transfer (thermal) analysis was imported and used as the predefined temperature. This temperature profile was applied in step 1 of the thermo-mechanical stress analysis. In the thermo-mechanical analysis, a pressure of 18 MPa representing the typical operating steam pressure was applied to the blade in the loading section of Abaqus CAE/2017 and the displacement/rotation boundary condition was specified on the trailing edge of the rotor such that the model was constrain in the axial direction [12]. This specified boundary conditions represent the real operating process of the blade.

Figure 1: (a) A scaled down model, (b) assembly mode and (c) meshed mode of a power plant turbine blade

4. Results and Discussion

The temperature distribution result and profile in figure 2(a), indicates that the maximum operating temperature of steam was used for the operation of the turbine blade and the 0.91 % drop in temperature in
the temperature output result is due to heat loss in the form of conduction and convection. The maximum heat flux was obtained at the root as shown in figure 2(b). This is due to the difference in temperature between the blade and the root which resulted in the transfer of heat from higher temperature region to lower temperature region.

![Temperature distribution result and profile](image1)

![Heat flux across the turbine blade in operation](image2)

Figure 2: (a) Temperature distribution result and profile and (b) heat flux across the turbine blade in operation

The thermo-mechanical stress distribution profile and output result of the blade is shown in figure 3. The maximum principal stress (443.3 MPa) is located at the root of the blade on the trailing edge. This is the region where the largest stress gradient was experienced. The maximum stress value of the steam turbine at this region under the operating condition of 550 °C and 18 MPa is far below the 896 MPa yield strength of Inconel 738LC [13]. Hence the blade will undergo several cycles prior to failure due to thermo-mechanical stress or thermal fatigue. figure 4 shows the strain distribution profile of the blade and as expected, the maximum strain (2.703 x 10^{-3}) was developed at the root of the blade on the trailing edge. This signifies that the failure of the blade will likely emanate from the root since it is the region with the propensity for crack initiation and propagation.

![Stress distribution result and profile across the thickness of the turbine blade](image3)

Figure 3: Stress distribution result and profile across the thickness of the turbine blade
The deformation profile across the turbine blade is shown in figure 5. The maximum deformation was obtained at the tip of the trailing edge. This signifies that the blade could also experience failure at this region during operation.

5. Conclusion
A numerical model for the analysis of thermo-mechanical behaviour of a power plant turbine blade with the material properties of SPS fabricated Inconel 738LC (nickel-based superalloy) was carried out in Abaqus CAE/2017. A sequentially coupled procedure was adopted for the simulation and the improved material properties of IN738LC alloy emanating from the SPS fabrication technique were used during the simulation. The chemical compositions of the alloy were also presented. In the simulated output result, the temperature distribution profile shows that high thermal efficiency was maintained and there was 0.91% drop in temperature as compared to the applied operating steam temperature. This slight decrease in temperature was due to the heat loss in the form of conduction and convection. The maximum value of stress and strain was developed on the root of the blade (trailing edge). Also, the maximum deformation was experienced at the tip of the trailing edge of the blade. This indicates that crack could initiate at the trailing edge on the root of the blade due to stress developed or the tip of the trailing edge being the location with maximum deformation. The value of the maximum stress developed (443.3 MPa) is far below the yield strength (896 MPa) of Inconel 738LC at the specified operating condition. Hence, failure of the blade due to thermal stress, strain or thermal fatigue will only occur after several cycles of operation. Also, the value of the stress developed by the SPS produced turbine blade compare favourably well with that
manufactured through other processes since they all survive several cycles prior to failure under the
specified operating condition.

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