The Effect of Master Heat Chemistry on Cracking in Investment Cast GTD444 Alloy

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Investment cast superalloys can crack during different steps of the casting process such as casting, knockout, and solution heat treatment. Identification of a cracked airfoil earlier in the processing would allow for cost reduction and more control over the entire process. Precision Castparts Corporation (PCC) has identified a smaller specification of GTD-444, a General Electric patented alloy, in an attempt to optimize castability and reduce rework of oxides and surface porosity. In order to understand how each element's concentration levels affect the yield, statistical analysis of past master heats was performed. In addition, an oxidation experiment was performed to understand oxidation of this alloy across a range of temperatures to identify a temperature range where cracking occurs. Oxidation along the crack surface would indicate cracks that were subjected to a high temperature regime. Inspection of cracked castings allowed for the identification of oxide layer along the crack surface. A master heat was poured using the recommendation provided to PCC resulting in reductions in both the number of cracked samples and rework percentage.

This work is sponsored by:
Precision Castparts Corporation- Airfoils
Mentor, OH

Project Background

Problem Statement

PCC-Airfoils manufactures industrial gas turbine blades and vanes made of the nickel-based superalloy GTD-444. These are cast using the directionally solidified (DS) investment cast technique followed by hot isostatic pressing and solution heat treatment. Due to the complexity of the DS casting process, some parts are scrapped due to cracks along the grain boundaries that form during production. Samples requiring rework to get the airfoil within specifications result in additional labor and machining costs. Rework can be defined as the additional machining and labor to eliminate surface porosity. Table 1 shows the composition of GTD 444.

Table 1. Elemental Composition of GTD – 444

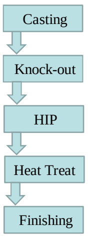
Element	Cr	Co	Mo	W	Ta	Nb	Al	Ti	Ni
Wt %	9.7	8	1.5	6	4.7	0.5	4.2	3.5	61.75

Goal

The goal of our project was to make a master heat recommendation to reduce the percent cracked parts and percent of parts requiring rework. Our project also aimed to identify the temperature range in the process these parts were cracking.

Technical Approach

Data analysis was performed on historical master heat chemistries, to determine if any particular alloying elements played a significant role in either cracking or rework percentages, or both. Microstructural analysis was performed on cracked airfoil samples received from PCC to examine the crack surface as well as the surrounding matrix. An oxidation experiment was conducted to understand oxidation of this alloy under controlled conditions across a range of temperatures. This was done to identify a temperature range in the process shown in schematic 1 where the cracking in parts was occurring.



Schematic 1. Showing the process for all parts

Experimental Procedure

Cracked Specimen Analysis

The as received airfoils were sectioned in the transverse direction to the crack to reveal the crack in cross-section. These sections were then mounted in Bakelite and polished to 1 µm using only SiC paper and diamond paste. The use of alumina suspension was omitted to avoid contamination of the oxide layer present at the crack surface.

These specimen were examined using optical and scanning electron microscopy to characterize the shape of the crack and surrounding microstructure.

Master Heat Chemistry

PCC Airfoils provided both cracking and rework percentages for 51 master heats along with the chemistry of each heat. Statistical analysis of this data was performed to identify key alloying elements that played a role in cracking and high levels of rework.

Oxidation Experiment

Cylindrical runners received from PCC Airfoils were sectioned into disks approximately 1 cm in thickness. These were mounted in Lucite, to avoid the elements in Bakelite affecting the SEM data, and polished to 1µm using SiC paper and diamond paste and removed from their respective mounts. Three specimen were placed in a box furnace under lab air for 1 hour at 1000˚F, 1200 ˚F, 1400 ˚F, 1600 ˚F, 1800 ˚F, and 2000 ˚F. Specimens were removed, allowed to air cool to room temperature. These specimens were remounted to aid in the preservation of the oxide layers. The samples were then polished carefully into the cross section to reveal the oxide layer and matrix metal. The oxide layer was examined in cross section using Scanning Electron Microscopy.

Results

Master Heat Chemistry Analysis

This analysis shown in figure 1 was preformed for all of the controllable elements. Hafnium showed the strongest correlation to crack and rework percentages.

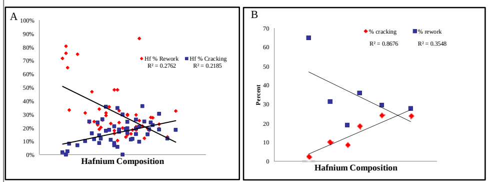


Figure 1. Plots of statistical analysis that were performed on the provided heat chemistry data. Plot A was generated from the complete data set of heats. Plot B was generated from master heats that contained similar compositions in all elements besides hafnium.

Oxidation Testing

Figure 2 represents an oxidation sample from 2000ºF which shows an oxide layer and the corresponding composition is shown in figure 3.

EDS Analysis of Oxidation Layer

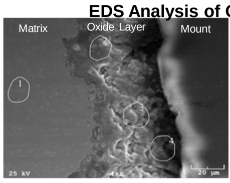


Figure 2. Secondary Electron SEM image showing oxide layer that resulted from exposure to 2000ºF for 1 hr.

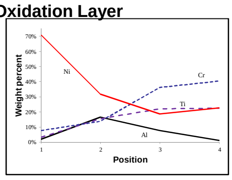


Figure 3. Displays the change of composition in weight percent of four elements over the distance of the oxide layer shown in Fig. 2.

SEM Dot Mapping

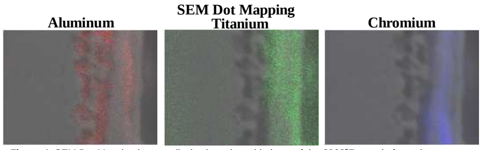


Figure 4. SEM Dot Mapping images display how the oxide layer of the 2000ºF sample forms in separate layers, aluminum forming the first layer, followed by titanium, and outside layer of chromium.

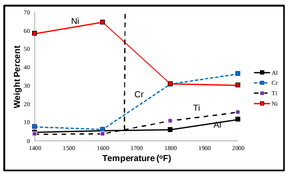
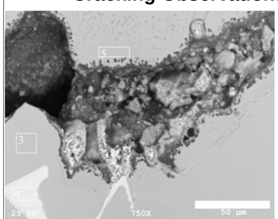
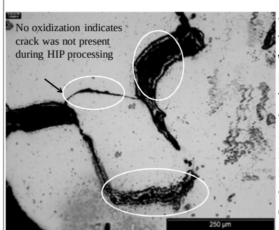


Figure 5. Displays the average elemental composition in weight percent in the oxide layer of four elements for the temperature range of 1400ºF to 2000ºF. Samples to the left of dashed line are a combination of matrix and oxide layer due to the spot size being to large relative to oxide thickness.

Cracking Observations of cast parts



- **Figure 6** (left) shows a crack in a tip shroud that has been completely through processing as shown in schematic 1
- Depleted zone in area 3 shows a depletion of chromium likely due to the formation of the oxide layer
- Area 5 has a spike of chromium, and aluminum due to those oxides readily forming



- **Figure 7** (left) shows the two forms of cracking that were present in the parts provided that have been through processing
- Oxides in the cracks on right and lower of the figure indicate crack present before high temperature regime
- The crack on the left has no oxides indicating it occurred in a low temperature regime or during handling

Discussion

Master Heat Chemistry Analysis

- Statistical analysis showed a strong correlation between the amount of hafnium and cracking/rework as shown in figure 1.
- Figure 1 shows a strong correlation of hafnium by holding other elements constant and observing the composition with cracking and rework percentages. Since hafnium showed opposite trends with cracking and rework a trade off was necessary.
- Cracked parts are more expensive than reworking which caused the recommendation of chemistry to weigh towards an increase in rework percentage to accommodate the reduction of cracking.
- Other elements were analyzed in a similar fashion in order to determine their effects on the solidification of GTD-444.
- After identifying all of the minor alloying elements that had a correlation to cracking a master heat chemistry was recommended to PCC.
- This recommended chemistry was used in the production of trial parts and produced zero cracks and low reworking percentages based on the initial trial parts produced to date.

Oxidation Testing

- Comparing the received samples and the oxidation testing shows that the parts had been through an oxidation processing that is above 1700ºF.
- Figure 5 shows the increase in oxide layers as the temperature increases
- The extent of this effect was shown in an attempt to highlight the amount of oxidation that occurs in the samples received. It allowed for the for the identification at what temperature range the oxidation is occurring and identifies the process step where cracks are occurring.
- Testing shows that the oxide layer is composed of primarily aluminum, titanium and chromium with chromium and titanium in the outermost layers and an aluminum oxide present through out the scale.
- Oxides produce a depleted zone near the surface which is most evident in the chromium dot map. The titanium dot map provides an idea of how this process occurs in a gradient and is only present near the oxidized surface.

Cracking Observations

- From optical imaging two different types of cracking were observed.
  - Cracks with filler particles were present before a high temperature regime
  - Cracks without filler particles were not present in high temperature regimes could be due to handling, mounting, or polishing
- SEM showed that the composition of the interior of the crack was composed of Al, Ti, and Cr oxides.
- Areas adjacent to the crack were depleted in aluminum and chromium

Recommendations

From the statistical analysis, a recommended heat chemistry was cast resulting in comparably low cracking and reworking percents in initial trials. The statistical analysis method should continue to be used in order to identify cracking an reworking correlations with heat chemistry. To better understand the heat chemistry correlation to cracking and reworking microstructural analysis of a cracked sample before the HIP and heat treatment stages should be preformed.