Proceedings of ASME Turbo Expo 2011
GT2011
June 6-10, 2011, Vancouver, British Columbia, Canada

GT2011-45743

MECHANICAL PROPERTY VARIABILITY OF CAST NI-BASE SUPERALLOY IGT COMPONENTS

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ABSTRACT

Reliable life predictions are economically vital to the Industrial Gas Turbine (IGT) Original Equipment Manufacturer (OEM). Improper understanding of component life can lead to a shortened service life interval, or in the worst case, component failure and forced outage. To understand component life, and assure safe life operation, components are qualified by demonstrating that the predicted stresses do not exceed the material capabilities. Predicted stresses are typically calculated through the Finite Element Method (FEM), while allowable material capabilities are determined using materials properties from an engineering design materials database.

The materials properties in the engineering design materials database are dependent on variables such as alloy chemistry and heat treatment, which are understood and included in allowable tolerances per qualification specification limits. The current approach for materials characterization to support IGT design is primarily with separately cast slab or bar material. This standardized material testing method is intended to encompass the properties for the multitude of components cast with that material. Whilst this approach tests the compositional properties, it does not take into account the significant influence of the material property dependence on dimension/geometry and position within a component. Since the quality of the design of a component is so closely related to the materials properties, it is imperative that the materials database data accurately represent the component material.

In this paper, the sources and magnitude of variability found in a cast turbine blade is investigated by testing samples machined from production cast turbine blades. These blades are cast from a polycrystalline Nickel-base superalloy commonly used for hot gas path turbine components. In order to improve design criteria, and accurately determine component life, a broader understanding of variability effects is needed.

As hypothesized, the engineering design materials database properties derived from cast slab/bar material are not necessarily representative of the local properties in critical regions of the components. Additionally, variations in local properties were discovered due to location in the component, and dimensions/geometry of the specimen.

The understanding gained in this investigation enables the IGT OEM to more reliably design components through a better understanding of the properties in the life limiting locations of a component. Optimizing the manufacturing processes to enhance these properties at specific locations within the component provides an additional capability to improve overall component reliability. Overall, this understanding allows for improved reliability of the IGT design life and makes use of the full potential of the chosen material for maximum economic benefit.

INTRODUCTION

Design Material Properties

Industrial Gas Turbine (IGT) original equipment manufacturer (OEM) components are designed to withstand the severe environment within the engine, and must continue functioning throughout their intended lifetime. Accurate projections of individual component service limits, failure margins, and risk, are an important aspect of the overall engine maintenance plan, and thus have a significant influence on the commercial success of the engine. Overly conservative life projections result in premature or unnecessary service costs, while non-conservative life projections can allow unexpected component failure and engine damage to occur. Therefore, much emphasis must be placed on understanding and modeling the parameters that influence the operability of the components over their lifetime.

Qualification of these components for service operation is typically fulfilled through numerical simulations with Finite Element Method (FEM) analyses of the geometry, loading, and operating conditions, and an evaluation of the anticipated failure mechanisms. The predicted component temperature, stress, and failure mechanisms are then compared with the relevant material strengths from an engineering design materials database. Parts or components are qualified if they demonstrate that the numerically predicted stresses do not exceed the design allowable material capabilities, such as ultimate, yield, fatigue, or creep rupture strengths.

To assure a low risk of failure, the design process includes conservative assumptions and safety margins to account for uncertainties in calculating the component boundary conditions, as well as minimum material properties. These minimum material properties are intended to account for variations in material properties and their dependence on manufacturing variables, such as heat treatment and chemistry. It has been found that the material property variation for the multitude of components cast with a material can be very large, often an order of magnitude. Since the design of a component is strongly dependant upon the materials properties, it is imperative that the materials properties database accurately describe the component's material properties.

A source of this discrepancy between the engineering design materials properties and the actual component material properties has been indicated to be a function of the material source used for the engineering design material property curves. Typically, engineering design material properties are created from a collection of separately cast slabs and bars, see Figure 1, a traditional approach that is followed for feasibility of test material cost and specimen design flexibility. Although the material chemistry and casting process is representative of the component, the geometry and resulting grain structures often do not correlate to the many regions of the component. Thus, the engineering design material properties may not be representative of the actual properties in the critical regions of specific components.

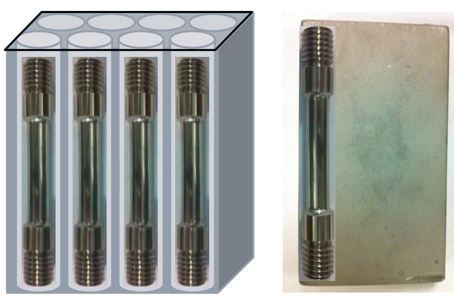

Figure 1. Engineering Design Database generated from separately cast slab/bar material.

Component Material Properties

To assure quality material requirements are satisfied in component manufacture, the material is verified to satisfy specifications limits through chemical and strength tests. Each Master Heat ingot of alloy is tested in this way for proper chemistry content, and sufficient material properties, prior to ingot melt and casting pour. This single test is expected to eliminate any deficient material early in the manufacturing process. If it exceeds the specification limits, many parts may be cast from this single Master Heat, as depicted in Figure 2.

As one could expect, there could be significant material property variation between and within Master Heats, even though the qualification tests satisfy the specification limits.

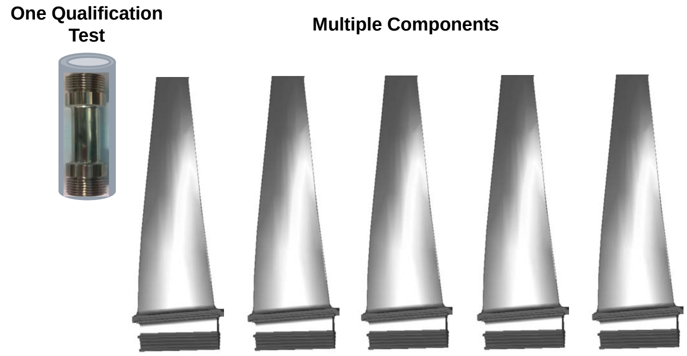

Figure 2. A single Qualification test approves material Master Heat (batch) for use in multiple parts.

Additionally, there can be significant material property variation within each part. This can be a result of casting variations in different regions of the parts [1], such as microstructure and grain structure, as well as the location and shape of the local region. For example, thin regions of a casting cool much more quickly than thick regions, resulting in smaller grain size, while casting gate design can influence the solidification process in other ways.

It is assumed in design that the Master Heat and component material variations are accounted for through the use of material design minimum properties. However, since the standardized test approach for the engineering design data is only intended to capture the compositional properties, it does not take into account the other influences of variability caused by the overall dimensions and position within a component. While microstructure and chemistry influence on properties have been extensively researched, there is a practical need to broaden the understanding of the actual component material property variability.

EXPERIMENTAL PROCEDURE

To investigate the sources and magnitude of variability found in turbine components, testing of production cast turbine blades was undertaken to compare against the engineering design database and Master Heat qualification data. A key feature of the turbine blade used for this analysis is the large variations in section size through the span of the blade. This allows for testing of dimensional/geometrical and positional effects within the blade. Creep rupture strength was chosen as the critical property for this component, and is expected to be sensitive to the material variations observed.

Material

The material chosen for this investigation is a gamma prime strengthened polycrystalline Ni-base superalloy (nominal chemistry can be found in Table 1 below).

Table 1. Nominal Ni-base superalloy chemistry.

Element	Ni	W	Co	Cr	Al	Ta	Hf	Ti	Mo	C	B	Zr
Alloy Chemistry	Bal	9.5	9.25	8.25	5.6	3.2	1.4	0.75	0.5	0.07	0.015	0.01

To ensure a consistent test data set, all testing was performed on the same style turbine blade, in the final production condition. The blades were even coated and processed for environmental purposes, as they would be before being installed in an engine. A template of the blade specimen positions (Figure 3a) coupled with water jet machining, assured accurate control of specimen blank location. Then, specimens were electrical discharge machined (EDMed) from the center of the blanked area, and metallurgically inspected, to remove all environmental coating and ensure only base material properties are present.

Test Specimens

To have an adequate understanding of the material variation, 180 specimens from 10 blades were tested (Table 2). To accommodate the blade thickness differences throughout the part, two styles of specimens were fabricated. A smaller diameter specimen (Figure 3b), was machined near the thin blade tip and trailing edge, and a large diameter specimen (Figure 3c) was machined from the thicker material available lower in the blade.

Testing Approach

To align with previous investigations, and the qualification tests, all creep rupture testing was performed at 760°C 690MPa., in accordance with the testing procedures outlined in ISO 204[2]. All testing was completed at the same test vendor, in a randomly assigned order to reduce bias in the test data.

Table 2. Specimen planned distribution for machined from component specimens.

Specimens per Blade		
Location	**Specimen Geometry**	**Quanity**
Upper Airfoil	Small Diameter Specimen	6
Mid Airfoil	Small Diameter Specimen	3
Mid Airfoil	Large Diameter Specimen	3
Lower Airfoil	Large Diameter Specimen	6
Total specimens per Blade		***18***
Total specimens (10 Blades)		**180**

Table 3. Engineering Design Database distribution statistics.

Engineering Database Material (Data points= 48)			
Goodness-of-Fit	**Weibull**	**Normal**	**Lognormal**
Anderson-Darling (adjusted)	2.87	2.951	0.675
Correlation Coefficient	0.937	0.848	0.981

Table 4. Qualification and Component distribution statistics.

Qualification Material (Data points=114)			
Goodness-of-Fit	**Weibull**	**Normal**	**Lognormal**
Anderson-Darling (adjusted)	0.598	3.667	1.306
Correlation Coefficient	0.991	0.907	0.971
Component Material (Data points=180)			
Goodness-of-Fit	**Weibull**	**Normal**	**Lognormal**
Anderson-Darling (adjusted)	0.806	2.034	1.598
Correlation Coefficient	0.995	0.984	0.976

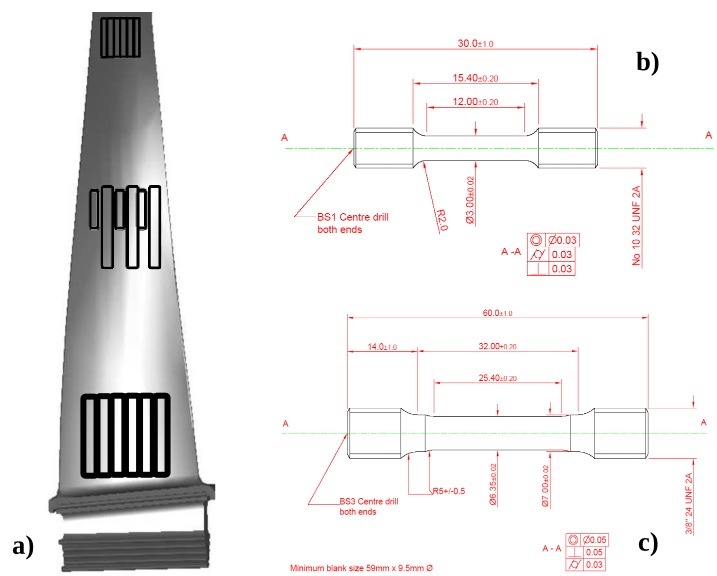

Figure 3. Machined from component specimen location template, and specimens drawings.

RESULTS AND DISCUSSION

The primary objective of this paper is to investigate the sources and magnitude of material property variability found in a cast turbine component. Creep rupture life was selected as the critical property for investigation, with three sources of material for comparison, 1) the engineering design database, 2) Master Heat qualification 3) and machined from component material.

In order to compare data from the engineering design database to that taken from qualification and blade specimens, all data in this investigation was normalized to the engineering design database average curve fit of creep rupture life. This normalization provides a consistent baseline for comparison of all the test results.

Additionally, a consistent statistical distribution was selected to allow comparison of the variations of each dataset. The best fit statistical distribution for the engineering design database data is a lognormal distribution, as indicated by the smaller Anderson-Darling statistic and higher Pearson correlation value (Table 3), and is typical of creep data [3]. While the best distribution fit for the qualification and component materials is not necessarily lognormal (Table 4), each of the following descriptive histograms is fit with a lognormal distribution for consistency of data comparison. Box plots and scatter plots are fit to a normal distribution and thus are used only for illustration purposes.

Overall Material Variation

The initial scale of variation investigated in this paper is the difference between the engineering design database, Master Heat qualification material, and machined from component material (Figure 4). This comparison provides an overall understanding of the difference between these sources of material properties that could be used in the component design process.

The Engineering design database data includes material compiled from a variety of casting vendors, master heats, test specimens, and test conditions. These 48 test data points were compared to a best fit curve of the overall trends of this data. With this normalizing factor, the distribution is centered at 1.0, and has a normalized variation (Figure 4a).

The Qualification data are all compiled from the same casting vendor and at a single test condition (760°C/690MPa). At the time of this study, there had been 114 Master Heat qualification tests completed as part of the normal blade production process. Based on the test results, it can be seen that there is a significant amount of variation in this data, which almost appears random over the range plotted (Figure 4b). Clearly, this data does not describe the component material. Therefore this data set is disregarded for the rest of this paper.

As described previously, 180 specimens, from 10 blades, and five Master Heats, were selected to evaluate the as manufactured material properties. These Component data show a consistent behavior with the engineering design database. Although the scatter is somewhat higher, the mean is near 1 as in the engineering design database (Figure 4c).

A direct comparison of the descriptive statistics of the Engineering design database and Component Material tests is shown in Figure 5. Although the mean for each does not vary considerably, the standard deviations of each data set is different (Table 5). Since design curves are based on minimum curves, this causes a large shift in the property curves that would be used for design.

Table 5. Mean and Standard Deviation of the Material Data Sets (based on Lognormal distribution).

Data Set	Mean (LN)	Std (LN)	Data Points
Engineering Database Mater	1.05	1.57	48
Component Material (All)	1.27	1.81	180

Table 6. Mean and Standard Deviation of the Heat to Heat Variation (based on Lognormal distribution).

Data Set	Mean (LN)	Std (LN)	Data Points
Heat 1	1.26	1.79	36
Heat 2	0.72	1.43	36
Heat 3	1.13	1.78	36
Heat 4	1.69	1.50	36
Heat 5	1.89	1.64	36

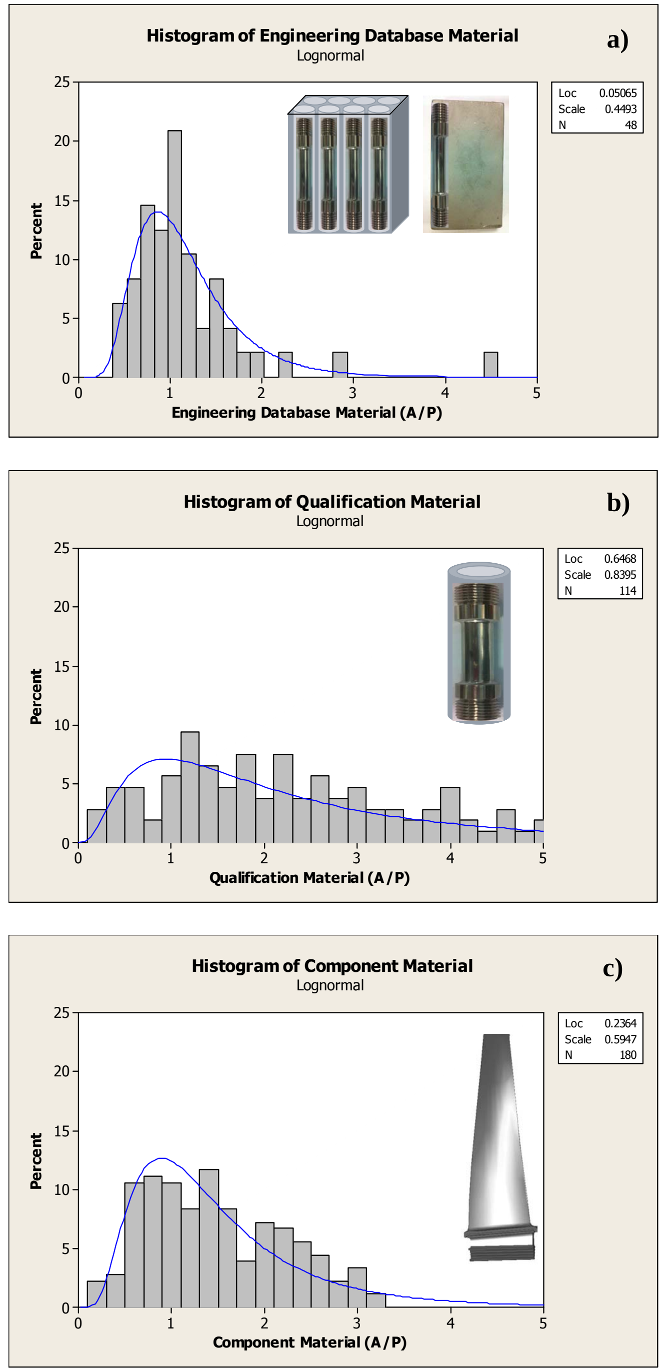

Figure 4. Histograms of a) Engineering Design Database, b) Qualification tests, and c) Machined from component tests.

Master Heat Variation

A potential point of uncertainly is known to be master heat to master heat variation. In this test program, there are 36 component test data points for each heat. Figure 6 shows the variation of master heat within the components tested. As can be seen in the figure, variation between heats is significant.

Each heat was also fit to a lognormal distribution to evaluate the mean and standard deviation (Table 6). As mentioned above, heat to heat variation ranges from a mean of 0.72 to 1.89 of the engineering database, but the variation remains relatively consistent between 1.43 and 1.79.

Location Variation

To evaluate the effect of the component location on the material properties, a systematic testing of the blade locations was completed. For the thicker sections near the base of the blade, referred to as the lower and mid airfoil, a larger diameter specimen was used. For the upper airfoil of the blade in which section thickness is limited, a smaller diameter specimen was used. At the mid airfoil, smaller diameter specimens were also tested to allow for direct comparison of the data collected for the upper airfoil.

As displayed in Figure 7a, and Table 7, there is little scatter between the lives of the mid and lower airfoil. However, the upper and mid airfoil vary in mean and standard deviation with more than 2 times variation in mean (Figure 7b and Table 7).

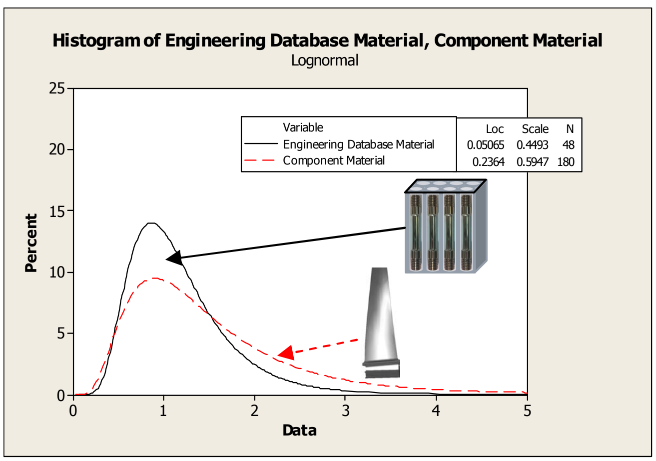

Figure 5. Comparison of Engineering Design Database and Machined from component tests distributions.

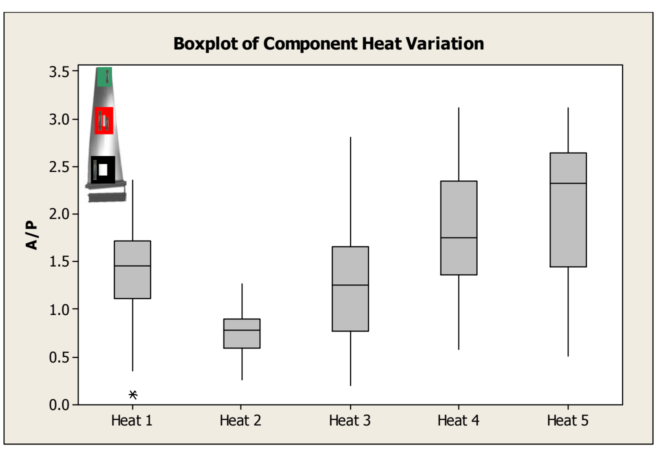

Figure 6. Master Heat to Master Heat Variation.

Table 7. Mean and Standard Deviation of the Material Data Sets (based on Lognormal distribution).

Data Set	Mean (LN)	Std (LN)	Data Points
Component Material (All)	1.27	1.81	180
Lower A/F Large Specimen	1.18	1.68	60
Mid A/F Large Specimen	1.46	1.68	30
Mid A/F Small Specimen	0.78	2.06	30
Upper A/F Small Specimen	1.61	1.61	60

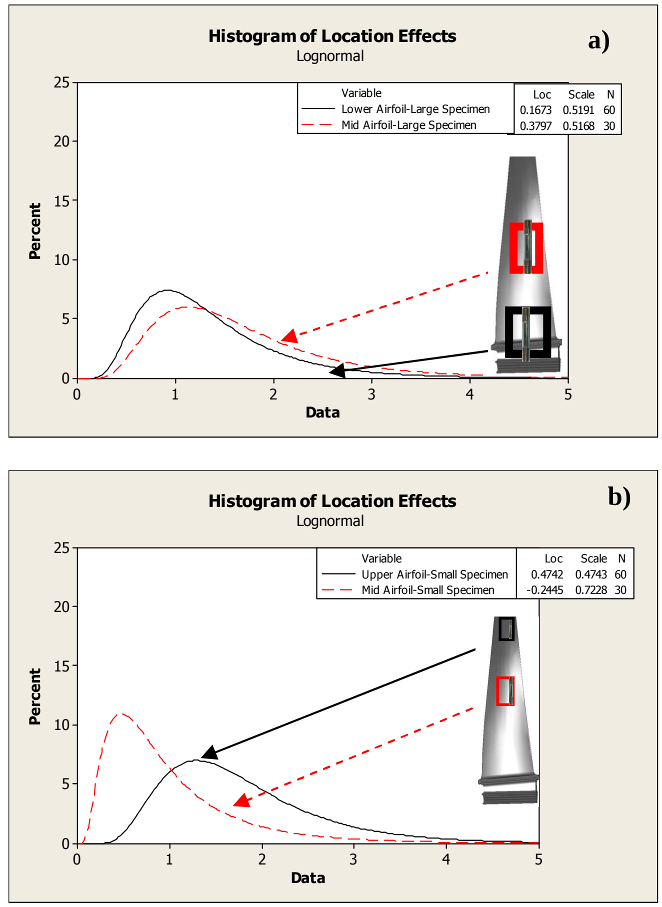

Figure 7. Component Material Location Variation

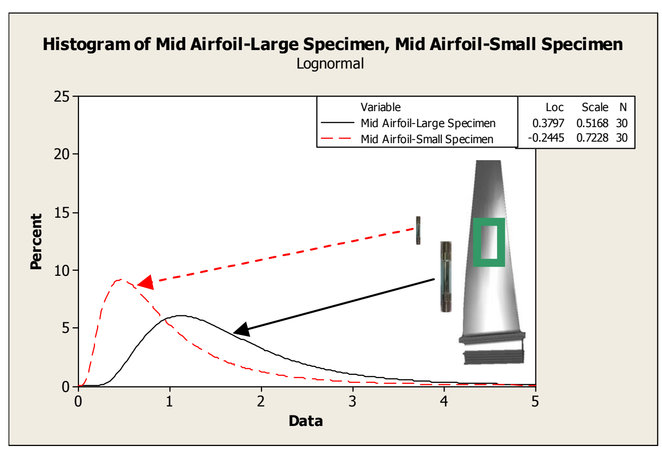

Figure 8. Specimen Size/Geometry Variation

Geometry Variation

From the previous section of blade testing, an understanding of the effect of specimen geometry can also be made. To accommodate a comparison of both the lower and upper airfoil, the mid airfoil was tested as both the large and small diameter specimen.

Figure 8 shows the variation in distribution fit of the large and small diameter specimens. An almost 2 times variation in mean is observed between the large and small diameter specimens from the same location (Figure 8 and Table 7). This can considerably affect the expected life for a single location within a component.

Master Heat Variation, Same Location

To illustrate the influence of master heat on blade to blade variation between the same locations in the components, a collection of the master heat data from the three distinct testing locations from the blade was fit to a box plots for each airfoil location. Figure 9a shows that within each location, a large variation in properties from master heat exists. This reflects the same trends seen in Figure 6. Figure 9b shows that a general trend exists within each blade that the lower and mid airfoil have similar properties while the upper airfoil has improved properties.

Modeling Uncertainty

In addition to material data scatter, there is considerable uncertainly from modeling. There is not a general approach to creep modeling that is representative of every material type, or that can accurately describe both long and short term behavior. Additional studies have also found that creep life predictions do not accommodate the scatter in creep life data and service-induced material degradation [4].

Even using a single model, variation exists due to uncertainty in the fit of the data. Using the parametric Bootstrap approach it is possible to assess this uncertainty using the Monte-Carlo simulation technique. In essence the Bootstrap method is based on the understanding of a basic statistical concepts that the life-time distribution can also estimated by sampling from the underlying distributions, and propagating the uncertainties through the lifing model [5, 6]. Based on the number of data points, and distribution within the material scatter, the curve fit (green lines) is relatively consistent (Figure 10), compared to the material property variation presented previously in this paper. Therefore, it is much more important to understand the material variation than the form of the life model.

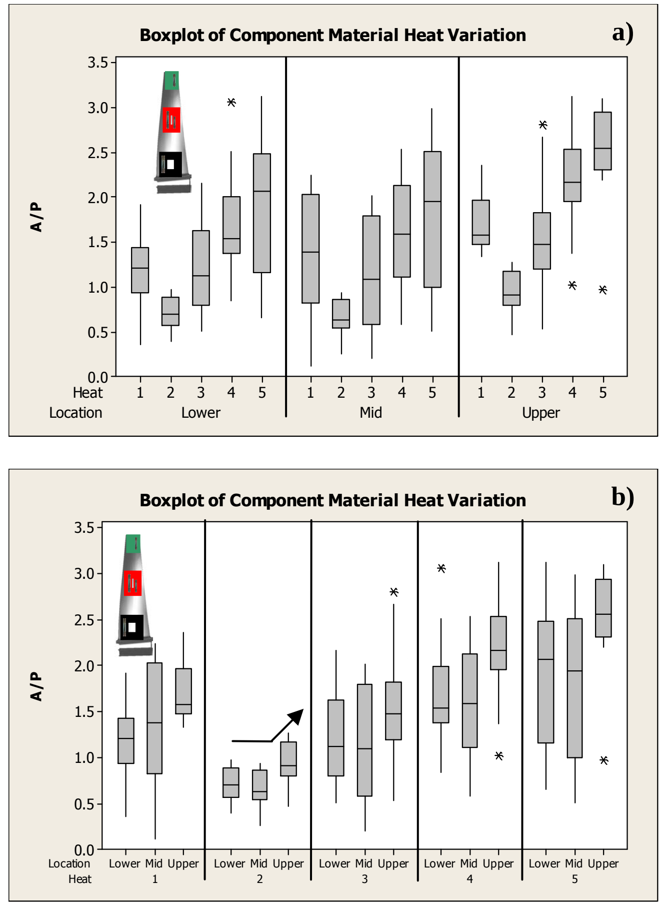

Figure 9. Component Material a) master heat variation and b) location variation.

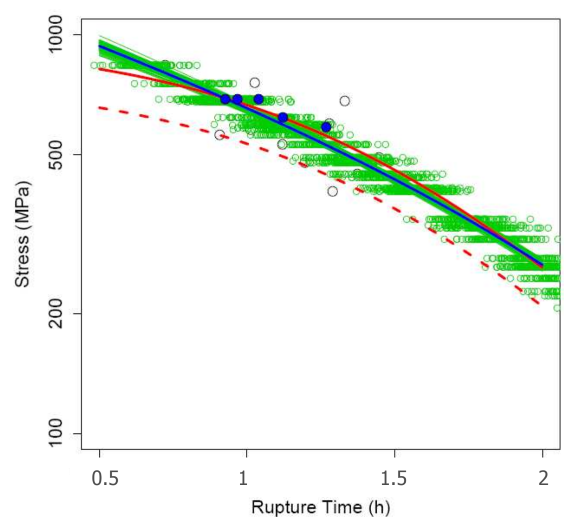

Figure 10. Uncertainty of Curve Fit of Normalized Engineering Database Material

CONCLUSIONS

The investigation of true materials properties is economically imperative to IGT OEM's operation. This paper shows that the engineering design data, or qualification data employed to qualify a master heat of material, is not sufficient to describe the component materials properties in all regions. It was also found that minimum properties based on engineering (slab/bar) data with safety factors do not correlate with component data distribution.

A different approach is suggested in which parts are designed to the critical life limiting areas of a component using relevant material properties. In addition, customized processing is suggested to optimize the life of a component at these location. This allows the design to make use of true material and manufacturing process capability, improving the reliability and accuracy of the IGT design life.

NEXT STEPS

To truly understand the processing variability scatter of a component, a more systematic study will be conducted in which testing will be performed on a single master heat. This additional evaluation of the material data variation is recommended to fully understand the life of a component. Furthermore, a detailed metallurgical analysis of the critical element chemistry and microstructure is suggested, in order to better clarify the cause of the large master heat variation.

ACKNOWLEDGMENTS

The authors would like to thank the following individuals at Siemens Energy for their support and knowledge: Cynthia L. Darling for support in developing a statistically significant test matrix; Dr. David W. Hunt for background knowledge of material scatter in components; Georg Rollman and Chirag B. Patel for curve fitting of engineering database material based on the Bootstrap Method.

PERMISSION TO USE

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