2016 University Turbine System Research (UTSR) Gas Turbine Industrial Fellowship Program

Final Report

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Introduction

Materials Technology is a global group within Siemens Energy with operations in in the United States, Germany, and China. This internship was hosted at the Charlotte, NC campus where the group's primary focus is research and development with respect to metals and coatings. They perform a wide variety of tasks ranging from material analysis, material selection, consulting work, and experimental work, with their primary concern being technology development. Interning for them has been a valuable learning experience that has been a great introduction into the gas turbine industry. This internship provided the opportunity to become more proficient with various materials topics as well as gain insight into the daily life as a materials engineer in the gas turbine industry.

The work performed during this fellowship can be broken down into three general components: data analysis, literature review, and a proposal for experimenting with metallic foams. Though discussed as separate topics, quite a few of the projects overlapped, requiring both data analysis and literature review. The data analysis and literature review that was performed will be briefly described in this report; however, the bulk of this report will be summarizing the proposed experiment.

Data Analysis

There were several projects that required analyzing data. One of the projects consisted of analyzing High Cyclic Fatigue (HCF) data in order to generate a Haigh diagram. This diagram is used by the design engineering team to determine if the material in question can withstand the vibratory stress of engine operation in the proposed design. Another project consisted of comparing creep data of different alloys. In another project, raw data was given in order to compare the rate of erosion of Thermal Barrier Coatings (TBC) currently under development.

Literature Review

A substantial part of the literature reviewed was for material comparisons. Mechanical and physical properties of similar alloys were compared through extensive literature search including published papers, material data sheets from vendors, and through the use of the company's materials database. After obtaining a general idea of their properties, presentations were created in order to easily see how the materials compared. A similar process was also used in order to determine trends for materials that were not within the company's material data base. Rather than making a presentation, a data package was created where all the information gathered about the material was combined into one source and used to determine a general trend in properties. After having a general idea of a material's properties, a specific property curve can be estimated and uploaded to the company's database to be referenced or used in the design process. Another task was to perform patent searches in order to determine the composition of various superalloys. One of the projects assigned was to create a comprehensive overview of metallic foams, discussing their properties, production methods, current uses, and their potential for use in the gas turbine industry. This project was further developed to create the experimental proposal described in this report.

Proposal

Metallic Foams for Industrial Gas Turbine Use

Abstract

The technological developments in the gas turbine industry have been all about increasing efficiency. One of the potential technologies or materials systems that could help in increasing the efficiency of a gas turbine is metallic foams. The properties of superalloys as metallic foams have not been extensively researched. Specifically, literature on the mechanical properties of superalloys as foams are severely lacking. The purpose of the proposed study is to expand on the knowledge of the mechanical properties of superalloy metallic foams using IN625 as a starting point. This study will utilize a total of 125 samples of IN625 undergoing various heat treatments (temperature range from 25 °C to 1100 °C), metallurgical analyses, physical testing, and mechanical testing.

Introduction

Industrial gas turbines (IGT) operate in environments with continuous cyclic exposure to high temperatures, strenuous mechanical loads, and are under constant exposure to corrosive and erosive factors. This harsh environment encourages the further development of technologies that would provide environmental protection while improving overall power generation. Several technological improvements allow the operation in increasingly severe environments including: changing chemical compositions, optimizing the components such as with complex cooling patterns, and the use of directionally solidified and single crystal blades. The evolution of coatings from simple bond coats to more complex thermal barrier coatings in combination of complex cooling schemes allow for turbine components to operate in conditions above the alloys melting point. All these technological advancements have one goal in mind: to increase efficiency and power. The increase in efficiency is a main driver of technological advancement. Currently, one of the most efficient IGT, a combined cycle turbine, is operating at 61.5% efficiency with inlet temperatures of 1,600°C [1]. This leads to the question "What is the natural progression of technological advancement that would lead to higher efficiencies?" There are numerous technologies that could attribute to this goal; one such technology is metallic foams. Currently, metallic foams have found uses in the aerospace industry as seals between stages in the engine and as structural parts in the turbines [2]. Their properties such as their low density, high temperature and mechanical stability, vibration dampening, and resistance to oxidation and corrosion [3] make them an option worth exploring for possible application within the IGT industry.

A greater part of the research that has been conducted on metallic foams use aluminum as the primary metal; however, there have been efforts to produce foams from other metals such as steels, zinc, and magnesium [4]. Few studies have been published on the use of superalloys as foams. Nickel based superalloy foams have been developed [5-7] and the technology exists to foam superalloys [8]. The mechanical properties of these foams have not been fully explored. Choe et al performed a study on the compressive creep properties of Ni-Al and Ni-Cr- Al superalloy foams at elevated temperatures. They found that Ni-Al foams have creep rates higher than Ni-Cr-Al foams. Both Angel et al and Queheillalt et al formed foams based upon Inconel 625 (IN625), a nickel-chromium based superalloy. Neither paper looked extensively at the effects of high temperature on the mechanical properties of IN625. Angel et al performed compression tests in temperatures up to 600°C, finding that compressive strengths are slightly reduced at increasing temperature and increased at higher densities. Queheillalt et al also performed compressive tests, finding the Young's modulus and yield strength's to be comparable to theoretical models, with no further exploration of mechanical properties. Both papers primarily focused on the foaming technique required to form the foam.

The focus of this proposal will be on furthering the knowledge of the mechanical properties of superalloy foams, in this case: IN625. The proposed experiment would perform tests that would mimic an IGT environment: high temperatures and high mechanical loads. The intended tests include temperature (SEM, density, porosity), creep, tensile, and fatigue tests.

Materials and Methods

Experimental design:

This study would utilize a total of 125 samples of IN625 (composition found in Table 1) undergoing various heat treatments and mechanical tests. The number of samples per test was chosen was based on Mead's resource equation (non-blocked) to ensure the data is statistically relevant.

$$E=N-T \qquad \text{(Eq. 1) [9]}$$

Where E is the degrees of freedom in error and should be between 10 and 20, N is the degrees of freedom in the number of samples, T is the degrees of freedom in the number of treatments. For example, according to this equation, 16 samples are required in order to be statistically relevant for the heat treatment test (T=3). This allows for 4 samples per temperature and test. Samples will be tested at 25°C, 500°C, 800°C, 1100 °C. These temperatures were chosen in order to create a range of temperatures typically experienced in an IGT. The maximum tested temperature was based upon the melting temperature of IN625 (1290 °C-1350 °C) [10]. The samples will undergo mechanical testing as well as a heat treatment with subsequent physical testing. Samples will be machined with a diamond saw in order to minimize cell damage [12]. All tests will follow recommendations made by Ashby et al in "Metal foams: a design guide" and/or Banhart in "Manufacture, characterisation and application of cellular metals and metal foams".

Ni	Cr	Fe	Mo	Nb (+Ta)	C	Mn	Si	P	S	Al	Ti	Co*
58.0 min	20.0-23.0	5.0 max	8.0-10.0	3.15-4.15	0.1 max	0.50 max	0.50 max	0.015 max	0.015 max	0.40 max	0.40 max	1.0 max

Table 1. IN625 composition. *If determined [10]

Foam Production

As Siemens does not produce its alloys in house, it would be up to the vendors to decide on the optimal route based on specifications given to them. These specifications could include properties such as porosity and pore size, density, and composition. Metallic foams can be foamed through several different routes, as seen in Figure 1. Due to the high temperature melting point of the IN625, the vendor would most likely want to go a powder precursor route. This would reduce cost as heating to IN625's melting point would not be required.

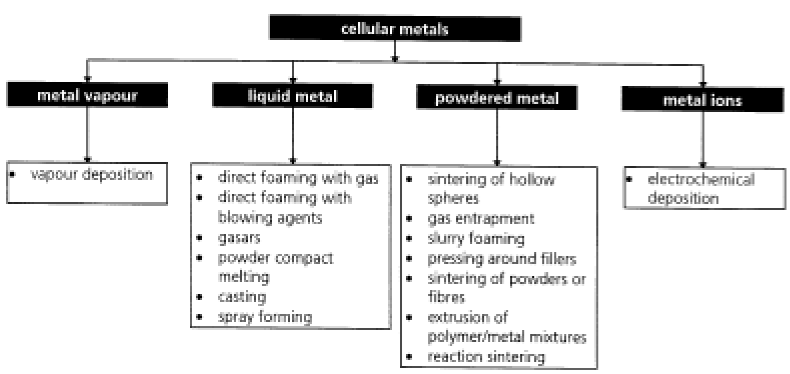

Figure 1. Methods for forming metallic foams [2].

It is suggested using a method similar as to what was described by Angel et al would result in a foam suitable for the proposed testing. Angel et al formed the foam through a process called Slip Reaction Foam Sintering (SRFS). This process is based on a metallic suspension, where metallic powders are mixed with a dispersant, solvent, and concentrated phosphoric acid. This process is visually described in Figure 2. As mentioned previously, Queheillalt et al formed a foam based on IN625. The foam was formed by converting reticulated polymer foam into carbon foam, which was used as a template for metallic particle coating. However, the final structure had a carbon core, which would not be suitable for the desired purpose. Thus the SRFS process would be more desirable.

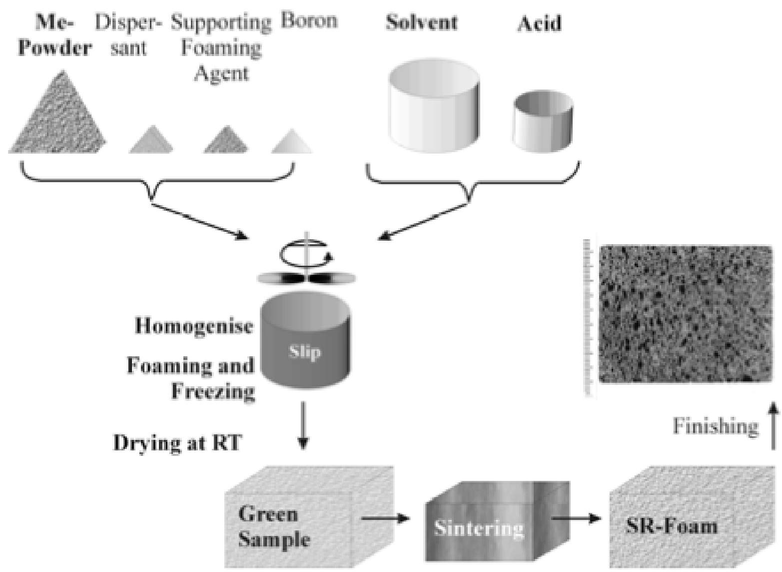

Figure 2. Slip Reaction Foam Sintering (SRFS) process [5].

The processing parameters would need to be adjusted in order to make the foam more suitable for the desired application. This would include optimizing density, pore size, and porosity.

Test Matrix

Treatment / Temperature (°C)	Samples							
	Heat Treatment & etc.	**Creep Test**			**Tensile Test**	**Fatigue Test**		
		100h	300h	1kh		1k c	10k c	100k c
25 (°C)	4	-	-	-	4	4	4	4
500 (°C)	4	5	5	5	4	4	4	4
800 (°C)	4	5	5	5	4	4	4	4
1100 (°C)	4	5	5	5	4	4	4	4

Heat Treatment, Physical Testing, and Metallographic Testing

As seen in the test matrix, a total of 16 samples will undergo heat treatment, physical testing, and metallographic testing. 4 samples will remain at room temperature (25°C) and all other samples will be placed into furnaces at 500°C, 800°C, and 1100°C with 4 samples per temperature. Samples will be held at temperature for 10 hours. They will be rapidly quenched in order to retain the microstructure. Samples will undergo density testing via mass measurements and Archimedes' principle. Pore size analysis will be completed to see if porosity remains constant. Samples will then be polished following metallographic standards and imaged with a scanning electron microscope (SEM). According to Figure 3, phase change begins to occur at higher temperatures. It is expected to find presence of carbides in samples treated at 1100°C (2012°F) and 800°C (1472°F).

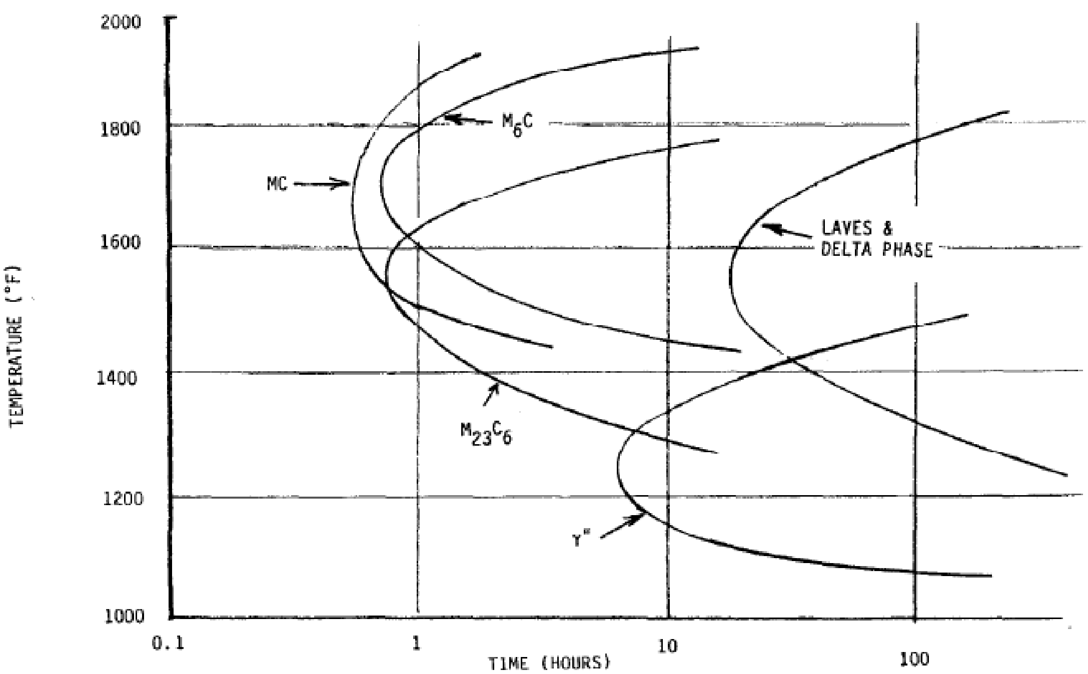

Figure 3. TTT diagram for A625 at high temperatures [11].

Mechanical Testing

Samples will undergo creep, tensile and fatigue tests. Typical standards for each test will be followed and all mechanical tests will be run at 500°C, 800°C, and 1100°C. Tensile and fatigue tests will also be run at 25°C. As seen in the test matrix, 16 samples will undergo tensile testing, fatigue tests will have 48 samples, and creep tests will have 45 samples. Tensile samples will be machined to shape, following ASTM E8-96a (or the Siemens equivalent), where the thickness should be at least seven times the cell size [12]. The type of fatigue test, whether it be low cycle or high cycle, will be determined based on the intended use of the foam. They will be performed at 1000 cycles, 10000 cycles, and 100000 cycles. Creep tests will be performed at 100 hours, 300 hours, and 1000 hours. The number of cycles for the fatigue test and the time duration for the creep test were chosen in effort to give a broad range of data.

Conclusions and Justification

Metal foams are a class of novel materials with a wide variety of applications. Their low density, high temperature resistance, and dampening properties give them the potential for use in the IGT industry. Metallic foams have already been implemented in the aerospace industry as structural components in turbines and as seals. As jet turbine engines and IGT are very similar, new technologies and developments in one industry could be implemented in the other, though not without some caveats. For example, replacing structural components in an IGT with metallic foams would not be feasible due to load limitations.

Previous studies for aluminum metallic foams have found that the fatigue strength of aluminum foams are comparable to full dense aluminum alloys but have lower creep ductilities than solid aluminum alloys [12]. Assuming that these trends are consistent with properties of foams in general, the expectant results of this study are that the properties on IN625 as a foam are comparable in some aspects, but primarily the properties should be less than that of solid IN625. Though the properties of foamed IN625 are expectant to be less than solid IN625, it still could have value in IGT applications. Azzi [8] suggested an application for the use of a nickel based metallic foam in a jet engine that would increase efficiency by reducing thermal cycling. This design suggests placing a ring of open cell metal foam directly in front of the turbine blades in order to create a more uniform temperature profile. In a jet turbine, placing metal foam in front of the turbine blades would aid in heat transfer, allowing the heat from the combustion chamber to mix with the cooler air from the primary air stream that surrounds the turbine blades. The more uniform temperature profile would lead to higher operating temperatures and thus an increase in efficiency [8]. A similar idea, with modifications, could be implemented in an IGT.

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