CREEP CHARACTERISTICS OF AUSTENITIC STAINLESS STEEL FOIL AT ELEVATED TEMPERATURE

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ABSTRACT

High efficiency and compact recuperator with thin foil corrugated air cell as the primary surface is employed in clean and efficient microturbine system (100 kW). Current primary surface recuperators are made of AISI 347 austenitic stainless steel foils that operate at gas inlet temperature of less than 650 °C and attain approximately 30 percent of efficiency. Efficiency of greater than 40 percent is possible with the increase in turbine inlet temperature to 1230 °C, and as a result recuperator inlet temperature increase to 843 °C. This study establishes base line creep rupture behaviour of AISI 347 austenitic stainless steel foils at operating temperature of 700 °C and applied stress of 100 MPa. Creep behaviour of the foil shows that the primary creep stage is short and creep life of the foil is dominated by tertiary creep deformation. The time to rupture for the foil specimen is 184 hours with the corresponding rupture strain of 8.6 percent. Creep curves for AISI 347 austenitic stainless steel foil at 700 °C, 100 MPa are represented by the modified Theta-Projection concept model with hardening and softening terms. The creep coefficients, θ_1 and θ_3, and the exponent α are -0.6849, 0.6726 and 0.0038 respectively. Theta-Projection parameters values of experimental creep at temperature of 700 °C and applied stress of range 54-221 MPa shows a sudden gradient change at applied stress of 150 MPa possibly due to different mechanism of dislocation movements and microstructure changes. Two different creep failure mechanisms for austenitic stainless steel foils are possible since the creep failure data falls very close to the boundary of dislocation and diffusion creep regions in the creep mechanism map for bulk material.

ABSTRAK

Kecekapan yang tinggi dan padat oleh penukar haba atau pemulih dengan sel udara berkerajang nipis terlipat sebagai permukaan utama digunakan dalam sistem turbin mikro bersih dan cekap (100 kW). Permukaan utama penukar haba terkini diperbuat daripada AISI 347 kerajang austenit keluli tahan karat yang beroperasi pada suhu salur masuk gas kurang daripada 650 ° C dan mencapai kira-kira 30 peratus daripada kecekapan. Keberangkalian mencapai kecekapan melebihi 40 peratus adalah dengan peningkatan suhu salur masuk turbin sehingga 1230 ° C, dan oleh itu suhu salur masuk pemulih meningkat kepada 843 ° C. Kajian ini menetapkan garis asas gaya laku pecah rayapan-pecah AISI 347 kerajang austenit keluli tahan karat pada suhu operasi 700 ° C dan tekanan gunaan 100 MPa. Gaya laku rayapan kerajang menunjukkan bahawa peringkat rayapan utama adalah mempunyai hayat yang pendek dan rayapan kerajang dikuasai oleh ubah bentuk rayapan ketiga. Masa untuk rayapan-pecah untuk spesimen kerajang adalah 184 jam dengan tekanan rayapan-pecah sebanyak 8.6 peratus. Lengkungan rayapan-pecah untuk AISI 347 kerajang austenit keluli tahan karat pada suhu 700 ° C, 100 MPa diwakili oleh konsep Unjuran-Theta terubahsuai dengan pengerasan dan terma pelembutan. Pekali rayapan, θ_1 dan θ_3, dan eksponen α adalah -,6849, 0,6726 dan 0,0038, masing-masing. Nilai Unjuran-Theta terubahsuai rayapan-pecah eksperimen pada suhu 700 ° C dan tekanan gunaan dalam lingkungan 54-221 MPa menunjukkan perubahan kecerunan yang mendadak pada tekanan gunaan 150 MPa kerana mekanisme yang berbeza pergerakan dan penempatan perubahan mikrostruktur. Dua kegagalan mekanisme rayap bagi kerajang austenit keluli tahan karat adalah kerana data kegagalan rayap jatuh menghampiri sempadan kawasan dislokasi dan peresapan di dalam peta mekanisme untuk bahan tebal.

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LIST OF ABBREVIATIONS

AISI	-	American Iron and Steel Institute
ASME	-	American Society of Mechanical Engineers
ASTM	-	American Society for Testing and Materials
CHP	-	Combined Heat and Power
Cr	-	Chromium
DG	-	Distributed Generation
EDX	-	Energy Dispersive X-ray Spectroscopy
FESEM	-	Field Emission Scanning Electron Microscope
HHV	-	Higher Heating Value
kW	-	kilowatt
LVDT	-	Linear Variable Differential Transformer
Mo	-	Molybdenum
MTG	-	Microturbine Generation
MW	-	Megawatt
Nb	-	Niobium
Ni	-	Nickel
ORNL	-	Oak Ridge National Laboratory
PID	-	Proportional-Integral-Derivative

NOMENCLATURE

ε_0	-	Instantaneous strain
ε_{cr}	-	Creep strain
$\varepsilon_{primary}$	-	Primary creep
ε_t	-	Total strain
$\varepsilon_{tertiary}$	-	Tertiary creep
°C	-	degree Celcius
s^{-1}	-	rate per second
t	-	Creep time
T	-	Operating temperature
T_m	-	Melting temperature
wt. %	-	Weight percentage
α	-	Rate constant
θ_1, θ_3	-	Parameters describing the primary and tertiary stages
θ_2, θ_4	-	Rate parameters characterize the curvature of the primary and tertiary stages

CHAPTER 1

INTRODUCTION

1.1 Background of Research

In recent years, it is widely accepted that Microturbine Generation (MTG) systems are exerting a pull on meeting customers' needs in the distributed-power-generation market. The main challenges facing the industrial companies are to provide a clean, efficient, reliable and affordable heat and power system. Microturbine is becoming known as a leading candidate in meeting the needs because of its size, potential for a relatively low cost, efficient and clean operations. They are used for stationary energy generation applications at sites with space limitations for power production.

Microturbines are ideally suited for distributed generation applications due to their flexibility in connection methods, ability to be stacked in parallel to serve larger loads, ability to provide stable and reliable power, and low emissions. Microturbines run at high speed and can be used either in power-only generation or in combined heat and power (CHP) systems. The size range for microturbines available and in development is from 30 to 250 kilowatts (kW), while conventional gas turbine sizes range from 500 kW to 250 megawatts (MW) [1].

Figure 2 shows the general flow of microturbine-based CHP systems. Typical microturbine generator system includes a compressor, combustor, turbine, alternator, recuperator and generator. Recuperated units use a sheet-metal heat exchanger that recovers some of the heat from an exhaust stream and transfers it to the incoming air stream. Microturbine Generations are small, high-speed power plants that usually include the turbine, compressor, generator and power electronics to deliver the power to the grid. These power plants typically operate on natural gas [2].

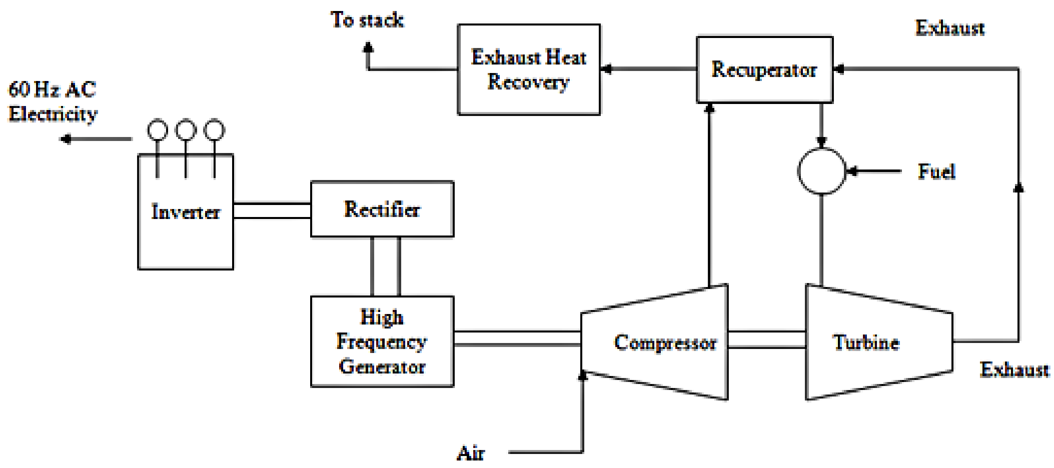

Figure 1.1 Microturbine-Based CHP System [2].

In a microturbine, a radial flow (centrifugal) compressor compresses the inlet air that is preheated in the recuperator using heat from the turbine exhaust. Then the heated air from the recuperator mixes with fuel in the combustor and hot combustion gas expands through the expansion and power turbines. The expansion turbine turns the compressor and turns the generator as well. Finally the recuperator uses the exhaust of the power turbine to preheat the air from the compressor [2].

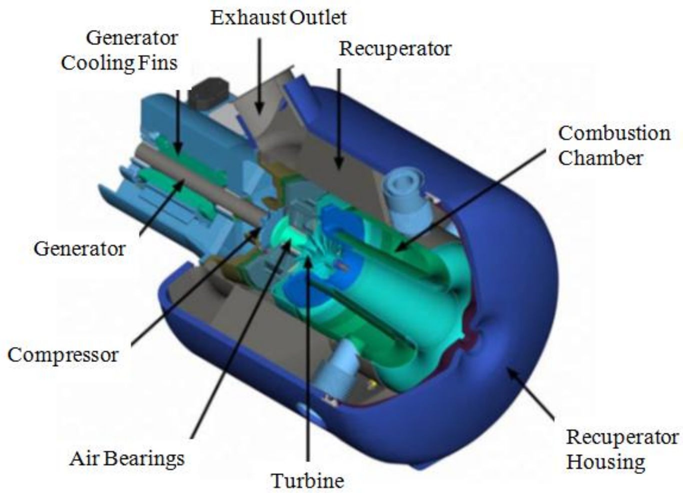

Figure 1.2 Microturbine Generation (MTG) Components [2].

Recuperator is a heat exchanger that uses the hot turbine exhaust gas (usually around 650 °C) to preheat the compressed air (usually around 150 °C) going into the combustor, thereby reducing the fuel needed to heat the compressed air to turbine inlet temperature. Clean and efficient microturbine system (100 kWe) employs compact, high efficiency heat-exchanger or recuperator with thin-foil folded air cell as the primary surface [3]. The corrugated pattern of the cell maximizes the primary surfaces area that is in direct contact with turbine exhaust gas on one side and compressor discharge air on the other. Figure 3 shows the illustration of the corrugated air cell construction in a typical recuperator.

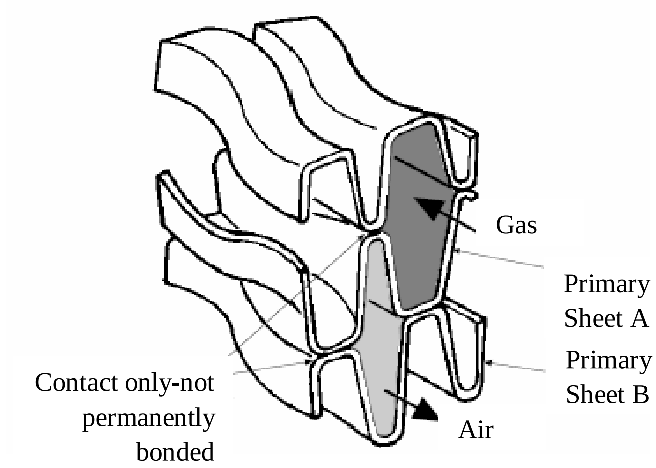

Figure 1.3 Primary surface sheets of compact heat exchanger surfaces [3].

Microturbine combined heat and power system efficiency is a function of exhaust heat temperature. Recuperator effectiveness strongly influenced by the microturbine exhaust temperature. Effectiveness in heat exchanger industry is for ratio of the actual heat transferred to the maximum achievable. Most microturbines include built in recuperator. The inclusion of a high effectiveness (90 percent) recuperator essentially doubles the efficiency of a microturbine with a pressure ratio of 3.2, from about 14 percent to about 29 percent depending on component details [1]. With the addition of the recuperator, a microturbine can be suitable for intermediate duty or price-sensitive base load service.

Current primary surface recuperators are made of AISI 347 stainless steel foils that operate at gas inlet temperatures of less than 650 °C and attain about 30 percent efficiency [4]. Efficiency target of greater than 40 percent is possible for low-compression ratios such as 5, with the increase in turbine inlet temperature to 1230 °C, and consequently recuperator inlet to 843 °C. At this elevated temperature level, the steel foils are susceptible to creep failure due to the fine grain size, accelerated oxidation due to moisture in the hot exhaust gas and loss of ductility due to the thermal aging. Severe creep deformation able to restrict gas flow, increase recuperator back-pressure and decrease overall efficiency.

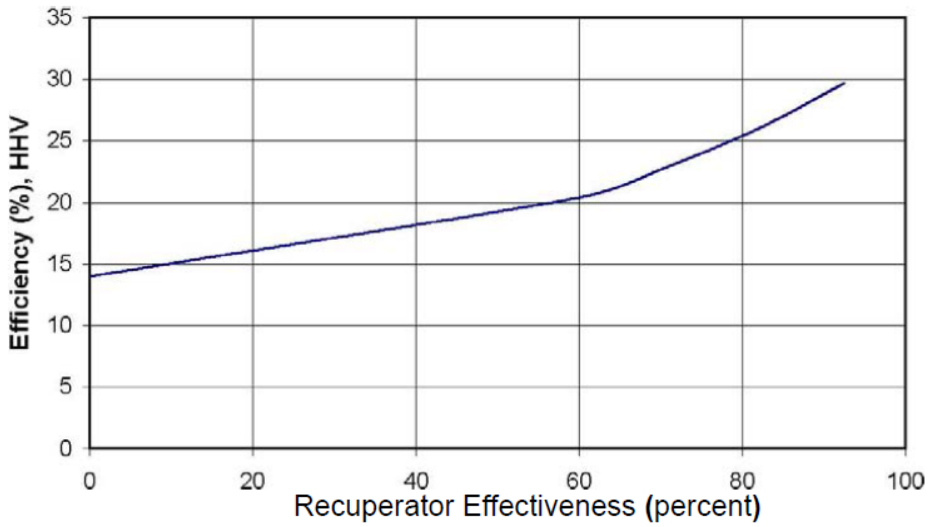

Figure 1.4 Microturbine efficiency as a function of recuperator effectiveness [1].

Creep deformation is mutually accommodated by a combination of elastic deformation, localized plastic deformation, non-uniform creep, grain boundary sliding and diffusion flow through grains, along grain and free surfaces [5]. The first step in developing recuperators with upgraded performance is to characterize the current technology. combination of oxidation and corrosion behaviour, and tensile and creep strengths determine the upper temperature and useful lifetime limits. In this respect, creep tests on commercial AISI Type 347 steel recuperator stock has been conducted [6]. Aging effects on the steel up to 30,000 hours above 700 °C has been established in terms of detrimental sigma phase formation [7].

Several stainless alloys including modified alloy 803 (25Cr, 35Ni), alloy 230 (22Cr, 52.7Ni, 2Mo) and alloy 120 (25Cr, 32.3Ni, 0.7Nb, 2.5Mo) showed better creep strenghts at 750 °C than AISI 347 stainless steel but at noticeable increase in materials costs [8]. Properties and behavior of AISI 347 steel is generally known for processing and fabrication into high-temperature components such as heat-exchanger piping and gas turbine parts. However, information on these alloys fabricated into thin foils (0.1-0.25 mm) for use in primary surface recuperators is limited or nonexistent.

Austenitic stainless steels are among the most widely used alloys for components operating in high temperature environment, in heat exchanger or recuperator and nuclear reactors. Hence characterizing the current AISI 347 steel foil for improvements in creep resistance at the expected extreme operation temperature condition is necessary.

1.2 Research Objectives

The objective of this study is to establish baseline creep characteristic and deformation mechanisms of AISI 347 austenitic stainless steel foils at elevated temperature of 700 °C and 100 MPa through the following tasks:

a) to establish tensile stress-strain diagram of the foil at room temperature
b) to establish creep curve of the foil at 700 °C and 100 MPa
c) to determine creep model for the foil based on Theta projection concept
d) to identify creep mechanism of the foil.

1.3 Scope of Study

The study covers for AISI 347 austenitic stainless steel foils with thickness of 0.25 mm. Microstructure and chemical composition analysis are performed on the as-received foil. Tension tests of the foil are conducted at room temperature. Creep tests are performed in laboratory air environment at isothermal temperature of 700 °C. The applied stress is 100 MPa. Fractographic study is carried out on the fractured foil specimen. Creep models are developed for describing the long-term creep deformation behaviour of the foils.

1.4 Significance of Study

There are numerous engineering components are working under higher temperature and are reaching their design life. Those components for instance aero engine turbine blades, nuclear power plant steam pipes, high pressure boilers and micro turbine. During long term service, the material has typically degraded and material damage has occurred. The material creep behaviour has to be characterized in order to properly judge the remnant creep life or to extend the service lifetime.

High efficiency heat exchangers are being developed for new distributed power technology systems particularly microturbines system. Recuperator is the part of microturbines that is responsible for a significant fraction of overall efficiency. Recuperators often require thin-section of austenitic stainless steels operating at elevated temperature ranges up to 800 °C. Most of the recuperators used austenitic stainless steel of Type 347 because of its oxidation resistance properties and competitive cost. At high temperatures which above 650 °C with the presence of moisture environment of the turbine exhaust gas, the material is susceptible to creep and oxidation. These will cause fouling and structural deterioration and leaks, rapidly reducing the effectiveness and life of the recuperator. Therefore the study is to establish creep characteristics and deformation mechanisms of AISI Type 347 austenitic stainless steel foils at 700 °C and 100 MPa.

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