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Creep and creep-rupture of Alloy 617

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ABSTRACT

The Ni-Cr-Mo-Co material Alloy 617 is the leading candidate for VHTR intermediate heat exchangers operating above 750 °C. Time-dependent properties are an important consideration in qualifying the alloy for construction of nuclear components. Creep behavior of several different heats of Alloy 617 has been evaluated in the temperature range of 800–1000 °C. Power law creep behavior was observed for the minimum creep rate, with a stress exponent of 5.6 and activation energy of approximately 400 kcal/Mol. The Monkman-Grant approach relating minimum creep rate to time to rupture gave a reasonable representation of the data for all of the testing with a slope of −0.84. Similarly, a modified Monkman-Grant fit the strain to failure data reasonably well. A Larson-Miller analysis was carried out to compare rupture behavior determined in the current experiments and historical data with well-known provenance over a wide range of conditions. It appears that the properties of modern heats of material are near the lower bound of rupture behavior when all of the data are considered in the same analysis.

1. Introduction

Alloy 617 is a commercial nickel based material that is the leading candidate for the intermediate heat exchanger of very high temperature (VHTR) nuclear reactors that are intended to produce process heat for applications such as hydrogen generation in addition to electricity production. In the US the rules for construction of nuclear components are contained in the ASME Boiler and Pressure Vessel (B&PV) Code, and time-dependent properties are an important aspect of qualifying the material for nuclear construction in the Code. Although the material will ultimately be used in a helium environment, and creep testing has been performed in a simulated VHTR environment (Kim et al., 2014a,b), the allowable stress values in the B&PV Code are based on the time-dependent behavior in air. Therefore, creep testing at 800–1000 °C in air is the emphasis of this paper.

Extensive characterization of Alloy 617 properties began in the 1970's and accelerated greatly with the high temperature gas cooled reactor programs that were carried out internationally through the early 1990's. Recently the interest in VHTR technology for process heat applications has resulted in a renewed interest in the creep and creep-rupture behavior of this alloy.

Alloy 617 has superior resistance to creep at temperatures above about 650 °C compared to iron based austenitic alloys including Alloy 800H. Unlike the 300 series stainless steels, for many temperatures and stresses of interest for VHTR applications Alloy 617 does not show clear steady state creep. Under many test conditions the alloy exhibits only an inflection between primary and extensive tertiary creep.

In this paper the results of recent experiments on creep and creep-rupture of Alloy 617 over the temperature range of 800–1000 °C are combined with historical values to present a comprehensive representation of the behavior of this alloy for use in design of nuclear components. Comparability with historical data is significant since modern mill practice incorporates an additional refining step, electro-slag re-melting, which has only recently become standard practice. Most modern heats also tend toward lower cobalt concentrations within the relatively broad acceptable range (10–15%) of the ASTM specification.

The time to creep-rupture of a large data set is described using a Larson-Miller formulation. A Monkman-Grant and modified Monkman-Grant approach are used to relate the time and strain to failure to the measured minimum creep rate. The activation energy for creep is approximated using a Zener-Hollomon approach.

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Table I
Chemical Composition of the Alloy 617 Plate (Weight Percent).

Source		Ni	Cr	Co	Mo	Al	Ti	Fe	Mn	Cu	Si	C	S	B
min	ASTM	44.5	20.0	10.0	8.0	0.8	–	–	–	–	–	0.05	–	–
max		–	24.0	15.0	10.0	1.5	0.6	3.0	1.0	0.5	1.0	0.15	0.015	0.006
VDM	INL	54.1	22.2	11.6	8.6	1.1	0.4	1.6	0.1	0.04	0.1	0.05	<0.002	<0.001
SMC	KAERI	bal	22.16	11.58	9.8	1.12	0.35	1.5	0.1	0.08	0.06	0.08	0.001	0.002
Haynes	KAERI	bal	22.2	12.3	9.5	1.06	0.41	0.95	0.03	0.03	0.08	0.08	<0.002	<0.002

2. Experimental procedure

2.1. Materials

The US VHTR research and development program has performed extensive property characterization on specimens machined from an Alloy 617 reference material plate (Wright et al., 2012). The reference plate is a 37 mm thick solution annealed plate with an average grain size of 150 μm and the composition given in Table 1.

The plate was produced by ThyssenKrupp VDM and supplied in the solution annealed condition. Solution treatment consists of holding at 1175 °C (2150 °F) followed by rapid cooling to room temperature, according to ASTM standards B166 and B168 (ASTM B166, 2011; ASTM B168, 2011). Creep testing has been performed by Idaho National Laboratory (INL) and Argonne National Laboratory (ANL) on specimens machined from this material.

Creep testing has also been performed by Korea Atomic Energy Research Institute (KAERI). Creep specimens tested at 850, 900, and 950 °C were machined from commercial-grade Alloy 617 solution annealed hot-rolled plate produced by SMC with a thickness of 16 mm and a grain size of approximately 300 μm (Kim et al., 2014b, 2015). Specimens tested at 800 °C came from an approximately 16 mm thick plate produced by Haynes (Kim et al., 2014a). The chemical composition of both heats is shown in Table I.

In addition creep-rupture data have been compiled from previous high-temperature reactor programs (NIMS Inconel 617 Stress Rupture Data, 1975; Baldwin et al, 1986; McCoy and King, 1985; Gentzbittel et al., 2007), and data originally generated by Huntington Alloys (now SMC), the vendor developing Alloy 617 (Huntington Alloys Data Package of Inconel 617, 1972; Maitra, 2015). Additional data have been published in the scientific literature (Cook, 1984). The data set has been limited to specimens with known chemistry that were tested in air, and represents multiple product forms and heats.

An optical micrograph showing the microstructure of the INL material from Tyssen-Krupp VDM is shown in Fig. 1. The solution annealed material exhibited equiaxed grains with an average grain size of 150 μm and is characterized by carbide banding parallel to the rolling direction. The bands range from approximately 100–300 μm wide. Within the carbide banded regions, the carbides form on what appears to be a prior sub-grain structure that is finer and independent of the present grain boundary structure as shown in Fig. 1. This microstructure is thought to be representative of most modern heats of Alloy 617, reflecting the current mill practice and the high temperature solution treatment.

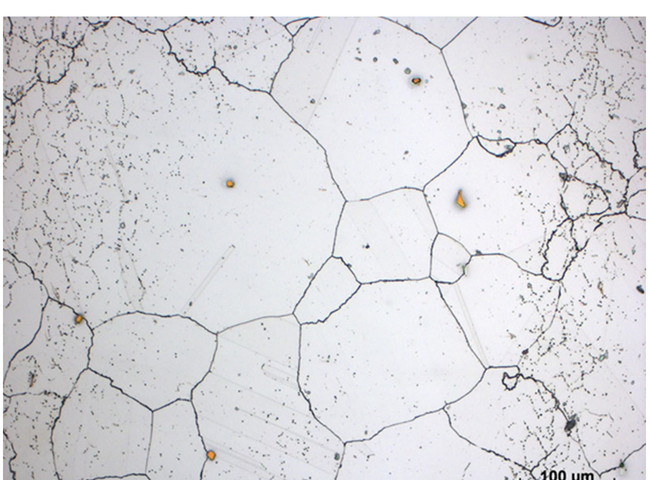

Fig. 1. Optical image of the microstructure of solution annealed Alloy 617.

2.2. Creep testing

2.2.1. INL

Cylindrical creep specimens, with nominal 6.35 mm reduced section diameter and gage length of 32 mm were machined in conformance with ASTM E 139 (ASTM E 139, 2011). Testing was performed in the range of 750–1000 °C using direct loaded creep frames with dead weight loading, with the exception of 750 °C tests which utilized a 20:1 lever arm. The specimen temperature was controlled to within ±3 °C of the target test temperature. Dual averaging LVDT transducers or Heidenheim linear encoded photoelectric gauges were used to monitor strain during the creep tests to a resolution of better than 0.01% strain. Most tests culminated in creep-rupture; however, in some cases creep tests were interrupted at a pre-determined strain for purposes of microstructural analysis.

2.2.2. ANL

Smaller cylindrical creep specimens, with a nominal 3.96 mm reduced section diameter and a reduced section of 19 mm were creep tested at 750, 850, and 950 °C. Direct-load creep frames were used to test the specimens with an LVDT extensometer to monitor strain. A three-zone furnace was used with test specimens centered in the middle furnace zone and the specimen temperature profile maintained within ±1 °C of the desired test temperature. The creep test was completed when the specimen ruptured and the system provided automatic cooldown (Natesan et al., 2012).

2.2.3. KAERI

Cylindrical creep specimens with a 30 mm gauge length and a 6 mm diameter, with the axis aligned with the rolling direction were tested. Load frames used a lever-arm ratio of 20:1. Strain was measured using an extensometer. Creep tests were controlled to ±2 °C during testing within the split three-zone furnace used for heating the specimen. Tests were performed at 800, 850, 900, and 950 °C for a range of stress levels following ASTM E139 (Kim et al., 2014a,b; Kim et al., 2015).