Materials Science & Engineering A 710 (2018) 47–56

Contents lists available at ScienceDirect

Materials Science & Engineering A

journal homepage: www.elsevier.com/locate/msea

Effect of thermal aging on microstructure, hardness, tensile and impact properties of Alloy 617

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ARTICLE INFO

Keywords:
Alloy 617
Thermal aging
Tensile strength
Microstructure
Fractographs

ABSTRACT

Influence of thermal aging on microstructural evolution and its effect on hardness, tensile and impact properties have been studied for Alloy 617. Aging was carried out at 1023 K up to 20,000 h duration on a solution annealed as-received alloy. Detailed microscopic investigation of the alloy revealed the precipitation of γ´ phase (rich in Al and Ti) along with $M_{23}C_6$ carbides during aging treatments. Thermal aging has imparted increased hardness and strength, however with decreased ductility and toughness. Yield stress (YS), though initially increases up to 5000 h of aging, and has shown a decreasing trend from 5000 to 10,000 h. Further aging up to 20,000 h has shown an anomalous increase in YS. Charpy impact test for 20,000 h aged sample showed a reduction in fracture energy (~ 85%) w.r.to as-received material along with a shift in fracture mode from transgranular ductile to intergranular brittle. The change in hardness and YS in aged Alloy 617 has been attributed to the aging-induced evolution of γ´ precipitates. The intergranular fracture associated with lower impact energy, as observed after prolonged aging duration, has been attributed to the grain boundary embrittlement originating from precipitation of $M_{23}C_6$ carbides at the grain boundaries.

1. Introduction

Globally, the fossil-fired power plants are facing technological challenges to maintain a critical balance between the ever increasing demands of electricity generation while simultaneously addressing the global warming issues by ensuring lower greenhouse gas (CO_2) emission. Towards doubling the electrical energy generation in coming decades [1] with aforesaid constrains, steam temperature between 973–1033 K and a pressure of 35 MPa have been envisaged in fossil-fired power plants. It is imperative that higher the steam temperature, the higher is the efficiency [2,3] of the plants. To this end, proper selection of the materials for the high-temperature components is mandatory to ensure component's integrity during the service conditions. In this domain, the Ni-based superalloys as a group of materials are showing acceptable physical, mechanical and chemical properties. One such potential candidate material is Alloy 617, which can adequately operate at temperatures well above 1073 K [4]. Alloy 617 is a class of solid-solution strengthened, austenitic [5] and tungsten-free superalloy [6]. It is expected to retain its creep strength well above 1073 K /35 MPa [7] and has excellent oxidation-reduction resistance [8] even at very high-temperature.

Alloy 617 has a face-centered cubic (FCC) structure [9], which is believed to draw its strength mainly from the solid solution strengthening mechanisms owing to elements like Mo and Co. However, during the exposure at higher temperature regime, formation of intermetallic compounds of type (Ni_3 (Ti, Al)), commonly known as γ´ precipitates have been widely reported in literatures [4,10]. In addition to this, there are reports for the formation of Cr-rich $M_{23}C_6$ carbides, often segregated at the grain boundaries after longer duration of aging [11]. This indicates towards aging induced microstructural evolutions, which would ultimately influence the mechanical properties of this alloy after long term exposures to the service temperatures.

Though this alloy might possess acceptable mechanical properties in the as-received condition, the effect of thermal aging on important mechanical properties in consequence to the microstructural evolution is always a matter of concern for the designers. Benz et al. [12] has reported that this alloy has a very high propensity for precipitation and microstructures evolution occurs even in aging for one hour at 1023 K. Though there have been efforts in literature to evaluate the mechanical properties, they are often restricted to the shorter duration of aging treatments [4,13–16]. Kirchhöfer et al. [13] has reported an increase in the hardness from 160 to 240 HV after an aging treatment on 973 K/1000 h. Ren et al. [14] has also reported that this alloy achieved the same level of hardness even for a shorter duration of aging, i.e for 973 K/100 h. For the tensile tests, Guo et al. [15] has reported an increase in yield stress (YS) up to 250 MPa for the aging condition on

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http://dx.doi.org/10.1016/j.msea.2017.10.078
Received 20 June 2017; Received in revised form 8 September 2017; Accepted 24 October 2017

Table 1
Chemical composition (wt%) of Alloy 617 employed in this study.

Elements	Ni	Cr	Co	Mo	Fe	Mn	Al	C
wt%	Bal.	22.1	11.6	9.4	0.12	< 0.01	1.2	0.06
Elements	Cu	Si	S	Ti	N	Nb	Vd	B
wt%	< 0.01	< 0.1	0.001	0.4	0.005	0.02	< 0.05	0.0036

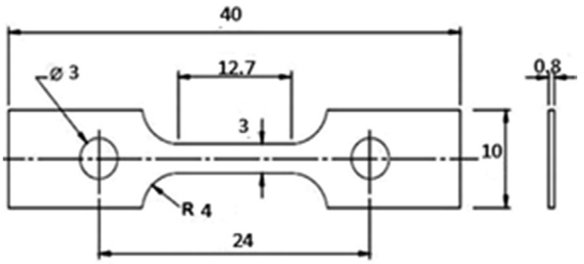

Fig. 1. Schematic representation of a miniaturized tensile specimen with given dimensions in mm.

1033 K/1000 h, with a decreasing trend for further aging treatments up to 3000 h. Nanstad et al. [16] reported a drop of 36% degradation of impact energy even after aging on 1023 K/ 200 h w.r. to 250 J for as-received specimen. Guo et al. [15] have also reported a significant reduction in the impact energy for the first 300 h of aging at 1033 K as compared to the as-received material. In spite of these efforts, an unequivocal conclusion regarding the role of microstructural evolution and the relevant mechanical properties is yet to be reached, especially after the long aging treatment. This paper envisages interpreting the mechanical properties like hardness, tensile behaviour, and Charpy impact energy of an Alloy 617 in the light of the microstructural evolution after aging treatments up to 20,000 h.

2. Experimental

2.1. Materials

The chemical makeup of the Alloy 617 used in this study is given in Table 1. The as-received alloy was cold finished, solution annealed at 1443 K and water quenched to retain a single phase FCC structure prior to aging. The specimens were received in tubular form with following dimensions: inner diameter (ID) of 28.1 ± 0.25 mm, a thickness of 11.9 ± 0.25 mm and a length of 700 mm. The thermal aging of the tubes was carried out in a muffle furnace. The aging conditions were maintained at 1023 K ± 2 K for 1000, 5000, 10000 and 20,000 h respectively followed by air cooling.

2.2. Characterization of microstructure, hardness, tensile and impact energy

Microstructural studies were carried out on as-received and thermal aged materials by light microscope (LM). For LM studies, the samples were prepared using 1 µm diamond polishing after the conventional mechanical polishing to obtain a mirror finished surface. For etching the polished surfaces, Aqua-regia (3HCL:1HNO_3) was used for the as-received one. For the aged material, electrolytic etching with a solution of 60% HNO_3 and 40% H_2O was carried out at room temperature (RT), using 1.5 V DC for time durations of 5–120 s.

Thin foils up to 80 µm thicknesses used for carrying out transmission electron microscope (TEM) studies of precipitates evolved during the aging treatments were also sectioned from the Charpy impact tested specimens with an initial dimension of 10 × 10 mm^2. Subsequently, discs of diameter 3 mm coupons were punched out to follow twin-jet electropolishing. The electrolyte used for jet thinning was 20% Perchloric acid ($HClO_4$) in a Struers Tenupol-5® at a temperature of about 243 K (± 1 K) at 15 V. The identification of phases and chemical characterization of precipitates were carried out by a combination of selected area electron diffraction (SAED) and energy dispersive spectroscopy (EDS) analysis.

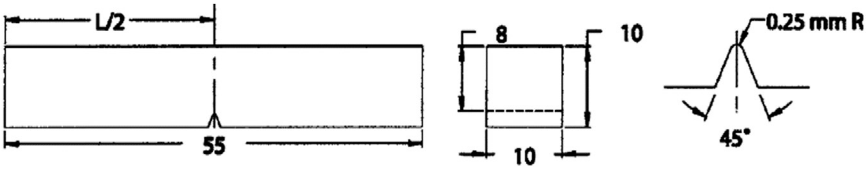

Fig. 2. Schematic representation of a Charpy impact specimen with given dimensions in mm.

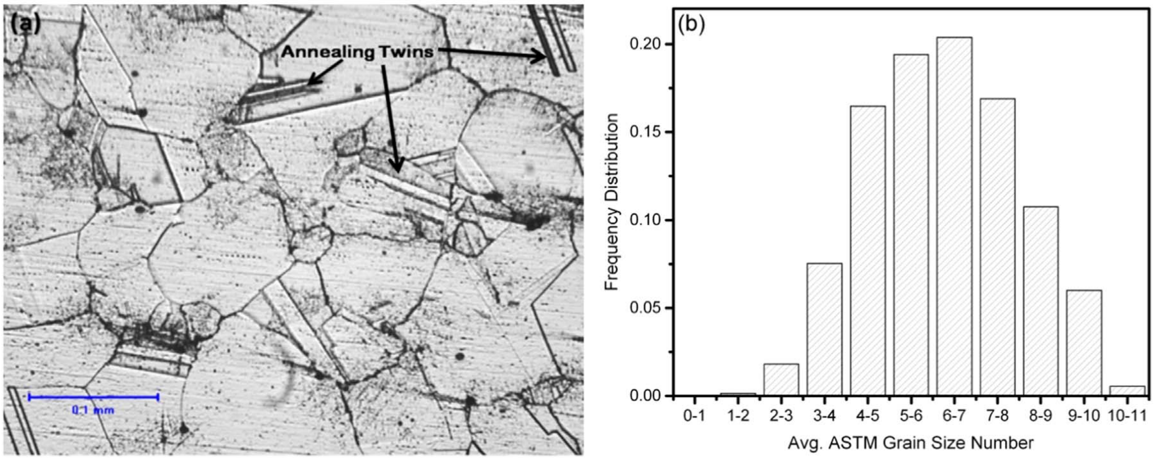

Fig. 3. Light micrograph of Alloy 617: (a) Microstructure of as-received condition, (b) Frequency distribution of the grain size in Alloy 617 vs ASTM number for the as-received condition.