Materials Science & Engineering A 641 (2015) 210–214

Contents lists available at ScienceDirect

Materials Science & Engineering A

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

Short communication

Effect of notch geometry on fracture features

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ARTICLE INFO

Article history:
Received 16 March 2015
Received in revised form
15 June 2015
Accepted 15 June 2015
Available online 16 June 2015

Keywords:
Superalloy
Stress triaxiality
Fracture
Dimple
Ridge

ABSTRACT

Fracture is the ultimate *continuum* of a material. Hence, it is possible that the fracture features contain the *signature* of the whole deformation process undergone due to variation in *triaxial state of stress* under tensile deformation. The two dimensional fracture features were correlated with the stress triaxiality ratio where initial inclusion content was unaltered. In order to test that, many tensile experiments of a superalloy were carried out at different notch geometries and fractographic investigation was done extensively to correlate the fracture features (ie., fractured grain size, extent of tearing ridge, dimple diameter and dimple number density) with the tensile properties.

1. Introduction

Superalloys generally exhibit excellent mechanical strength, superior creep properties, good surface stability and first class corrosion resistance in a variety of environments. Alloy 625 under study is a nickel based superalloy rich in alloy additions [1]. These alloys are widely being utilized in the heavy water plant for manufacturing ammonia cracker tubes [2]. These tubes are mainly designed for $\approx 10^5$ h of life time for service. It is evidenced from the open published literature [3] that several cracker tubes occasionally fail much below the anticipated design life of the component. Although the initial tube material is in solution treated and thus single phased condition; microstructures of service exposed alloys are shown to contain precipitation of many phases (i.e., delta, laves, different carbides, γ'' etc.), which has been reported elsewhere [4]. These precipitates cause degradation of mechanical properties liable to their premature failure. There are many studies available in the published domain monitoring both the characterization of microstructure generated [5,6] and evaluation of tensile and work hardening properties [7,8] at different conditions of the present alloy under study; but the studies relating to fracture characteristics to trace the entire deformation and fracture processes for this material are scanty.

It is well established that ductile fracture occurs by damage accumulation process involving void nucleation, growth and coalescence under the influence of favorable plastic strain and the hydrostatic tensile stress [9–12]. Damage is essentially controlled by the chemistry of the material, initial inclusions or second phase particles' fractions with their size/shape distribution, stress triaxility, strain, stress, strain rate, strain path, grain size, initial crystallographic micro-texture and the temperature of deformation [13]. Voids frequently initiate at comparatively small strains, and material failure is mainly controlled primarily by the void growth and coalescence. Void growth is predicted to depend on stress-state in a sensitive manner [14]. The preferred sites for void nucleation are: inclusions, second phase particles, and their interfaces with the matrix; in case of high purity metals, voids can nucleate even at grain boundary triple points also [15]. In Table 1, few nucleation sites of voids as has been experimentally observed by many eminent researchers are listed with the corresponding alloy systems. Under tension, voids nucleate prior to necking but after a neck is formed and hydrostatic stresses develop, the void formation becomes more prominent [27]. The size, shape, density and occurrence of void nucleating particles have strong influence on ductile fracture process. According to Garrison et al. [11], as the fracture process continues, void nucleates at larger particles; grow while voids are nucleated at smaller particles. The process becomes more complex when material contains several types of second phase particles. The fracture surfaces of the alloys failing by ductile nature are generally covered by segments of different sized dimples which coalesce to produce the fracture path consisting of *tearing ridge* [28]. These ridges that generally represent the boundaries where the different planes on the fracture surface met each other are used to locate the crack initiation sites and its propagation paths. The apparent signature of the shear localization is a fracture surface consisting of fine, closely spaced, submicron sized dimples [29] whose widths are much larger than

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http://dx.doi.org/10.1016/j.msea.2015.06.044
0921-5093/

Table 1
Review – void nucleation sites.

Scientists	Year	System	Void/crack nucleating sites
Greenwood et al. [16]	1954	Cu, α-brass, Mg–Ni	Grain boundary
Kear et al. [17]	1967	Ni-alloy	Planer slip bands
Broek [18]	1973	Al–Cu alloy	Within grain body
Chan et al. [19]	1980	α+β Titanium	Twin-matrix interface
Bowen et al. [20]	1986	C–Mn weld metals	Inclusion
Maloney et al. [21]	1989	HY-180 steel	Inclusion-matrix interface
Pardoen et al. [22]	1996	Copper	Cobalt oxide inclusions
Goto et al. [23]	1999	HY-100 Steel	Inclusion-matrix interface
Bandstra et al. [24]	2001	HY-100 steel	Inclusion-matrix interface
Das et al. [13]	2013	AISI 304LN SS	Phase interfaces
Das et al. [25,26]	2014	HP-40	Grain boundary triple points and grain boundary

their depths. Deformation paths at various stress-states/strain-states would control not only the mechanical behavior of the material, but the void nucleation and growth process also [30,31].

Das et al. [32–38] has already experimentally demonstrated the concept of inter-relationship between the deformation properties and fracture for different alloys. Since deformation and fracture are influenced and controlled to a large extent, by the same set of factors, a fracture surface should keep a *signature* of the entire deformation process which was operative. In order to test the hypothesis that the ductile fracture features can be correlated to mechanical properties, it is necessary to vary systematically the density and type of the void-initiating particles contained in a microstructure. Such a scheme has been implemented in super-alloy 625 in the present research through a variation in stress triaxiality ratio ($\tau=\sigma_m/\sigma_{eq}$) without altering the microstructure.

2. Experimental

The material used for experiment is a service exposed (by 20,000 h) Inconel 625 ammonia cracker tube received from heavy water plant with chemical composition (by wt.%): 3.25Fe–16.54Cr–9.04Mo–3.2Nb–0.15Mn–0.54Si–0.26Ti and bal Ni. Initial inclusion fraction of the material is 0.00015 and the grain size is $\approx 165 \pm 5$ µm. Threaded round bar solid smooth tensile specimens with gauge length of 30 mm and gauge diameter of 6 mm and notched specimens with same dimensions and notch at central location with a depth of $\approx$ 1.0 mm and included angle of 60° with four different root radius 0.1, 0.5, 0.8 and 1.2 mm have been fabricated from the tube. The corresponding stress triaxiality ratios (τ) (i.e., 2.3, 1.3, 1.1, 0.9 and 0.3 for smooth) for all the specimens designed was calculated from the equation of Bridgeman documented in reference [39]. Tensile tests with a nominal displacement rate of 0.2 mm/min have been carried out for all the specimens till fracture in a universal screw driven testing machine under laboratory air environment and a video camera is attached for monitoring the change in diameter of the specimens. All tests have been carried out under computer control such that sufficient data points are collected for constructing the engineering stress–strain curve of the material at different notch geometries. Many tensile experiments were carried out and the repeatability of the tensile properties data was checked carefully. Variation of strength and ductility properties data with respect to the stress triaxiality ratio (σ_m/σ_{eq}) is shown in Fig. 1. Fractographic characterization was done for all the representative fractured specimens in a scanning electron microscope (SEM) under secondary electron imaging mode to record the fractographic features. A set of fields was observed under SEM at an operating voltage of 20 kV throughout.

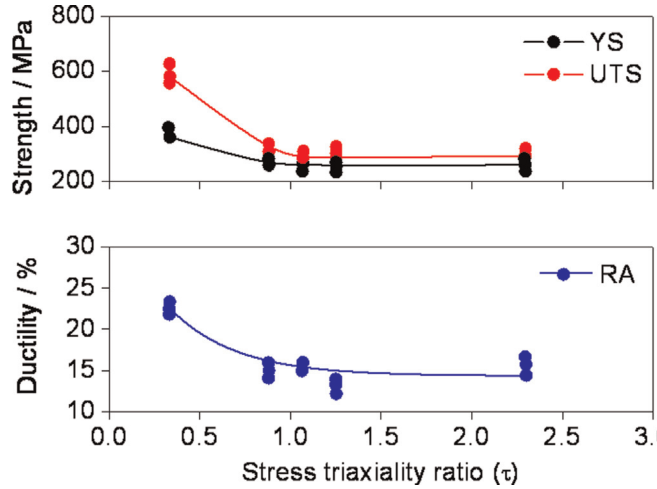

Fig. 1. (Color online) Strength (i.e., YS and UTS) and ductility (RA) variation with stress triaxiality ratio (τ) of service aged Inconel 625 alloy at displacement rate of 0.2 mm/min under laboratory air environment.

Five suitable magnifications have been chosen in all cases so that representative fracture features are recorded. Fractographs of selected stress triaxiality ratio conditions (i.e., τ=0.3, 0.9 and 2.3) are shown in Fig. 2. Extensive quantitative metallographic (i.e., stereology) technique has been employed on the digital fractographs to characterize the two-dimensional fracture features (i.e., fractured grain size, extent of tearing ridge, dimple number density, dimple diameter and their distribution) on the fracture surfaces for all the fractured specimens. All the fractographs from each notch geometry have been analyzed to arrive at an average value of the above parameters.

3. Results and discussion

The imposition of stress triaxiality ratio ($\tau=\sigma_m/\sigma_{eq}$) significantly causes a "harder" response of the soft phase (i.e., γ matrix) whereas a "softer" response of the hard phase (i.e., most of the precipitates) which has been reported elsewhere [40]. Fig. 1 depicts that as the τ is raised, both YS and UTS of the alloy decreases drastically. The nominal variation of τ strongly influences the tensile behavior of the material. The decrease in YS and UTS with the increase in τ is mainly attributed to the ease of dislocation movement during tension [41]. A well-known characteristic of void growth is its strong sensitivity to τ and also a dependence on strain hardening properties of the material [14]. The precipitates (i.e, γ″, Ni_2(Cr, Mo)), already present in the γ (fcc) matrix strongly interacts with the dislocation when strained. This activity is increasing and getting more complex with the imposition of nominal variation of τ. On the other hand, ductility in the form of reduction in cross-sectional area (RA) decreases significantly as τ is increased, which seems to be logical as pointed out by Jablokov et al. [42] in his elegant study for HY 100 steel. It has been well established and documented that with the increase in τ, there is decrease in grain size in a polycrystalline alloy [43]. Das et al. [44,45] has already explained that the damage accumulation inside the material under tension decreases drastically when τ is raised for high strength low alloy steels at ambient temperature. It has also been shown from the void growth data that the strain induced void growth occurs in a manner that is very sensitive to stress-state [44,45].

Fig. 2(a–c) corresponds to the fractographs for different τ of the present alloy. According to the visual impression on these fractographs, it has been found that with the increase in τ, the average