Journal of Alloys and Compounds 649 (2015) 500–504

Contents lists available at ScienceDirect

Journal of Alloys and Compounds

journal homepage: http://www.elsevier.com/locate/jalcom

Evaluation of equivalent accumulation area of internal defects based on statistical law of yield loads

Zhichao Ma [a], Hongwei Zhao [a, *], Changyi Liu [a], Luquan Ren [b]

[a] School of Mechanical Science and Engineering, Jilin University, Changchun 130025, China
[b] Key Laboratory of Bionic Engineering Ministry of Education, Jilin University, Changchun 130025, China

ARTICLE INFO

Article history:
Received 9 May 2015
Received in revised form
20 July 2015
Accepted 21 July 2015
Available online 22 July 2015

Keywords:
Tensile
Indentation
Ti-6Al-4V
Internal defects
Yield loads

ABSTRACT

In this paper, in order to evaluate the approximate equivalent accumulation area S_{dmax} of initial internal defects in the dangerous cross section of structures, a series of Vickers indentations were prepared on the gage part of well polished Ti-6Al-4V specimens as emebedded defects, the indentation areas S_v were compared with S_{dmax}. With various S_v, approximate Gaussian distribution of the yield loads was obtained based on mathematical expectation $E(F_s)$ and standard deviation $\sigma(F_s)$, and the changing rule of $E(F_s)$ as a function of S_v was obtained. A decrement of $E(F_s)$ of 2.6% was obtained when S_v increased from 3654.4 μm^2 to 6982.8 μm^2. The approximate ratio of S_{dmax} to the initial sectional area S_o was evaluated as 3.0%.

1. Introduction

Inherent defects of materials, such as micro voids and porosities, generated from material preparation and manufacturing process, would seriously affect the static and fatigue mechanical properties of materials [1–5]. For example, Judd et al. [3] indicated that if porosity increased by 1%, the fatigue strength and fatigue life of composite materials would decrease by 7% and 50% respectively. On the other hand, the precise and quantitative detection of each initial micro internal defect [5,6], especially for defects at micro/nano scale, is frequently difficult, time-consuming and complicated [5,5–7], and the equivalent accumulation area S_{dmax} of all internal defects in the dangerous cross section is not generally taken into consideration when calculating yield load or allowable load. Therefore, the calculation of equivalent area S_{dmax} would affect the engineering application of materials and optimal design of structure. Non-destructive testing (NDT) technology [6–15], such as ultrasonic scanning [8–12], image measuring [13,14] and laser scanning technologies [15], have been widely applied. The detection probability and reliability of NDT technologies directly affect the calculation accuracy of the size, distribution and equivalent area of defects [16,17]. R. J. Zhou et al. [5] proposed a nondestructive low-noise interferometric imaging method to detect nanoscale defects, and a 20 nm wide defect in large nanopattern was detected by using optical interferometric microscopy. J. K. Lee et al. [6] evaluated the elastic wave's characteristic on the defects in the weld of stainless steel materials using guided wave and acoustic emission. However, existing technologies and prediction methods are difficulty to realize the evaluation of equivalent accumulation area of defects S_{dmax} in the dangerous cross section, especially for the micro/nano scale defects, S_{dmax} could not be quantitative detected easily and rapidly. Based on linear elastic theory, Murakami et al. [18] proposed a corresponding relation between microscopic defect area and fatigue stress amplitude. While, for materials with complicated microstructure, multilayered composite materials for instance, due to the acoustical anisotropy, high acoustic attenuation coefficient and high frequency dispersion coefficient, the detection of micro/nano scale defects is much complicated [12]. In addition, the actual allowable load, which is determined by the production of yield stress and actual cross section area excluding the area of defects, is relatively lower than the directly measured allowable load. Therefore, the evaluation of S_{dmax} would promote the service reliability of structure.

In this paper, a series of Vickers indentations were prepared on the gage part of well polished Ti-6Al-4V specimens [19,20] as embedded defects, the indentation areas S_v were compared with S_{dmax}. Based on various S_v, approximate Gaussian distribution of the

* Corresponding author.
E-mail addresses: zcma@jlu.edu.cn (Z. Ma), hwzhao@jlu.edu.cn (H. Zhao), changyi_liu@126.com (C. Liu), lqren@jlu.edu.cn (L. Ren).

http://dx.doi.org/10.1016/j.jallcom.2015.07.204
0925-8388/

yield loads with calculated mathematical expectation $E(F_s)$ and standard deviation $\sigma(F_s)$ was obtained. Finally, the approximate ratio of S_{dmax} to initial sectional area S_o was evaluated.

2. Experimental method

Fracture failures of standard uniaxial tensile specimens, including the failures under static load or cyclic load, generally occur in the dangerous cross section, namely the cross section contains maximum equivalent accumulation area S_{dmax} of all internal and surface defects. For well polished specimens with high surface quality, internal defects are the primary factor to affect the calculation of S_{dmax}. Therefore, the evaluation of S_{dmax} would be contributed to the accurate calculation of allowable load F_m. Fig. 1 illustrates the evaluation method of S_{dmax}, the equivalent area S_d in an arbitrary cross section could be considered as the summation of each micro initial defect. On the premise that the yield stress is a constant value, via the statistical law of yield loads based on a relatively large sample number, S_d could be quantitatively evaluated. Embedded defects [13] with known area in various cross sections could be prepared to be compared with S_d. Theoretically, If the defect area S_{lower} (cross section i in Fig. 1) is lower than S_{dmax}, during uniaxial tensile tests, the mathematical expectation $E(F_s)$ of yield load of specimens with embedded defect would be same with undisposed specimens. On the other hand, if the defect area S_{upper} (cross section ii) is larger than S_{dmax}, $E(F_s)$ of specimens with embedded defect would be relatively smaller than the $E(F_s)$ of undisposed specimens. In this paper, various indentations were prepared as embedded defects, combining with the changing rule of $E(F_s)$, the approximate value of S_{dmax} could be effectively evaluated. Considering that the areas of initial defects in cross sections i and ii (S_{di} and S_{dii}, respectively) are far lower than S_{dmax}, the expression of allowable load F_m, including S_{dmax}, initial cross section area S_o, yield stress σ_s and safety coefficient n_s, could be described as:

$$F_m \leq (S_o - S_{d\ max})\frac{\sigma_s}{n_s} \tag{1}$$

The indentations were prepared by commercial (micro) Vickers hardness testers, considering that the upper limit of indentations' diagonal lengths obtained from Vickers (micro) hardness tests was

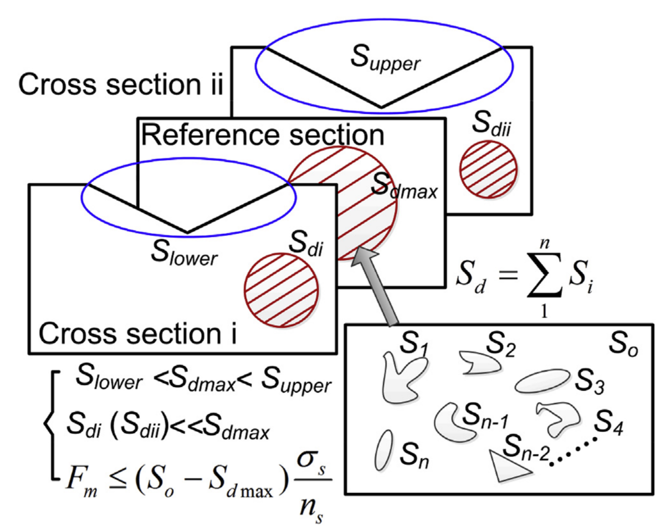

Fig. 1. Calculation of S_{dmax} of internal defects via the summation of each micro internal defect, and Vickers indentions were prepared on various cross sections as emebedded defects to be compared with S_{dmax}.

generally several hundred microns, accordingly, miniature specimens and corresponding miniature *in situ* tensile tester were adopted. The composition, function, gripping method and advantages of the *in situ* tensile tester (Fig. 2a) have been reported in detail in our previous work [21]. Also seen from Fig. 2a, a commercial optical microscope (Olympus, DSX500) was adopted, and the three-dimensional imaging and measurement functions were convenient to examine the indentation morphology. Fig. 2b shows the specific size of the gage part of a well polished Ti–6Al–4V specimen, initial cross section area S_o of the specimen was 1.323×10^5 μm. The specimen was fabricated via wire cutting, and mechanical polishing was adopted to obtain smooth surface to weaken the influences of surface scratch defects. In addition, as shown in Fig. 2c, three-dimensional morphology of the prepared indentation with known diagonal length d and indentation depth h was captured by the microscope software, and two diagonals of indentation were parallel and perpendicular to the tensile direction, respectively. Fig. 2d shows the geometric profile of the Vickers indenter's tip and corresponding indentation defect area S_v by calculating the product of d and h.

3. Results and discussion

Without embedded indentation defects, representative tensile load–displacement curve of Ti-6Al-4V specimen including a local segment near the yield load was obtained as shown in Fig. 3a. The transition point at which plastic deformation began was hard to define with precision. However, the offset yield strength, determined by the stress corresponding to the stress–strain curve and a line parallel to the elastic part of the curve offset by a specified strain, could be uniformly adopted to determine the yield load F_s and avoid the practical difficulties of measuring the proportional limit or elastic limit [22]. For materials with obvious linear portion, a specified strain offset of 0.2% was widely adopted to define the yield strength, such as ASTM: E8/E8M-15a [23]. As shown in Fig. 3a, F_s approximately ranged from 100 N to 120 N, considering the specific width (0.63 mm) and thickness (0.21 mm) of the specimen, when the strain offset was set as 0.002, the corresponding yield strength σ_s and yield load F_s were calculated as 874.5 MPa and 115.7 N respectively, and an approximate elastic modulus of 109.3 GPa was obtained. Since the offset yield strength was the stress required to produce a slight amount of plastic deformation, and the calculated F_s was very close to the transition point at which plastic deformation began, the offset was specified as a strain of 0.2%. Moreover, the offset was also appropriate for the calculation of F_s without embedded defects. Based on the testing method of F_s and a specimen number of 50, without embedded defects, under the same experimental conditions, including specimen processing technology, gripping method, strain rate (10^{-3} s^{-1}), statistical law of yield loads F_s of Ti-6Al-4V specimens was obtained as shown in Fig. 3b. F_s ranged from 96.9 N to 131.4 N, and the mathematical expectation $E(F_s)$ and standard deviation $\sigma(F_s)$ of yield loads were calculated as 115.03 N and 9.46 N, respectively. An approximate Gaussian distribution of F_s was obtained. In order to promote the comparative efficiency between the indentation defect area S_v and S_{dmax}, as shown in Fig. 4, four indentations with indentation loads ranging from 0.98 N to 9.8 N were prepared as embedded defects. By the movement of linear platforms integrating with the hardness tester and the observation of optical microscope with high resolution, the adjustment of indentations' position was achieved and the connection of each indentation's diagonal lines was parallel to the tensile direction. When the indentation load F_i was 9.8 N, the corresponding d, h and S_v were measured as 78.8 ± 2.4 μm, 15.7 ± 0.6 μm and 618.6 μm^2 respectively. If the other small initial