Journal of Nuclear Materials 461 (2015) 171–177

Contents lists available at ScienceDirect

Journal of Nuclear Materials

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

Fractal characteristics of fracture morphology of steels irradiated with high-energy ions

Yongqiang Xian [a,b], Juan Liu [a,b], Chonghong Zhang [a,*], Jiachao Chen [c], Yitao Yang [a], Liqing Zhang [a], Yin Song [a]

[a] Institute of Modern Physics, Chinese Academy of Science, Lanzhou 730000, China
[b] University of Chinese Academy of Science, Beijing 100049, China
[c] Paul Scherrer Institute, Villigen PSI, Switzerland

HIGHLIGHTS

- Fractal dimensions of fracture surfaces of steels before and after irradiation were calculated.
- Fractal dimension can effectively describe change of fracture surfaces induced by irradiation.
- Correlation of change of fractal dimension with embrittlement of irradiated steels is discussed.

ARTICLE INFO

Article history:
Received 29 August 2014
Accepted 9 March 2015
Available online 13 March 2015

ABSTRACT

A fractal analysis of fracture surfaces of steels (a ferritic/martensitic steel and an oxide-dispersion-strengthened ferritic steel) before and after the irradiation with high-energy ions is presented. Fracture surfaces were acquired from a tensile test and a small-ball punch test (SP). Digital images of the fracture surfaces obtained from scanning electron microscopy (SEM) were used to calculate the fractal dimension (FD) by using the pixel covering method. Boundary of binary image and fractal dimension were determined with a MATLAB program. The results indicate that fractal dimension can be an effective parameter to describe the characteristics of fracture surfaces before and after irradiation. The rougher the fracture surface, the larger the fractal dimension. Correlation of the change of fractal dimension with the embrittlement of the irradiated steels is discussed.

1. Introduction

The concept of the fractal dimension (FD) related to irregular objects with a self-similar property provides a basis for the quantitative characterization of the tortuosity of fracture surfaces. A number of studies have focused on the fractal characteristics of fracture surfaces since Mandelbrot et al. first introduced this concept to materials science in 1984 [1]. And a variety of methods were proposed to determine fractal dimension of fracture surfaces for the last two decades. The method of sections perpendicular was used to determine the fractal dimension of fracture profile in relation to the distance from the blunted crack tip [2], and the results indicate that the fractal dimension of fracture surface profile shows a wavy character as the distance from the fatigue crack tip changes. Slit island method (SIM) [1] was first used to estimate the fractal dimension of fracture surfaces acquired from Charpy impact test in 1984. After that, a non-destructive technique which is a combination of slit island technique and digital image technique was used to determine the fractal dimension of fracture surface of concrete [3]. The combination of digital image technique and computer technique contributes to the development of a non-destructive technique for determining the fractal dimension of fracture surface [4–13]. The fractal characterization of multi-scale porous scaffold was estimated by means of image processing (IP) and box counting method [9]. The image used for IP was obtained from scanning electron microscopy (SEM). de Campos et al. [10] found a correlation between the stretch zone width and fractal dimension with specimen thickness based on image stacks acquired from a Nikon Epiphot 200 reflected light microscope equipped with a Diagnostic Instruments Spot Insight Color QE digital camera. Digital image usually worked together with box counting method in determining the value of FD [8–13]. Details of box counting method are described in Refs. [14,15]. An improved modification method of determining FD based on SEM images was proposed in Ref. [11], which possessed high accuracy and stability.

* Corresponding author at: Institute of Modern Physics, Chinese Academy of Sciences, No. 509, Nanchang Road, Lanzhou 730000, Gansu Province, China. Tel.: +86 931 4969036; fax: +86 931 4969201.
E-mail address: c.h.zhang@impcas.ac.cn (C. Zhang).

http://dx.doi.org/10.1016/j.jnucmat.2015.03.022
0022-3115/

Exploration on relation between the fractal dimension of fracture surfaces and mechanical properties of steels underwent conventional treatment has been done by many researchers [3,7,10–12]. However studies on fracture surfaces acquired from irradiated steels with energetic ions or neutrons were rarely reported. Ferritic/martensitic steels or austenitic stainless steels have been chosen as candidate materials for the liquid metal container of European Spallation Source [16]. And oxide dispersion strengthened (ODS) high-Cr ferritic steels have been chosen as candidate materials for fuel cladding tubes in Generation IV or the blanket components in fusion DEMO reactors [17,18]. In the present work, fractal dimensions of fracture surfaces of these two kinds of steels under conditions of high-energy ion irradiation were calculated, by applying the technique of IP combined with box counting method. Correlation of values of FD with irradiation embrittlement is discussed.

2. Materials and methods

2.1. Experimental procedures

The materials investigated in this paper are solution annealed AISI 304L stainless steel irradiated with 800 MeV protons and ODS high-Cr ferritic steels irradiated with 122 MeV Ne-ions. Details of the steel specimens and the irradiation conditions are given in Refs. [16,17]. For the 304L stainless steel irradiated with 800 MeV protons (to a damage level of 7.8 dpa at about 250 °C), tensile tests were performed on specimens with a gauge volume of $5 \times 1.5 \times 0.6\ mm^3$ at room temperature, using a 2 kN MTS tensile machine equipped with a video-extensometer so that the elongation could be measured directly in the gauge area. After tensile testing, the fracture surfaces were observed with a scanning electron microscope (SEM) to identify the fracture mode [16]. For the ODS ferritic steel (MA956) irradiated with 122 MeV Ne ions (to a damage level of 0.7 dpa/350 appm-Ne at about 440 °C), mechanical properties were evaluated by the small-ball punch test technique (SP) using disks of 3 mm in diameter cut from the un-irradiated and irradiated specimens [17]. The fundamentals and scheme of the small-ball punch test were described previously [18]. In the present test with SP, balls with a diameter of 1 mm made of sapphire were used. The displacement rate is 0.017 mm per second. Specimens were tested at room temperature and 500 °C, respectively. In the case of test at 500 °C, the test chamber was pumped to a vacuum of 10^{-4} Pa, and the specimen stage was kept at 500 °C for 10 min before the load was applied. After the small-ball punch test, the fracture areas of the specimens were observed with SEM.

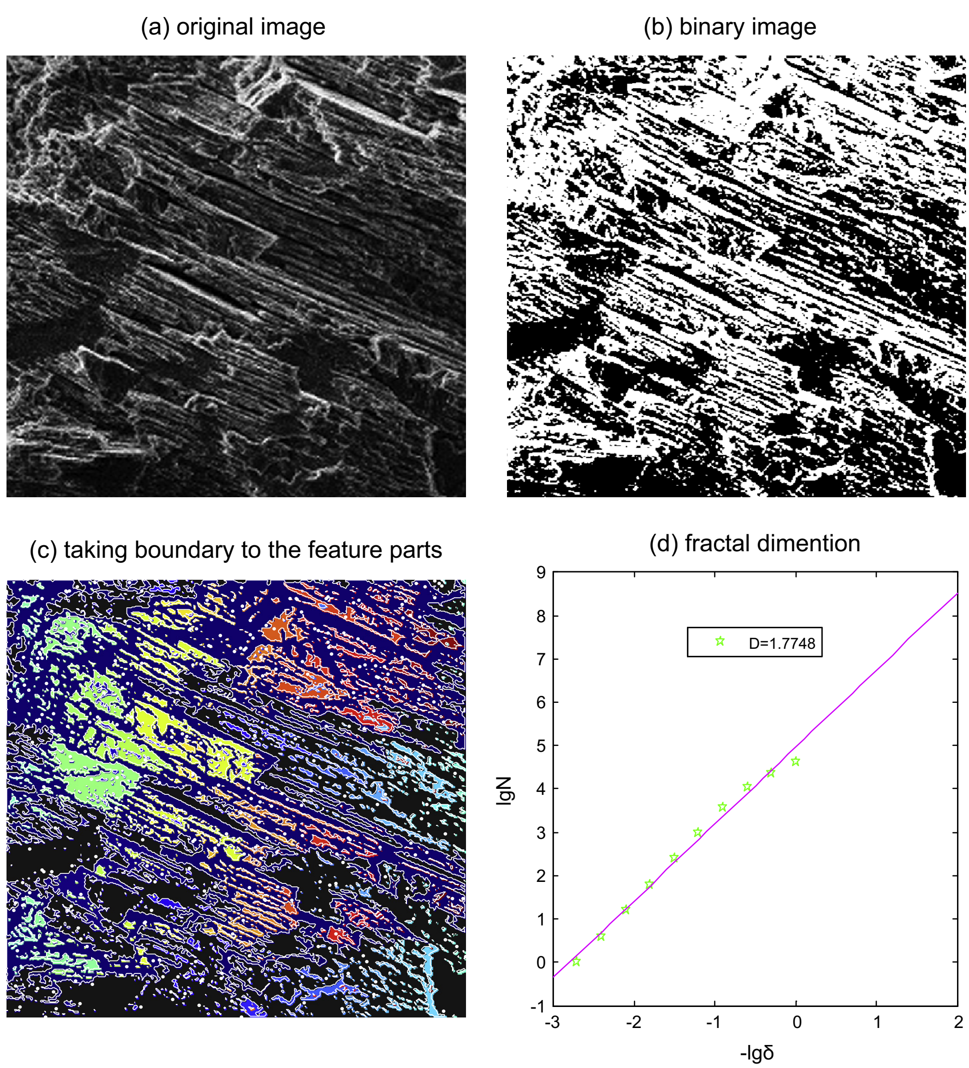

Fig. 1. (a) Original SEM image of a fracture area in a creep-tested 304L steel specimen, (b) binary image, (c) boundary taken to the feature parts of the binary image, and (d) determined fractal dimension.