Journal of Nuclear Materials 503 (2018) 205–225

Contents lists available at ScienceDirect

Journal of Nuclear Materials

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

Experimental and computational correlation of fracture parameters K_{Ic}, J_{Ic}, and G_{Ic} for unimodular and bimodular graphite components

Awani Bhushan, S.K. Panda*

Department of Mechanical Engineering, Indian Institute of Technology (Banaras Hindu University), Varanasi 221005, India

A R T I C L E I N F O

Article history:
Received 7 November 2017
Received in revised form
5 March 2018
Accepted 5 March 2018
Available online 9 March 2018

Keywords:
3D J integral
Bimodularity
Contour integral
Fracture toughness
Graphite
Strain energy release rate
Weibull

A B S T R A C T

The influence of bimodularity (different stress ~ strain behaviour in tension and compression) on fracture behaviour of graphite specimens has been studied with fracture toughness (K_{Ic}), critical J-integral (J_{Ic}) and critical strain energy release rate (G_{Ic}) as the characterizing parameter. Bimodularity index (ratio of tensile Young's modulus to compression Young's modulus) of graphite specimens has been obtained from the normalized test data of tensile and compression experimentation. Single edge notch bend (SENB) testing of pre-cracked specimens from the same lot have been carried out as per ASTM standard D7779-11 to determine the peak load and critical fracture parameters K_{Ic}, G_{Ic} and J_{Ic} using digital image correlation technology of crack opening displacements. Weibull weakest link theory has been used to evaluate the mean peak load, Weibull modulus and goodness of fit employing two parameter least square method (LIN2), biased (MLE2-B) and unbiased (MLE2-U) maximum likelihood estimator. The stress dependent elasticity problem of three-dimensional crack progression behaviour for the bimodular graphite components has been solved as an iterative finite element procedure. The crack characterizing parameters critical stress intensity factor and critical strain energy release rate have been estimated with the help of Weibull distribution plot between peak loads versus cumulative probability of failure. Experimental and Computational fracture parameters have been compared qualitatively to describe the significance of bimodularity. The bimodular influence on fracture behaviour of SENB graphite has been reflected on the experimental evaluation of G_{Ic} values only, which has been found to be different from the calculated J_{Ic} values. Numerical evaluation of bimodular 3D J-integral value is found to be close to the G_{Ic} value whereas the unimodular 3D J-value is nearer to the J_{Ic} value. The significant difference between the unimodular J_{Ic} and bimodular G_{Ic} indicates that G_{Ic} should be considered as the standard fracture parameter for bimodular brittle specimens.

1. Introduction

Bimodularity introduces uncertainty in failure characteristics of many structures leading to unreasonable compromise on factor of safety of high risk structures. The phenomena though is present at elemental scale for most materials, the scale of their severity varies from material to material, being predominant for brittle materials, where a safe guard of flow stress induced plasticity is not present. Therefore, many catastrophic fracture of brittle structures remain unanswered leading to critical design fallacy.

Structural materials exhibiting different stress-strain curves in compression and tension are termed as bimodulus materials. Not only anisotropic and orthotropic materials such as composites, but also some traditional isotropic materials as ceramics, graphites may also have different moduli in tension and compression. In the case of bimodulus materials the constitutive matrix is a function of stress. Though the stress-strain relationship is actually curvilinear, but it is approximated as bilinear with different slopes. Hence the analysis of structures made up from bimodulus materials is more involved. Two basic material models viz. Ambartsumyan [1–7] and Bert [8–11] are being most widely used for characterizing such bimodulus behaviour. Ambartsumyan material model is based on the criterion of positive-negative signs of principal stress state at a point in a stressed body. This model has found its application mostly to isotropic materials having bimodulus characteristic. Bert material model is based on the criterion of positive-negative signs in the longitudinal strain of fibers in orthotropic materials, and

* Corresponding author.
E-mail address: pandask@bhu.ac.in (S.K. Panda).

https://doi.org/10.1016/j.jnucmat.2018.03.012
0022-3115/

hence has its significance in research for laminated composites. The elasticity theory of Ambartsumyan material model considers the dependence of moduli both on material properties and also the state of stress at the point. In retrospect, elastic modulus has nonlinear characteristics and it is related to the material, shape, boundary conditions, and external loads on the structure. The main difficulty in the analysis of bimodulus planar structures is that of locating the neutral surface. Since the element moduli depend on the sign of the stress which is unknown a priori, the iterative techniques need to be developed to find the layer in which there is no strain. Along with this, a simplified linearized mechanical model is necessary for optimization study of such problems. In this respect Finite Element Method (FEM) based analytical and iterative procedures are found to be appropriate and most comprehensive for studying the reliability and failure characteristics of bimodulus material structures. The bimodular Ambartsumyan linear model based on the rules of elastic continuum mechanics has the assumption that the stressed body is continuous, homogeneous, and isotropic and all deformations are small enough to have theory of superposition valid for all response characteristics. The linearized constitutive model simplifies the tension-compression stress strain plots into two straight lines, whose tangents at the origin are discontinuous.

In this work an endeavor has been made to systematically analyze the fracture behaviour of bimodular material graphite being chosen for the study. The choice of graphite is because, apart from being a reliable refractory material having high temperature stability, its applications are manifold in critical areas of nuclear energy.

Graphite is currently being used for the construction of the major core components such as the fuel block, reflector, moderator and core support critical structure in a nuclear reactor. This will be a key material in the development of Very High Temperature Reactor (VHTR) for the six next-generation nuclear reactor systems within the Generation IV International Forum [12]. The VHTR is considered to be the Next Generation Nuclear Reactor (NGNR) in the evolutionary development of high-temperature gas-cooled reactors with significant advantage of inherent safety, high thermal efficiency, process heat application capability, low operation and maintenance costs, and modular construction [13,14].

Graphite material characterization can have widely different textures and pore-size distributions, as well as the subcritical crack like formations. The physical properties of artificial graphite are mostly anisotropic due to the hexagonal layer lattice structure of its crystallites and its degree of orientation during processing [15–17]. As such different grades of graphites can be manufactured with different average grain sizes. Typically, coarse-grained material has grains larger than 4 mm; medium-grained material has grains smaller than 4 mm; fine-grained material has grains smaller than 100 μm; and superfine, ultrafine, and micro-fine materials have grain sizes smaller than 50 μm, 10 μm, and 2 μm, respectively. Nuclear grade graphite has grain size falls within a range from medium to ultrafine. As graphites are manufactured by extrusion or molding process, the resulting grain structure has a biased orientation with respect to material coordinates. Usually, material properties are measured either along the grain orientation i.e. parallel to the extrusion direction and perpendicular to the molding axis; or against the grain orientation i.e. perpendicular to the extrusion direction and parallel to the molding axis. This explains the anisotropic or more accurately the transverse isotropic behaviour of graphite materials [18,19]. Due to large scatter in flaws and its distribution, size scaling and extrapolation from lab scale coupon tests to actual components in reactor service has been difficult for graphite components. Therefore, proper design of test specimen configuration, test method, and the analysis of mechanical properties test data for extrapolation should be carried out for a certain degree of reliability and satisfactory performance of such structures. In this regard, Weibull statistical methods are found to be efficient in not only reducing the number of experimentations for predicting the mechanical behaviour, but also based on this ASTM standard procedures and analytical expressions are developed for size scaling from component to component and from one loading configuration to another. The probability of fracture from material test results of lab scale specimen, translation and scaling of such data to predict the probability of fracture of actual in service component involve a need to understand the influence of the state of stress on the fracture strength of test coupons and components [20,21].

When a material exhibits bimodular characteristics, this problem is challenging, because the characterization of state of stress invokes quantification of elastic moduli whether in tension or compression. In this work, the graphite is being considered to be isotropic exhibiting bimodularity. Within the nuclear reactor environment, graphite components are subjected to neutron irradiation under high temperature, resulting in changes in physical and microstructural properties. Failure and fracture behaviour of graphite components are very critical to the reliability of core structures. Presence of crack like defects drastically enhances the probability of failure of graphite components. Material parameters such as elastic modulus and fracture resistance happen to be the lead parameters in postulating the life of such structures. Therefore, accurate characterization of the fracture properties of nuclear graphite qualitatively and quantitatively is important to the integrity or safety of a VHTR [13]. Apart from critical fracture parameters such as stress intensity factor, strain energy release rate and critical value of *J*-integral, the fracture behaviour of nuclear grade graphite material is also dependent on the size and shape of specimen [22–25]. In flexural condition, probability of failure is affected by the state of stress of tensile or compressive regions. Then evaluating the location neutral plane is significant to understand the criticality of stress state. When a material exhibit different elastic characteristic in tension and compression, then accurate designing of such structures poses multiple challenges of stress dependent elasticity problem. The singularity of crack tip stress field under such loading state become complicated to find a closed form solution. Ignoring such real scale phenomenon leads to unacceptable failure evidences of bimodular material structures. Therefore, modified design procedures are to be laid to take into account the validity of different stress vs strain behaviour. Materials exhibiting different mechanical behaviour in tension and compression are addressed in literature as bimodular material. The bimodularity has been found to severely affect the probability of failure of cylindrical specimens tested in three point and four point flexural loading conditions [26].

The concept of Bimodular material was first explored by Saint-Venant [27]and it was revisited by Timoshenko [28]. The concept of bimodulus material was extended to two-dimensional materials by Ambartsumyan [2–7,29,30] postulating a Multi-modulus elasticity theory. He suggested a three-dimensional, stress-strain law for isotropic bimodulus materials and developed such relations for orthotropic plates. Tabaddor [31–33] developed constitutive equations for the more general case of bimodulus materials formulating the generalized stress-strain laws for the anisotropic bimodularity. He employed finite element procedures for analyzing the two dimensional bimodulus beam. N. Kamiya presented a method of analysis of the bending of bimodulus elastic plates employing Ambartsumyan-Khachatryan's model for isotropic bimodulus materials [34,35]. This problem may be reduced to the conventional problem of minimizing the potential energy of the plate as a whole. A simply supported thin square plate subjected to lateral load was analyzed numerically by simplex method. Results