Computational Materials Science 50 (2011) 3403–3409

Contents lists available at ScienceDirect

Computational Materials Science

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

Strain gradient plasticity theory for modeling J_{IC} of functionally graded steels

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ARTICLE INFO

Article history:
Received 14 May 2011
Received in revised form 5 June 2011
Accepted 27 June 2011
Available online 20 July 2011

Keywords:
Functionally graded austenitic steel
Tensile stress
Fracture toughness
Strain gradient plasticity theory
Statistically stored dislocations
Geometrically necessary dislocations

ABSTRACT

Functionally graded ferritic and austenitic steels were produced through electroslag refining by setting the austenitic and carbon steels with appropriate thickness as electrode. Fracture toughness of the specimen in terms of J_{IC} has been studied and modeled regarding the mechanism-based strain gradient plasticity theory. The yield stress of each layer was related to the density of the statistically stored dislocations of that layer and by assuming Holloman relation for the corresponding stress–strain curve, tensile strength and tensile strain of the constituent layers was determined via numerical method. J_{IC} of each layer was related to the corresponding area under stress–strain curve of that layer and finally by applying the rule of mixtures, J_{IC} of functionally graded steels was determined. The obtained results of the proposed model are in good agreement with the experimental ones.

1. Introduction

Development of functionally graded materials (FGMs) is of technological importance which encourages the researchers to produce applicable FGMs with the lowest residual stresses. There are a wide variety of FGMs where variations in elastic constants appear. But a main group of FGMs are those in which variations in strength emerge. In fact, in all structures consisting of multiphase materials, composites, or functionally graded materials, strength variations are inherent. Therefore, considerations of theses group of FGMs are inevitable [1].

The first published experimental evidence that a gradient in yield stress influences the behavior of cracks was performed by Suresh et al. [1]. They conducted fatigue experiments on an explosion clad bimaterial consisting of a ferritic and an austenitic steel. A practical application of this experimental finding has been reported in Suresh et al. [2] Kolednik [3] provided an analytical model to explain why gradients in yield stress affects the crack growth behavior. It was demonstrated that a yield stress gradient induces an additional term of the crack driving force, which leads to an increase or decrease of the effective crack driving force. Becker et al. [4] modeled fracture toughness measured by SE(T) specimen with cracks perpendicular and along the strength gradient strength and homogeneous Young modulus using Weibull statistics. Bezensek and Hancock [5] studied the fracture toughness of functionally graded steels produced with laser welding.

Functionally graded steels (FGSs) have recently been produced from austenitic stainless steel and carbon steel using electroslag refining (ESR) [6,7]. In these composites, by selecting the appropriate arrangement and thickness of the primary ferritic and austenitic steels as electrodes, it is possible to obtain composites with several layers consist of ferrite, austenite, bainite and martensite. The resultant composites using two slices of original ferrite (α_0) and original austenite (γ_0) is as below;

$$(\alpha_0\gamma_0)_{el} \xrightarrow{R} (\alpha\beta\gamma)_{com}$$

where α, β and γ are ferrite, bainite and austenite phase in the final composite respectively; *el* is electrode; *com* is composite and *R* is remelting.

Diffusion of chromium, nickel and carbon atoms which taking place at the remelting stage in the liquid phase controls the chemical distribution of chromium, nickel and carbon atoms in the produced composites. The thicknesses of the bainitic and martensitic layers depend on the thickness of the corresponding primary slices in the electrode and process variables (voltage, current intensity and the drawing velocity of the product). The transformation characteristics of FGSs have previously been investigated, in that the diffusion coefficients of chromium, nickel, and carbon atoms at temperatures just above the melting point of iron were estimated. Also, the thicknesses of the emerging bainite and martensite phases were determined [6].

Furthermore it has been shown that the tensile strength of the FGS composites depends on the composition and number of layers and those has been modeled based on the tensile behavior of individual phases [7]; to do so the yield stress of each layer in the composites was related to the microhardness value of that layer.

In the previous studies, Chary impact energy of functionally graded steels in crack divider configuration [8–11] and in crack

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0927-0256/$ - see front matter
doi:10.1016/j.commatsci.2011.06.038

arrester configuration [11,12] was experimentally examined and modeled by different methods. In addition, the ductile to brittle transition of the specimens was studied in a series of works [13–17]. Fracture toughness of these specimens in terms of J_{IC} in both crack divider [18–20] and crack arrester [20,21] configurations was also investigated. The tensile behavior of oblique layer functionally graded steels was the other property which studied in the previous studies [22,23]. Finally prediction Vickers hardness [24] and tensile strength [25] of functionally graded steels by the mechanism-based strain gradient plasticity theory was the other works done in this area.

In this work, fracture toughness of FGSs in terms of J_{IC} for FGSs has been modeled by the concept of mechanism-based strain gradient plasticity theory (MSG) [26] which is unique among strain gradient theories because it is established directly from the Taylor dislocation model [27,28]. The intrinsic material length in MSG is identified as $(G/\sigma_{\mathrm{ref}})^2b$, where b is the Burgers vector which is the essential property of dislocations, G is the elastic shear modulus, and σ_{ref} is a reference stress in plasticity (e.g. yield stress). The dislocation density ρ is composed of the density ρ_s for statistically stored dislocations (SSD) which accumulate by trapping each other in a random way [29], and the density ρ_G for geometrically necessary dislocations (GND) which are required for compatible deformation of various parts of the nonuniformly deformed material [29–32]. The density of geometrically deformed dislocations is linked to the gradient of plastic strain [18,32]; while the density of statistically stored dislocations is linked to the relation between stress and plastic strain in uniaxial tension [33]. The flow stress is then determined from the plastic strain and plastic strain gradient via the Taylor dislocation model [33]. The superiority of the present model to the previous one [7] is that the microhardness of each layer (i.e. microhardness profile) is not required for determining tensile strength.

2. Experimental procedure

To make FGSs, a miniature ESR apparatus was used. The consumed slag was a mixture of 20% CaO, 20% Al_2O_3 and 60% CaF_2. The original ferritic and austenitic steels (α_0 and γ_0) which used as electrodes were commercial type AISI 1020 and AISI 316 steels respectively. The chemical composition of the as-received ferritic and austenitic steels is given in Table 1.

Ferritic and austenitic steel slices were joined by spot welding in form of 2-piece electrode for remelting. The thickness of each slice in the primary electrode was 150 mm.

Remelting was carried out under a constant power supply of 16 kV A. After remelting, the composite ingots were forged and then hot rolled down to the thickness of 30 mm. Forging and rolling operations were carried out at 980 °C and then specimens were air-cooled.

Because of limitation of specimen dimensions, fracture toughness measurement in terms of K_{IC} was not possible. Thus, fracture toughness in terms of J_{IC} test was carried out on specimens at 18 °C. Specimens' dimension was in accordance to the ASTM E1820 [34] and it is illustrated in Fig. 1. Three-point bend specimens were used to investigate the fracture toughness of the composites. The notch depth was 8 mm and a 2 mm fatigue pre-crack was introduced at the end of notch root by applying 3-point cyclic loading under frequency of 10 Hz. The single specimen method using unloading–reloading procedure was performed. After loading a specimen, a partial unloading up to 10% of the maximum load was applied and then the specimen was reloaded up to the maximum load. Calculation of the maximum load is given in the ASTM E1820 [34] standard and according to the previous work [7] the yield stress of the specimen was determined by the rule of mixtures. Fracture toughness of FGS specimens with the starter crack normal to the graded layers (crack divider configuration) was measured.

Table 1
Chemical composition of original alpha and gamma steels.

	%C	%Si	%Mn	%P	%S	%Cr	%Ni
γ_0	0.07	1	2	0.045	0.03	18.15	9.11
α_0	0.2	0.3	0.2	0.05	0.05	–	–

Fracture toughness and tensile properties of as-received ferritic and austenitic steels which were annealed at 980 °C and then were air-cooled and fracture toughness and tensile properties of single-phases analogous to the selected layers was also measured. The production method of single-phase specimens with chemical composition and mechanical properties identical to the selected layers was similar to the previous work [7]. To do this, fracture toughness and tensile test specimens of the same composition and mechanical properties to the selected layers were produced. Initially, the average chemical composition of the selected layers was obtained (Table 2). Afterward, samples with chemical composition in accordance to the average chemical composition of single-phase specimens were produced by means of a vacuum induction furnace. Similar to the primary composites, the hot-pressing process was carried out at 980 °C, followed by air cooling. Through trial and error (i.e., confirming the chemical composition and changing the cooling rate), the samples with the nearest hardness to single-phase specimens were selected and fracture toughness and tensile test specimens from the samples were made. Fracture toughness and tensile test results of single-phase specimens produced from the sample are shown in Table 3.

As the previous work [6] indicate, a bainite layer is produced during remelting stage approximately in the middle of the forged specimen. Therefore, two series of fracture toughness specimens were produced (one from ferritic and the other from austenitic graded region) in which bainite layer was not placed as shown in Fig. 2. The fracture toughness of FGSs in crack divider configuration (Fig. 3) was evaluated by J_{IC} test at 18 °C.

To investigate the variation of hardness in composites, Vickers microhardness test was employed using 1 kgf weight.

Tensile specimens from the boundary layers were made. Tensile tests were carried out under extension rate of 0.1 mm/s. Specimens dimension was in accordance to the ASTM E8 standard and it is shown in Fig. 4. The as received rod was annealed at 980 °C and then air-cooled.

3. Modeling

To model fracture toughness of functionally graded steels, tensile strength of the constituent layers were determined by means of mechanism-based strain gradient plasticity theory. Fig. 5 illustrates tensile test results of the studied steels. Tensile strength of each layer in the ferritic and austenitic graded steel may be obtained based on the tensile strength of boundary layers as follows: the composites are considered as m_γ layers labeled by $\gamma_1, \gamma_2, \ldots, \gamma_m$ in graded austenitic steel where γ_m is assumed to be the last layer in the opposite side of γ_1 layer (with the chemical composition identical to the original austenitic steel) and m_α layers labeled by $\alpha_1, \alpha_2, \ldots, \alpha_m$ in graded ferritic steel where α_m is assumed to be the last layer in the opposite side of α_1 layer (with the chemical composition identical to the original ferritic steel). To simulate the tensile strength of the steel, tensile test specimens analogous to γ_m and α_m layers were made; initially, the average chemical composition of the layer was obtained by electron probe microanalysis equipped with low atomic number layer analytical