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Application of strain gradient plasticity theory to model Charpy impact energy of functionally graded steels

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ABSTRACT

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

1. Introduction

There is an extensive literature on compositionally graded materials (CGM's) as exemplified by the work from Suresh and Mortensen [1]. Many applications of CGM arise in ceramic–metal systems and in traditional systems such as carburized steels used to improve a specific property such as wear resistance. However the possibility of using a simple geometric arrangement of compositionally graded phases in metallic systems enables materials to be designed to control a range of plastic properties and fracture processes [2]. The fabrication process of FGMs is a quite complex task. In this sense, most published works deal with laminated samples that are formed by homogeneous layers of different compositions. On the contrary, continuous FGMs are scarcely reported. An extraordinary effort has been made in order to develop continuous FGMs in a wide range of systems and it has been attained in several works [3–5]. In this way, functionally graded steels (FGSs) have recently been produced from austenitic stainless steel and carbon steel using electro slag 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 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

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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, Charpy impact energy of 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 $(G/\sigma_{ref})^2 b$, 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 KVA. 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.

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 Charpy specimens were produced (one from ferritic and the other from austenitic graded region) in which bainite layer was not placed as shown in Fig. 1. The impact energy of FGSs in crack divider configuration (Fig. 2a) was evaluated by Charpy impact test at 18 °C using standard sized specimens (10 × 10 × 50 mm) according to the ASTM E23 [34]. Specimen has a V-shaped notch with a flank angle of 45° and depth of 2 mm. The tip radius of notch is 0.25 mm. The dimension of the specimens is shown in Fig. 2b.

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. 3. The as received rod was annealed at 980 °C and then air-cooled.

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	–	–

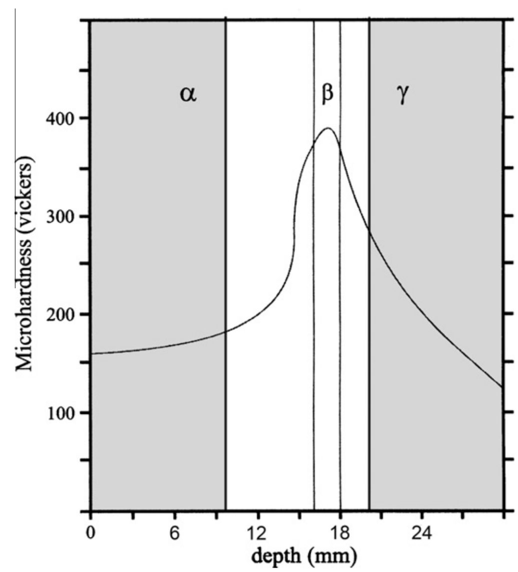

Fig. 1. Experimental vickers hardness profile and the regions of preparing Charpy impact specimens from functionally graded austenitic and ferritic steels (gray regions).

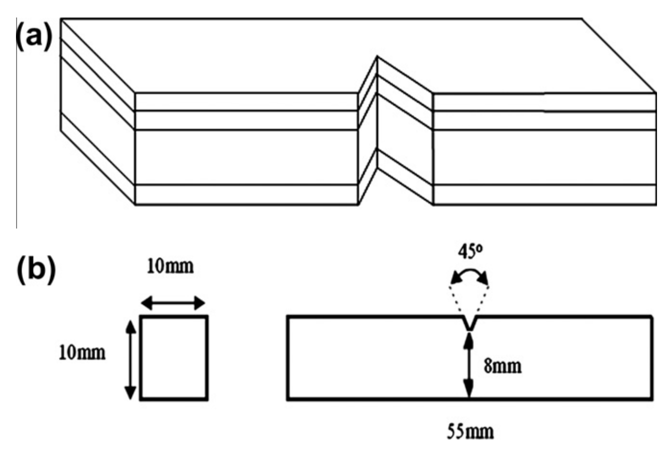

Fig. 2. (a) Configuration of composite Charpy test specimens in the form of crack divider and (b) dimension of Charpy impact test specimens.

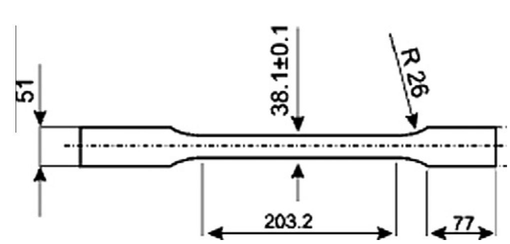

Fig. 3. Dimension of tensile composite specimen (mm).