Computational Materials Science 50 (2011) 3442–3449

Contents lists available at ScienceDirect

Computational Materials Science

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

Strain gradient plasticity theory to predict the input data for modeling Charpy impact energy in functionally graded steels

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ARTICLE INFO

Article history:
Received 8 June 2011
Received in revised form 30 June 2011
Accepted 4 July 2011
Available online 23 July 2011

Keywords:
Functionally graded steel
Charpy impact energy
Hardness prediction
Finite element simulation
Strain gradient plasticity theory
Statistically stored dislocations
Geometrically necessary dislocations

ABSTRACT

In the present work, Charpy impact energy of functionally graded steels composed of graded ferritic or austenitic layers which were produced by electroslag remelting in both crack divider and crack arrester configurations has been modeled by finite element method. By means of the mechanism-based strain gradient plasticity theory, the hardness of each layer in functionally graded steels was related to the density of dislocations of that layer. After that, the yield stress of each layer was estimated by supposing a linear relation between predicted hardness of each layer and its yield stress and by assuming Holloman relation for the corresponding stress–strain curve of that layer, tensile strength and tensile strain was determined. The utilized data for each layer of functionally graded steels in finite element modeling was the predicted stress–strain curve of that layer obtained from strain gradient plasticity theory. A relatively good agreement between experimental results and those obtained from simulation was observed.

1. Introduction

Charpy V-notch (CVN) impact test is a widely used test on notched specimens which are submitted to the impact of a hammer with the given kinetic energy [1]. Some researchers have tried to mathematically model Charpy impact behavior of monolithic materials [2–6]. Although some of these models seems promising, but none of these works show realistic results because of their simplifications and assumptions. Therefore, several works have been carried out focusing on evaluating impact behavior utilizing more accurate instrumented Charpy impact test [2,3,7–13]. Also, some models have been recently proposed to model Charpy impact behavior using neural network [14–18]; these models are at their infancy and need to be extended.

A comparatively good method has been developed to predict Charpy impact behavior of materials by numerical modeling specially using finite element method (FEM). Among those are FEM modeling of Charpy impact energy of different materials especially structural steels [4,19–29]. Mathur et al. [22] have presented a 3D analysis of failure modes in the Charpy V-notch specimens. Tvergaard and Needleman [27] have analyzed the effect of weld orientation in Charpy specimens by 3D simulation. Hong et al. [28] performed the Charpy test with notch position varied within HAZ and reported that the absorbed energy is influenced by notch position with respect to various microstructures and it was reduced as notch position approach to the base material. Jang et al. [29] have simulated Charpy impact energy of heat affected zone with different notch tip positions.

Very few fracture experiments, particularly dynamic fracture, of FGMs have been reported. Among them, crack tip deformation and fracture parameter history in functionally graded glass-filled epoxy were evaluated for low velocity impact loading by Rousseau and Tippur [30]. Guo and Noda [31] studied the dynamic response of a functionally graded layered structure with a crack crossing the interface with in-plane impact loading condition. Xu et al. [32] investigated the plane strain problem of semi-infinite cracks in an infinite functionally graded orthotropic material with opening and in-plane shear impact loading modes. Bezensek and Hancock [33] studied the toughness of laser welded joints of low alloy steel under mode I and mixed mode configuration along with Charpy impact tests.

Functionally graded steels have been produced by electroslag remelting process (ESR) [34]. Studies on transformation characteristics of FGSs produced from austenitic stainless steel and plain carbon steel has revealed that as chromium, nickel and carbon atoms diffuse at remelting stage, alternating regions with different transformation characteristics are created. When appropriate arrangement and thickness of original ferritic (α_0) and original austenitic (γ_0) steels is selected to make electrodes, composites with graded ferrite and austenite regions together with bainite layers may be made as follows [34]:

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doi:10.1016/j.commatsci.2011.07.007

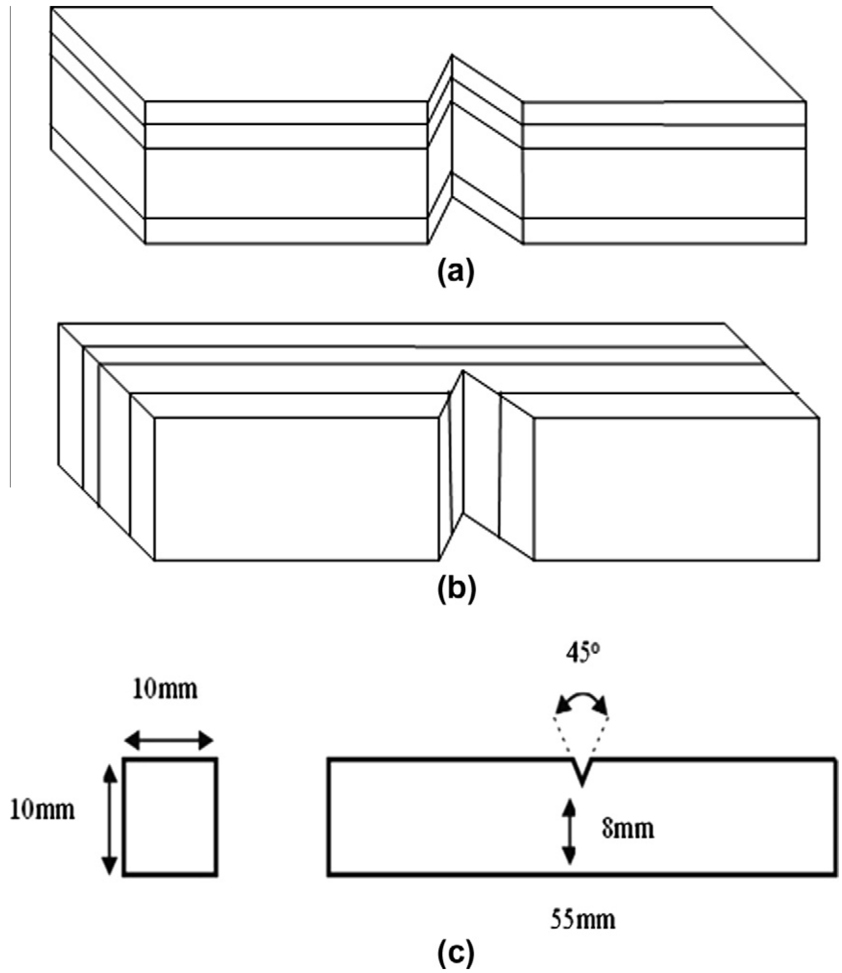

Fig. 1. Schematic representation of composite Charpy test specimens in the form of (a) crack divider and (b) crack arrester. (c) Dimension of Charpy impact test specimens.

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

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

In the previous studies, Chary impact energy of functionally graded steels in crack divider configuration [35–38] and in crack arrester configuration [38,39] 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 [16–18,40,41]. Fracture toughness of these specimens in terms of J_{IC} in both crack divider [42–44] and crack arrester [44,45] configurations was also investigated. The tensile behavior of oblique layer functionally graded steels was the other property which studied in the previous studies [46,47]. Prediction Vickers hardness [48] and tensile strength [49] of functionally graded steels by the mechanism-based strain gradient plasticity theory was the other works done in this area. Recently, Charpy impact energy of the specimens was analytically modeled by strain gradient plasticity theory [50,51].

Charpy impact energy of $\alpha\beta\gamma$ and $\gamma M\gamma$ functionally graded steels with notch tip perpendicular to the graded layers (i.e. crack divider configuration as shown in Fig. 1a) has been modeled previously by two methods. In both methods, Charpy impact energy of the composite was considered to be the sum of the Charpy impact energy of constituent layers by means of the rule of mixtures. In one method, Charpy impact energy of each layer was related to the area under stress–strain curve of that layer [35] and in the other model, the Charpy impact energy of each layer was related to the Vickers microhardness of that layer [36]. Although the experimental results of the impact energy of the composites showed a good agreement with those obtained from analytical models, however some deviations between the results was observed for composites with martensite layer. Charpy impact energy of $\alpha\beta\gamma$ and $\gamma M\gamma$ composites with the notch tip parallel to the gradient (i.e. crack arrester configuration which is shown in Fig. 1b) and with different location and distances of the notch tip with respect to the bainite or martensite intermediate layers has also been studied [39]. For crack arrester configuration, no accurate mathematical modeling was presented except that done by finite element simulation [38]. In that work [38], the modified stress–strain curve was used as the input data for each constituent layer. In addition, utilizing strain gradient plasticity theory to model Charpy impact energy of FGSs in crack divider configuration was reported in our previous works [50,51].

In this work, Charpy impact energy of ferritic and austenitic FGSs in both crack divider and crack arrester configuration has been numerically simulated by 3D finite element method. The difference between the present work and the previous ones [50,51] is that in the previous work, the analytical model was presented while in the present work, 3D finite element simulation has been utilized. The data used as input parameters in the present work were the stress–strain curve data acquired by the concept of mechanism-based strain gradient plasticity theory (MSG) [52] which is