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Simulation Charpy impact energy of functionally graded steels by modified stress–strain curve through mechanism-based strain gradient plasticity theory

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ABSTRACT

In the present work, Charpy impact energy of functionally graded steels produced by electroslag remelting composed of graded ferritic or austenitic layers in both crack divider and crack arrester configurations has been modeled by finite element method. The yield stress of each layer was related to the density of the statistically stored dislocations of that layer and assuming by Holloman relation for the corresponding stress–strain curves, tensile strengths of the constituent layers were determined via numerical method. By using load–displacement curves acquired from instrumented Charpy impact tests on primary specimens, the obtained stress–strain curves from uniaxial tensile tests were modified. The data used for each layer in finite element modeling were predicted modified stress–strain curves 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

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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];

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

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]. Finally 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 were 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 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 were the stress–strain curve data acquired by the concept of mechanism-based strain gradient plasticity theory (MSG) [52] which is unique among strain gradient theories because it is established directly from the Taylor dislocation model [53,54]. The intrinsic material length in MSG is identified as $(G/\sigma_{\mathrm{ref}})^2 b$, 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 [55], and the density ρ_G for geometrically necessary dislocations (GND) which are required for compatible deformation of various parts of the nonuniformly deformed material [55–58]. The density of geometrically deformed dislocations is linked to the gradient of plastic strain [56]; while the density of statistically stored dislocations is linked to the relation between stress and plastic strain in uniaxial tension [59]. The flow stress is then determined from the plastic strain and plastic strain gradient via the Taylor dislocation model [59]. The superiority of the present model to the previous one [38] is that the hardness of each layer (i.e. hardness profile) is not required for determining tensile strength.

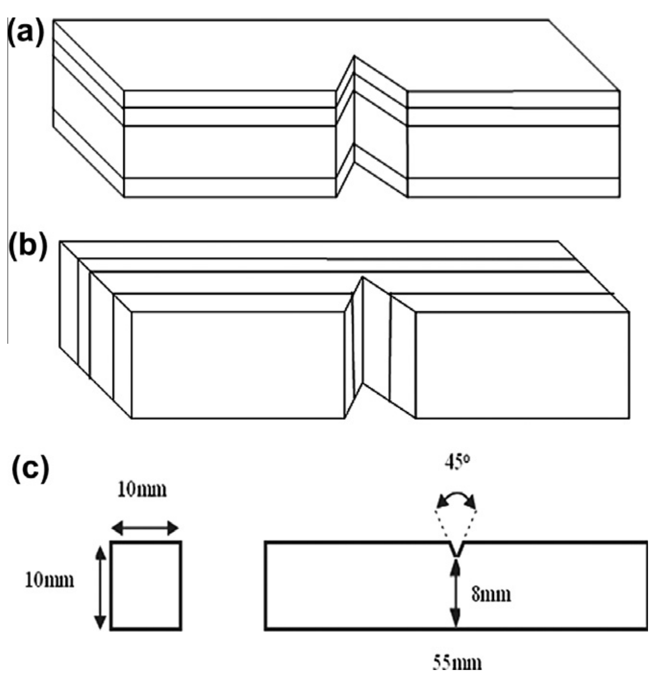

Fig. 1. Schematic representation of composite Charpy test specimens in the form of (a) crack divider and (b) crack arrester. (c) Dimension of Charpy impact test specimens.

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 a 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 16KVA. After remelting, the composite ingots were forged down to the thickness of 30 mm. Forging operation was carried out at 980 °C and then specimens were air-cooled.

The impact energy of FGSs in crack divider (Fig. 1a) and crack arrester (Fig. 1b) configurations was evaluated by Charpy impact test at 18 °C using standard sized specimens (10 × 10 × 50 mm) according to the ASTM E23 [60]. The 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

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	–	–