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Modeling fracture toughness of functionally graded steels in crack arrester configuration

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ABSTRACT

By utilizing plain carbon and austenitic stainless steels with different thicknesses and arrangements as electrodes of electroslag remelting, functionally graded steels containing graded ferritic and austenitic regions together with bainite and martensite intermediate layers were produced. Fracture toughness of the functionally graded steels in crack arrester configuration has been demonstrated to depend on the position and sense of the graded region in which the crack is located. When a propagating crack experiences an upward gradient of fracture toughness, the fracture toughness of the composite is increased and vice versa. An analytical model has been presented for predicting fracture toughness of the composites. Also 3D numerical simulation by conducting finite element method has been presented. There is a good agreement between experimental results and those obtained by the analytical and numerical models.

1. Introduction

Functionally graded materials (FGMs) are multi-phase systems, which their composition varies gradually in some directions to obtain unique mechanical, thermal and electrical properties that distinguish them from the conventional composites, which in general have discrete and piecewise nature with sharp interfaces [1,2]. 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 multi-phase materials, composites, or functionally graded materials, strength variations are inherent. Therefore, considerations of theses group of FGMs are inevitable [3].

The first published experimental evidence that a gradient in yield stress influences the behavior of cracks was performed by Suresh et al. [3]. 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. [4] and Kolednik [5] 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. [6] 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 [7] studied the fracture toughness of functionally graded steels produced with laser welding. A method of creating a functionally graded structural member by transforming its material at cryogenic temperatures has been presented by Skoczen' [8]. The technique consisted in imposing on a stainless steel bar kinematically controlled torsion until the phase transformation threshold is reached and the material starts transforming itself close to the outside radius of the bar.

Recently, functionally graded steels with strength gradient were produced from austenitic stainless steel and plain carbon steel using electroslag remelting (ESR) [9]. By selecting appropriate arrangements and thicknesses of the original ferritic steel ($\dot{\alpha}$) and original austenitic steel ($\dot{\gamma}$) as electrodes, it is possible to obtain composites with several layers consist of ferrite, austenite, bainite and martensite.

$$(\dot{\alpha}\dot{\gamma})_{el} \xrightarrow{R} (\alpha\beta\gamma)_{com}$$
$$(\dot{\gamma}\dot{\alpha}\dot{\gamma})_{el} \xrightarrow{R} (\gamma M\gamma)_{com}$$

where α, β, γ and M are ferrite, bainite, austenite and martensite phases in final composite, respectively, *el*, *com* and *R* represent electrode, composite and remelting, respectively.

As alloying elements such as carbon, chromium and nickel atoms diffuse, alternating regions with different transformation

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characteristics are created. The diffusing atoms individually or together stabilize different phases such as bainite or martensite. Thicknesses of bainitic and martensitic layers depend on the thicknesses of the primary electrodes and process variables [10].

Transformation characteristics [9], tensile properties [10] and Charpy impact energy [11–13] of FGSs have previously been studied. Predicting the fracture resistance properties of FGSs by static loading seems essential. Therefore, in this work, fracture toughness, J_{IC}, of FGSs has been investigated with the starter crack along the layers (i.e. crack arrester con figuration).

2. Experimental procedure

Similar to the previous works [9–13], a miniature ESR apparatus was used to produce FGSs. The slag consumed was a mixture of 20% CaO, 20% Al_2O_3 and 60% CaF_2. The original ferritic and austenitic steels which employed as electrodes were commercial type AISI 1020 (with 0.2 wt% C, 0.3 wt% Si, 0.2 wt% Mn, 0.05 wt% S and 0.05 wt% P) and AISI 316 (with 0.07 wt% C, 1 wt% Si, 2 wt% Mn, 0.045 wt% S, 0.03 wt% P, 18.15 wt% Cr and 9.11 wt% Ni) steels.

Two arrangements of ferritic and austenitic steel slices in the form of 2- and 3-piece electrodes were spot welded for remelting. The height of each slice in primary 2-piece $\dot{\alpha}\dot{\gamma}$ electrode was 100 mm. For 3-piece $\dot{\gamma}\dot{\alpha}\dot{\gamma}$ electrode, the height of the middle slice was 25 mm and that of neighboring slices was 87.5 mm.

Remelting was done under a constant power supply of 16KVA. After remelting, the composite ingots were hot-pressed at 980 °C down to the thickness of 30 mm and then were air-cooled.

Due to limitation of specimen dimensions, fracture toughness measurement in terms of K_{IC} was not possible. Fracture toughness in terms of J_{IC} test was carried out on specimens at 18 °C. Specimen dimensions was in accordance to the ASTM E1820 [12] 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

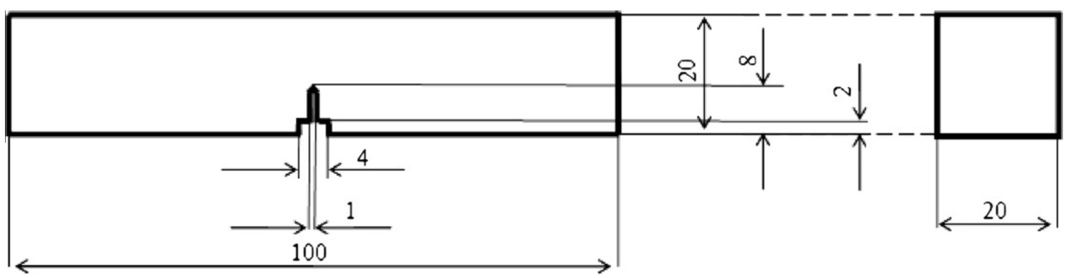

Fig. 1. Dimension of 3-point bend specimen (mm) for fracture toughness test.

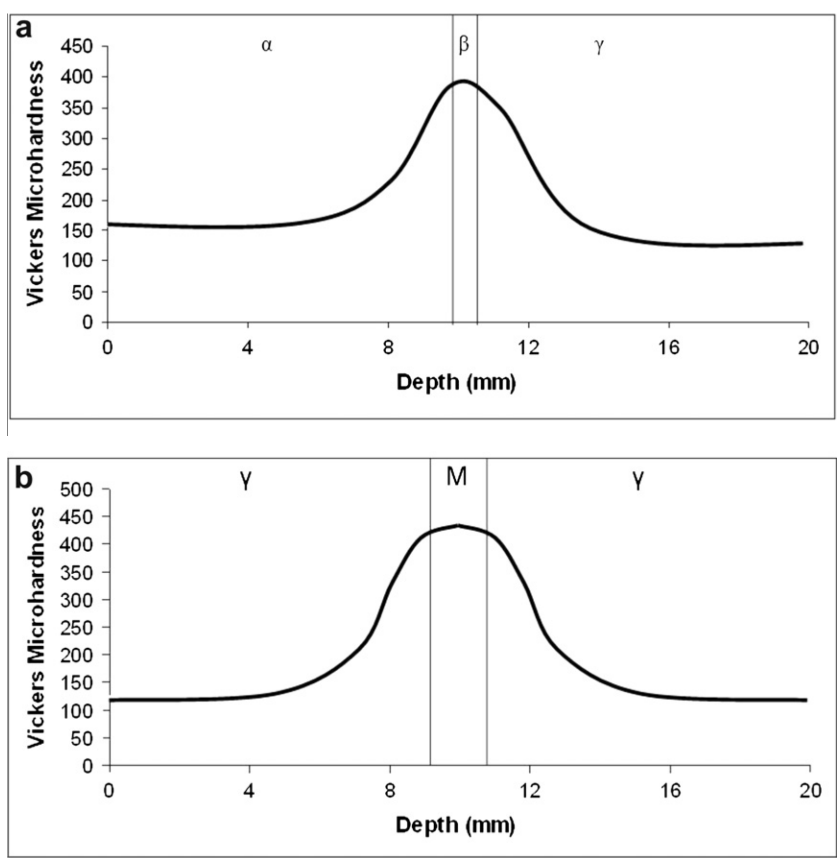

Fig. 2. Vickers microhardness profile versus depth in (a) $\alpha\beta\gamma$ and (b) composite.