Relationship between Charpy Impact Energy and Notch Tip Position in Functionally Graded Steels

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ABSTRACT. *Functionally Graded Steels (FGSs) are a possible solution to improve the properties of steels made by Martensite and Bainite brittle phases. These phases are usually present in the interface between the carbon ferritic steel and the stainless austenitic steel. FGSs materials are widely investigated in the recent literature but only few works have been devoted to investigate the impact energy in the case of crack arresters.*

To partially fill this gap, the effect of the distance between the notch tip and the position of the median phase on the Charpy impact energy is investigated in the present paper. The results show that when the notch apex is close to the median layer the impact energy reaches its maximum value due to the increment of the absorbed energy by plastic deformation ahead of the notch tip. On the other hand when the notch apex is far from the median layer, the impact energy strongly decreases. Keeping into account the relationship between the Charpy impact energy and the plastic volume size, a new theoretical model has been developed to link the composite impact energy with the distance from the notch apex to the median phase. The results of the new model show a sound agreement with previous results taken from the literature.

INTRODUCTION

Functionally graded steels (FGSs) may be produced during welding of alloy steels. Jang et al. [1] studied experimentally and numerically the effects of notch position on

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the failure behavior and energy absorption when the Charpy impact test was performed at -1°C. Carbon steel plate with a thickness of 25 mm was welded and specimens were fabricated from the welded plate. The Charpy impact tests were then performed on specimens having different notch positions varying within HAZ. A series of 3-D FE analysis which simulate the Charpy test were also carried out.

Recently, FGSs have been produced by electroslag remelting (ESR) [2]. Studies on transformation characteristics of FGSs produced from austenitic stainless steel and plain carbon steel have shown that as chromium, nickel, and carbon atoms diffuse at remelting stage, alternating regions with different transformation characteristics are created in the material. By selecting appropriate arrangement and thickness of original ferritic and original austenitic steels as electrodes, composites with graded ferrite, and austenite regions together with bainite or martensite layers may be made [2].

In Refs [3, 4] Charpy impact energy of crack divider specimens was measured experimentally and the obtained results show that the impact energy of the specimens depends on the type and the volume fraction of the present phases. A theoretical model based on the rule of mixtures, which correlates the impact energy of FGSs to the impact energy of the individual layers through Vickers microhardness of the layers, was obtained in [3]. Following parallel tracks, Charpy impact energy of FGSs produced by electroslag remelting in the form of crack arrester configuration has been investigated in [3].

Nazari [4] obtained the impact energy for all layers in the case of crack divider of FGSs utilizing the relation between the impact energy of each layer and the surrounded area of stress-strain diagram. The results obtained in that study indicate that the notch tip position with respect to bainite or martensite layer significantly affects the impact energy. The closer the notch tip to the tougher layer, the higher the impact energy of the composite due to increment of energy absorbed by plastic deformation zone ahead of the notch and vice versa. Empirical relationships have been determined to correlate the impact energy of FGSs to the morphology of each layer [5].

As stated in Ref. [4] for crack arrester configuration, no accurate mathematical modeling was presented except that done by finite element simulation. The aim of the present work is to develop a new analytical model for the assessment of the Charpy impact energy of FGSs in the form of a crack arrester configuration. The outputs of the proposed model are compared with the experimental results taken from the recent literutaure showing a sound agreement.

THEORETICAL MODEL

Initial Analysis

The experimental charpy impact energy of FGSs in the form of crack arrester configuration has been obtained by Nazari and Aghazadeh [5]. That work showed that the impact energy of $\alpha\beta\gamma$ composite when the notch is in the austenitic region is higher than in the case in which the notch is in the ferritic region. This is due to the fact that the plastic region at the notch tip, and then the capability to absorb energy, is larger when the notch is in the austenitic region.

When the notch tip is close to the bainitic layer but remaining in the austenitic region the impact energy decreases while, on the other hand, the impact energy increases if the notch is placed in the ferritic region. Furtheremore, variaion of impact energy in austenitic region of γMγ composite is the same of austenitic region of αγβ composite.

A link between the impact energy and the size of the plastic region has been obtained in [6]. The equation is as follows:

$$CV = Nr_y + M \tag{1}$$

where CV is the impact energy, r_y is the plastic region radius, N and M are constants which depend on the material. Considering the Von-Mises yield criterion, the following relation is obtained for the plastic region size of a homogenous material under plane strain conditions and mode I loading [6].

$$r_y = \alpha \left(\frac{K_{IC}}{\sigma_y} \right)^2 \times \cos^2\left(\frac{\theta}{2}\right) \times \left[(1-2\nu)^2 + 3\sin^2\left(\frac{\theta}{2}\right) \right] \tag{2}$$

where ν is Poisson ratio, K_{IC} is the material's fracture toughness, σ_y is the yield stress and α is a constant. Eq. (2) shows that the the plastic region size varies as a function of the angle, θ. In order to neglect the effect of the angle on the size of the plastic region, the following new equation is proposed to assess the impact energy in the case of a crack arrester:

$$CV_{FG(d)} = M + \left[\frac{A_{rFG(d)}}{A_{rH(d)}} \right]^{\frac{1}{2}} \times (CV_{H(d)} - M) \tag{3}$$

Eq. (3) depends on the distance of the notch tip from median phase of FGS (d) and on the type of the considered composite.

$CV_{H(d)}$ is the impact energy of the layer containing the notch tip. $A_{rH(d)}$ is the area of the plastic region for a homogenous specimen with the properties of the layer containing the notch tip. $A_{rFG(d)}$ is the area of the plastic region for a FG specimen in which the mechanical properties vary along the direction of the notch bisector line.

In crack divider specimen, the mechanical properties for all layers have been obtained from ferritic/austenitic layer to median baintic/martensitic layer (*X* denotes the distance from ferritic/austenite layer in the work by Nazari [4]). In the crack arrester specimen, the distance between notch tip and median bainite/martensite position is denoted here as *d*. The mechanical properties at the notch tip in crack arrester specimen could be obtained by determing them in the same position of the crack divider specimen.

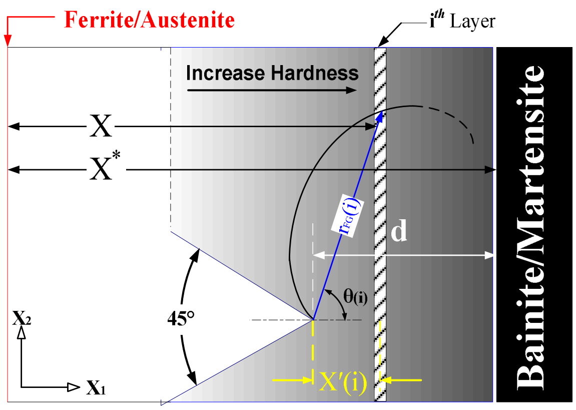


Figure 1. Profile of the plastic region in front of the notch tip in the graded region of a FGS (crack arrester configuration)

In order to determine the mechanical properties of the layer containing the notch tip, it has been supposed that the fracture toughness (K_{IC}) and yield stress (σ_y) vary exponentially with respect to the direction X:

$$K_{IC}(X) = D_1 \exp(D_2 X) \quad (4)$$

$$\sigma_y(X) = D_3 \exp(D_4 X) \quad (5)$$

where X is the distance of the layer from the crack divider specimen edge, D_i are the constants that can be obtained by imposing the appropriate boundary conditions shown in Table 1.

The fracture toughness ($K_{IC(d)}$) and the yield stress ($\sigma_{y(d)}$) corresponding with the layer containing the notch tip could be obtained by substituting $X=X^*-d$ in the Eqs. 4 and 5.

By considering Eq. 2, A_{rh} can be obtained as follows:

$$A_{rH(d)} = 2\left[\frac{1}{2}\int_{\theta=0}^{\theta^*} r_H^{\,2}(\theta)d\theta\right] = \alpha^2\left(\frac{K_{IC(d)}}{\sigma_{y(d)}}\right)^4 \int_{\theta=0}^{\theta^*} f(\theta)^2 d\theta$$
$$= \alpha^2 \times \left(\frac{D_1}{D_3}\right)^4 \times \exp\left[4(D_2 - D_4)(X^* - d)\right] \times I_1 \quad (6)$$

where

$$I_1 = \int_{\theta=0}^{\pi}\left\{\cos^2\frac{\theta}{2}\left[(1-2\nu)^2 + 3\sin^2\frac{\theta}{2}\right]\right\}^2 d\theta \quad (7)$$

Eq. 7 gives values independent of the type of the composite and the values of the distance d. I_1 is equal to 2.2594 for ν=0.33.

For determining A_{rFG}, since $(K_{IC}/\sigma_y)^2$ varies at different layers ahead of the notch, the influence of the angle, θ, and the radial distance have to be considered simultaneously.

In order to evaluate A_{rFG}, a layer ahead of the notch is considered in the graded region, being $X'_{(i)}$ the distance from the notch tip. In Figure 1, $r_{FG(i)}$ and $\theta_{(i)}$ indicate the vectorial radius and vectorial angle of the plastic region with respect to the i^{th} layer. By considering Eq. 2, $r_{FG(i)}$ can be expressed as follows:

$$r_{FG(i)} = \alpha \times H(X'_{(i)}) \times f(\theta_{(i)}) \tag{8}$$

$$H(X'_{(i)}) = \left(K_{IC}(X'_{(i)}) / \sigma_y(X'_{(i)})\right)^2 \tag{9}$$

where $K_{IC}(X'_{(i)})$ and $\sigma_y(X'_{(i)})$ are the fracture toughness and the yield stress correspondending to the i^{th} layer. The relationship between the radius and the angle of the plastic region and the position of the considered layer can be expressed as follows:

$$X'_{(i)} = r_{FG(i)} \cos(\theta_{(i)}) \tag{10}$$

By combining Eqs 8 and 10 the following expressions can be derived:

$$\frac{X'_{(i)}}{H(X'_{(i)})} = \alpha f(\theta_{(i)}) \cos(\theta_{(i)}) \tag{11}$$

$$H(X'_{(i)}) = \left(\frac{K_{IC}(X'_{(i)})}{\sigma_y(X'_{(i)})}\right)^2 = \left(\frac{D_1}{D_3}\right)^2 \exp\left[2(D_2 - D_4)(X^* - d + X'_{(i)})\right] \tag{12}$$

By using Taylor's series expansion ($\exp(x)=1+x+O(x^2)$) and neglecting the higher order terms, $X'_{(i)}$ assumes the following form:

$$X'_{(i)} = \frac{\alpha \times A \times f(\theta_{(i)}) \cos(\theta_{(i)})}{1 + \alpha \times B \times f(\theta_{(i)}) \cos(\theta_{(i)})} \tag{13}$$

$$A = \left(D_1 / D_3\right)^2 \left[1 + 2(D_2 - D_4)(X^* - d)\right] \tag{14}$$

$$B = -2(D_2 - D_4)\left(D_1 / D_3\right)^2 \tag{15}$$

By substituting $X'_{(i)}$ into Eq. 8, the radius $r_{FG}(i)$ is derived as follows:

$$r_{FG}(\theta_{(i)}) = \alpha \left(\frac{D_1}{D_3}\right)^2 \times \left[1 + 2(D_2 - D_4)\left(X^* - d + \frac{\alpha \times A \times f(\theta_{(i)}) \cos(\theta_{(i)})}{1 + \alpha \times B \times f(\theta_{(i)}) \cos(\theta_{(i)})}\right)\right] \times f(\theta_{(i)}) \tag{16}$$

By integrating Eq. (16), A_{rFG} is obtained as follows:

$$A_{r_{FG}} = \int_{\theta=0}^{\theta=\pi} r_{FG}^{\,2}(\theta) d\theta = \alpha^2 \times \left(\frac{D_1}{D_3}\right)^4 \times \left\{ \left[1+4(D_2-D_4)(X^*-d)+4(D_2-D_4)^2(X^*-d)^2\right] \times I_1 + 4\alpha \times A \times \left[2(D_2-D_4)^2(X^*-d)+(D_2-D_4)\right] \times I_3 + 4\alpha^2 . A^2 . (D_2-D_4)^2 \times I_2 \right\} \qquad (17)$$

where I_2 and I_3 are defined according to the following expressions

$$I_2 = \int_{\theta=0}^{\theta=\pi} \frac{f(\theta)^4 \times \cos^2(\theta)}{\left[1+\alpha \times B \times f(\theta)\cos(\theta)\right]^2} \qquad (18)$$

$$I_3 = \int_{\theta=0}^{\theta=\pi} \frac{f^3(\theta)\cos(\theta)}{1+\alpha \times B \times f(\theta)\cos(\theta)} d\theta \qquad (19)$$

These integrals contain parameter B which depends on the composite type (boundary conditions and X^*) according to Eq. 15. Therefore, I_2 and I_3 have to be calculated for each graded region. These integrals are independent of d.
M is calculated as follows taking advantage of Eq. 1:

$$M = \left[r_{y(1)} CV_{(2)} - r_{y(2)} CV_{(1)} \right] / \left[r_{y(1)} - r_{y(2)} \right] \qquad (20)$$

Subscripts 1 and 2 correspond to the mechanical properties of the austenite-ferrite layers (located at the outer edge region, in the composite) and baynite-martensite (median phase in the composite) from graded regions, respectively.

Application of model for αβγ and γMγ functionally graded steel

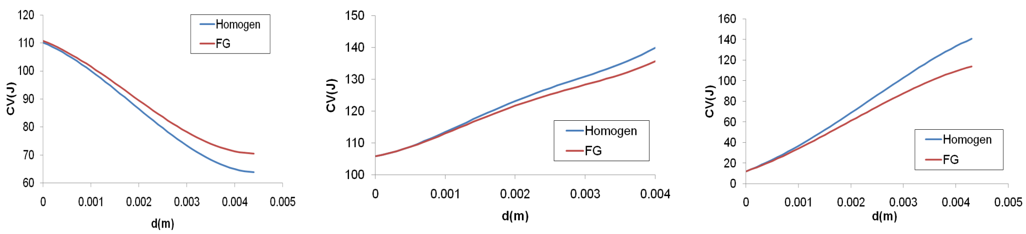
The mechanical properties of the different phases of FGSs are reported in Table 1.

Table 1. Mechanical properties of single phase steels in the composite [4, 7]

Property / Single phase	Yield Strength [MPa]	Impact Energy CV [J]	K_{IC} [MPa.m$^{0.5}$]	Poisson Ratio ν
Ferritic	245	64	45.72	0.33
Austenitic	200	140	107.77	0.33
Bainitic	1025	108	82.08	0.33
Martensitic	1440	11	6.09	0.33

By using as boundary conditions the values reported in the Table 1 the constants of Eqs. (6), (17) and (20) have been obtained. By substituting Eqs. (6), (17) and (20) into Eq. (3), the impact energy for different types of FGSs has been derived as a function of the notch tip position, *d*.

$CV_{H(d)}$ is the impact energy of a layer which is at the distance (X^*-d) from the crack divider specimen edge. For different distances from the notch tip to the median phase of the composite, $CV_{H(d)}$ has been evaluated following the method proposed in Ref. [4]. By substituting $CV_{H(d)}$ in Eq. 3, the impact energy of the FGS, $CV_{FG(d)}$, has been obtained. The variation of the impact energy both for the homogeneous material and for the FG steel as a function of the distance from the notch tip to the median layer are shown in Figure 2.



(a) (b) (c)

Figure 2. Variation of the impact energy of Functionally Graded (FG) steel and homogenous ones made of the Adhesive layer of the notch tip versus distance d : a) ferritic region in $\alpha\beta\gamma$ composite (X^*=4mm), b) austenitic region in $\alpha\beta\gamma$ composite (X^*=4.4mm), c) austenitic region in $\gamma M\gamma$ composite (X^*=4.25mm)

Figure 2 shows that the impact energy when the notch is in the ferritic region of the composite is always greater than the value obtained from the homogenous material characterized by the mechanical properties of the layer corresponding to the notch tip.

On the other hand, in the other cases, the impact energy of graded materials is always lower than that corresponding to the homogenous specimen. In order to investigate the accuracy of the model, the results are compared with the experimental data taken from Ref. [5]. The impact energy for three values of parameter *d* are reported in Table 2.

The comparison shows that Eqs. 21-23 allow to predict the impact energy with good accuracy in the case of $\alpha\beta\gamma$ composite. The deviation between theoretical predictions and experimental results increases for the case of $\gamma M\gamma$ steel. For that material, in fact, the two phases with high variation in brittleness and ductility are close each other. In this case, the influence of the strain rate should be considered to improve the accuracy of the predictive model.

Table 2 Comparison between impact energy of the model and experimental data for different distances of the notch tip from median phase in FGSs

d (mm)	**1**		**2**		**3**	
FGS Type	CV_{exp} [5]	$CV_{Eq. (3)}$	CV_{exp} [5]	$CV_{Eq. (3)}$	CV_{exp} [5]	$CV_{Eq. (3)}$
αβγ (α)	99	101.22	85	86.43	75	73.40
αβγ (γ)	111	113.51	119	123.27	125	131.36
γMγ	25	23.15	44	50.50	83	87.91

CONCLUSION

1. A new analytical model is proposed to evaluate the Charpy impact energy of functionally graded steels with a crack arrester configuration. Different distances of the notch tip from the median phase of the composite are considered as well as the size of plastic region ahead of the notch tip.
2. The results from the model are discussed for two types of FGSs (αβγ and γMγ). The minimum average error has been obtained when the notch is in the ferritic region of αβγ composite. The maximum average error is obtained for γMγ composite.
3. The impact energy of the FGSs is compared with the specimen made of the homogeneous material corresponding to the notch tip layer. The results show that the impact energy in the ferritic region of αβγ composite is higher than that corresponding to the homogeneous material. On the other hand, in the other cases, the impact energy of graded materials is always lower than that corresponding to the homogenous specimen.

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