Effect of notch depth and notch root radius on the J-integral in the plates made of functionally graded steel

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ABSTRACT. *In this paper, the effect of notch root radius and notch depth on the J-integral in the plates made of functionally graded steel in the form of crack divider configuration and weakend by U-notch under mode I loading was investigated. Two different types of functionally graded steel containing $\alpha\beta\gamma$ and $\gamma M\gamma$ were simulated utilizing finite element method (FEM). This simulation was confirmed comparing the obtained results with the experimentalones. Then, the effect of notch radius and notch depth on the J-integral was considered. The resaults showed that in both type of functionally graded steelsl, J-integral increased with increasing of notch depth and decreased with increasing of notch root radius.*

INTRODUCTION

The J-integral represents a way to calculate the strain energy release rate, or work (energy) per unit fracture surface area, in elastic and elastic-plastic material and is now considered in U and V notchs by researchers. Chen, and Lu [1] proved if integration path contains the semicircular of U-notch, J-integral is independent of path but if integration path does not contain all semicircular part of notch, J-integral is dependent of first and last point of the path. Filippi and Lazzarin [2] determined the distributions of the elastic principal stress around U and V notch analatycally . Berto and Lazzarin [3] evaluated J- integral for U- and V- blunt notches under mode I loading and materials obeying a power hardening law. Berto and Lazzarin[4] determined Relationships between J-integral and the strain energy evaluated in a finite volume surrounding the tip of sharp and blunt V-notches. Barati and Alizadeh [5] obtained the relationship

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between J-integral and averaged strain-energy density for U-notches in the case of large control volume that contain total curvature of notch. Troyani and Hernandez [6] calculated theoretical stress concentration factors for short flat bars with opposite U-shaped notches subjected to in-plane bending be finite element method. Barati and Alizadeh [7] suggested new and practical equations suitable for calculations of J-integral under bending loading in the case of a material obeying a linear elastic law. Com and Mariani [8] used extended finite element to simulate of quasi-brittle fracture in functionally graded materials. Barati [9] showed that with increasing of depth notch, strain density energy increased and with decreasing of notch root radius, strain density energy first increased and then decreased. Nazari [10] presented an analytical model for predicting fracture toughness in functionally graded steel in crack arrester configuration. Nazari and Aghazadeh [11] presented a mathematical model for predicting fracture toughness in functionally graded steel in crack divider configuration by using the rule of phase mixtures. Barati [12] investigated the depth effect on J-integral of U-notch in arrester configuration in functionally graded steel.
In the present work, the effect of notch radius and notch depth on the J-integral in a plate weakend by U notch under mode I loading was investigated. The plate was made of functionally graded steel (FGS) in the form of crack divider configuration and two types of FGS containing ferrite-bainite-austenite ($\alpha\beta\gamma$) and austenite-Martensite-austenite ($\gamma M\gamma$) were studied.

Experimental procedures

The initial materials were prepared from simple carbon steel *AISI 1020* and austenitic stain steel *316L* in the form of ingots with 45 mm diameter. The chemical composition of these materials is shown in Table 1.

Table 1. Chemical composition of original ferrite and austenite Steels

	%C	%Si	%Mn	%P	%S	%Cr	%Ni
316L(γ_0)	0.07	1	2	0.04	0.03	18.15	9. 11
AISI1020(α_0)	0.2	0.3	0.2	0.05	0.05	-	-

The initial electrodes were prepared from the cutting operation of these bars and were connected to each other with co_2 welding according to desired *FGS*s type. A three- part electrode containing a two-part austenitic with the length of 92 mm and a median one-part ferritic with the length of 26 mm was used to make martensitic samples. Also, a one-part austenitic with the length of 105 mm and a one-part ferritic with the length of 125 mm were used to make bainitic sample. Then, these electrodes were welded to the end of a 200 mm bar and were put in the ESR furnace vertically. The furnace contained a square copper mold with the 70×70 mm ^{2} area section and a steel plate (Figure. 1). The plate which had a circular cavity with 80 mm diameter in its center was connected to the supply power. The other pole of this supply power was connected to the bar. The starter which is shown in Figure.2 was welded on the plate cavity in the form of a hollow cylinder with rectangular section of 40×40 mm^2 and height of 52 mm. This starter was filled with some slag. In the start of the operation, utilizing the activation of supply power, the starter was melt and filled the plate cavity. Afterwards, some other slag was added to the mold continuously and this leads to increase in the electrical resistance. This slag contained 70% fluoride-calcium and 30% aluminum-oxide and had 1500 gr weight. The slag role was the production of heat in order to make the melt bath from the initial electrode with the electrical induction between the electrode and the bottom of mold plate. The slag composition was selected according to melt composition purification in melting process and chemical composition compatible. The floating height of electrode in slag bath was constant and it was about 5 mm. The obtained ingots had the height of 62 mm. Utilizing polishing and etching processes, a graded region in the median part of ingots with 20 mm height, was obtained. The etching solution, Kalling, was contained 5 gr copper-chloride, 100 ml hydro-chloricacid, 100 ml water and 100 mm ethanol. Then, the hot hydraulic press in 980ºC temperature was used to decrease the ingot height to 31 mm. This height was also decreased to 30 mm with grinding process. Finally, the specimens with 100 mm length, 20 mm width, 10 mm height were obtained. Moreover, the U-notch with 8 mm depth and 2.5 mm radius were produced on the obtained specimens utilizing the wire cut process. The fracture test was done and the load-displacement information was recorded via a computer device (Figure. 2). Utilizing this curve, the J-intgegral was obtained.

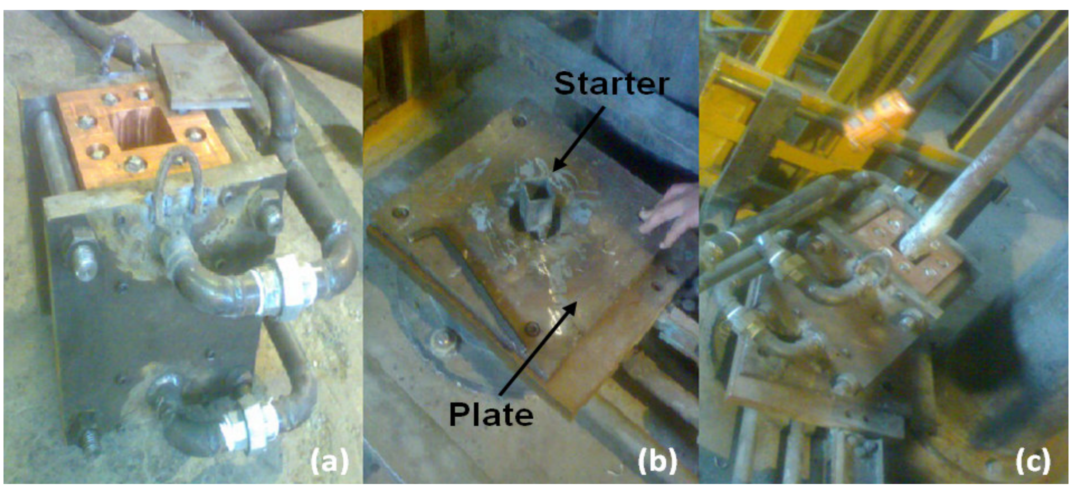


Figure 1. Necessary instruments (a) mold, (b) starter and plate (c) ESR instrument [13]

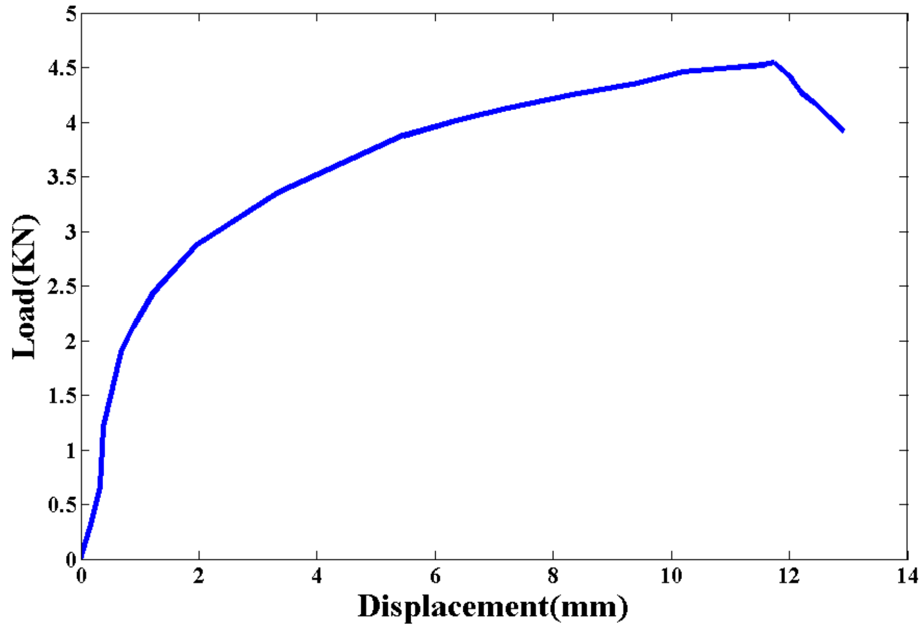
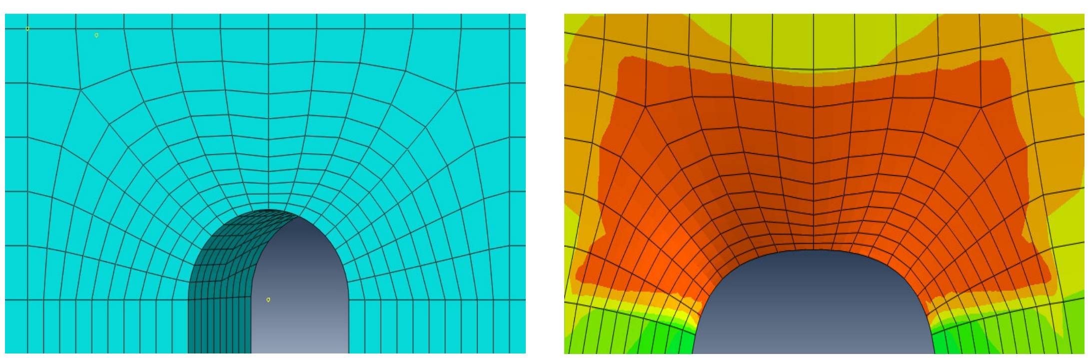


Figure 2. Variation of Load with respect to the Load displacement point in a $\alpha\beta\gamma$ specimen with U-notch (8mm notch depth and 2.5mm notch radius)

Finite element method (FEM)

Finite element siumlation was done utilizing ABAQUS 6.10 software. The pecimens with different depth and with different root radius for both type of FGSs were simulated. Due to the change of mechanical properties in thickness direction (crack divider configuration), more elements were considered in the thickness direction and around the notch tip (Figure. 3).



(a) (b)

Figure 3. FEM modeling of U-notch for **a)** Undeformed specimen **b)** Deformed specimen

The J-integral obtained from FEM simulation was compared with the experimental one. This was done for different notch root radius and notch depth and it showed a good agreement between them. Table2 shows the percent of error between the FEM results and experimnetal ones.

Table 2. Percent of error between Finite element method and experimental results for calculating of J-integral

FGS	$\gamma M\gamma$ (in different radius)	$\gamma M\gamma$ (in different depth)	$\alpha\beta\gamma$ (in different radius)	$\alpha\beta\gamma$ (in different depth)
Error (%)	4.883%	5.308%	4.214%	4.701%

Resaults

Variation of FEM and experimental J-integrl versus the notch depth for $\alpha\beta\gamma$ and $\gamma M\gamma$ FGSs are shown in Figure 4 and Figure 5, repectively. Thses figures show a good agrrement between the FEM and experimental results. Moreover, these figures show that with increasing the notch depth, the J-integral value increases.

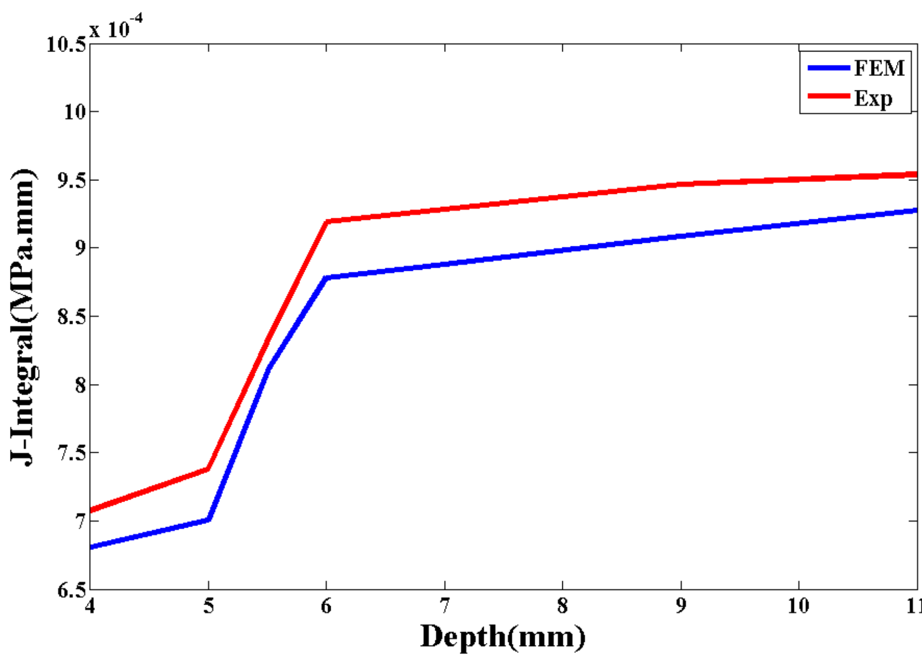


Figure 4. Effect of depth on value of J-integral in αβγ FGS specimen and comparison FEM results with experimental ones (under constant bending loading 2KN)

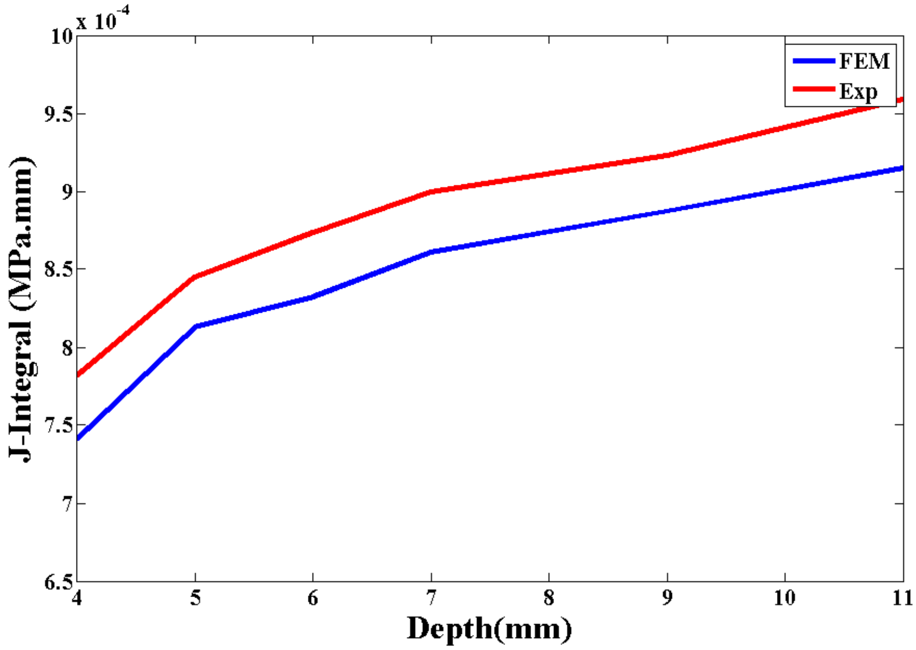


Figure 5. Effect of depth on value of J-integral in γMγ FGS specimen and comparison FEM results with experimental ones (under constant bending loading 2KN)

Variation of FEM and experimental J-integrl versus the notch root radius for $\alpha\beta\gamma$ and $\gamma M\gamma$ FGSs are shown in Figure 6 and Figure 7, repectively. Thses figures show a good agrrement between the FEM and experimental results. Moreover, these figures show that that with increasing the notch radius, the value of J-integral decreases.

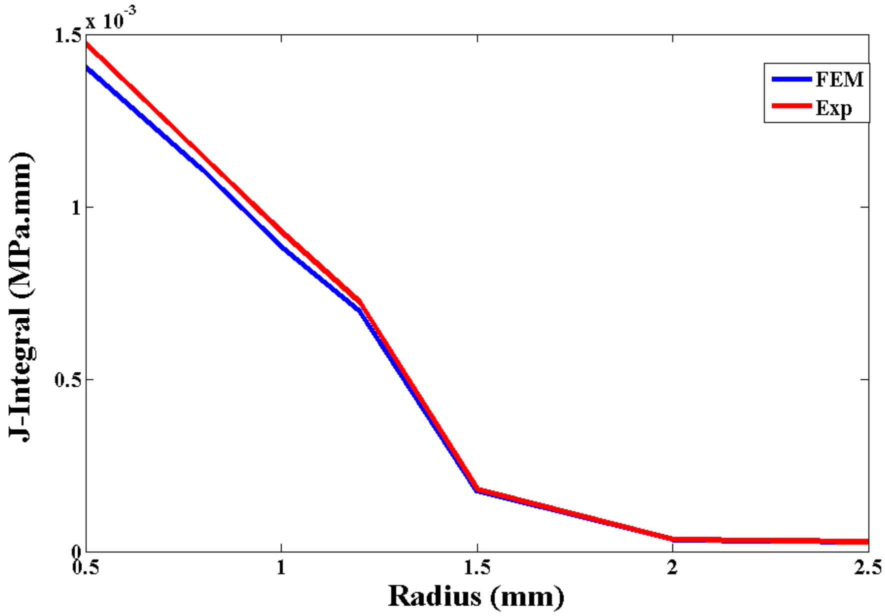


Figure 6. Effect of radius on value of J-integral in αβγ FGS specimen and comparison FEM results with experimental ones (under constant bending loading 2KN)

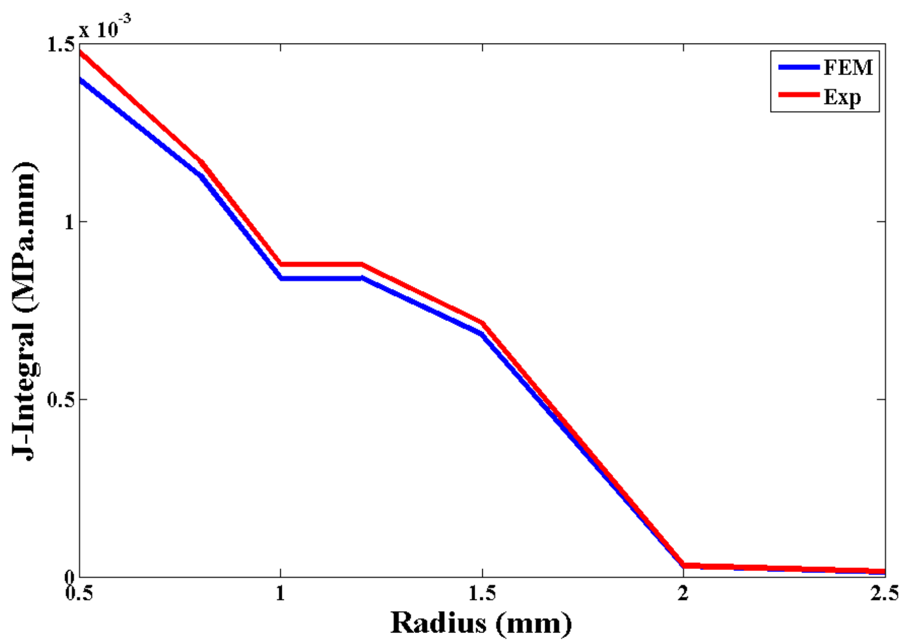


Figure 7. Effect of radius on value of J-integral in γMγ FGS specimen and comparison FEM results with experimental ones (under constant bending loading 2KN)

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