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 weakened by U-notch under mode I loading was investigated. Two different types of functionally graded steel containing αβγ and γMγ were simulated utilizing finite element method (FEM). This simulation was confirmed comparing the obtained results with the experimental ones. Then, the effect of notch radius and notch depth on the J-integral was considered. The results showed that in both type of functionally graded steels, 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 notches 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 analytically. 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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In the present work, the effect of notch radius and notch depth on the J-integral in a plate weaken 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>
<thead>
<tr>
<th></th>
<th>%C</th>
<th>%Si</th>
<th>%Mn</th>
<th>%P</th>
<th>%S</th>
<th>%Cr</th>
<th>%Ni</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>316L($\gamma$)</strong></td>
<td>0.07</td>
<td>1</td>
<td>2</td>
<td>0.04</td>
<td>0.03</td>
<td>18.15</td>
<td>9.11</td>
</tr>
<tr>
<td><strong>AISI1020($\alpha$)</strong></td>
<td>0.2</td>
<td>0.3</td>
<td>0.2</td>
<td>0.05</td>
<td>0.05</td>
<td>-</td>
<td>-</td>
</tr>
</tbody>
</table>

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 FGSs 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$^2$ 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 mm² 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-chloric acid, 100 ml water and 100 mm ethanol. Then, the hot hydraulic press in 980°C 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-integral was obtained.

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

Finite element simulation was done utilizing ABAQUS 6.10 software. The specimens 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).

**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)

**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. Table 2 shows the percent of error between the FEM results and experimental ones.

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

<table>
<thead>
<tr>
<th>FGS</th>
<th>γMγ (in different radius)</th>
<th>γMγ (in different depth)</th>
<th>αβγ (in different radius)</th>
<th>αβγ (in different depth)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Error (%)</td>
<td>4.883%</td>
<td>5.308%</td>
<td>4.214%</td>
<td>4.701%</td>
</tr>
</tbody>
</table>

**Results**

Variation of FEM and experimental J-integral versus the notch depth for αβγ and γMγ FGSs are shown in Figure 4 and Figure 5, respectively. These figures show a good agreement 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 $\gamma M_\gamma$ FGS specimen and comparison FEM results with experimental ones (under constant bending loading 2KN)

Variation of FEM and experimental J-integral versus the notch root radius for $\alpha\beta\gamma$ and $\gamma M_\gamma$ FGSs are shown in Figure 6 and Figure 7, respectively. These figures show a good agreement between the FEM and experimental results. Moreover, these figures show that with increasing the notch radius, the value of J-integral decreases.
Figure 6. Effect of radius on value of J-integral in $\alpha\beta\gamma$ 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 $\gamma\gamma$ FGS specimen and comparison FEM results with experimental ones (under constant bending loading 2KN)
REFERENCES