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# Study on the J-integral of Shallow Interfacial Cracks in Ceramics-Metal Joint†

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**Abstract**

*In this paper, the J-integral of shallow interfacial cracks in the Ceramics-Metal joint for plane problems was numerically studied using the finite element method. The effects of crack length, modulus of elasticity and stress condition on the J-integral of shallow interfacial cracks in the heterogeneous cracked body were discussed in detail. Conclusions show that the J-integral of shallow interfacial crack in Ceramics-Metal joint increases rapidly compared with that in homogeneous body as the crack length becomes small. There exists a critical crack length $(a/W)_c$ below which the dimensionless parameter J changes strongly. The critical crack length $(a/W)_c$ increases with the increase of material parameter $E_C/E_M$. The possibilities of existing shallow cracks near the interface and crack propagation are discussed in detail.*

**KEY WORDS:** (Interfacial Crack) (Ceramics-Metal Joint) (Fracture Mechanics) (Finite Element Method)

## 1. Introduction

The stress concentration and singularity on the boundary of ceramics-metal joint resulting from the differences of material properties such as modulus of elasticity and Poison's ratio of dissimilar materials have been investigated by a number of researchers theoretically and numerically[1)-3)]. In general, a significant stress concentration exists at the edge of the interface of the joint between dissimilar materials under tensile load. Such stress concentration can be reduced by optimizing or changing the shape of the metal part[4),5)]. Because of the stress concentration on the boundary of ceramics-metal joint, crack initiation and its propagation may likely occur at the interface of ceramics and metal. The applications of fracture mechanics principles can provide a fundamental understanding of the effects of various factors on the fracture of the joint between dissimilar materials[6),7)]. A large number of research works on the stress intensity factors of interfacial crack were done[8),9)]. Because the stress and strain fields of heterogeneous body with a interfacial crack are quite different from those of homogeneous body, it is necessary to estimate the stress intensity factors, $K_I$ and $K_{II}$. The energy release rate and J-integral are also commonly used as fracture mechanics parameters. The reference [10] studied the G value of edge crack existing along bond line of joint composed of dissimilar materials using the boundary element method. The effects of the geometry and the ratio of modulus of elasticity on the G value of joint were investigated.

The shallow cracks always exist in engineering structures including the boundary of ceramics-metal joint. From the view of fracture mechanics parameters, investigating the fracture behavior of shallow cracks on the interface of ceramics-metal joint may be significant for understanding the possibility of crack initiation and crack propagation. In this paper, the J-integral of shallow interfacial crack of ceramics-metal joint was studied using the finite element method. The effects of crack length, modulus of elasticity and stress condition on the J-integral of interfacial crack were analyzed. Further, based on the information, the possibilities of existing shallow crack and its propagation were discussed in detail.

## 2. Model and Computation

The double-edge crack and single-edge crack specimen under remote tension as shown in **Fig. 1 (a)** and **(b)** were selected as models for finite element analysis. The typical finite element mesh is shown in **Fig. 1 (c)**. The meshes consist of eight-node isoparametric elelments. The zone near crack tip consists of several layers of circular rings of elements which were centered about the crack tip. The singularity at the crack tip was modeled by deforming the

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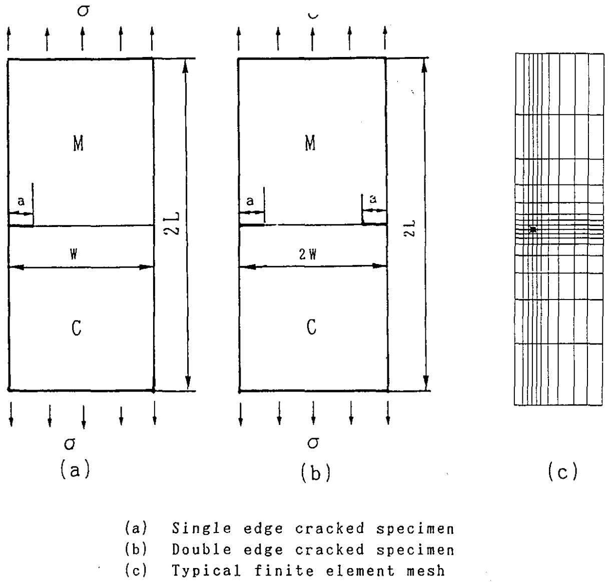


**Fig. 1** Configurations of specimen and finite element mesh

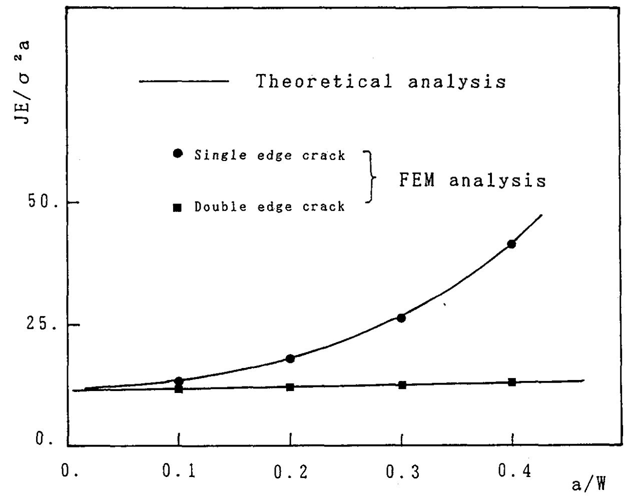


**Fig. 2** The comparision of J-integral vs a/W between theoretical and finite Element analysis

elements at the tip to triangles with single-edge of the element shrunk into one point at the crack tip and the mid-side nodes nearest to the tip were moved to the quarter points.

The modulus of elasticity and poisson's ratio of metal and ceramics are denoted as $E_M$, $\nu_M$ and $E_C$, $\nu_C$, respectively. The crack length parameter a/W is chosen as 0.01, 0.1, 0.2, 0.3, and 0.4. The material parameter $E_C/E_M$ is assumed to be 2, 5, and 10, while the Poison's ratio is kept constant and it is assumed to be 0.33. Three paths of the J-integral were taken and the J value was then calculated as the mean of the three different paths.

**Figure 2** illustrates the comparison between the J-integrals for homogeneous cracked body which is given as the analytical solution and that computed by the finite element method. A good agreement is observed between theoretical and numerical analysis. In the case of the single-edge crack specimen the dimensionless parameter J increases with the parameter a/W. On the other hand, it does not show visible change with the crack length parameter a/W for double-edge crack specimen.

To demonstrate that the J-integral for the interfacial crack in heterogeneous material is also path independent, some of the results for heterogeneous materials are shown in **Table 1**. The J-integral for three different paths and the error are shown in the table. since the maximum value of the error is only 1.3%, the J-integral can be considered as path independent in the case of the interfacial crack discussed in this report.

**Table 1** Computed results of J-integral

| $E_C/E_M$ | a/W | path 1 | path 2 | path 3 | avr. | er(%) | type |
|---|---|---|---|---|---|---|---|
| 2 | 0.2 | 3.28 | 3.29 | 3.35 | 3.31 | 1.3 | D |
| 5 | 0.01 | 0.249 | 0.250 | 0.247 | 0.249 | 0.8 | D |
| 10 | 0.3 | 8.39 | 8.42 | 8.45 | 8.42 | 0.4 | S |
| 2 | 0.01 | 0.199 | 0.200 | 0.199 | 0.199 | 0.5 | D |
| 5 | 0.2 | 4.74 | 4.77 | 4.79 | 4.77 | 0.6 | S |
| 10 | 0.1 | 1.54 | 1.52 | 1.53 | 1.53 | 0.6 | S |

Note: D double-edge crack specimen
S single-edge crack specimen

## 3. Result and discussion

**Figure 3** shows the relation between the dimensionless parameter J and the crack length parameter a/W of the double-edge crack specimen of ceramics-metal joint under remote tension in plane stress condition. The dimensionless

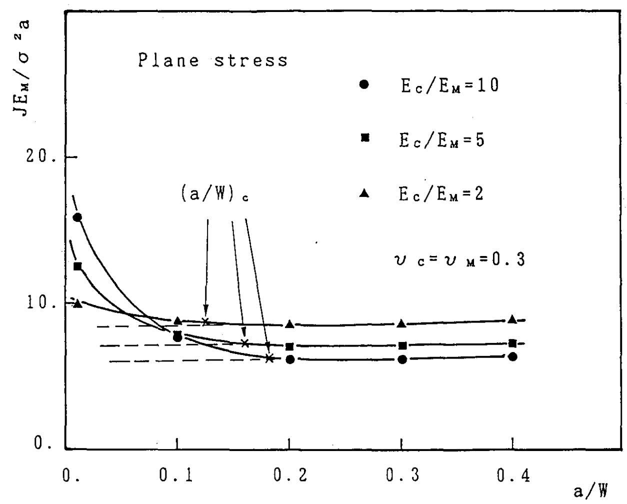


**Fig. 3** The J-integral vs. a/W for different ratio of Young's modulus ($E_C/E_M$) of double-edge cracked specimen in remote tension (plane stress problem)

parameter J changes with the crack length parameter a/W. Especially when the crack length parameter a/W is less than about 0.1, the dimensionless parameter J changes strongly with the crack length parameter a/W. It has been noted from Fig. 2 that the dimensionless parameter J almost has a linear relation to the crack length parameter a/W for the double-edge crack in the homogeneous material. The same characteristic can be observed in Fig. 3 when the crack length parameter a/W is larger than a certain value which has much to do with the material parameter $E_C/E_M$. from the comparison between Fig. 2 and Fig. 3 clear difference can be observed for small value of a/W and J-integral shows rapid increase when the material is heterogeneous. Such difference is the effect of heterogeneity of the joint and the maximum value of a/W for which this effect is observed can be considered as a critical value showing the transition. Such critical value is denoted by $(a/W)_C$, According to this definition, the critical value, $(a/W)_C$, is about 0.12 when the material parameter $E_C/E_M$ equals 2.0, about 0.14 when the $E_C/E_M$ is 5.0, and about 0.18 when the $E_C/E_M$ is 10.0. The critical value $(a/W)_C$ increases with the increase of the $E_C/E_M$. **Figure 4** shows the curve of dimensionless parameter J vs. crack length parameter a/W of double-edge crack specimen in plane strain condition. Conparing Fig. 4 with Fig. 3, it can be seen that the effect of stress concentration on the dimensionless parameter J for small value of a/W is bigger in plane strain case than in plane stress case. However, the critical values, $(a/W)_C$, in plane strain condition are almost the same as those in plane stress condition.

**Figures 5** and **6** show the relations between the dimensionless parameter J and the material parameter $E_C/E_M$ for different crack length of double-edge crack specimen in

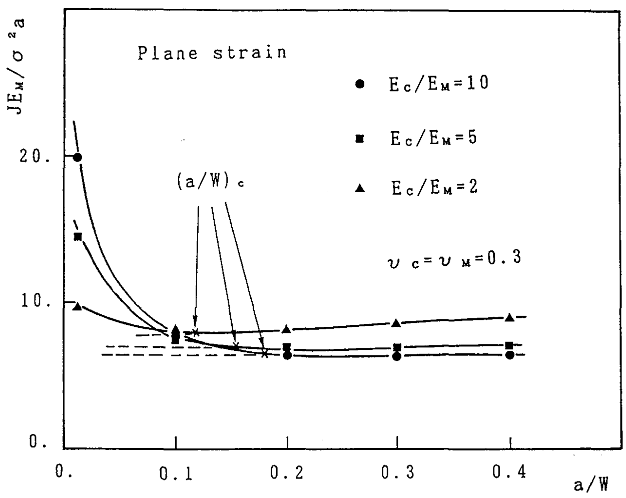


**Fig. 4** The J-integral vs. a/W for different ratio of Young's modulus ($E_C/E_M$) of double-edge cracked specimen in remote tension (plane stress problem)

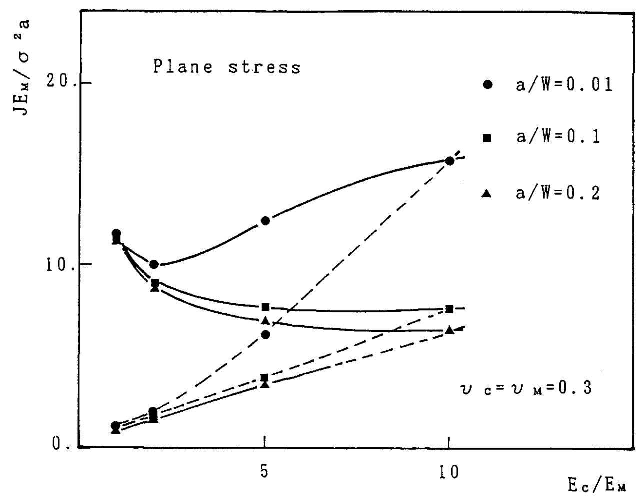


**Fig. 5** The J-integral vs. $E_C/E_M$ for different crack length of double-edge cracked specimen in remote tension (plane stress problem)

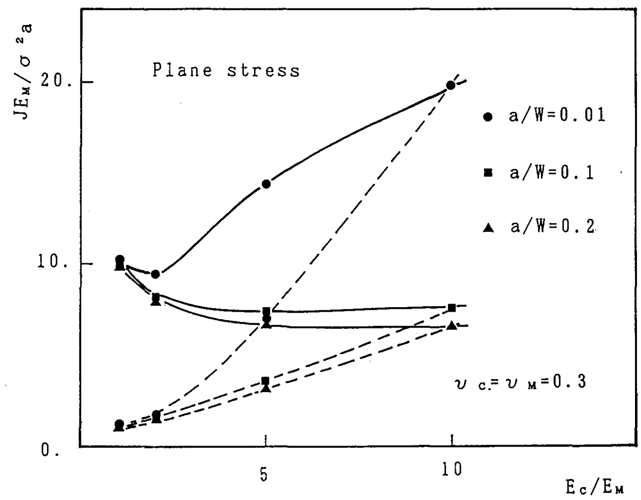


**Fig. 6** The J-integral vs. $E_C/E_M$ for different crack length of double-edge cracked specimen in remote tension (plane strain problem)

plane stress and plane strain condition, respectively. When the material parameter $E_C/E_M$ is 1.0, the material is homogeneous. The solid lines denote the cases in which $E_C/E_M$ is changed with keeping $E_M$ unchanged, and the dashed lines denote the cases with keeping $E_C$ unchanged. It can be seen that, the J-integral of a crack in the heterogeneous joint is larger than that of a crack in homogeneous ceramics and it increases with the parameter $E_C/E_M$. The J-integral of the heterogeneous joint increases rapidly when the crack length parameter a/W is less than a certain value. In the contrary, the J-integral for the heterogeneous joint is smaller than that for the homogeneous metal, and it decreases with the material parameter $E_C/E_M$ when the crack length parameter a/W is larger than about 0.1. When the crack is very shallow, such that a/W=0.01, the dimensionless parameter J shows a minimum value at about $E_C/E_M = 2.0$. The minimum value is less than that of homogeneous metal ($E_C/E_M = 1$).

When the initiation and the propagation of the crack are discussed, both the crack driving force and the fracture toughness should be considered. In general, the fracture toughness of ceramics-metal joint is a function of various factors including material properties and bonding temperature and so on. However, discussions will be given only from the view of crack driving force in the present paper. According to the fracture criteria, when the crack driving force is equal or larger than the crack resistance, the crack will initiate or propagate. From this point, the larger the crack driving force is, the larger the possibility of crack initiation or propagation will be. From the above discussion, the value of J-integral of an interfacial crack in the heterogeneous joint is larger than that of a crack in the homogeneous ceramics and smaller than that for homogeneous metal. Thus, the possibility of existing crack in the joint is larger in ceramics side than in metal side. Further, the possibility of existing shallow cracks is larger than existing deep cracks because the J-integral of joint increases strongly when the crack becomes shorter. When the $E_C/E_M$ is larger than a certain values, the shallow cracks also can exist in metal region. Comparing Fig. 5 with Fig. 6, the possibility of existing shallow crack is larger in plane strain condition than in pane stress condition.

**Figures 7** and **8** illustrate the relations of dimensionless parameter J to crack length parameter a/W of single-edge crack specimen under remote tension in plane stress and plane strain conditions, respectively. The dimensionless parameter J has a minimum value with the crack length

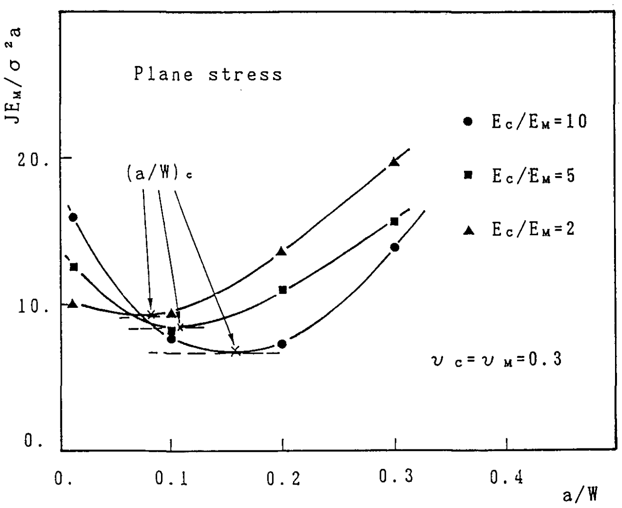


**Fig. 7** The J-integral vs. a/W for different ratio of young's modulus ($E_C/E_M$) of single-edge cracked specimen in remote tension (plane stress problem)

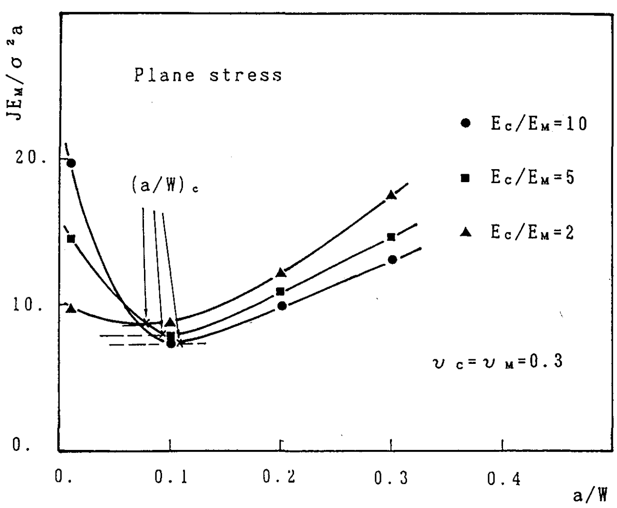


**Fig. 8** The J-integral vs. a/W for different ratio of young's modulus ($E_C/E_M$) of single-edge cracked specimen in remote tension (plane strain problem)

parameter a/W. As mentioned above for the double-edge crack specimen, a/W corresponds to the minimum J value is defined as $(a/W)_C$. the $(a/W)_C$ increased with the increase of material parameter $E_C/E_M$. And the critical values in plane stress condition are larger than those in plane strain condition.

**Figures 9** and **10** show the curves of dimensionless parameter J vs. material parameter $E_C/E_M$. Comparing the computed results for single-edge crack specimen with those for double-edge crack specimen, it can be inferred from the view of crack driving force that the possibility of existing shallow crack is almost the same both in single-edge and in double-edge cracks and that the possibility of crack propagation is larger for single-edge crack than for double-edge cracks.

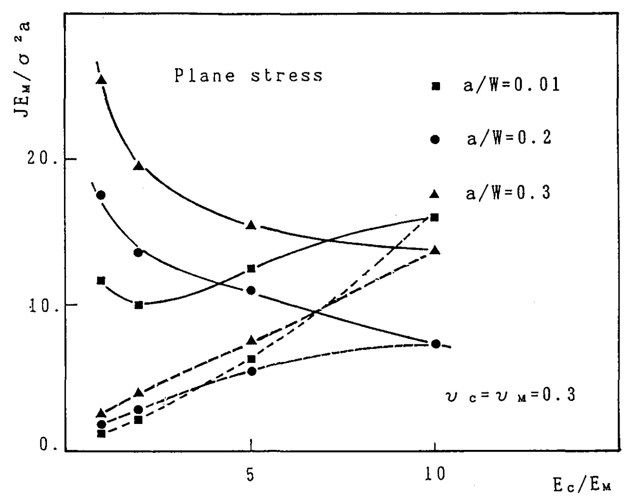


**Fig. 9** The J-integral vs. $E_C/E_M$ for different crack length of single-edge cracked specimen in remote tension (plane stress problem)

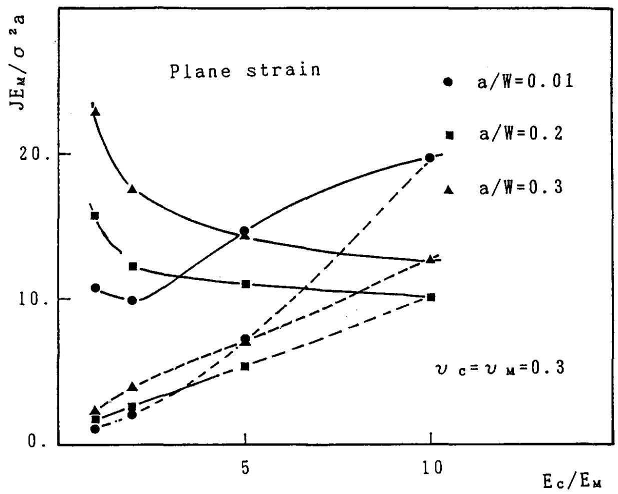


**Fig. 10** The J-integral vs. $E_C/E_M$ for different crack length of single-edge cracked specimen in remote tension (Plane strain problem)

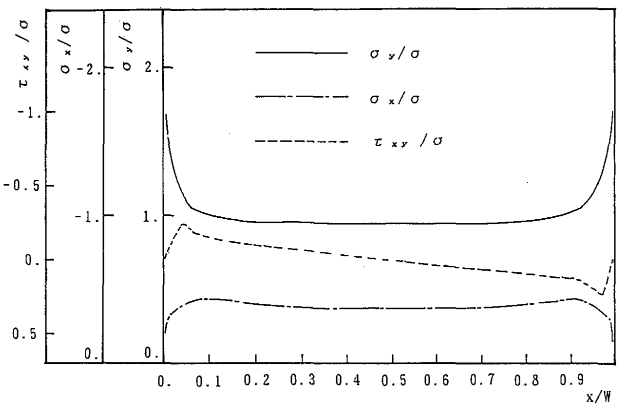


**Fig. 11** The stress distribution along the section in harder side of heterogeneous joint under tension

The stress distribution along the interface of the joint without crack is shown in **Fig. 11.** The material parameter $E_C/E_M$ is assumed as 10.0 and the Poison's ratios are assumed to be the same, i. e. $\nu_C = \nu_M = 0.33$. As seen from the figure, the strong stress concentration is observed in the region within 1/10 of the width W from the boundary. Thus, when the crack length parameter a/W is less than about 0.1, larger stress concentration resulting from heterogeneity of the joint will show significant effect on the stress field near the crack. As a result, the J-intergral will increase largely compared to homogeneous body with a crack. On the other hand, when the crack length parameter a/W is larger than 0.1 the stress concentration resulting from the heterogeneity becomes small. Hence, its effect on the J-integral also becomes small. This is a very simple interpretation about the J-integral of interfacial crack in ceramics-metal joint. The interaction of stress concentration near the boundary of ceramics-metal joint with that resulting from the crack and the redistribution of stress filed due to introducing a crack would require further investigation.

## 4. Conclusions

Through the systematical computations and discussions about the J-integral of interfacial crack in the two types of ceramics-metal joint specimen, the following conclusions are drawn.

(1) The J-integral of a shallow crack in the heterogeneous body increases strongly compared to that of a crack in the homogeneous body when the crack is short.
(2) For a given material parameter $E_C/E_M$, there exists a critical crack length value, $(a/W)_C$, below which the dimensionless parameter J changes strongly. The critical crack length value, $(a/W)_C$, increases with the increase of material parameter $E_C/E_M$.
(3) The defference in stress condition for single-edge and double-edge crack specimens has strong effect on the J-integral of shallow interfacial crack.
(4) The J-integral is relatively large for the plane strain condition compared to that for the plane stress condition.
(5) The possibility of crack existence may be larger in ceramics than in metal, and it is larger for the shallow crack than for the deep crack.
(6) When the materal parameter $E_C/E_M$ is larger than a certain values the shallow cracks also may exist in metal region
(7) The characteristic of shallow crack is basically the same for both single-edge and double-edge cracks.

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