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Numerical Study of Stress Triaxiality and Fracture Driving Force for Notched Specimen with Mechanical Heterogeneity

Jianxun Zhang* and Hidekazu Murakawa**

Abstract

The effects of welding mechanical heterogeneity on the ductile fracture parameters of notched round-bar tensile specimens were investigated numerically using a large deformation finite element method. The parameter $U = \int \exp(1.5F_\sigma) d\varepsilon_p$ *is introduced as a driving force to ductile fracture. The stress triaxiality and the driving forcee are computed in the fully yielding condition and the ductile fracture possibility is also discussed. The results show that the mechanical heterogeneity of the weldment has large effects on the stress triaxiality and the driving force . The stress triaxiality and the driving force increase both with the increase of yielding stress and with the decrease of strain hardening property in evenmatched weldments. With a decrease of weld metal width, the stress triaxiality and the driving force increase for an undermatched weldment and decrease for an overmatched weldment. The stress triaxiality and the driving force increase with a decrease of weld metal width when the strain hardening property of base metal is larger than that of weld metal and decrease with a decrease of weld metal width when the strain hardening property of base metal is lower than that of weld metal.*

KEY WORKS: (Ductile fracture) (Stress triaxiality) (FEM.)

1. Introduction

It is well known that weldments are very sensitive parts of a structure with regard to brittle fracture and ductile fracture because of the inherent characteristics such as metallurgical, geometrical defects and very heterogeneous material properties. More and more attention has been paid to the effects of mechanical heterogeneity on the fracture of weldments[1-3]. The mechanical heterogeneity of the weldment means that there are differences in yielding stress and other mechanical properties in the welded region because of the heating process and phase transformation. Basically, the yielding stress is different between base metal and weld metal in the mismatched weldment. In paticular, the mechanical heterogeneity is very large in the heat affected zone (HAZ). The mechanical heterogeneity of the weldment exerts an influence, not only on the joint performance of welds, but also on the evaluation of fracture toughness requirements. The effects of the mechanical heterogeneity of a weldment on the fracture toughness features of the base metal near the weld metal were studied experimentally[4]. The tests were done by measuring the COD of three point bend specimens extracted from overmatched weldment. The results show that the crack initiation toughness, the crack growth resistance and the tearing modules of the base metal near the weld metal zone are greatly affected by the mechanical heterogeneity of the weldment. The above phenomena are explained from the view of ductile restraint in the weldment. The effects of the mechanical heterogeneity of the overmatched weldment on the ductile fracture behavior of the base metal and the weld metal were investigated experimentally making use of notched round-bar tensile specimen[5]. It was concluded that the mechanical heterogeneity of a weldment has certain effects on the plastic strain at fracture, the stress triaxiality at fracture, the critical void growth and the material constant C. The critical void growth in steel welds composed of steel matrix and spherical inclusions with different size distributions was investigated carefully[6]. The void nucleation and growth in the ductile fracture of mild steel containing a weldment are dependent on stress triaxiality and plastic strain. It is found that the critical void growth values determined by experimental

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measurement are not sensitive to the stress triaxiality factor. In order to improve the reliability of a welded structure, it is very important to understand the ductile fracture of the weldment with mechanical heterogeneity. In accordance with the notched specimen used in the research into ductile fracture, the effects of mechanical heterogeneity in a mismatched weldment on the ductile fracture parameters were investigated numerically using a large deformation finite element method. The stress triaxiality and the driving force are computed in the fully yielding state and the ductile fracture possibility is also discussed.

2. Driving force for void growth

Much research work has been done on the ductile fracture of mild steels containing weld metal based on micro mechanical models and experiments[7-9]. The ductile fracture of mild steel containing weldments can be described as a progressive process with the void nucleation, void growth and coalescence. It is reported for a given material that the crack nucleation and growth resistance are functions of plastic strain and stress triaxiality, which in turn are affected by geometrical variables such as size and geometry of the test piece or relative crack size.

According to the theoretical Rice-Tracey model for void growth, which was derived for a fully plastic material of infinite extent with one spherical void, the void grows under the combined effects of the applied plastic strain and stress triaxiality. The rate of the void growth is given by[7]:

$$\frac{dR}{R} = A d\varepsilon_p \exp(1.5F_\sigma) \quad (1)$$

where, R is the void radius, $d\varepsilon_p$ increment of the plastic strain, $F_\sigma = \sigma_m / \bar{\sigma}$ the stress triaxiality which is the ratio of main stress σ_m to Von Mises equivalent stress $\bar{\sigma}$,

The equation(1) can be integrated as following:

$$\frac{R}{R_0} = \exp[A\int \exp(1.5F_\sigma) d\varepsilon_p] \quad (2)$$

where, R_0 is the radius of the corresponding inclusion.

From equation(2), it can be seen that the void growth is proportional to a certain combination of plastic strain and stress triaxiality. From this point, the parameter U can be defined:

$$U = \int \exp(1.5F_\sigma) d\varepsilon_p \quad (3)$$

This parameter expresses the driving force for void growth. If the void grows to its critical value, the driving force U will become the material constant U_c. When the change of the stress triaxiality is not taken into account during strain history and the plastic strain is very small, the material constant U_C can be calculated by the following[7]:

$$U_c = (\bar{\varepsilon}_p)_c \exp(1.5F_\sigma) \quad (4)$$

The material constant U_C expresses the critical void growth in the form of macroscopic parameters. The parameters in equation(4) can be obtained by experiment. Therefore, the criterion for fracture initiation can be expressed as:

$$U \geq U_c \quad (5)$$

The void coalescence will take place if the driving force U is equal to, or larger than, the material constant U_C. The driving force U can be calculated by numerical methods.

3. Model and calculation

The tensile bar specimen with notch is widely used in research work about the ductile fracture of materials. A notched bar specimen with mechanical heterogeneity is used in this numerical investigation as shown in **Fig.1**. The size of the specimen is length 2L=80 mm, and diameter D=10 mm, and R=3.8 mm. The ratio of weld metal width to the diameter of notched section, H/d is varied from 0.0 to 0.6. Due to the symmetry, the finite element mesh for the upper-right of specimen was done with 1672 elements and 1748 nodes of four-node isoparametric element. The minimum size of mesh is 0.01 mm. The computations were done by using self-developed axisymetrical larger deformation elastic plastic finite element code.

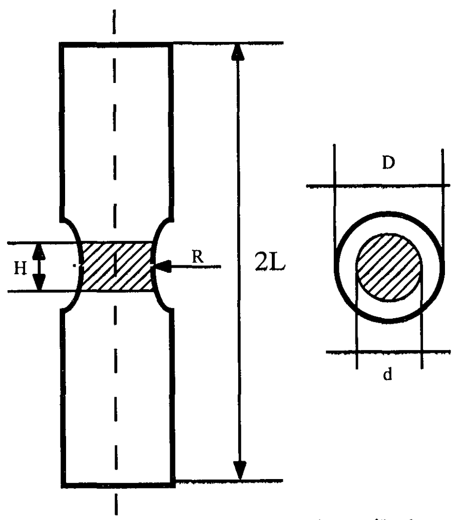

Fig.1 Numerical model of notched tensile bar.

It is assumed that the weldment consists of both base metal and weld metal in this computation. This assumption is well used in the analysis of mismatched weldment in which the difference of yielding stress between weld metal and base metal is the main parameter causing mechanical heterogeneity. The effect of the HAZ can be neglected because of its narrow width comparing with the weld metal width. The base metal used in the numerical analysis was assumed to be a pressure vessel steel with liner hardening property. The weld metal and base metal are assumed to have the same elastic modulus, E and the same Poisson's ratio, γ. Weld strength mismatch factor, M, is the ratio of yielding stress of the weld metal to that of base metal. With regard to the practice in welding production, three values of M were selected: M=0.8 (undermatch), 1.0(evenmatch) and 1.2(overmatch). The ratio of liner strain hardening parameter, G to elastic modulus, E is selected to be 0.0, 0.005, 0.01, 0.05 and 0.5.

The stress triaxiality and driving force, U, change with the loading level. On the other hand, the structure will be considered to fail in practical design when it reaches full yielding at one section of the structure. Therefore, the critical values at the full yielding of cross section in the center of the notched specimen were calculated. In the following discussion, the driving force U to ductile fracture is simply called the driving force.

4. Result and Discussion

The stress triaxiality and the driving force of homogeneous metal or evenmatched weldment with different yielding stresses are shown in **Fig.2**. The yielding stresses of materials are assumed as 280MPa, 350MPa and 420MPa with no strain hardening. It can be seen from **Fig.2** that the stress triaxiality and the driving force along the radial direction is heterogeneous. The maximum of stress triaxiality appears at about the half of the radius. The maximum of the driving force is nearer to the surface of the specimen. The driving force increases with the increase of yielding stress of the base metal. From the point of view of ductile fracture, it can be inferred that the material with larger yielding stress would be more sensitive to ductile fracture than that with lower yielding stress in the fully yielding state if the materials have the same ductile fracture properties, for example, the same shape, size and distribution of inclusions. Of course, the loading capacity of specimen with larger yielding stress is higher than that of specimen with lower yielding stress. It is shown in **Fig.2** that the distribution and magnitude of the stress triaxiality are the same for different yielding stresses. This means that the yielding stress has no or little effect

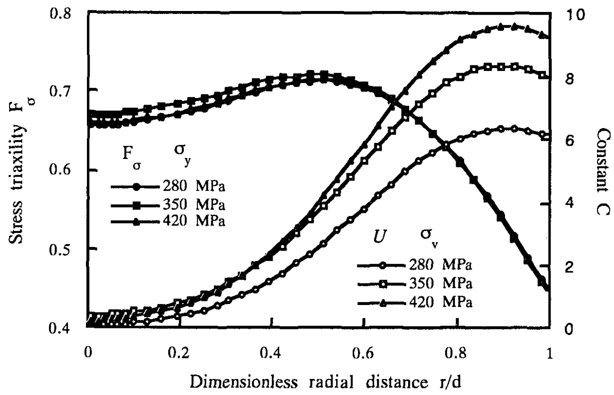

Fig.2 Stress triaxiality and driving force U in homogeneous material.

on the stress triaxiality. From the theoretical analysis, the stress triaxiality of notched bar tensile specimen at fully yielding state can be expressed as:

$$F_\sigma = \frac{1}{3} + \ln(1 + \frac{d}{4R}) \qquad (5)$$

The parameters in equation(5) are shown in Fig.1. The magnitude of the stress triaxiality equals 0.712 according to the shape of specimen. Comparing with the stress triaxiality shown in **Fig.2**, the stress triaxiality calculated from equation(2) is nearer to the maximum of the stress triaxiality computed by FEM in the fully yielding state.

The effects of weld metal width on the stress triaxiality of undermatched weldment are illustrated in **Fig.3**. The materials used are those with no strain hardening both in weld metal and base metal. It can be seen from **Fig.3** that the stress triaxiality increases with the decrease of weld metal width. It becomes the same as that of the base metal when the ratio of weld metal width to cross section radius, H/d, is larger than 0.45. The heterogeneity of stress triaxiality becomes larger when the weld metal width gets more narrow. The maximum of stress triaxiality becomes larger and nearer to the surface of the specimen with a decrease of weld metal width. The stress triaxiality can't be estimated correctly using equation(5) because of the mechanical heterogeneity.

The driving forces of the undermatched weldment with different weld metal widths are shown in **Fig.4**. It is important to notice from **Fig.4** that the driving force increases with a decrease of weld metal width and that the maximum value of the driving force changes very

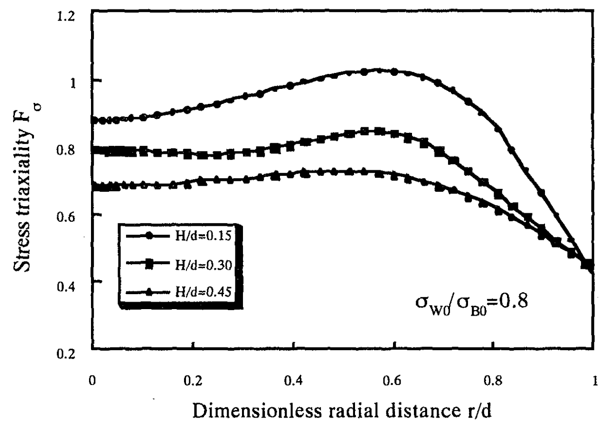

Fig.3 The distribution of stress triaxiality in under matched weldment.

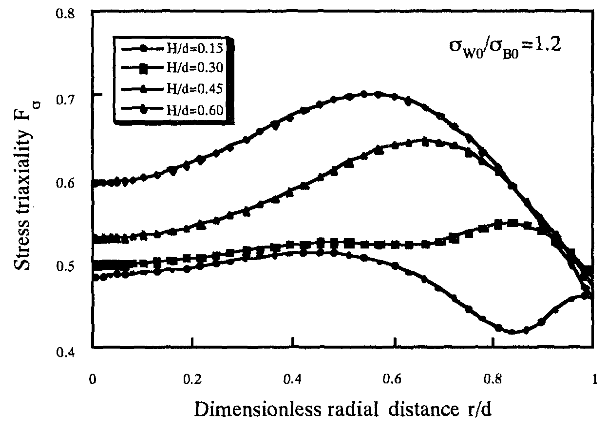

Fig.5 The distribution of stress triaxiality in overmatched weldment.

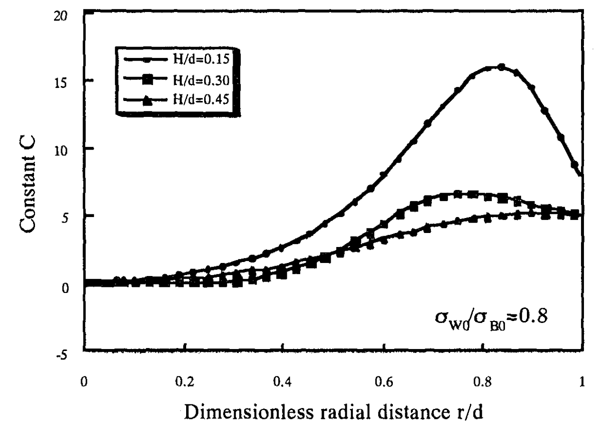

Fig.4 The distribution of driving force U in under matched weldment.

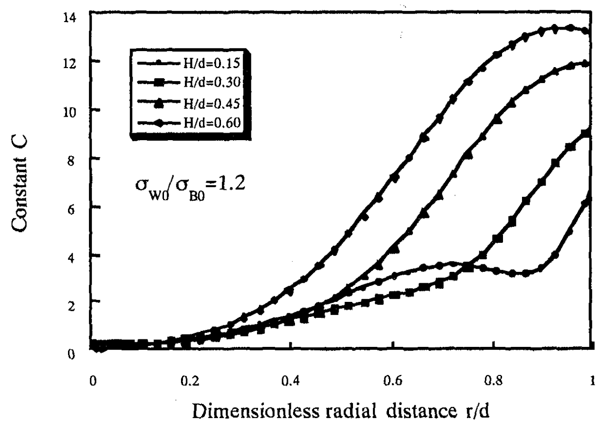

Fig.6 The distribution of driving force U in overmatched weldment.

significantly when the ratio H/d is less than 0.30. As discussed before, the parameter U expresses the driving force to ductile fracture. The larger the driving force, the larger the possibility of ductile fracture. Compared with the driving force of homogeneous materials shown in **Fig.2**, the driving force is larger in undermatched weldments than in evenmatched weldments. It seems that the undermatched weldment easily reaches the critical value of ductile fracture if the material constant is not affected by mechanical heterogeneity.

The distributions of stress triaxiality of overmatched weldment for different weld metal widths are shown in **Fig.5**. The materials used are those with no strain hardening either in weld metal or base metal. It becomes seen that the stress triaxiality decreases with the decrease of weld metal width. It gets to the same as that of the base metal when the radio H/d is larger than 0.60. The heterogeneity of the stress triaxiality becomes smooth when the weld metal width becomes more narrow. The maximum of stress triaxiality becomes smaller and nearer to the surface with a decrease of weld metal width. It can be inferred that the overmatched weldment has larger stress triaxiality than evenmatched weldment.

The effects of weld metal width in overmatched weldments on the driving force U are illustrated in **Fig.6**. The matching ratio M is assumed as 1.20 in the overmatched weldment. It can be seen that the driving force U decreases with a decrease of weld metal width.. Compared with the driving force of homogeneous material and undermatched weldment, the driving force is less in overmatched weldment than that in evenmatched and undermatched weldment. In the other words, the overmatched weldment is more difficult to get to the critical value of ductile fracture material constant than the evenmatched and undermatched weldment. In the case of the same weld metal, plastic strain in the base metal would be more in an overmatched weldment than in an undermatched weldment. It can be conjectured that the stress triaxiality concentration will occur near the interface of weld metal and base metal, and will decrease with an increase of weld metal width.

In general, the matching factor of mismatched weldment expresses the difference of yielding stress between weld metal and base metal. However, the yielding stress will be increased for the strain hardening material when plastic strain occurs. The matching factor will be changed after the appearance of plastic strain and will be dependent on the loading level. Therefore, some attention should be paid to the stain hardening property of the material for any relatively complete study about the properties of mismatched weldment.

Effects of strain hardening properties of base metal and weld metal on the stress triaxiality of evenmatched weldment are displayed in **Fig.7**. The change in the strain hardening property of base metal and weld metal is expressed by the ratio of strain hardening slope to elastic modulus, G/E. The parameter G/E changes from 0.0 to 0.5. It is indicated that the stress triaxiality decreases with an increase of strain hardening exponent. The maximum of stress triaxiality becomes smaller with the increase of strain hardening exponent. It can be concluded that the stress hardening property would improve the stress triaxiality.

The driving force U of evenmatched weldment with different strain hardening property are shown in **Fig.8**. The parameter G/E changes from 0.0 to 0.5. It can be seen that driving force decrease with the increase of strain hardening exponent. The maximum of driving force becomes smaller and nearer to surface as the increase of strain hardening property. From the view of ductile fracture, the driving force is smaller for material with larger strain hardening property.

The effect of strain hardening property of weld metal on ductile fracture parameters of evenmatched weldment was calculated in the next. The weld metal has strain hardening property 0.05. The base metal is that with no strain hardening. The effect of weld metal width on the stress triaxiality of evenmatched weldment is shown in **Fig.9**. It can be seen that the stress triaxiality are almost independent on the weld metal width. It seems that the stress triaxiality is determined by the property of weld metal when the base metal is that with no strain hardening.

The effects of weld metal width on and driving force U of evenmatched weldment are illustrated in **Fig.10**.

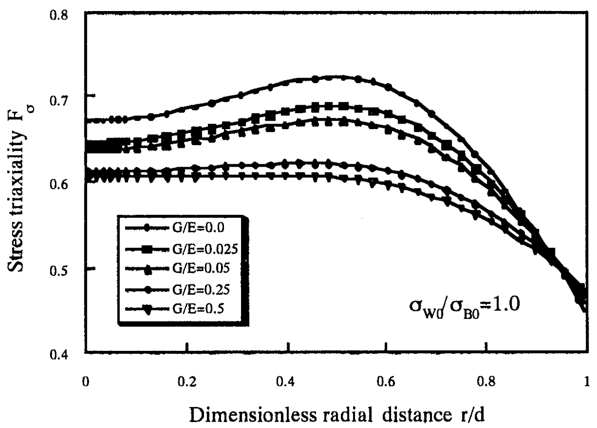

Fig.7 Stress triaxiality in even matched weldment with deferent strain hardening.

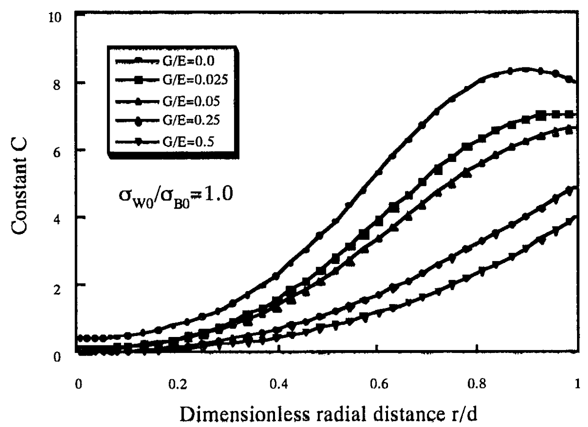

Fig.8 Driving force U in even matched weldment with deferent strain hardening.

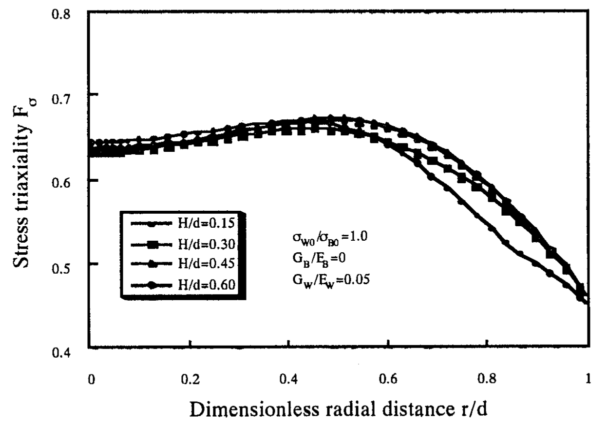

Fig.9 The stress triaxiality in evenmatched with strain hardening only in weld metal.

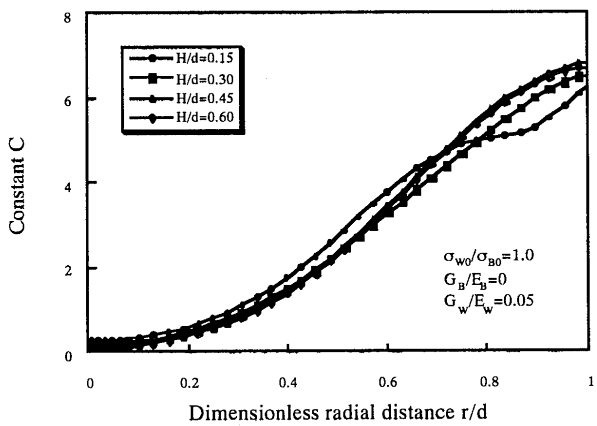

Fig.10 The driving force U in evenmatched with strain hardening only in weld metal.

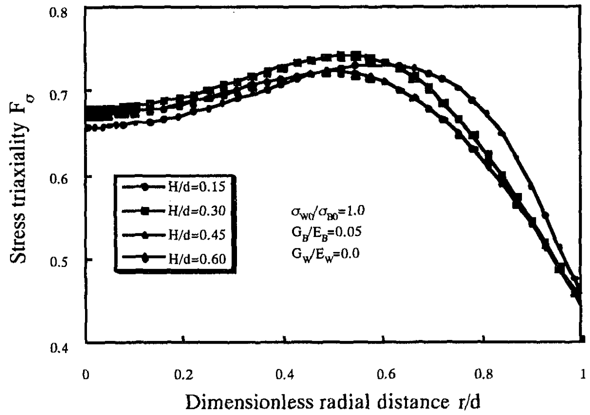

Fig.11 The stress triaxiality in evenmatched with strain hardening only in base metal.

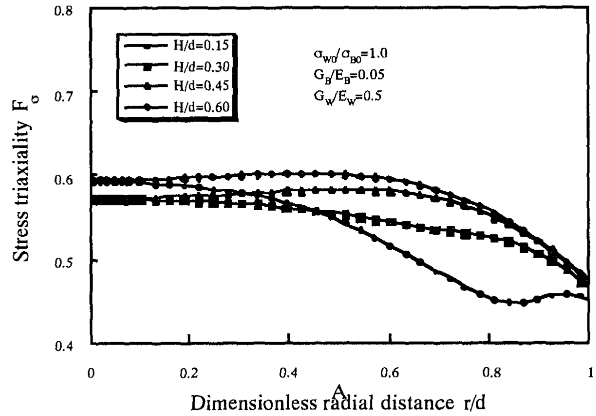

Fig.13 The stress triaxiality in evenmatched with strain hardening only in base and weld metal.

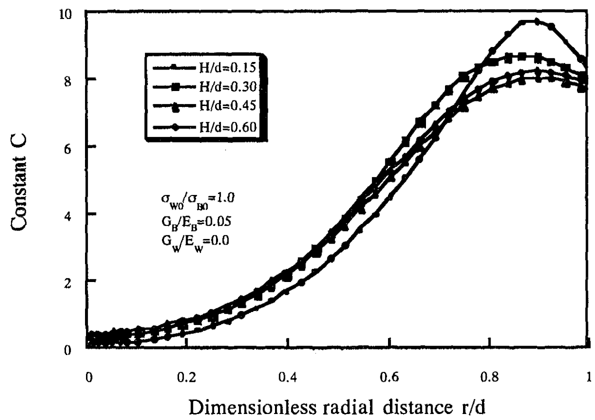

Fig.12 The driving force U in evenmatched with strain hardening only in base metal.

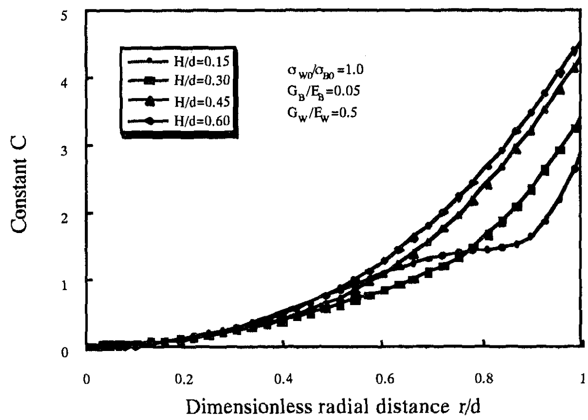

Fig.14 The driving force U in evenmatched with strain hardening only in base and weld metal.

The driving forces are not changed so much for the variation of weld metal width. It can be interpreted from the distribution of plastic strain. The larger plastic strain would occur in the base metal because of the increase of yielding strain in the weld metal.

The ductile fracture parameters for the evenmatched weldment were studied in the case of the weld metal without strain hardening and base metal with strain hardening. The influences of weld metal width on the stress triaxiality and the driving force U are shown in **Fig.11** and **Fig.12**. The strain hardening parameter, G/E is assumed as 0.05 in base metal. It is indicated that the stress triaxiality remains almost the same and the driving force U increases slightly with a decrease of weld metal width.

The stress triaxiality and driving force U for evenmatched weldment with strain hardening both in base metal and weld metal are shown in **Fig.13** and **Fig.14**. The strain hardening property of base metal and weld metal are assumed as 0.05 and 0.5 respectively. It can be seen that the stress triaxiality and driving force U decrease with the decrease of weld metal width. This is similar to what happened in overmatched weldment. As discussed before, the yielding stress will increase when plastic strain occurs. And the simultaneous yielding stress will increase with an increase of plastic strain. Then the matching state of the weldment will also change with the increase of plastic strain. This means that the matching state of the weldment is dependent on the loading history.. It can be guessed that the effect of strain hardening on the ductile fracture parameter will become larger as the plastic strain increases. Therefore, the importance of the matching state of the weldment should be taken into account when the plastic strain occurs.

5. Conclusion

Through a numerical investigation of the effects of mechanical heterogeneity in mismatched weldment on the stress triaxiality and driving force U to ductile fracture, the followin results were shown as follows.

(1) The parameter $U = \int \exp(1.5F_{\sigma}) d\varepsilon_p$ is introduced as a driving force for ductile fracture from the point of view of the theoretical model of ductile fracture.

(2) The mechanical heterogeneity of a weldment has large effects on the stress triaxiality and driving force U. The radial distributions of stress triaxiality and driving force U are heterogeneous.

(3) The stress triaxiality and driving force, U, increase both with an increase of yielding stress and with a decrease of strain hardening property for evenmatched weldment. With the decrease of weld metal width, the stress triaxiality and driving force U increase for undermatched weldment and decrease for over-matched weldment.

(4) The stress triaxiality and driving force, U, increase with a decrease of weldment width when the strain hardening property of base metal is larger than that of weld metal and decrease with a decrease of weld metal width when the strain hardening property of the base metal is lower than that of weld metal.

(5) It can be assumed that the undermatched weldment is more sensitive to fracture than an overmatched weldment from the computed results and in view of ductile fracture theory.

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