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Numerical Investigations on Ductile Constraint near Crack Tip in Weldment with Mechanical Heterogeneity †

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Abstract

The stress triaxiality near the crack tip can be used to reflect the ductile constraint in elastic-plastic fracture mechanics of metallic materials. The J-integrals and stress triaxiality near the crack tip in a weldment with mechanical heterogeneity were numerically investigated. The effect of ductile constraint on the ductile fracture of the weldment with mechanical heterogeneity was also discussed. The standard three-point bend specimen was analyzed numerically in the plane strain condition. The mechanical heterogeneity of a mis-matched weldment is described by the matching property M, and the weld metal width parameter H/C. In order to keep the same image for the matching property effect on performance of the mis-matched weldment, it is supposed in this paper that the matching property M should be the ratio of the yielding strength of the weld metal to that of base metal in the condition of the same base metal yielding stress, and the ratio of the yielding stress of base metal to that of weld metal in the condition of the same weld metal yielding stress. The matching property of weldment and the width parameter of weld metal have a large effect on the stress triaxiality near crack tip. The larger the matching property is, the small the stress triaxiality near the crack tip. The stress triaxiality near the crack tip is dependent on the property of weld metal when the weld metal width parameter H/C is less than 0.63 in this investigation.

KEY WORDS: (Mis-matching Weldment) (Ductile Constraint) (Stress Triaxiality) (Finite Element Method) (Mechanical Heterogeneity)

1. Introduction

The performance of a welded structure is strongly dependent on the performance of the weldment because of its inherent characteristics including metallurgical and geometrical defects and very heterogeneous material properties. The behavior of a weldment is greatly influenced by the mis-match of the weldment. More and more attention has been paid to the effect of mechanical heterogeneity on the fracture mechanics driving force parameters, COD or J-integral, and on the fracture toughness requirement [1-3]. It is shown that mechanical heterogeneity affects not only the joint performance of welds but also the evaluation of fracture toughness requirements. Although the mechanical heterogeneity of a weldment is very complex in the welded region, the assumption that the weldment consists of only base metal and weld metal with homogeneous properties is very useful and successful for investigating the performance of the weldment.

The effect of the mechanical heterogeneity of an over matched weldment on the fracture toughness features of the base metal near the weld metal by changing the crack location from fusion line was studied experimentally [4]. The experiments were done making use of measurement of the COD of three-point bend specimens under static loading. The results show that the crack initiation toughness, the crack growth resistance and the tearing modules of the base metal near weld metal zone are greatly affected by the mechanical heterogeneity of the weldment. Further experimental work was done on the effects of the mechanical heterogeneity of the weldment on the ductile fracture behaviors of the base metal and the weld metal using tensile notched bars[5]. It was shown that the mechanical heterogeneity of the 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 effects of mechanical heterogeneity in mismatched weldments were investigated numerically using the ductile fracture parameters of notched round-bar tensile specimens and large deformation finite element methods. The combination of stress triaxiality and plastic strain is proposed as a driving force for ductile fracture from the

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point of view of the theoretical model of ductile fracture. The stress triaxiality and driving force are computed in the fully yielding condition and the ductile fracture possibility is also discussed. The results show that mechanical heterogeneity of the weldment has large effects on the stress triaxiality and driving force[6)].

In this paper, the focus is on the effect of weldments with mechanical heterogeneity on the ductile constraint near the crack tip in plane strain conditions for three-point bend specimens. The stress triaxiality is taken as a measurement of ductile constraint near the crack tip. Different matching properties and weld metal widths are taken into account on the ductile constraint near the crack tip. The J-integrals and stress triaxiality near the crack tip in the weldment with mechanical heterogeneity were calculated numerically. The effect of ductile constraint on the ductile fracture of the weldment with mechanical heterogeneity was discussed at the same time.

2. Ductile Constraint and Stress Triaxility

The stress and strain field near the crack tip is affected by many parameters connected with material properties, crack body geometry, stress state and so on. The stress intensity factor K can be used to characterize stable and unstable fracture in small-scale yielding condition (LEFM) and J-integral or COD in large-scale plastic deformation condition (EPFM). In fact, the stress and strain distributions near the crack tip are one kind of approach solution. The K and J characterize the amplitudes of the first and only singular term in a series expansion consisting of several higher order terms that describe the stress field ahead of the crack tip. The contribution of the second order terms depends on the distance from the crack tip; the geometry and size of the crack body, and the extent of crack tip plasticity.

As one approaches very near to the crack tip, the singular term dominates the magnitude of the stress and the contribution from the other terms can be neglected. However, if one moves further from the crack tip, that is no longer the case. The damage leading to fracture in almost all instances develops ahead of the crack tip. Imagining a situation in which the damage develops, or at least begins to develop, in a region where the contribution to the local stress from the higher order terms is significant. The multi-parameter criteria to describe the stable and unstable fracture are developed because the higher order terms are geometry and size-dependent. The K-T criterion is the one used in elastic fracture mechanics, and K-Q criterion is developed to meet elastic-plastic situations. The T-stress and Q-factor are proposals, which take account of the crack tip constraint[7)].

It is predicted from metallurgical researches that the nucleation and growth of voids play an important role for the fracture process of ductile metallic materials, which cannot be described by conventional continuum mechanics. In structural materials, the voids nucleate mainly at second phase particles and inclusions. Usually, the micro-voids can be divided into two families, i.e., larger voids and smaller voids. The larger voids nucleate from inclusions at relatively low strains and smaller voids nucleate from carbides or precipitates at considerably larger strains. Consequently, void growth takes place due to the plastic deformation of surrounding matrix material and final failure occurs when the larger voids coalesce with each other or link up with a nearby crack tip via a void sheet consisting of voids nucleated from smaller particles [8,9)].

The amount of plastic flow in a specimen or component is determined by the so-called constraint of the structure, which reflects the specimen geometry and the type of loading (bending or tension). The increase of constraint causes the increase of stress triaxiality. Owing to its importance for the crack growth behavior of a cracked structure it is necessary to quantify the constraint as well as the stress triaxiality. A physical definition of the stress triaxiality is given by the ratio of the hydrostatic stress and the von Mises equivalent stress. The significance of this ratio for void growth is well known; namely, the support of void growth on the micro mechanical level thus causing damage in the process zone. The stress triaxiality changes not only along the crack front but also with the distance from the crack tip and the ligament angle. In the present paper, the maximum stress triaxiality ahead of crack tip is used to characterize the constraint.

3. Model and calculation

The mechanical heterogeneity of a mis-matched weldment is very complex in real situations. From the view of taking the important feature of the problem, it is very useful and widely used to assume that the weldment consists of both base metal and weld metal in this computation. Both the weld metal and base metal are the metallic materials with the stress-strain behavior in simple tension according to the following power law,

$$\frac{\varepsilon}{\varepsilon_0} = \frac{\sigma}{\sigma_0} \qquad \sigma \le \sigma_0 \qquad (1)$$

$$\frac{\varepsilon}{\varepsilon_0} = \alpha\left(\frac{\sigma}{\sigma_0}\right)^n \qquad \sigma > \sigma_0 \qquad (2)$$

where, the weld metal and base metal are assumed to have the same elastic modulus, E and the same Poisson's ratio,γ. The yielding stress of the base metal is taken as 392MPa, 490MPa and 588MPa. The yielding stress of the weld metal is taken as 392MPa, 490MPa, 490MPa and 784MPa. The matching property, M, is the ratio of the yielding stress of the base metal or weld metal to that of the weld or base metal, which is dependent on the study case.

The three-point bend specimen with W=50mm and a/W=0.5 was used in finite element calculation as shown in **Fig.1**. The width of weld metal over the ligament width C=(W-a) is taken as 0.19, 0.38, 0.63 and 0.79 respectively. The finite element mesh used in the numerical analysis for the three-point bend specimen is shown in **Fig.2**. The half specimen is meshed according to its symmetry. The meshes consisted of 1304 isoparametric elements with 2456 nodes. In the large strain gradient zone the mesh was refined. The minimum mesh size near the crack tip is about 1/1000 of

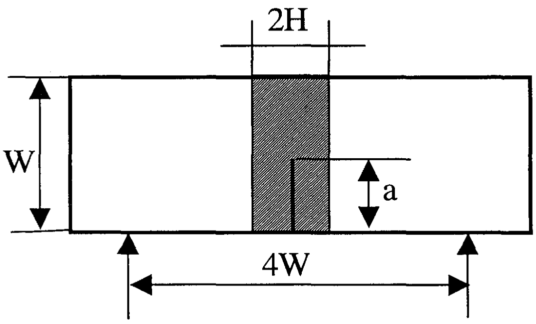

Fig.1 The three-point band specimen with weldment used in numerical analysis

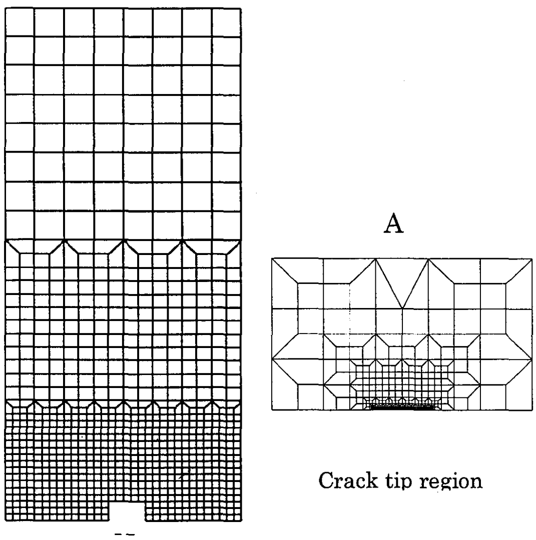

Fig.2 Finite element meshing in all calculations with 1304 elements and 2456 nodes.

ligament length. The numerical evaluation of the J-integral was conducted incrementally through Gauss-point integration of the elements on the path with a standard weight function according to the reference [10]. The J-integral was calculated as the mean value for five different paths across the base metal and weld metal far from the crack tip.

4. Results and Discussion

4.1 The definition of matching property

In general, the matching property of weldment is defined as the ratio of yielding or tensile strength of weld metal to that of base metal. **Figure 3** shows the development of the J-integral with applied load in different matching properties. The J-integral of

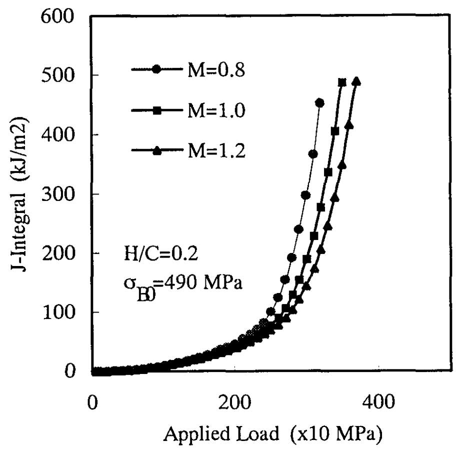

Fig.3 The J-integral development with applied load at different mismatching with the same yielding stress of base metal

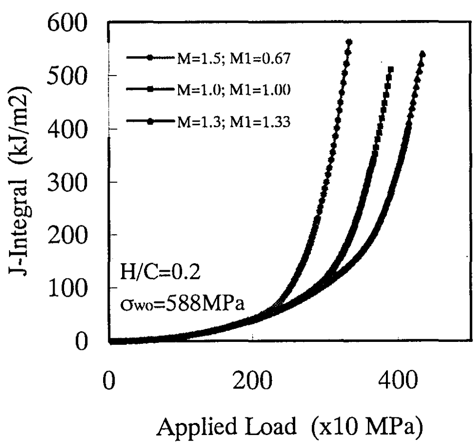

Fig.4 The J-integral development with applied load at different mismatching with the same yielding stress of weld metal

weldment is larger as the matching property decreases for a given load. That is because the larger deformation occurs in the weldment when the yielding stress of the welding metal is less than that of the base metal. It is traditional and reasonable for mis-matched weldment for the calculation of J-integral with applied load. However, the other calculation of the J-integral for mis-matched weldments is illustrated in **Fig.4** with the same yielding stress of weld metal by changing the yielding stress of the base metal in order to study the matching property effect. As usual, if the matching property is taken as the ratio of the yielding stress of the base metal to weld metal, the conclusion is that the J-integral of the mis-matched weldment is larger with an increase of matching property. This result is contrary to that obtained from Fig.3. That is not the mistake of calculation but the definition of matching property. As an example, let us define a new matching property, M1, as the ratio of the yielding stress of base metal to that of weld metal, the same result with Fig.3 can be got. Therefore, in order to keep the same image about the matching property effect on some performance of the mis-matched weldment, it is supposed in this paper that the matching property M should be the ratio of the yielding strength of weld metal to that of base metal in the condition of the same base metal yielding stress, and the ratio of the yielding stress of the base metal to that of weld metal in the condition of the same weld metal yielding stress. The new definition of matching property is shown in **Fig.5**.

4.2 Effect of matching property

Fig.6 shows stress triaxiality near the crack tip for homogeneous material with different applied loads. It can be seen from Fig.6 that there is a maximum value of the stress triaxiality near the crack tip and that the maximum value increases with applied load. **Figure 7** shows the effect of yielding stress on the stress triaxiality near the crack tip for homogeneous material. The larger the yielding stress, the smaller is the stress triaxiality near the crack tip at same applied load. It seems that the ductile constraint becomes larger with a decrease of yielding stress. From the view of crack driving force of the ductile fracture caused by void nucleation and growth, it is implied that the crack growth is easier for the material with lower yielding stress than

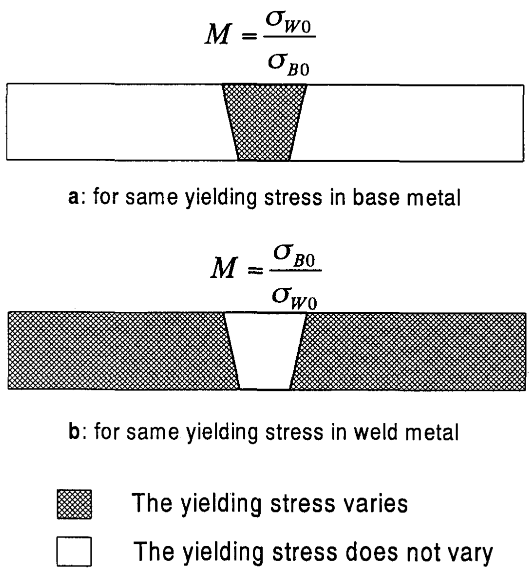

Fig.5 The definition of matching property M in the mis-matched weldment

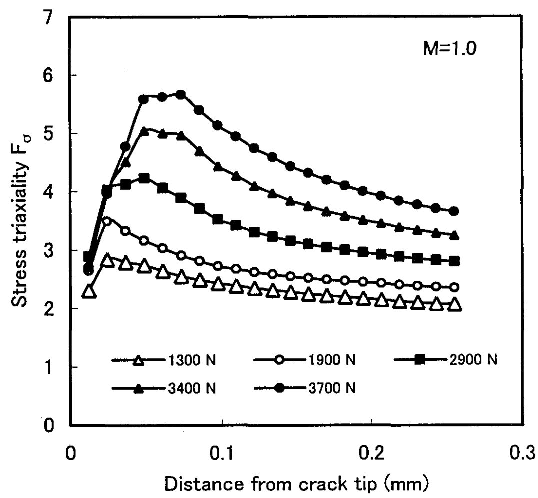

Fig.6 The stress triaxiality near the crack tip with applied load for homogeneous material

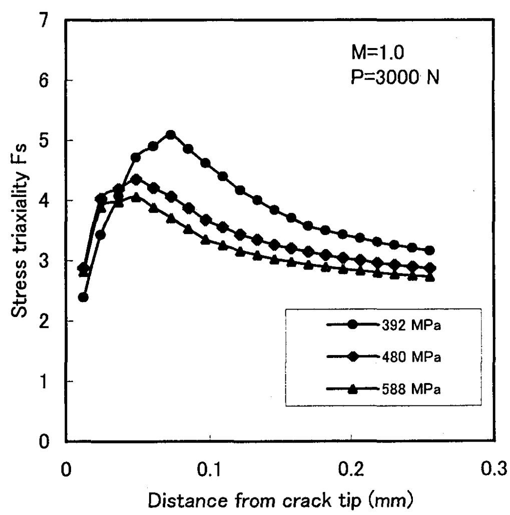

Fig.7 The stress triaxiality near the crack tip with different yielding stresses of the homogeneous material

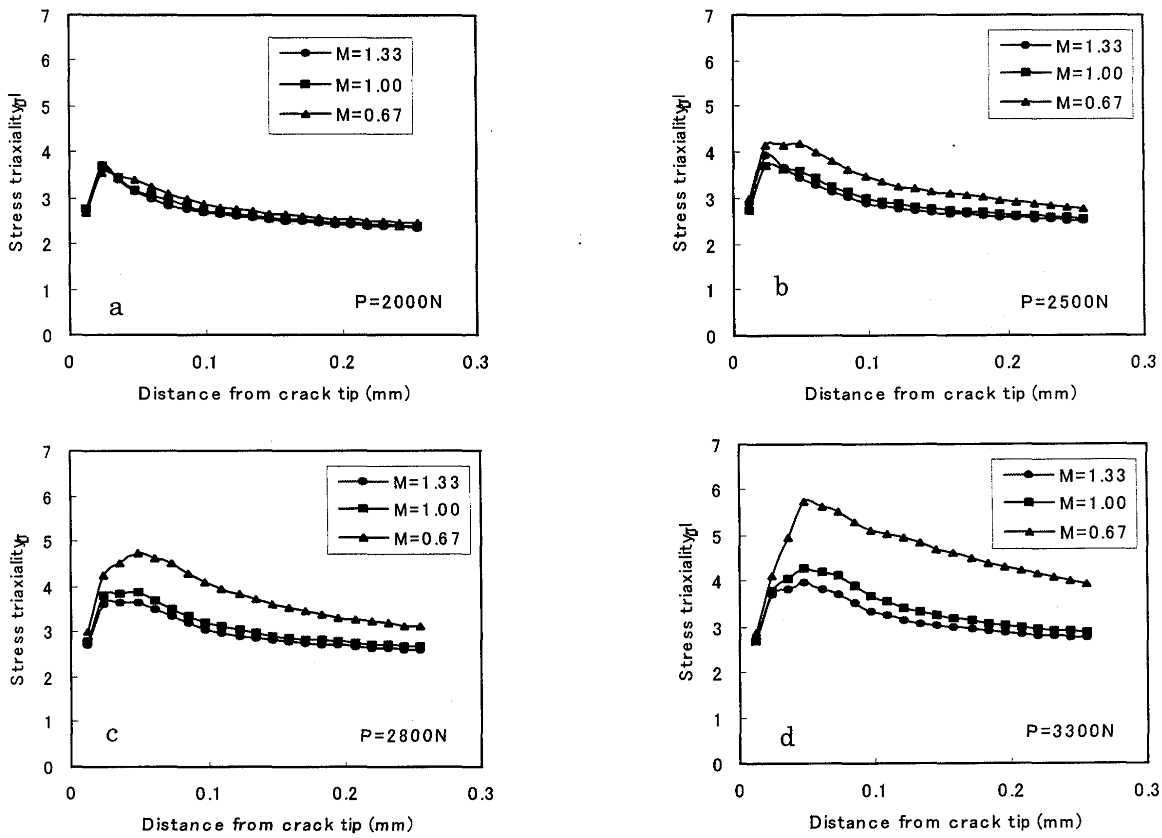

Fig.8 The stress triaxiality near the crack tip for mis-matched weldments at different applied load levels with the same yielding stress of weld metal.

one with higher yielding stress if the strain-hardening exponent is the same.

Figure 8 indicates the stress triaxiality near the crack tip with different applied load for different matching properties. The yielding stress of the weld metal is kept the same in the calculation. The Matching property, M, is defined as the ratio of yielding stress of base metal to that of weld metal. It is shown from Fig.8 that the stress triaxiality of an under-matched weldment is larger than that of an over matched weldment, that the larger the applied load, the larger is the effect of matching property on the stress triaxiality. It seems that the under-matched weldment will cause larger changes in stress triaxiality than over matched weldment with the same applied load. Therefore, it is reasonable to suppose that the under-matched weldment is more sensitive to ductile fracture than the over-matched weldment. Compared with the J-integral calculation shown in Fig.4, the larger the J-integral, the larger is the stress triaxiality near the crack tip.

4.3 Effect of weld metal width

Figure 9 and **10** show the effect of weld metal width on the stress triaxiality near the crack tip in overmatched weldment under different applied load levels. It indicates that the larger the weld metal width, the smaller is the stress triaxiality near the crack tip. It should be noticed that the yielding stress of weld metal is higher than that of base metal. It is easy to understand that the larger the weld metal width, the larger is the stress triaxiality when definition of the matching property is the ratio of the yielding stress of base metal to weld metal. Therefore, only the classical definition of matching property should be taken in the situation to study the other factors, except matching property. The weld metal width has no effect on the stress triaxiality when the weld metal width is larger than 0.63 times the ligament size. The location with maximum of stress triaxiality is not changeable with applied load. **Figures 11** and **12** show the influence of weld metal width on the stress triaxiality near the crack tip in under matched weldment with different applied load levels. It can be seen that the weld metal width has a large effect on the stress triaxiality and that it has no effect when the weld metal width is larger than 0.63 times the ligament size. The effect of weld metal width is little when the applied

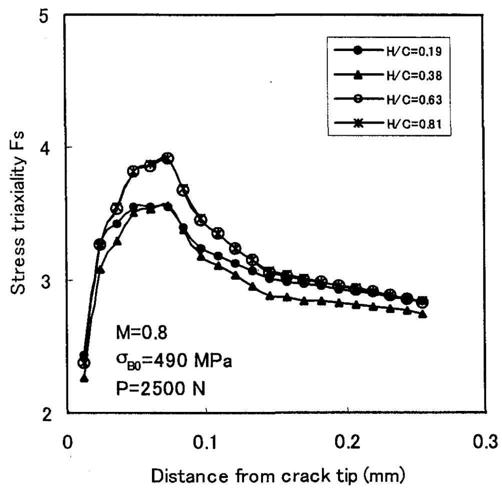

Fig.9 Effect of weld metal width on stress triaxiality near the crack tip for under matched weldment at the load of 2500 N

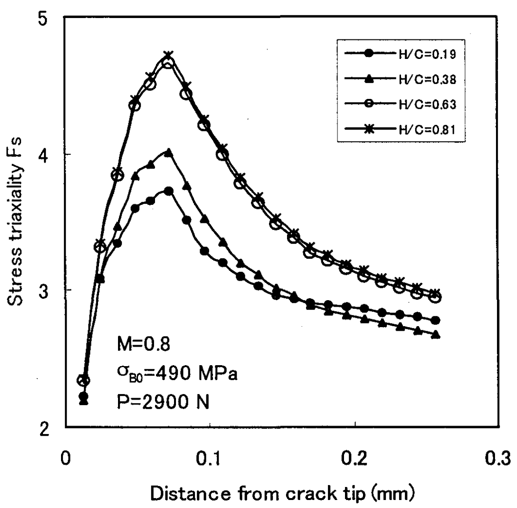

Fig.10 Effect of weld metal width on stress triaxiality near the crack tip for under matched weldments at the load of 2900 N

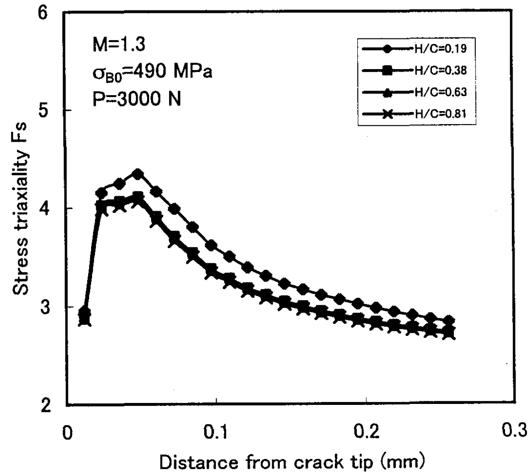

Fig.11 Effect of weld metal width on stress triaxiality near crack tip for over matched weldments at the load of 3000 N

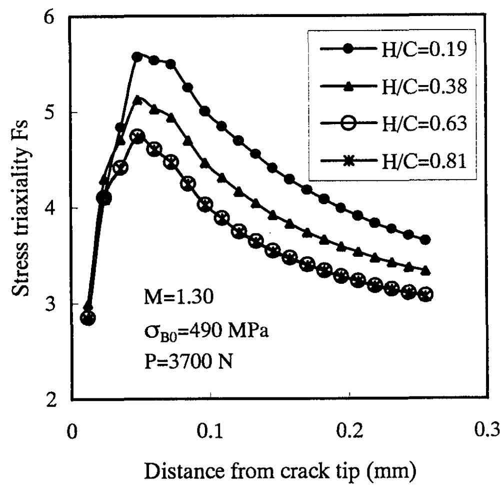

Fig.12 Effect of weld metal width on stress triaxiality near crack tip for over matched weldments at the load of 3700 N

load is smaller, both in over matched or under matched weldments.

5. Conclusion

The ductile constraint in the mis-matched weldment was numerically investigated making use of finite element code. The stress triaxiality near the crack tip is taken as an important parameter to describer the ductile constraint. The conclusion shows the followings.

1. There exists a maximum value of stress triaxiality near the crack tip. The stress triaxiality near the crack tip becomes larger with a decreasing of yielding stress in homogeneous materials.
2. In order to keep the same image about the matching property effect on some performance of the mis-matched weldment, it is supposed in this paper that the matching property M should be the ratio of the yielding strength of weld metal to that of base metal in the condition of the same base metal yielding stress, and the ratio of the yielding stress of base metal to that of weld metal in the condition of the same weld metal yielding stress.
3. The matching property of mismatched weldment has a larger effect on the stress triaxiality near the

crack tip. The stress triaxiality becomes larger with the decrease of matching property. The under matched weldment is more sensitive to ductile fracture because it has larger ductile constraint than an over matched weldment.

4. The weld metal width has strong effect on stress triaxiality near the crack tip when the weld metal width is narrow. And it has little effect when the weld metal width is larger than 0.63 times the ligament in the studied cases.

References

1) K.-H.Schwable, Effect of weld metal mis-match on toughness requirements: some simple analytical considerations using the engineering treatment model (ETM). International Journal of Fracture 62, 1-24.
2) K.Satoh, and M.Toyoda, Fracture Toughness Evaluation of Welds with Mechanical Heterogeneity, Transaction of Japan Welding Society, 1982, 13(1)
3) M.Zhang, Y.W.Shi, and J.X.Zhang, Numerical Study on Failure Assessment Curve of Weldment, Petroleum and Chemical Engineering Equipment, Vol.26(2), 1997, 6-11
4) J.X.Zhang, and Y.W.Shi, The Study on Ductile Fracture of the Over-Matched Weldment with Mechanical Heterogeneity, International Journal of Pressure Vessel and Piping, Vol.75, 1998, 773-776.
5) J.X.Zhang, and Y.W.Shi, The Effect of Welding Mechanical heterogeneity on fracture toughness feature of base metal, International Journal of Pressure Vessel and Piping, Vol.72, 1997, pp199-202
6) J.X.Zhang, and H.Murakawa, Numerical Study of Stress Triaxiality and Fracture Driving Force for Notched Specimen with Mechanical Heterogeneity, Trans. JWRI, Vol.27(2), (1999), 81-87.
7) Saxena A. Nonlinear Fracture Mechanics for Engineers, CRC Press, 1998,
8) Brocks W., and Schmitt W., The second parameter in J-R curves: constraint or triaxiality? Constraint effect in Fracture: Theory and Applications, ASTM STP 1244, 1995, 209-231.
9) O'Dowd N.P., Shih C.F., Family of crack tip fields characterized by a triaxiality parameter - II fracture application. Journal of Mechanics and Physics of Solids, 1991, 39, 989-963.
10) Oven D.R.J., and Fawkes A.J., Engineering Fracture Mechanics: Numerical Methods and Application, Swansea, Pineridge Press Ltd. 1983