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Effect of Weld Profile on Plastic Eta Factor

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ABSTRACT

Experimental evaluation of fracture toughness is essential for carrying out fracture integrity assessment of primary piping components of nuclear power plant. For homogeneous fracture specimens, testing procedures and evaluation of fracture toughness is well established. Since girth welds are invariably present in any nuclear piping system accurate fracture assessment of these welds also is an important aspect of integrity assessment. In this work effect of weld strength mismatch and weld slenderness on plastic η factor is systematically examined. Effect of weld grove on plastic η factor is also quantified. In addition, for accurate estimation of plastic η factor of fracture specimens having dissimilar metal weld (DMW), crack in different zones of dissimilar weld are postulated. Detailed 2-D finite element analyses are performed on three point bend (TPB) specimen having dissimilar weld for actual weld profile.

INTRODUCTION

Fracture toughness testing , such as J-integral test, is an important part of structural integrity assessment based on fracture mechanics methodology. Fracture toughness, in terms of J integral, is measured using the experimental load-displacement data and a calibration factor, often referred as the plastic η factor. Conventionally, fracture toughness is evaluated by performing tests on fracture specimens like deeply cracked three point bend (TPB) specimen and compact tension (CT) specimen. For homogeneous fracture specimens, testing procedures and evaluation of fracture toughness is well established. Since girth welds are invariably present in any nuclear piping system accurate fracture assessment of these welds also is an important aspect of integrity assessment. To evaluate fracture toughness of these welds, specimens are fabricated from pipe having girth welds. In general, mechanical properties of base and weld materials are different which is often referred as weld strength mismatch. Several studies have revealed that Plastic η factor of mismatch welds depend not only on strength mismatch of base and weld material (ratio of yield strength of weld to base material) but also on weld width. The mismatch effect on the plastic η factor for centre crack plate (CCP) and Single edge crack plate (SE (CP)) specimens was investigated by Lei et al. [1] by incorporating the modified definition of an equivalent stress strain relationship using slip line field theory. Further Oh et al. [2] extended this approach to see the effect of structural geometry and crack location on crack deriving force for crack in weld. Xuan et al. [3] proposed modified plastic η factor for mismatch CT specimens by using equivalent homogeneous material model based on limit load analysis. All these investigation are based on the assumption that the limit load of a mismatch specimen can be used to obtain an equivalent homogeneous specimen. This assumption works well for some cases but may not be applicable in general. To overcome this problem Kim et al. [4] used detailed FE analysis to obtain plastic η factor of mismatch welded specimens. All the above investigation has modeled the actual weld profile as a idealized simple rectangular strip with uniform weld width. However, no detailed analysis has yet been performed to demonstrate the validity of this weld idealization via-a'-via the actual weld profile. In reality, specimen fabricated from pipe weld has varying weld width due to weld profile. To evaluate plastic η factor of these welds, it is necessary to carry out systematic studies considering strength mismatch effects and the actual weld profile.

Dissimilar metal weld (DMW) is also widely used in nuclear power plant. Typically, dissimilar metal weld (DMW) joint is used to connect the low alloy steel (SA508Cl3) pressure vessel with Austenitic stainless steel (SS304LN) primary piping component. A suitable material for Buttering (SA508Cl3 side) and filler wire are used for DMW. The mechanical properties of base, butter and weld metal differ substantially. Due to high strength mismatch in the various zones of fracture specimens having DMW, the estimation of Plastic η factor is not straight forward.

In this work, detailed 2-D finite element (FE) analysis are performed to quantify the strength mismatch effect on plastic η factor with actual weld profile for similar welded TPB specimens. 2-D FE analyses are also carried out on idealized rectangular strip with uniform weld width. All 2-D analyses were performed under plane-strain condition. Both CMOD and LLD based plastic η-factor were computed. Wide range of mismatch ratio and weld slenderness ratio were accounted to cover all practical cases. Solutions of plastic η factor obtained for such an idealized weld model were compared with that of actual weld profile. For accurate estimation of plastic η factor of fracture specimens having dissimilar metal weld (DMW), crack in different zones of dissimilar weld are postulated. Detailed 2-D finite element analyses are performed on three point bend (TPB) specimen having dissimilar weld for actual weld profile.

THEORY

Fracture toughness in terms of J-Integral in laboratory is measured from the area under experimental load – LLD records, using following equation [5]

$$J = \frac{K^2}{E^{'}} + \eta_P^{VLL} \frac{U_P^{VLL}}{Bb} \tag{1}$$

Here, K is the linear elastic stress intensity factor, E′ = E for plane stress case and E′ = E / (1-ν^2) for plane strain case, E and ν denote Young's modulus and Poisson's ratio, respectively, U_P^{LLD} denotes the plastic component of area under load – LLD curve as shown in Fig. 1, B and b denote the specimen thickness and initial ligament length respectively and η_P^{LLD} is plastic factor based on load -LLD record. Fracture toughness can also be calculated from load – CMOD data, using

$$J = \frac{K^2}{E^{'}} + \eta_P^{CMOD} \frac{U_P^{CMOD}}{Bb} \tag{2}$$

Here U_P^{CMOD} denotes the plastic component of area under load – CMOD curve as shown in Fig 2. It has been argued that the use of load-CMOD records, instead of load–load line displacement records, gives more robust and accurate J estimation particularly for shallow crack testing [4].

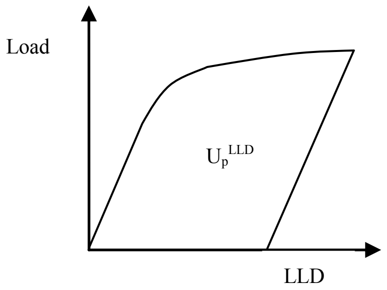


Fig.1: Plastic area under experimental Load-displacement records

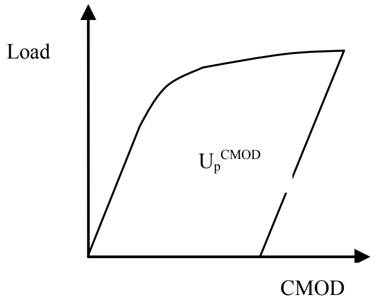


Fig. 2: Plastic area under experimental Load- CMOD records

EVALUATION OF PLASTIC η FACTOR OF CT AND TPB SPECIMENS HAVING SIMILAR WELD USING FINITE ELEMENT ANALYSIS

Bases on J-integral and load – LLD (or CMOD) data obtained from FE analysis, the values of plastic η factors can be evaluated using eq. (1) or (2). In the present investigation detailed 2D elastic–plastic FE analyses are performed on CT and TPB specimens. To avoid problems associated with incompressibility, reduced integration eight-node elements were used. Materials were modeled as isotropic elastic– perfectly plastic obeying the J_2 flow theory and a small geometry change continuum FE model is employed.

For specimens having similar weld, FE model considered an idealized bi-material having sandwich structure with straight weld strip, without any heat affected zone (HAZ). Relative crack depth for specimens are fixed at a/W = 0.5. Wide range of mismatch ratio and weld slenderness ratio are covered to cover all practical cases. Mismatch ratio (M) is define as

$$M = \sigma_{yw}/\sigma_{YB} \tag{4}$$

Here σ_{YW} is yield strength of weld material and σ_{YB} is yield strength of base material. In FE analysis, the value of M is systematically varied from M = 0.5 to 2.0. Note that the range of M from 0.5 to 2 covers most practical cases.

For mismatched specimen, weld slenderness is another important parameter define as

$$\Psi = (W - a) / H \tag{5}$$

Here W, a and H denote the specimen width, the crack length and the half width of the weld, respectively. In the present work, the value of ψ was systematically varied, ranging from 1 to 20. The two materials, that is, weld and base materials were assumed to have the same elastic properties (E and ν), but different yield strengths, σ_{YW} and σ_{YB}.

Results of CMOD based Plastic η factor of Three Point Bend Specimens (TPB) having Similar Weld

Solutions obtained from FEA for plane strain TPB specimen are given in Fig. 3, for a wide range of M and ψ, showing strong mismatch effects on plastic η factor. The value of η_P^{CMOD} increases with degree of under matching and vice versa. For overmatch welds with $\psi > 1$, the value of η_P^{CMOD} decreases sharply and then increases gradually approaching the value of the homogeneous specimen ($\eta_P^{CMOD} \rightarrow 2.6$) for $\psi >> 1$. On the other hand, for under-matching $\psi \approx 1$, the η_P^{CMOD} value gradually increases with ψ, and then decreases to attain the value corresponding to homogeneous case. Thus, using the value of η of the homogeneous specimen, fracture toughness will generally be under predicted (conservative estimate) for under-matched welds, but over predicted (non-conservative estimate) for overmatched welds. The effect of M and ψ on plastic η factor is more pronounced in over-matching case.

Results of CMOD based Plastic η factor of Compact Tension Specimens (CT) having Similar Weld

Solutions of η_P^{CMOD} obtained from FE analysis for plane strain CT specimen are given in Fig. 4, for a wide range of M and ψ showing strong mismatch effects. The trend of η_P^{CMOD} with M and ψ is similar to that of TPB specimen for non-hardening case.

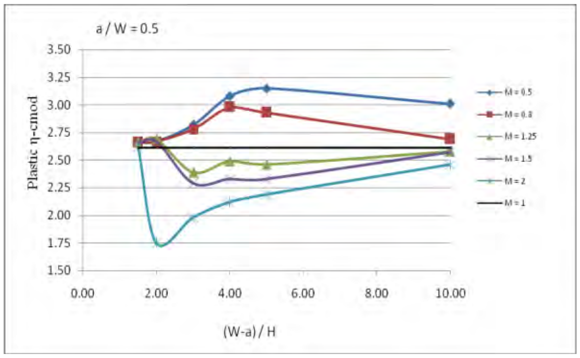


Fig. 3: Variations of non-hardening FE plastic η factor solutions With M and (W−a) / H for plane strain, TPB specimen having similar weld.

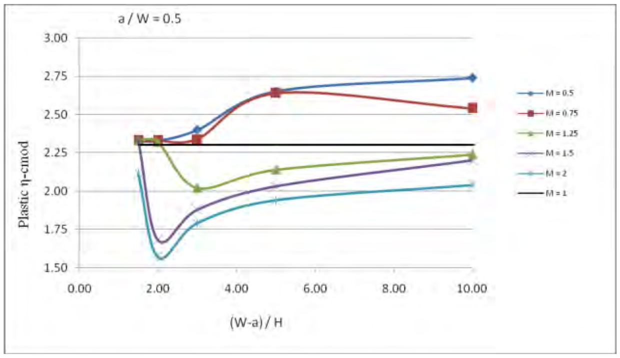


Fig. 4: Variations of non-hardening FE plastic η factor solutions With M and (W−a) / H for plane strain, CT specimen having similar weld.

EFFECT OF WELD PROFILE ON PLASTIC η FACTOR OF TPB SPECIMEN HAVING SIMILAR WELD

In this study the effect of weld profile on a TPB specimen having weld centre crack is analysed. If it is assumed that the specimens are machined in such a way that the length (S) of the specimen is in the longitudinal direction of the pipe, width (W) of the specimen is in the thickness direction of the pipe, and the thickness of the specimen is in the circumferential direction of the pipe then the actual weld profile would be something similar to that shown in Fig. 5.The specimen so obtained would have a varying weld width due to weld groove. The idealized TPB specimen having uniform weld width ($2H = (2H_1+2H_2)/2$), where H is half of weld width of idealized specimen , 2H1 is weld width at top of actual specimen and 2H2 is weld width at bottom of actual specimen is shown in Fig-6.

For the present case $2H_1 = 20$ and $2H_2 = 9$. Mesh adopted for FE analysis for actual and idealized specimen is shown in fig-7.

FINITE ELEMENT MODEL

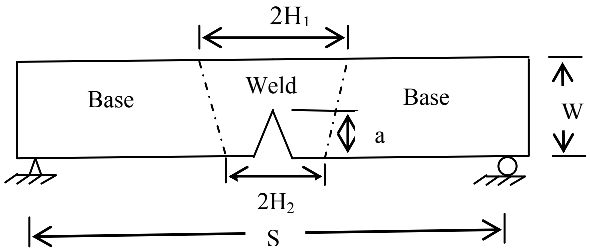


Fig.5: Actual TPB specimen with weld centre crack

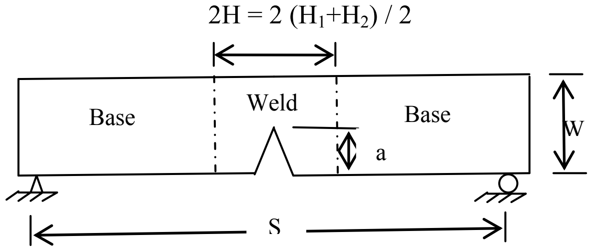


Fig.6: Idealized TPB specimen with weld centre crack

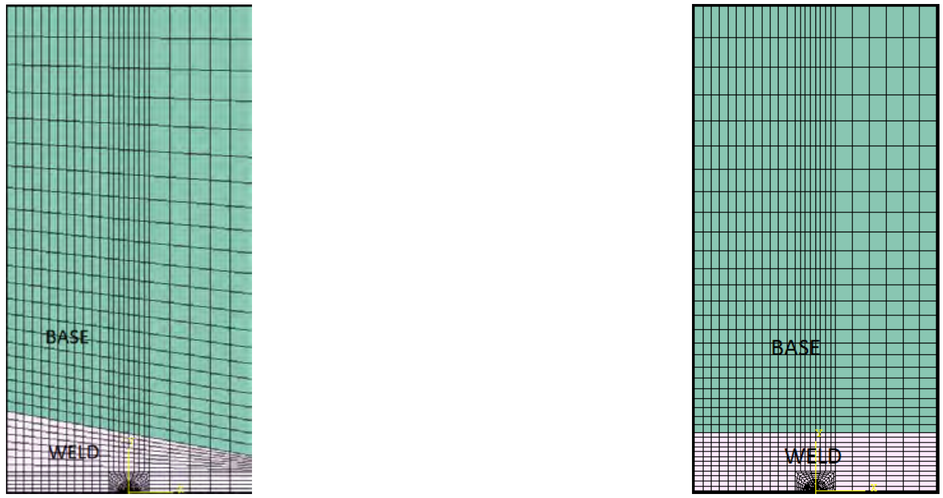


Fig.7: Half model of FE mesh for TPB Specimen. a) With actual weld profile. b) With idealized rectangular weld profile

To quantify the effect of weld groove on plastic eta factor, FE analyses are performed on TPB specimens having similar weld with actual weld profile and there corresponding idealized weld model. For the analysis relative crack depth (a / W): 0.3, 0.5 and 0.7 are considered. Wide range of mismatch ratio (M): 0.5, 1.5 and 2 are accounted.

Comparison of plastic η factor of TPB specimens having similar weld with actual weld profile and their idealized weld model

From FE analysis, Plastic η factor based on CMOD (η_P^{CMOD}) was calculated by using J-integral and load – CMOD data. The resulting solutions for plane strain TPB fracture specimens having similar weld with actual weld profile and their idealized weld model are given in Figs. 8 to 10. Solutions Provided by ASTM for η_P^{CMOD} are also plotted along with these results.

For crack depth (a / w) = 0.6 results of Plastic η factor for actual weld profile and their idealized weld model is nearly equal for all the considered mismatch ratio. i.e. Idealization of actual weld profile is well acceptable for this crack depth.

For crack depth (a / w) = 0.5 results of Plastic η factor for Idealized weld model and actual weld profile is nearly equal for mismatch ratio 0.5 to 1.25. However, for M=1.5 results of idealized weld model is giving significantly lower value of Plastic η factor than that of actual weld profile. Such a behavior can be explained from the plastic deformation pattern. For the idealized weld model, the plastic deformation penetrates into the base material, where as for actual case it is confined within the weld material as shown in fig.11. For this case actual weld profile model behave like homogeneous model, that's why Plastic η factor of actual weld profile is nearly equal to that of homogeneous specimen. For M=2 for both actual and idealized cases plastic deformation penetrate into the base material due to higher mismatch in strength, that's why Plastic η factor for actual and idealized case are nearly equal and deviating significantly with that of homogeneous specimen.

For crack depth (a / w) = 0.3 results of Plastic η factor for Idealized weld model and actual weld profile is well within limit of 5% for mismatch ratio varying from 0.5 to 1.5. However, for M>1.5 results of idealized weld model is giving higher value of Plastic η factor than that of actual weld profile. The actual weld profile for the case (a/w)= 0.3 has narrow weld width near the crack tip as compared to that of idealized weld profile. Hence, for the actual weld profile for M=2 plastic deformation penetrate in the base material more than that for the idealized weld profile. Thus, the Plastic η factor of actual weld profile is deviating more from homogeneous specimen than the idealized similar welded specimen.

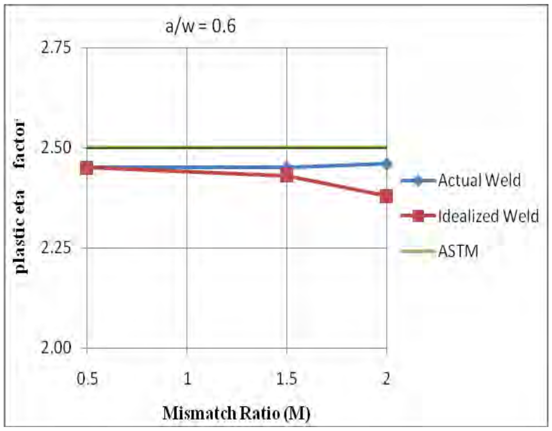


Fig.8: Variations of non-hardening FE plastic η factor solutions With M for plane strain, TPB specimen having similar weld (a/w = 0.6) with actual and idealized weld profile.

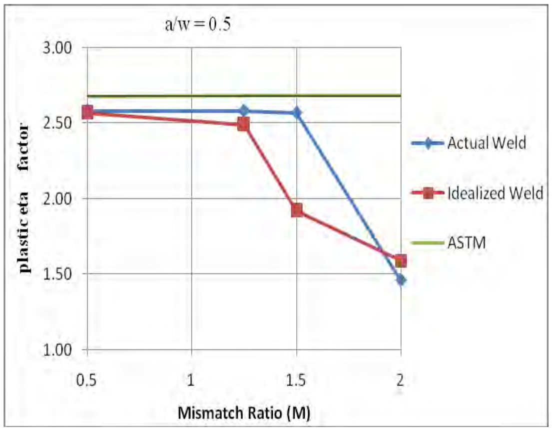


Fig.9 : Variations of non-hardening FE plastic η factor solutions With M for plane strain, TPB specimen having similar weld (a/w = 0.5) with actual and idealized weld profile.

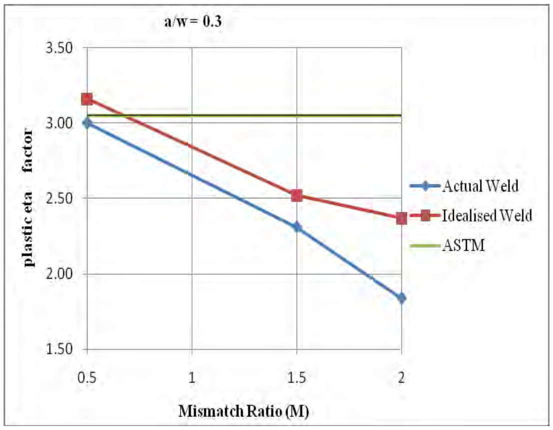
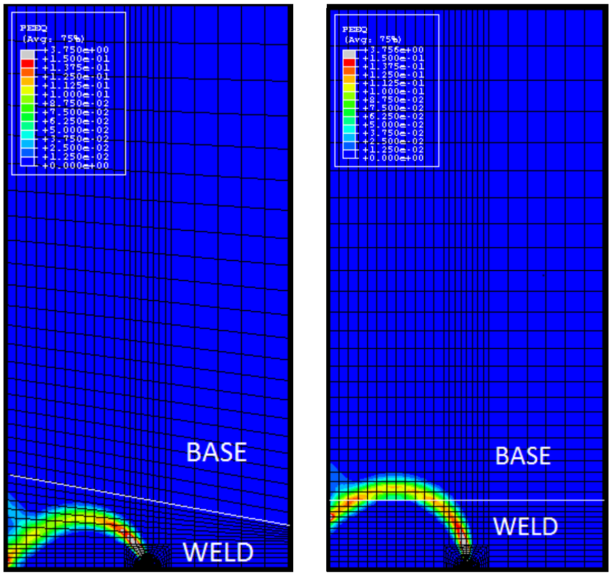


Fig.10: Variations of non-hardening FE plastic η factor solutions With M for plane strain, TPB specimen having similar weld (a/w = 0.3) with actual and idealized weld profile.



(a) (b)

Fig. 11 : Plastic deformation field of a/W = 0.5, M = 1.5 a) Actual weld profile. b) Idealisd weld profile.

EVALUATION OF PLASTIC η FACTOR OF TPB SPECIMENS HAVING DISSIMILAR METAL WELD (DMW)

For accurate estimation of plastic η factor of fracture specimens having dissimilar metal weld (DMW), crack in different zones of dissimilar weld are postulated. Detailed 2-D finite element analyses are performed on three point bend (TPB) specimen having dissimilar weld with actual weld profile. For the analysis relative crack depth (a / W) = 0.6 and four material model are used. Idealize elastic perfectly plastic material with reference stress ($\sigma_f = (\sigma_Y + \sigma_U)/2$) are used, where σ_f is reference stress, σ_Y is yield stress of material and σ_U ultimate tensile strength of material. Tensile strength and young's modulus of elasticity of the different zones of dissimilar metal weld is given in table 1 [6].

Table.1: Tensile properties of different materials of the dissimilar metal weld joint [6]

Material	young's modulus of elasticity (E) MPa	yield stress (σ_Y) MPa	Ultimate tensile strength (σ_U) MPa	Reference stress (σ_f) MPa
WELD	1.82E5	448	587	518
Butter	2.04E5	417.8	631	524
LAS	2.27E5	536.4	675	606
SS	1.94E5	245	588	417

Results of plastic η factor of TPB specimens having dissimilar metal weld (DMW)

From FE analysis, Plastic η factor based on CMOD (η_P^{CMOD}) are calculated for TPB specimen having DMW with postulated crack in different regions of DMW. The resulting solutions for plane strain TPB fracture specimens having DMW are provided in table 2. Solutions Provided by ASTM (homogeneous specimens) of η_P^{CMOD} are also tabulated along with these results.

It is observed that plastic η- factors for interfacial crack in dissimilar metal weld specimens are quite close (within 5%) to those of standard homogeneous specimens. For these interfacial crack plastic deformation occur only in weakest material as shown in figs. 13 ,15 and 16, i.e. it behave like homogeneous specimen. Moreover, when crack is lying in the centre of weld again no appreciable influence on plastic η- factor is observed because of plastic deformation confined within weld region as shown in fig- 12. However, when crack is located at the centre of buttering, η- factor is approx 10% higher than that of homogeneous specimen. In the case of buttering having center crack plastic deformation field penetrates in the weak weld region as shown in fig- 14.

Table 2: plastic η- factors for TPB specimen having DMW (a/W = 0.6) with postulated crack in different zones of dissimilar metal weld joint.

Crack location	Plastic η factor η_P^{CMOD}	ASTM η_P^{CMOD}
Weld center crack	2.4	2.5
Weld and Butter interface crack	2.56	2.5
Butter center crack	2.66	2.5
Butter and LAS interface crack	2.63	2.5
Weld and Austenitic steel interface crack	251	2.5

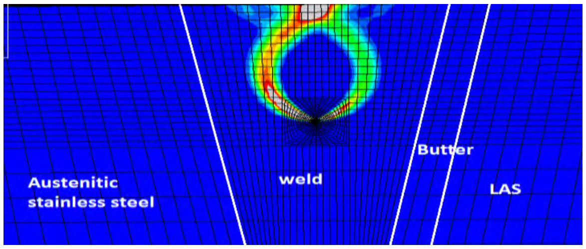


Fig.12 : Plastic deformation field of weld center crack TPB specimen having DMW (a/W = 0.6).

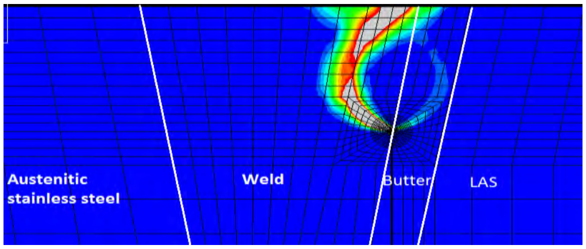


Fig. 13 : Plastic deformation field of Weld and Butter interface crack TPB specimen having DMW (a/W = 0.6).

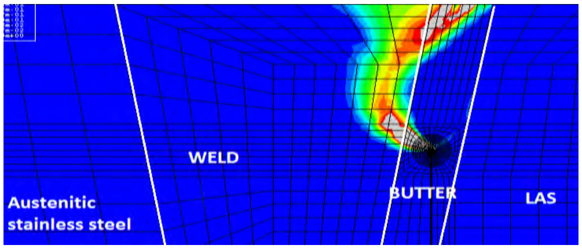


Fig.14 : Plastic deformation field of Butter center crack TPB specimen having DMW (a/W = 0.6).

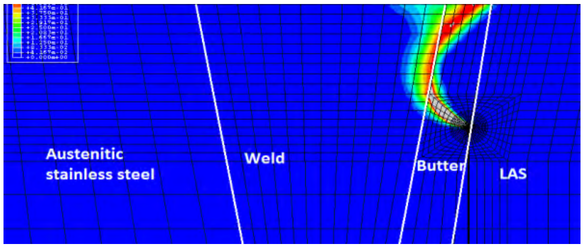


Fig .15 : Plastic deformation field of Butter and LAS interface crack TPB specimen having DMW (a/W = 0.6).

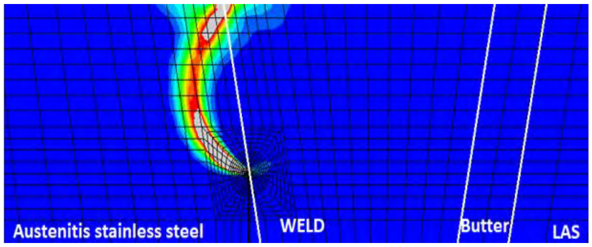


Fig.16 : Plastic deformation field of Weld and austenitic stainless steel interface crack TPB specimen having DMW (a/W = 0.6).

CONCLUSION

- For over-match welds plastic η-factor evaluated for non-hardening material model are lower while for under match welds gives higher value as compare to that of homogeneous material model. This implies that the use of ASTM based plastic η-factors for over-match weld would lead to un-conservative estimate of fracture toughness in design. And vice -Versa is true for under-match welds.

- To evaluate the Plastic η factor for a TPB specimen having similar weld, assumption of idealized rectangular weld model of actual weld profile works well for most of the cases, however, in some cases significant differences do occur.

- Plastic η- factors for interfacial crack of TPB specimens having dissimilar weld are quite close (within 5%) to those of standard homogeneous specimens. Moreover, when crack was lying in the centre of weld again no appreciable influence on plastic η- factor are observed.

- For the crack located at the centre of buttering η- factor is approximately 10% higher than that of homogeneous specimen.

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