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PRESTRAIN HISTORY EFFECT ON DUCTILE FRACTURE OF PIPELINE STEELS

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ABSTRACT

Before or during operation, pipelines may suffer from plastic pre-deformation due to accidental loading, cold bending or ground movement. One of the examples is the so-called pipe reeling process. In order to ensure effective and safe pipeline transports, it is important to evaluate the pre-deformation (pre-strain) induced pipe properties changes and include their effects into lifetime design and structural integrity assessment.

In this study, single edge notched tension (SENT) specimen was used to simulate the effect of a plastic pre-straining cycle on the crack tip driving force and near tip stress fields. The so-called complete Gurson model developed by the authors has been applied to simulate the ductile fracture behaviour. It has been shown that plastic prestrain cycles will alter the relation between the crack tip driving force and crack tip stress fields – the crack tip constraint. In general the crack tip constrain will be increased and the fracture resistance will be reduced by the prestrain history. This effect must be included in future structural integrity assessment of pipeline components.

INTRODUCTION

There are many engineering scenarios where steel components are subject to plastic deformation due to accidental loading, cold bending and ground movement and the effect of the plastic deformation on further deformation and loading capability should be assessed. Reeled pipe, Fig. 1, is a typical example where the effect of plastic strain history (prestrain) on the fracture behaviour needs to be quantified. In order to properly tackle the problem, the prestrain history should be precisely simulated using constitutive models capable of describing cyclic and non-linear material behaviour [1]. It is known that prestraining will introduce strain hardening and anisotropy. Prestrain from these industrial processes will not only modify the yield behaviour but, more importantly, influences in a detrimental manner the local failure mechanisms and macroscopic fracture (cleavage and ductile) initiation toughness and fatigue properties [2-6]. Recently the authors [7] have studied the effect of strain path changes on microvoid coalescence using the unit-cell model approach. It has been observed that the effect of void shape changes induced by uniaxial prestraining on void coalescence is relatively small, while the effect of local plastic strain hardening and residual stresses in the void ligament after prestraining is significant. Pre-straining also

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induces microvoid nucleation which will further influence the final ductile fracture behaviour. In a recent study, the authors have applied so-called modified boundary layer model (MBL) together with the complete Gurson model (described below) to study the effect of prestrain induced void nucleation on fracture initiation toughness [8].

In the present study, a 2D SENT specimen was selected to study the effect of a symmetric prestrain cycle on the crack tip driving forces, crack tip constraint as well as ductile fracture resistance. SENT specimen has been selected, because it has been demonstrated that the crack tip constrain level in a SENT specimen is more close to the constraint level in a pipe than other fracture mechanics specimens [9]. The complete Gurson model implemented in ABAQUS was used to simulate the ductile crack growth. Symmetric prestrain cycles (first tension then compression) with amplitude up to 0.4% have been considered. The results clearly indicate that the prestrain cycle will significantly influence the crack tip constrain level and the crack tip resistance will be reduced.

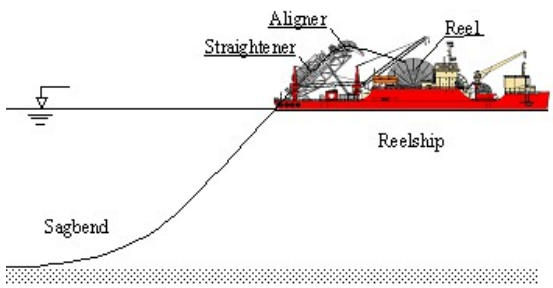

Fig. 1 Schematic plot of the pipe reeling process (provided by TONOR).

THE COMPLETE GURSON MODEL

For pipeline steels and other engineering materials, it is widely recognized that ductile fracture is controlled by nucleation, growth and coalescence of microvoids. In the past decades, substantial efforts have been devoted to the understanding of void mechanisms. Micro - mechanical model-based approaches for describing ductile fracture as a consequence of void nucleation, growth and coalescence have received considerable attention. Among the available models, the micro-mechanical model originally proposed by Gurson and later modified by Tvergaard and Needleman [10] has shown to be able to describe the ductile fracture behaviour. The Gurson-Tvergaard can be written:

$$\phi(q,\bar{\sigma},f)=\frac{q^2}{\bar{\sigma}^2}+2q_1 f\cosh\left(\frac{3q_2\sigma_m}{2\bar{\sigma}}\right)-1-(q_1 f)^2=0$$

where f is the void volume fraction. In the above equation, q_1 , q_2 are constants introduced by Tvergaard [10], σ_m is the mean normal stress, q is the conventional von Mises equivalent stress, $\bar{\sigma}$ the flow stress of the matrix material. It should be noted that above Gurson-Tvergaard is not able to predict microvoid coalescence.

Recently a complete Gurson model has been introduced by the authors [11-13]. The complete Gurson model is a combination of the Gurson model [13] which deals with microvoid nucleation and growth, and a physical microvoid coalescence criterion based on the plastic limit load model by Thomason [14].

In the complete Gurson model void coalescence is not determined by any critical void volume fraction value. The commonly used critical void volume fraction f_c is not a material constant. Therefore, in terms of the complete Gurson model, ductile fracture is exclusively linked to the void nucleation parameter. Detailed description of the complete Gurson model can be found in [11]. The complete Gurson model was implemented into ABAQUS using a user material subroutine UMAT with a specially designed numerical algorithm [15].

FEM MODELS AND MATERIALS

A SENT specimen has been used for the present study. It is now widely understood that fracture resistance depends on crack tip constraint level and the crack tip constraint is influenced by geometry, thickness, crack size and loading level. In the past years efforts have been spent to search appropriate fracture mechanics specimens which have similar crack tip constraint level as cracks found in pipes. Both numerical and experimental studies have demonstrated that the crack tip constraint level at SENT specimens is a good representation of the pipe cracks [9].

Fig. 2 schematically shows the SENT specimen used. The initial crack size (a) considered is 4 mm and other dimensions are *a/w*=0.143 and *L/w*=4.1. The specimen dimensions and applied loading have chosen such that buckling during compression is avoided. A remote homogenous displacement controlled boundary condition (clamped) was applied. Because of the symmetry, half of the SENT specimen was modelled in finite element analysis. The crack was modelled with an initial opening of 0.02 mm.

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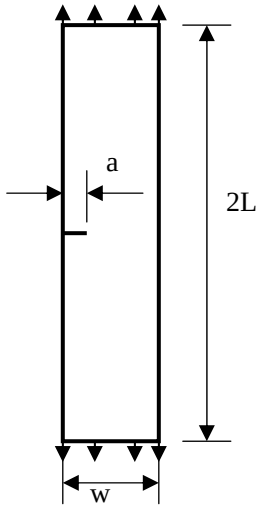

Fig. 2 Schematic plot of the SENT specimen.

Fig. 3 a) shows the global mesh used for modelling the SENT specimen. 4-node plane strain elements were used. The local mesh around the crack tip is shown in Fig. 3b. There are 2433 elements and 2579 nodes in the half model. Because ductile crack growth is the main concern of the study, a mesh with regular square elements has been utilized at the crack tip. This technique has been used in early studies of ductile fracture using the complete Gurson model [11]. During the prestrain cycle partly or whole crack faces will be closed. A rigid analytical plane has been defined in the model to simulate the contact of crack faces. The rigid plane is shown in Fig. 3a as a horizontal line.

A model material with power law hardening [16] has been used. The yield stress considered was 400 MPa and plastic strain hardening exponent is 0.05. The hardening used is in representative of the lower level of hardening found in the X60-X65 pipe steels. Fig. 4 displays the material true stress-strain curve used. The Young's modulus is 200000 MPa and Poisson ratio is 0.3. In the analysis with the complete Gurson model, an initial void volume fraction 0.005 was applied.

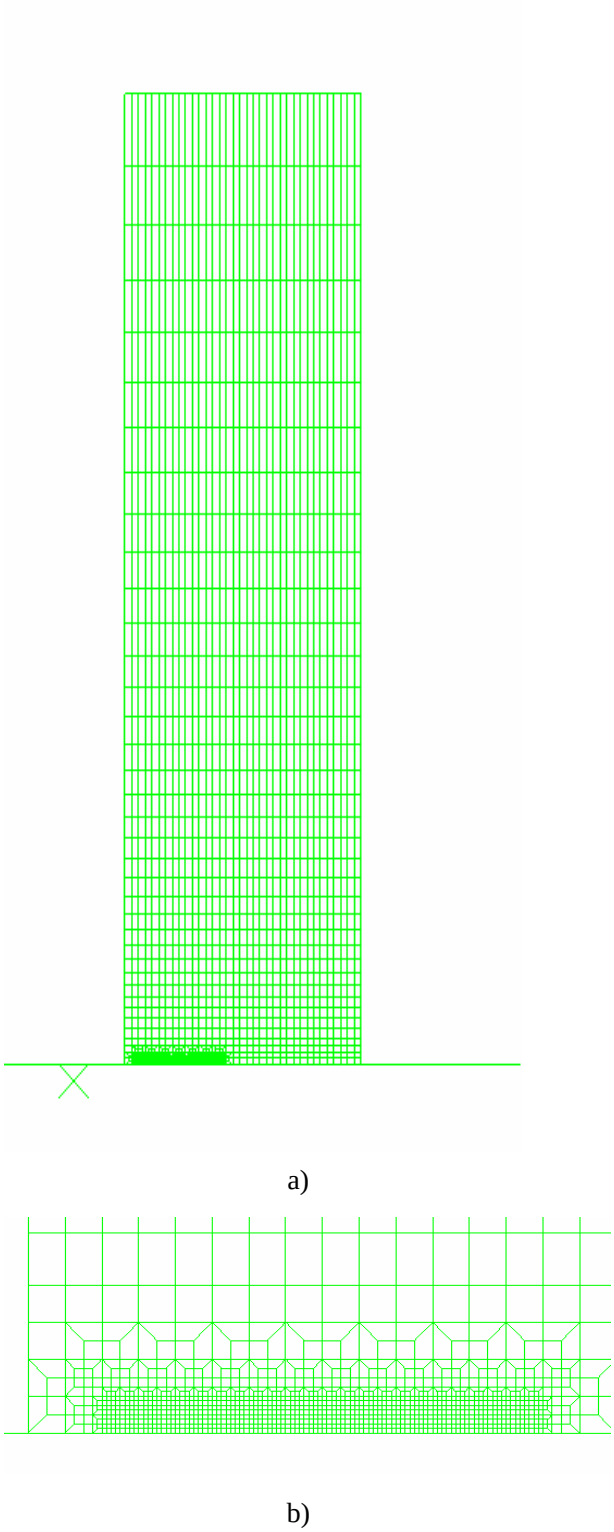

Fig. 3 Finite element mesh used in the analysis, a) global mesh, b) local mesh.

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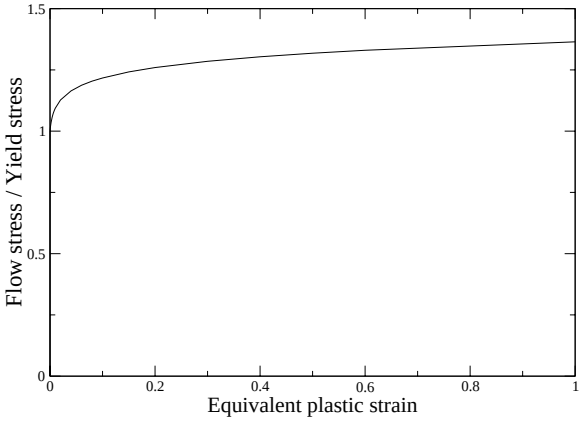


Fig. 4 Material flow stress - equivalent plastic strain data used in the analysis. The yield stress is 400 MPa and plastic hardening exponent 0.05.

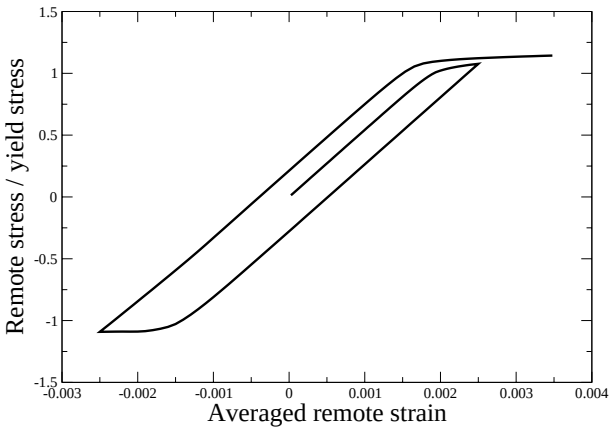
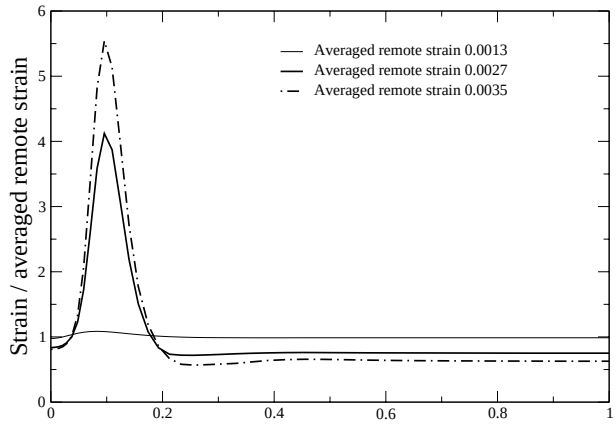
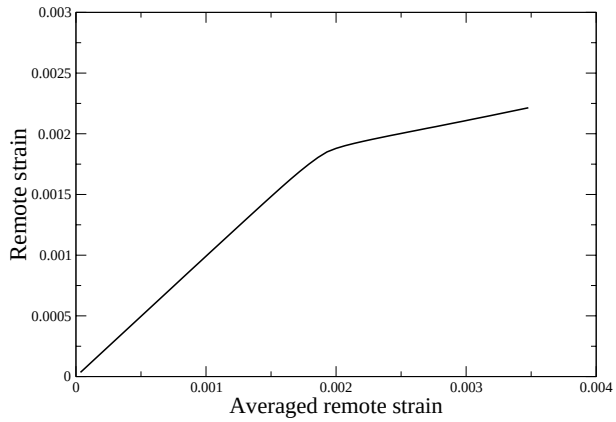


Fig. 5 Typical prestrain cycle considered.

Industrial reeling process contains several prestrain cycles [17, 18]. In this fundamental study a simpler problem was studied. The prestrain history was represented by a symmetric (the tension-compression amplitudes are equal) prestrain cycle which was then followed by a monotonic tension. Fig. 5 shows a typical prestrain cycle considered in the study. Prestrain was characterized by the averaged remote strain which is measured by dividing the applied displacement by the initial specimen length *L*. The averaged remote strains varied from 0 to 0.4%. The amplitudes of the prestrains in this study are close to the prestrains considered in [17].

The strain distribution along the central axis of the specimen at different straining levels is displayed in Fig. 6a. When the averaged remote strain is small, the axial distribution is almost horizontal and strain far away from the crack is equal to the averaged remote strain.





b)

Fig. 6 a) Strain distribution along the central axis, b) averaged remote strain versus remote strain.

For the specimen analyzed it can also be observed from Fig. 6a that the strain in the region close to the crack plane (less than 20 % of the half specimen length) is significantly elevated compared with the averaged strain. The strain far away from the crack plane (distance larger than 1/4 of the specimen length) is homogenous and can be used to define the remote strain.

For the sake of convenience, the averaged remote strain has been used for presenting the results. The remote strain versus average remote strain is shown in Fig. 6b. We can observe that when the averaged strain is less than 0.2%, the remote strain is nearly equal to the averaged strain. The averaged remote strain, however, overestimates the remote strain when it is lager than 0.2%.

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EFFECT OF PRESTRAIN ON CRACK TIP STRESS AND CONSTRAINT

Five prestrain cycles have been analyzed in total, together with one case with monotonic tension. The averaged remote strain versus CTOD curves for the six cases are shown in Fig. 7. It must be noted that the crack modelled has an initial opening 0.02 mm and therefore a maximum closure 0.02 mm is possible. In all the cases considered the specimen was loaded by tension first. Reverse loading was applied at different averaged remote strain levels. In the loading path, a typical elastic-plastic CTOD versus remote strain behaviour can be observed. The CTOD increases slowly in the beginning and rapidly when substantial yielding has reached. In order to simplify the notation, the first (slow increasing) part is called elastic and the second (rapid increasing) part is called plastic. It is interesting to note that during the reverse loading, the CTOD decreases also slowly in the beginning of loading (elastic unloading) and decrease rapidly when compressive loading has induced yielding. The remote strain versus CTOD curves are similar to the results of [17], where a similar study on the strain history has been carried out. Fig. 7 shows that all the prestrain cases resulted in some residual CTOD at the end of reverse loading. Fig. 8 plots the residual CTOD versus prestrain amplitudes. The residual CTOD is nearly a linear function of the prestrain applied.

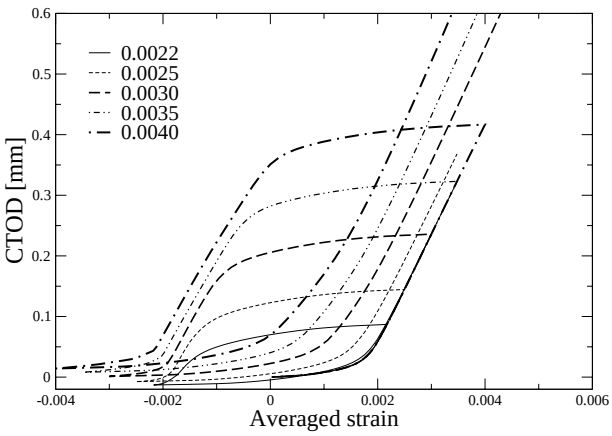

Fig. 7 Averaged strain versus CTOD for different pre-strain levels. The numbers in the legend indicate the prestrain amplitude.

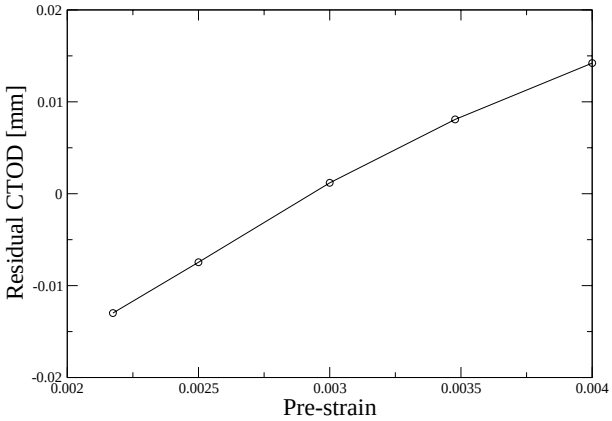

Fig. 8 Effect of pre-strain on the residual CTOD.

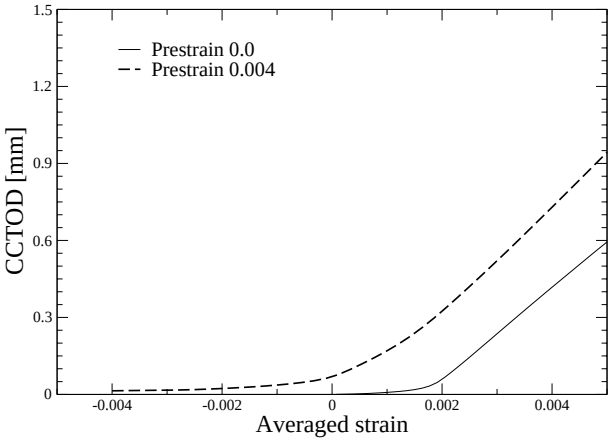

Fig. 9 Comparison of the reloading curve for the case with prestrain 0.004 with the monotonic loading case.

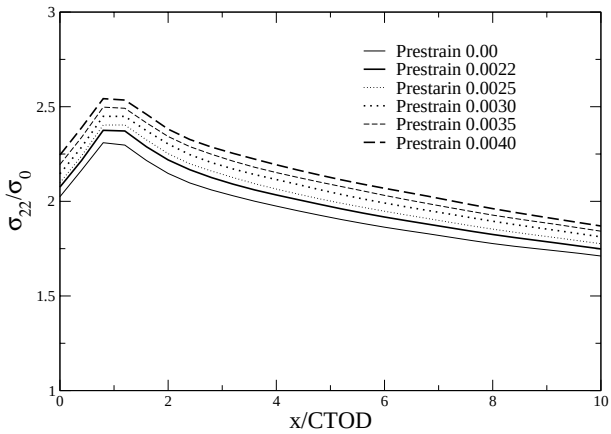

Fig. 10 Effect of pre-strain on the crack tip opening stress distribution at CTOD 0.25 mm.

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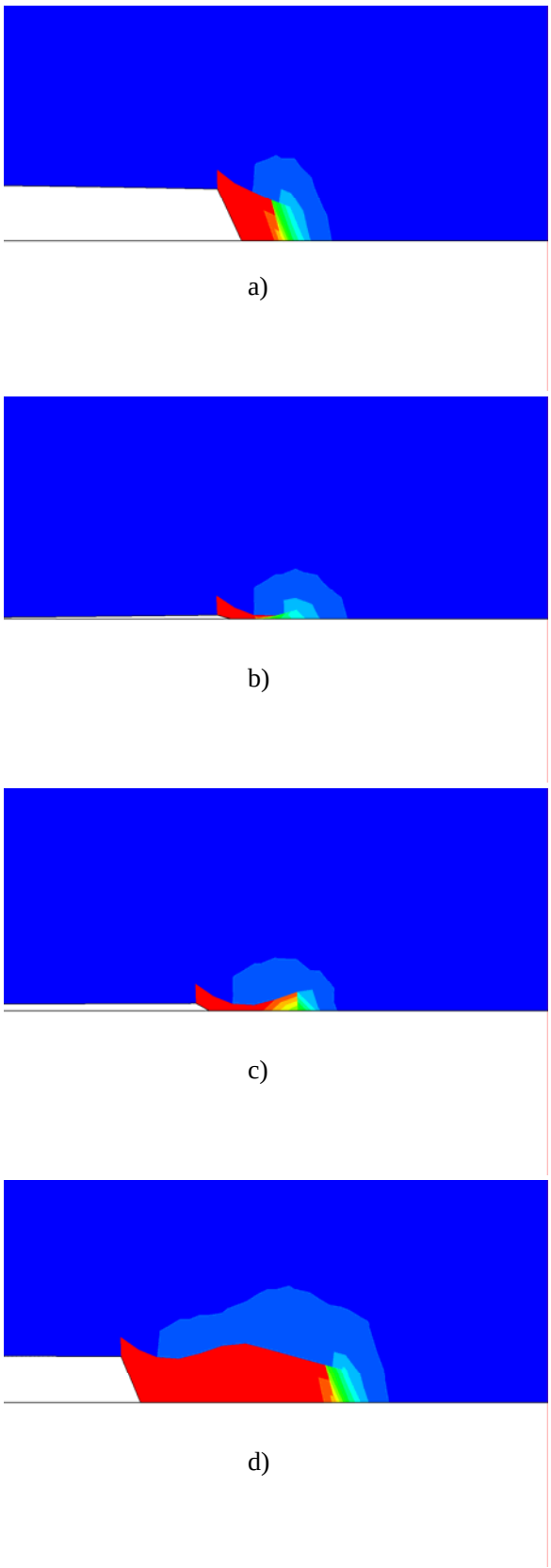

Fig. 11 Damage and crack growth during the prestrain cycle and further ductile tearing. The prestrain applied was 0.0035.

Fig. 9 compares the reloading behaviour of the case with 0.004 prestrain with the monotonic loading case. It can be observed that the elastic part after the prestrain cycle is much longer than the monotonic loading case (2.5 times). This can be explained by the severe strain hardening occurred at the crack tip during the prestrain cycle. The slopes of the plastic parts look similar to each other and seem to be less influenced by the prestrain cycle. One interesting question is how we can calculate the reloading curves without performing a real prestrain cycle analysis. This question has been explored in [19]. The results tend to indicate that monotonic analyses with trimmed stress-strain curve can be used to generate the reloading curves after the prestrain cycle. With this approach, a real cyclic analysis can probably be avoided.

Prestrain cycle will not only modify the shape of the CTOD curve. It is also important to investigate whether the prestrain cycle will influence the crack tip stress fields – constraints. When the crack tip plastic zone size is very small compared with the specimen geometry, there is one-to-one relation between CTOD and the crack tip stress fields. The one-to-one relation will be broken when the crack tip plasticity is large and a constraint parameter has been introduced to characterize the crack tip stress field, in additional to the CTOD. Fig. 10 plots the crack tip opening stress distributions at a CTOD 0.25 mm for the 6 cases analyzed. It is very interesting to note that even the CTOD are the same for the six cases, the crack tip opening stresses are different. Compared with the monotonic loading, prestrain cycle has

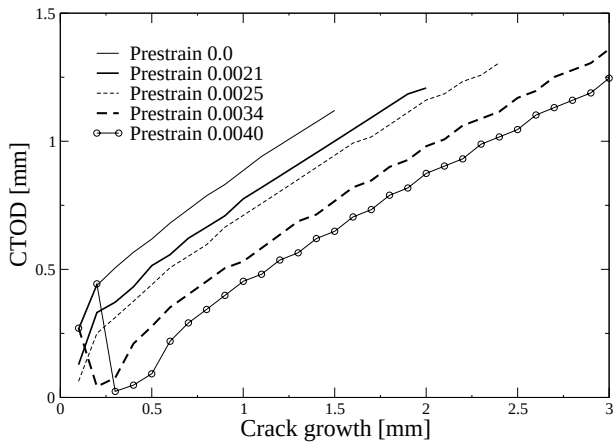

Fig 12 Effect of pre-strain cycle on the ductile crack growth behavior.

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EFFECT OF PRESTRAIN ON CRACK TIP DUCTILE FRACTURE BEHAVIOUR

The complete Gurson model described above has been applied to study the ductile fracture behaviour of the SENT specimen. An initial void volume fraction 0.005 has been used. No intermediate microvoid nucleation was considered. Because of the complete Gurson model, no critical void volume faction needs to be specified. The critical void volume fraction automatically determined by the complete Gurson model is about 0.04. The initial void volume fraction has been chosen in such a way that crack growth in the monotonic loading case will start at a CTOD about 0.25 mm.

The ductile crack growth behaviour for the case with prestrain 0.0035 is shown in Fig. 11 and the CTOD resistance curves for the six cases are shown in Fig 12. It has been found that when the prestrain is smaller than 0.002 (in the elastic region) the prestrain effect on the CTOD resistance can be neglected. However, Fig 12 shows that when the prestrain is 0.0021 the fracture resistance in the reloading part is clearly reduced. When the prestrain is 0.0034, a small amount ductile crack growth occurs in the first tensile loading. In the second tensile loading ductile crack initiation will start at a much lower CTOD. The reduction of CTOD resistance can be explained by Fig. 11. Ductile damage and small amount of crack growth already occurred by the end of the first tensile loading (Fig. 11a). The crack tip damage zone is distorted during the reverse compressive loading (Fig. 11b). Crack will start to open immediately when the second tensile loading starts and the ductile damage will be accumulated (Fig. 11c). At nearly the same CTOD, the damaged zone and ductile crack growth in the second tensile loading (Fig. 11d.) is much larger than that in the first tensile loading.

CONCLUDING REMARKS

The effect of prestrain history on the crack tip stress fields and ductile fracture has been investigated by using finite element method and the complete Gurson model. Prestrain cycle will result in strong hardening at the crack tip. The residual CTOD at the crack tip has been found to increase proportionally with the prestrain amplitude. By comparing the stress fields from different prestrain cycles at the same CTOD it has been shown that the prestrain significantly elevate the crack tip constraint. The increased crack tip constraint influences the ductile fracture resistance. The effect has been quantified by the complete Gurson model. The present results indicate that it is important to take the prestrain effect into structural integrity assessment of pipeline. An experimental program should be undertaken to validate the findings in this paper.

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