THE EFFECT OF PRE-STRAIN ON THE FRACTURE TOUGHNESS OF LINE PIPE STEEL

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ABSTRACT

Oil and gas pipelines may be subject to high plastic strains before they enter service and during operation, either intentionally or accidentally; examples included denting, cold bending, land slides, subsidence, frost heave, earthquake loading, reeling, and wrinkling or buckling.

The published literature indicates that this plastic deformation, or pre-strain, has a detrimental effect on the fracture toughness of steel; it reduces the resistance to crack initiation, reduces the resistance to crack growth, and increases the transition temperature.

A programme of tests, and numerical and theoretical analyses has been undertaken to investigate the effect of tensile pre-strain on the fracture toughness of line pipe steel. The material tested in the study was an API 5L X80 line pipe steel. The results of tensile, notched tensile, fracture toughness (*J*-integral and CTOD) and Charpy V-notch impact tests of virgin (not pre-strained) and pre-strained material are discussed. The results of the numerical study are also discussed. It is shown that the effect of pre-strain can be simulated numerically using a finite element model incorporating the influence of material damage through a Gurson-Tvergaard constitutive model. The relative importance of changes in the stress-strain curve (increased yield strength, reduced ductility, etc.) of the virgin material, and material damage (void nucleation and growth, etc.) during the introduction of pre-strain, on the reduction in toughness due to pre-strain are discussed.

The effect of tensile pre-strain on fracture toughness can be characterised in terms of the effect of pre-strain on: the yield strength, the strain hardening capacity, and the fracture strain of the virgin material. A semi-empirical relationship, based on the theoretical model, is proposed for predicting the effect of pre-strain on toughness. The relationship is expressed in terms of the true strain at the tensile strength of the virgin material. The relationship is conservative with respect to the test data reported here and in the literature. The implications of pre-strain for the design, construction and operation of pipelines are considered.

1 INTRODUCTION

Oil and gas pipelines are designed using recognised pipeline design codes, which typically limit the applied stresses and strains to below yield. However, pipelines may be subjected to higher plastic strains before they enter service and during operation, either intentionally as a result of the method of installation, or a requirement of the design and operation, or accidentally. The material subjected to high plastic strain, or pre-strain, will have different material properties to that of the 'virgin' material. Plastic deformation causes work hardening; the yield strength is increased, but the strain hardening capacity of the material is reduced and the ductility is reduced. The published literature on the effect of pre-strain indicates that it has a detrimental effect on the fracture toughness of steel. Pre-strain reduces the resistance to crack initiation, reduces the resistance to crack growth, and increases the transition temperature. Therefore, pre-strain will affect the response of the material to operational loads and its resistance to damage.

Conventional design practice does not explicitly consider the effect of pre-strain on the material properties. However, the trends towards using high strength line pipe steels, and to designing to operate at higher stresses and strains, mean that historical experience and empiricism may be inappropriate or non-conservative. Additionally, the development of more accurate methods for assessing mechanical damage, to replace the existing semi-empirical methods, will require that the effects of pre-strain be explicitly considered.

This paper summarises the results of an investigation of the effect of static, uniaxial, tensile pre-strain on the fracture toughness of line pipe steels, with the objectives of: understanding and quantifying the effect of pre-strain on toughness, identifying the properties of the virgin material that determine the severity of the effect, and developing a model for predicting the effect. The study comprised experimental, numerical and theoretical analyses. More detailed information on the work conducted during the study can be found in Cosham [1-5].

2 EXPERIMENTAL STUDY

The material tested in the experimental study was an API 5L X80 line pipe steel (1219.2 mm (48 in.) diameter, 15.9 mm wall thickness). Samples of the virgin material were subject to pre-strains of approximately 2.7 percent and 6.5 percent engineering strain. The lower level of pre-strain is similar to that in a pipeline subject to frost heave, whilst the higher level of pre-strain is similar to that caused by denting. Longitudinal sections were flame cut from the 48 in. diameter pipe and then ‘pre-strain blanks’ (essentially, very large tensile specimens) were machined from these sections. The pre-strain blanks were not flattened. Pre-strain was introduced in uniaxial tension. Test specimens were machined from the parallel section of the pre-strain blanks. The direction of pre-strain was transverse to the direction of fracture in the test specimens.

For comparative purposes, samples of the virgin material were also artificially strain aged by heating at 250°C for two and a half hours in an electric furnace and then cooling slowly to room temperature. Test specimens were then machined from the strain aged material.

Tensile, notch tensile, fracture toughness (*J*-integral and crack tip opening displacement (CTOD)), and Charpy V-notch (CVN) impact tests of virgin, pre-strained and strain aged material were conducted. All of the tests were conducted at room temperature.

3 NUMERICAL STUDY

The numerical study was based on the material and test specimen geometries considered in the experimental study. The finite element (FE) analyses were conducted using ABAQUS/Standard v6.2. Large scale, non-linear, geometry effects were considered. The constitutive model assumed

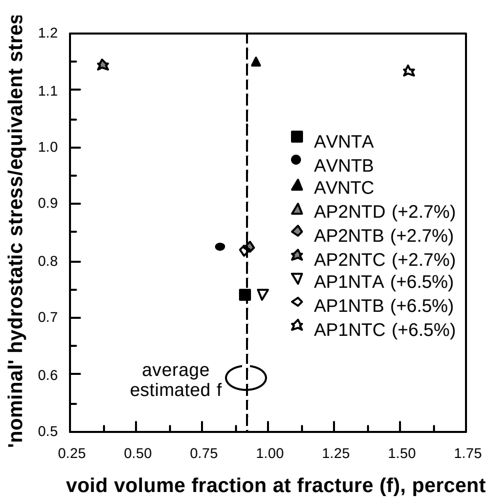

Figure 1: Effect of pre-strain and stress state on estimated void volume fraction at fracture

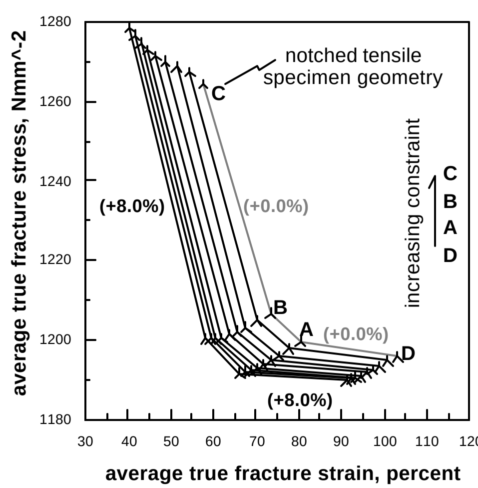

Figure 2: Effect of pre-strain on true stress and true strain at fracture in notched tensile t est

isotropic hardening. The effect of softening due to void growth was included using the modified Gurson-Tvergaard model of porous metal plasticity. Axi-symmetric FE analyses of the notched tensile geometries and the experimental results were used to calibrate a plane strain FE model of a compact tension test specimen. Based on the notched tensile tests and FE, it was assumed that the estimated void volume fraction at fracture is independent of pre-strain and stress state (see Figure 1). The trends in the FE results of notched tensile tests (see Figure 2) agreed with the test data; pre-strain reduces the true fracture strain. The effect of the properties of the virgin material on the reduction in toughness caused by pre-strain was investigated.

4 THEORETICAL STUDY

A theoretical model of the effect of tensile pre-strain on fracture toughness was derived using the local approach. The effect of pre-strain is expressed in terms of the ratio of the fracture toughness of the pre-strained material to that of the virgin material (J^*/J or d^*/d) (an asterisk denotes the properties of the pre-strained material). The HRR singularity was used to describe the stress and strain field around the crack tip. A stress-modified, critical strain-controlled model was used for ductile fracture, and a critical stress-controlled model was used for cleavage (brittle) fracture.

5 DISCUSSION

Based on the findings of the experimental, numerical and theoretical studies of the effect of static tensile pre-strain, as reported in Cosham [1-5], and the published literature, the effects of tensile pre-strain can be summarised as follows, and are discussed in more detail below:

1. It increases the yield and tensile strength (see Figure 3), and reduces the strain hardening capacity; the yield to tensile ratio tends to unity.
2. It decreases the ductility, as measured by the strain at the tensile strength (see Figure 4), the percentage elongation at fracture, or the true fracture strain.
3. It reduces the critical J-integral (see Figure 5) and CTOD (i.e. J_m and d_m), the fracture initiation toughness, and, at higher levels of pre-strain, the tearing resistance.
4. It increases the transition temperature, and may cause the fracture mechanism of the virgin material to change from ductile to cleavage.

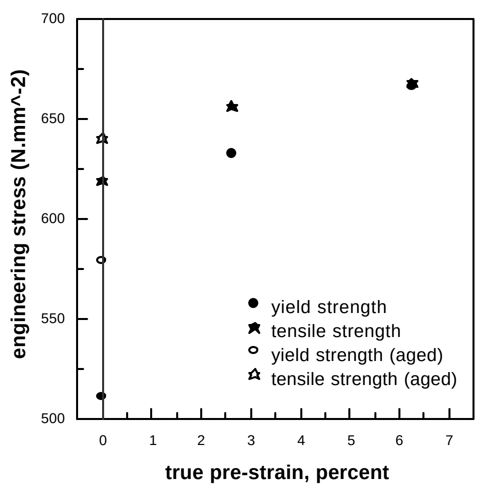

Figure 3: Effect of pre-strain and strain aging on yield and tensile strength

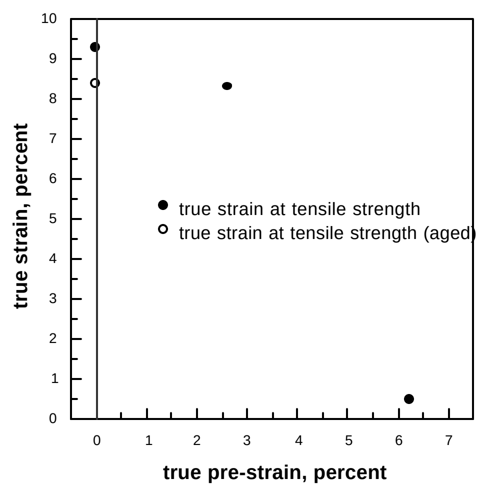

Figure 4: Effect of pre-strain and strain aging on true strain at tensile strength

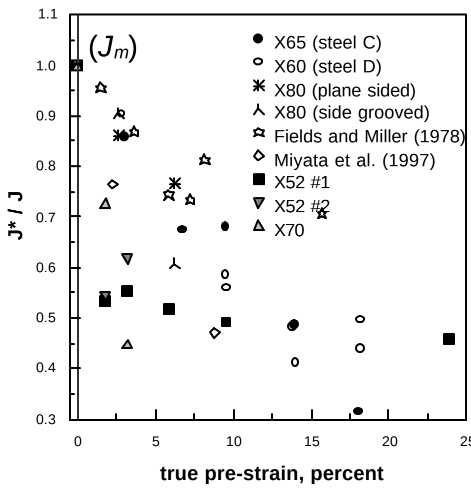

Figure 5: Effect of pre-strain on toughness

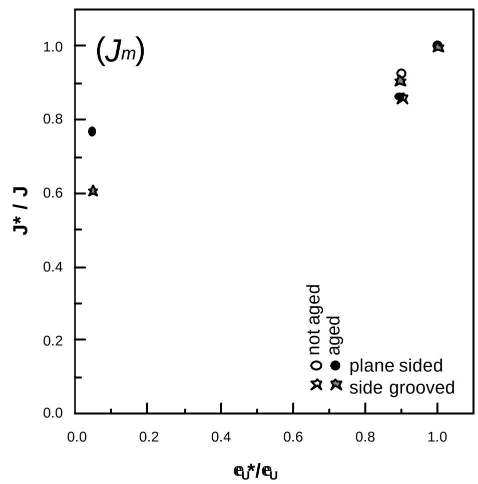

Figure 6: Effect of strain aging and pre-strain on toughness and strain at tensile strength

Figure 5 includes test data from Hagiwara [6,7] (steels C and D), Leis [8,9] (X52#1, X52#2 and X70), Fields [10] and Miyata [11].

The trends of the published data, the experimental data, the numerical analyses and the theoretical model are consistent. Reasonable agreement was obtained between the predictions of the theoretical model for ductile fracture and the experimental data.

The effect of tensile pre-strain on toughness can be attributed to: the increase in the yield strength, the decrease in the strain hardening capacity, and the decrease in the fracture strain. This conclusion is supported by the observation that the trends in the tensile properties and toughness of strain aged material, or material subject to high strain rates, are similar to those seen in pre-strained material (see Figure 6). Material damage, in the form of the nucleation and growth of voids during the introduction of pre-strain, does not appear to be a significant factor in the reduction in toughness caused by pre-strain.

The stresses and strains around the crack tip are higher in the pre-strained material compared to the virgin material. If the fracture mechanism is ductile, the void growth rate is higher, so crack initiation and stable crack growth occur at lower applied values of J and d. If the fracture mechanism is cleavage, the Weibull stress is higher, with similar implications for crack initiation and unstable crack growth. Consequently the fracture toughness is reduced by pre-strain. The increase in the transition temperature caused by pre-strain can also be explained in terms of the effect of pre-strain on the stress and strain field around the crack tip.

The properties of the virgin material that influence the effect of pre-strain on toughness are: the yield strength, the ductility (as defined by the strain at the tensile strength or the fracture strain), the strain hardening behaviour, the volume fraction of void nucleating particles, and the transition temperature. The effect of pre-strain will be greatest when the fracture mechanism changes from ductile to cleavage, i.e. when the fracture mechanism of the virgin material is ductile, and then the pre-strained material is within the transitional region or on the lower shelf.

The study has shown that the effect of pre-strain on toughness is greater for virgin materials with a low ductility (defined by the strain at the tensile strength or the fracture strain), a low strain hardening capacity, or a high fraction of void nucleating particles.

Fracture toughness tests of different steels subject to tensile pre-strain can be compared if the

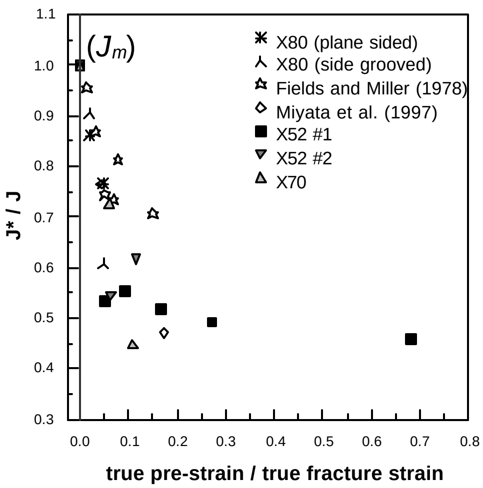

Figure 7: Effect of pre-strain on toughness

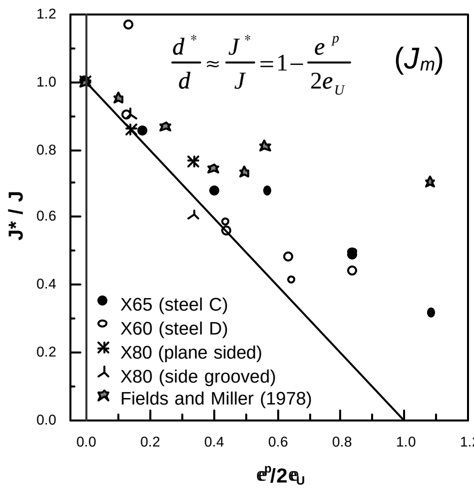

Figure 8: Effect of normalised pre-strain on toughness and the semi-empirical model

test data is expressed in terms the ratio of the toughness of the pre-strained material to that of the virgin material (J^*/J or d^*/d), and the ratio of the true pre-strain to the true fracture strain of the virgin material, measured in a tensile test (e^p/e_C). Normalising the true pre-strain by e_C reduces the scatter and reveals the general trend (see Figure 7 and compare with Figure 5). The theoretical model also indicates that this is an appropriate normalisation for ductile fracture. The toughness reduces significantly at low levels of pre-strain, relative to the fracture strain, but tends to a plateau at higher levels of pre-strain, although the data for high levels of pre-strain is limited. It is unclear whether the normalisation would result in a common plateau for different steels, because the reduction in toughness depends on the transition temperature of the virgin material and the temperature shift caused by pre-strain. The virgin materials shown in Figure 7 failed by ductile fracture. Most of the pre-strained materials were also ductile (although the fracture mechanism is not always clearly indicated in the published test data), except for a couple of the Hagiwara tests at high pre-strain. The ratio d^*/d will be less than J^*/J because of the effect of pre-strain on yield strength, but the difference observed experimentally is less than that predicted theoretically.

The true fracture strain can be replaced by the true strain at the tensile strength of the virgin material, measured in a tensile test (e^p/e_U), albeit with an increase in scatter. A semi-empirical relationship, based on the theoretical model, is proposed for predicting the effect of pre-strain on toughness, in terms of e_U of the virgin material (see Figure 8). The relationship is conservative with respect to the test data.

The effect of pre-strain on toughness cannot be reliably characterised using the CVN test. It may give misleading and non-conservative results. The test data includes cases where a reduction in fracture toughness is not accompanied by a significant reduction in CVN impact energy.

6 CONCLUSIONS AND RECOMMENDATIONS

1. Tensile pre-strain reduces toughness. The effect of tensile pre-strain on toughness will be more severe in older line pipe steels, compared to modern steels, and more severe in modern high grade line pipe steels, compared to modern lower grade steels.

2. The effect of pre-strain on the stress-strain response and the toughness of the virgin material should be considered in the design of pipelines subject to levels of plastic strain outside the range of conventional design practice. Designs involving plastic strains in excess of 2 percent, or very high grade steels (X80 and above) should be considered.
3. The effect of pre-strain on the material properties needs to be considered in the development of more accurate models for predicting the behaviour of mechanical damage and other defects in pre-strained material. Neglecting the effect of pre-strain can be non-conservative.
4. Line pipe steel specifications should require that the tensile stress-strain curve of the line pipe is measured and recorded; as a minimum the strain at the tensile strength and the true fracture strain should be quoted on mill certificates.

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