DUCTILE-BRITTLE TRANSITION FRACTURE MODE AND THE OCCURRENCE OF ABNORMAL FRACTURE APPEARANCE IN X65 Q & T SEAMLESS PIPELINE STEEL

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Abstract

The new generation of advanced high strength steels for oil & gas transportation exhibit better mechanical response and fracture toughness not only in corrosive media, but also in arctic environments. In particular, under these latter conditions, X65 Q&T pipeline steels do not reveal a clear ductile-to-brittle transition (DBT) temperature and, in some cases, inverse fracture. It is still unclear the actual causes of this phenomenon typically observed in impact tests such as Charpy and drop-weight tear experiments. This study aims at the understanding of the underlying mechanisms controlling this abnormal behavior, which leads mostly to disqualifying a particular material for a certain engineering application. In general, thorough mechanical and material characterizations are intended to be conducted in order to unveil the relationship between microstructure characteristics and structural configurations. By means of a phenomenological fracture model, the statistical nature of the brittle fracture and the size effects will be deemed into a more general computational damage framework incorporating also ductile fracture from the upper shelf energy region.

1. Introduction

In previous study on X65 Q&T seamless pipeline steel was fully characterized mechanically at room temperature under quasi-static and dynamics loading conditions [1], [2]. As a result, the onset of ductile fracture at different stress states and strain rates were determined within a damage indicator framework based on the so-called Modified Mohr-Coulomb (MMC) model [3]. The implementation and calibration of the MMC model was first achieved under quasi-static conditions by devising custom-design samples extracted directly from the structural component. By means of a hybrid experimental-numerical method, different well-controlled strain paths can be developed to cover a wide range of possible failure modes; this includes general shearing, axisymmetric tension and compression, and tension plane strain accompanied by a very detailed FE analysis. Subsequently, as second stage, the material was tested under dynamic loading condition, where not only the rate-dependent nature of the onset of fracture was identify as a necessary condition for fracture propagation, but also post-initiation softening was introduced in order to describe critical (stable) crack growth at high speed. It turns out that the rate-dependent features were introduced into the constitutive modeling of plasticity and fracture. The model was then validated against measured data of Drop Weight Tear Test (DWTT) carried out at -5 ^{o}C with samples having chevron notch [2]. It needs to be mentioned that the comparison of the underlying model with experiments is quite good as the model only predicts ductile fracture features at room temperature. This, in part, is due to microstructure characteristics following a manufacturing process that pushes down the DBT point and thus favoring ductile fracture mechanism instead of cleavage rupture. There exist a pressing necessity to test the model for more stringent temperature conditions, typically observed in arctic environment where temperature can easily oscillates between -20 ^{o}C and -60 ^{o}C where inverse fracture may occurs. The present investigation seeks to understand the underlying mechanisms controlling this abnormal behavior on X65 Q&T steels.

2. Experimental and numerical program

a. Determination of plasticity and fracture properties at specimen level under three different low temperatures (-15 ^{o}C, -30 ^{o}C and -45 ^{o}C). - The experimental program will include free-crack specimen geometries resembling different stress states (from axisymmetric tension to generalized shear) and selected fracture mechanics samples (such as CT's or SENB's).

b. Development of a coupling theory for ductile-brittle transition region considering temperature and constraint effects. - Based on the above experimental results, a comprehensive database of material behavior at different strain rates and temperatures can be established. Since the statistical nature of the measured outcomes, the two-parameter Weibull fracture model is employed to determine the likelihood of cleavage rupture for a given temperature. One of the salient features of this model is its micromechanics based approach that considers cleavage at different length scales and thus providing connection with the global response. Moreover, the constraint effect needs to be including by means of pre-cracked fracture mechanics samples. Previous step only addresses the probability of failure under cleavage without mention about ductile fracture mechanism, which is rather frequently observed in fracture morphologies of cracked components. For that purpose, the Modified Mohr-Coulomb model will be extended to include cleavage rupture in addition to the already incorporated ductile fracture settings. After all, the MMC model has many features that one would expect of a cleavage model and is indeed based on brittle fracture theory [5]. The missing key features of the MMC that needs to be incorporated:

- Statistical effects
- Size effects (which are an outcome of the statistical effects)

Once these points have been addressed, a sound-like engineering approach can be proposed along with its numerical implementation in VUMAT material subroutine.

c. Parametric study on the occurrence of abnormal fracture appearance (AFA) and abnormal fracture behavior (AFB). - A comprehensive parametric study will be performed to determine the likelihood of AFA and AFB occurrences in impact tests such as DWTT with different thickness sizes and crack configurations. This study will shed some lights into the phenomenological behavior of the material under different levels of constraint.

3. References

[1] Paredes M, Lian J, Wierzbicki T, Cristea ME, Münstermann S, Darcis P. *Modeling of plasticity and fracture behavior of X65 steels: seam weld and seamless pipes*. IJF 213: 17-36, 2018.

[2] Fudlailah P, Paredes M. *Fracture behavior of X65 Q&T seamless pipeline steel under different strain rates and stress states.* Proceedings of the ASME 2020 37th International Conference on Ocean, Offshore and Arctic Engineering, OMAE 2020. June 28- July 3, 2020, Fort Lauderdale, FL USA.

[3] Igi S, Sakimoto T, Kondo J, Hioe Y, Wilkowski G. *Modified West Jefferson Burst Test for Assessment of Brittle Fracture Arrest in Thick-Wall TMCP Line-pipe steel with high charpy energy*. Proceedings of the 2016 11th International Pipeline Conference, IPC 2016. September 26-30, 2016, Calgary, Alberta, Canada.

[4] Paredes M, Grolleau V, Wierzbicki T. *On ductile fracture of 316L stainless steels at room and cryogenic temperature level: An engineering approach to determine material parameters.* Materialia 10:100624, 2020.

[5] Bai Y, Wierzbicki T. *Application of extended Mohr-Coulomb criterion to ductile fracture. Int J Fract 161:1-20, 2010.*