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Evaluation of dynamic fracture toughness based reference temperature (T_0^{dy}() of modified 9Cr–1Mo steel in phosphorus embrittled and cold-worked condition

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Abstract

In the present study, the DBTT of a high phosphorus bearing modified 9Cr–1Mo steel in normalized and tempered (N&T) condition and also after 5% and 10% cold work, has been evaluated by extending the reference temperature (T_0) based Master Curve approach to dynamic loading conditions. The reference temperature in dynamic loading condition (T_0^{dy}) thus determined is found to be significantly high for the N&T Mod.9Cr–1Mo steel as compared to plain 9Cr–1Mo steel. Cold-work effect was not found to be significant in T_0^{dy} evaluation of Mod.9Cr–1Mo steel. The high T_0^{dy} of the present Mod.9Cr–1Mo steel is attributed to a fracture initiation mechanism predominated by decohesion of prior austenitic grain boundaries at the fatigue pre-crack front. This is attributed to segregation of phosphorus along the prior austenitic grain boundaries causing embrittlement, supported by SEM and Secondary Ion Mass Spectrometry (SIMS) observations.

Keywords: DBTT; Fracture toughness; Reference temperature; Master Curve; Cold work

1. Introduction

Tempered martensitic steels are presently under active consideration as wrapper materials [1,2] for Fast Breeder Reactors (FBRs) aiming to achieve high burnup (>200,000 MWD/T), due to their inherent resistance against fast neutron (∼1 MeV) induced void swelling and the consequent dimensional instability as observed in austenitic stainless steels. However, unlike austenitic stainless steels, these steels are prone to transitions in fracture mode from ductile to brittle as the temperature decreases. To compound this, neutron irradiation leads to an increase in the ductile–brittle transition temperature (DBTT), the temperature at which this transition takes place, which is a grave concern for handling of spent fuel subassemblies. From this point of view, amongst the family of tempered martensitic steels, 9Cr–1Mo steel and its different modified forms are the currently favoured choice [3] since these have exhibited lowest irradiation induced shift in DBTT. The DBTT of these materials in the unirradiated conditions is therefore an important input for material selection.

Amongst the DBTT evaluation procedures, the reference temperature approach (reference temperature, T_0, defined as the temperature at which the material yields a 100 MPa m$^{0.5}$ as median fracture toughness for 1 in. thickness) and the description of variation of fracture toughness with temperature by an invariant shape Master Curve concept [4] have been claimed to be appropriate. This is because the Master Curve indexing parameter, T_0, for the material is obtained from actual fracture toughness data determined from fatigue pre-cracked specimens incorporating the scatter in fracture toughness via a three parameter Weibull distribution. However, ASTM E 1921-05 [4], the existing standard to evaluate T_0 is restricted to only quasi-static loading condition and there is a need to extend its application to dynamic loading condition. This is because under dynamic loading the increase in local flow stress lowers the fracture toughness in the transition temperature regime and hence the reference temperature under dynamic loading (T_0^{dy}) would be more conservative as compared to the quasi-static counter part (T_0). The applicability of the E-1921 Master Curve shape under dynamic loading condition needs verification and in a prior work by the

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authors, the applicability of the Master Curve at dynamic loading condition has been verified with plain 9Cr–1Mo steel [5]. There are only a few efforts reported in literature for determining T_0 at high loading rates [6,7] and a globally accepted standard is yet to be developed. This is mainly because of inherent uncertainties in selecting the proper loading rate which could strike a balance between high stress intensity factor rate for dynamic condition, and minimum inertial oscillations, enabling accurate determination of the fracture load [8]. In this study, an appropriate loading rate has also been selected to reasonably satisfy these competing requirements.

In the nuclear pressure vessel steels, DBTT has been found to be extremely sensitive to the trace level impurities, mainly phosphorus (P) [9,10]. Data from literature shows that in these pressure vessel steels, an increase in P-content even by 0.004 wt.% shifts the T_0 upward by ∼60 °C [11,12]. However, most of the studies in this direction have been on low-Cr class of steels, and studies on the effect of higher P on the DBTT of higher Cr steels is scanty. It is also important to characterize the combined effect of cold work, as some amount of residual cold work is unavoidable in fabrication processes of wrapper tubes. The present study aims at characterizing the DBTT of a Mod.9Cr–1Mo steel containing high P by evaluating the dynamic fracture toughness based reference temperature (T_0^{dy}). The effect of cold work of the steel on T_0^{dy} also has been incorporated.

2. Experimental

2.1. Material

30 mm thick plate of Mod.9Cr–1Mo steel in normalized and tempered (N&T) (as heat treated) condition, is the starting material for this study. Its chemical composition, in weight percent, is given in Table 1a. The steel was normalized at 1095 °C/1 h and tempered at 780 °C/1 h.

As the result obtained in this work has been compared with earlier results with plain 9Cr–1Mo steel [8,13], for a better clarity of the readers, some details of the chemical composition and microstructure of the plain 9Cr–1Mo steel is placed herewith. It is well known that presence of V and Nb as trace element in Mod.9Cr–1Mo modifies it from the plain 9Cr–1Mo steel. However, both the Mod.9Cr–1Mo steel and plain 9Cr–1Mo steel in normalized and tempered condition possesses tempered martensitic microstructure as shown in Fig. 1a and b. In the range of resolution of optical microscopy they do not exhibit any appreciable microstructural differences. The chemical composition of plain 9Cr–1Mo steel is given in Table 1b. It may be observed that other than V and Nb, there are differences in chemical composition with respect to other major and trace elements. It is important to note that the phosphorus content in Mod.9Cr–1Mo steel is significantly higher compared to that in the plain 9Cr–1Mo steel.

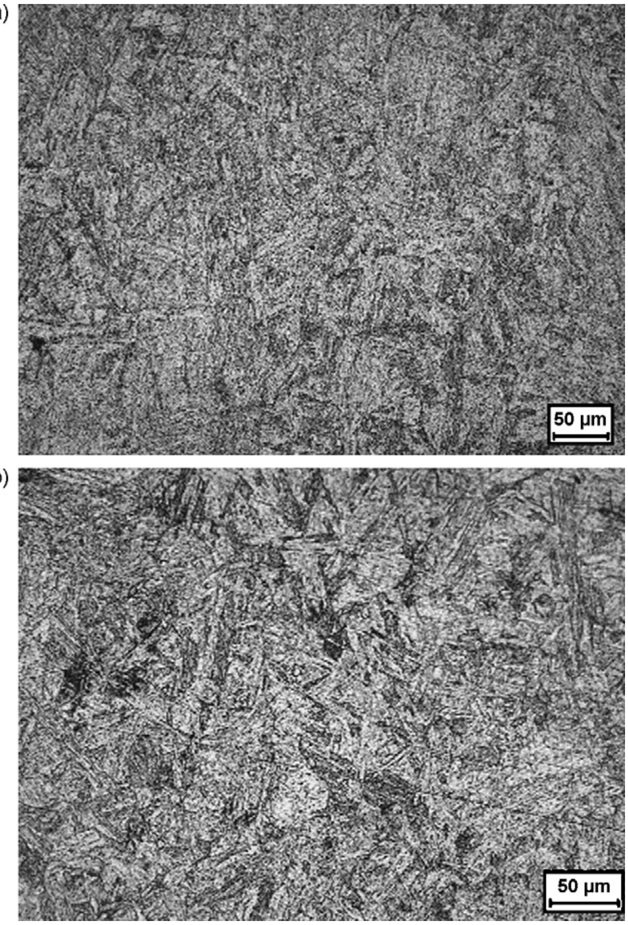
(a)
(b)


Fig. 1. (a and b) Optical microstructure of Mod.9Cr–1Mo steel (as received, 0% CW) and plain 9Cr–1Mo steel showing tempered martensitic structure in both the cases.

Table 1a
Chemical composition of Mod.9Cr–1Mo steel

Elements	Composition (wt.%)
C	0.12
Cr	9.420
Mo	1.00
Ni	0.13
Si	0.470
S	0.007
P	0.020
Al	0.021,
Nb	0.10
V	0.250
Fe	Balance

Table 1b
Chemical composition of plain 9Cr–1Mo steel

Elements	Composition (wt.%)
C	0.10
Cr	8.44
Mo	0.94
Ni	0.17
Si	0.48
S	0.002
P	0.007
Al	0.011
Fe	Balance