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A dynamic fracture-toughness-based reference temperature characterization for the weld metals of modified 9Cr–1Mo steel in two different weld positions

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Abstract

The ductile–brittle transition temperatures (DBTT) of modified 9Cr–1Mo steel welds from two different weld positions, namely down hand (1G) and overhead (4G), have been evaluated and compared using the ASTM E 1921-05 based reference temperature (T_0) approach, but under dynamic-loading conditions. The reference temperatures thus obtained, termed as T_0^{dy} to signify the dynamic condition, have been found to be higher for the 4G position than the 1G position. A scanning electron microscopic study of the fracture surfaces close to the fatigue crack front reveals that while lath boundary fracture is the dominant mechanism for brittle crack initiation in both the welds, the higher T_0^{dy} value is linked to the higher concentration of probable crack initiation sites in the 4G position. The experimentally obtained Weibull slope in both the welds has been found to be different (7.526 and 7.205 for the 1G and 4G positions, respectively) from the 'fixed slope of 4' assumption, used in ASTM E 1921-05. However, in the present instance, the 'fixed Weibull slope of 4' concept yields more conservative T_0^{dy} values compared to those obtained using the experimentally determined Weibull slope. For these welds, the RT_{NDT}-based ASME K_{IR} curve proved to be ultra-conservative compared to the realistic dynamic fracture toughness variation described by the Master Curve indexed with T_0^{dy}.

Keywords: Fracture toughness; Reference temperature; Modified 9Cr–1Mo welds

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1. Introduction

Towards developing the weld consumables for tempered-martensitic steels, fracture-mechanics-based characterization of the ductile–brittle transition temperature (DBTT) is of importance to prevent catastrophic failure of structures, often originating from brittle fracture of welded joints. The fracture toughness in the DBTT regime, for ferritic steels in general, is known to exhibit significant scatter originating from the random distribution of cleavage initiation sites [1–3]. The cleavage initiation sites are referred to as the weakest points prone to easy cracking in the form of brittle precipitates, inclusions, weak inter-phase boundaries, etc. and the particular operating mechanism is dependent upon the steel's composition and the inherent microstructural constituents [4–7]. For welds in particular, the scatter in fracture toughness can be more significant because of their characteristic inhomogeneity and random inclusion distribution. High inclusion content produced by a flux, used for shielding purposes, is known to considerably reduce the toughness of the weld metal of modified 9Cr–1Mo steel [8,9] while addition of Ni to the weld metal has been found to be beneficial. Welds produced by the gas tungsten arc welding process are generally cleaner than those produced by the shielded metal arc welding (SMAW) process and many studies attribute the observed better toughness of GTA welds compared to SMA welds to the low inclusion contents. In addition to the welding process, the toughness of the weld metal is also affected by the welding position employed. Depending on whether welding is carried out down hand (1G), horizontal (2G), vertical (3G), overhead

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(4G), etc., the properties of the weld joint can vary. One of the reasons for this is the contribution of gravity to metal transfer; in the down hand position metal transfer across the arc is assisted by gravity while in the overhead position, gravity works against metal transfer. Further, in the case of manual welding, it becomes increasingly difficult to control the various welding parameters as the welding position changes from 1G to 4G. Hence, in general, the properties of a weld joint prepared in the 4G position are inferior to those of the weld joint prepared in the 1G position. A recent study on modified 9Cr–1Mo weld metals produced in three different welding positions, 1G, 3G and 4G has shown that the toughness of weld metal produced by 3G and 4G is inferior to that of the weld metal produced by the 1G position [10]. The 1G or down hand position is the most widely used and convenient welding position for making butt welds between plates while the 4G or overhead position is the most difficult position to carry out butt welding of plates. However, in the case of fabrication of large components like pressure vessels, welding in different positions cannot be avoided (especially in site welding) and hence it is essential to ensure that welds produced at different positions have adequate properties both with respect to integrity of the structures and the service performance. Thus, to ensure structural safety, it is important to evaluate and compare the DBTT of weld metals produced in different welding positions.

To take into account the scatter in fracture toughness towards predicting a DBTT of engineering significance, the recently developed reference temperature (T_0) approach, as standardized in ASTM E 1921-05 [11], is claimed to be appropriate as it takes into account the scatter in fracture toughness via a statistical model based on a three-parameter Weibull distribution; T_0 is defined as the temperature at which the median fracture toughness (cumulative probability of failure = 0.5) of $100\,\mathrm{MPa\,m^{0.5}}$ is obtained for specimens of 1 in thickness equivalence. The T_0 determination method [11] however is standardized only for quasi-static loading conditions. Under dynamic loading, the rate-sensitive material flow properties enhance the crack front stresses, suppress plasticity, increase constraint and thus reduce fracture toughness. Thus, for conservative design against brittle fracture, there is a need to evaluate the DBTT under dynamic loading. Earlier, there have been successful efforts by Moitra et al. [12–14] with 9Cr–1Mo and modified 9Cr–1Mo base materials to evaluate T_0 under dynamic loading and the term thus evaluated was named T_0^{dy} to differentiate it from the quasi-static counterpart. Thus it would be appropriate to obtain the T_0^{dy} parameter for characterizing the DBTT of weld metals from different weld positions.

This paper reports the results of a campaign undertaken to characterize the DBTT of a Mod.9Cr–1Mo steel weld metal deposited in two different weld positions, namely 1G and 4G, by determining the reference temperature under dynamic loading (T_0^{dy}). The dynamic fracture toughness of the welds has been evaluated by instrumented Charpy tests on fatigue-pre-cracked specimens. The corresponding T_0^{dy} results have been analyzed in terms of the fracture mechanisms operating in the two types of welds, identified by qualitative assessment of the individual fracture surfaces. The application of the Weibull distribution in scaling the scatter in fracture toughness and the effect of Weibull slope on T_0^{dy}, while evaluating the fracture resistance in the transition temperature regime, also have been reviewed.

2. Material and experimental

2.1. Weld metal composition and welding parameters

The indigenously developed Mod.9Cr–1Mo electrode has the chemical composition: Cr—9.00, Mo—1.00, Ni—0.52, Mn—0.75, C—0.10, P—0.01, S—0.008, Si—0.32, V—0.21, Nb—0.065, N—0.06, Co—0.015, Al—0.01, Cu—0.05, Sn—0.008. Weld joints were prepared using these electrodes by the shielded metal arc welding (SMAW) procedure in the 1G and 4G positions with 30-mm-thick mild steel base plates after buttering with the same electrode. A schematic of the welds in the IG and 4G positions is shown in Fig. 1.

Other welding parameters were: joint type—single-V; pre-heat temperature—250 °C; inter-pass temperature—200–250 °C; weld speed—2.5–2.8 mm/s; current—105–130 A; voltage—20–25 V; number of passes—1G-37/4G-28; post-heating—300 °C /2 h; and PWHT—760 °C/3h/FC.

2.2. Instrumented pre-cracked Charpy (PCVN) testing

2.2.1. Pre-cracking of Charpy-V notch specimens

Charpy impact specimens were fatigue pre-cracked in a 20 kN resonant fatigue testing machine with an R-ratio of 0.10 in compression. The pre-cracking aimed to achieve an approximate a_0/W of 0.5, where a_0 is the initial crack length and W is the width of the specimen. However, after testing, the a_0 of individual specimens was measured more accurately from the broken half of the tested specimen by a traveling microscope, using ten-point averaging {(9 points from interior + mean from two surface crack lengths)/10}.

2.2.2. Instrumented pre-cracked Charpy testing

All pre-cracked Charpy (PCVN) impact tests were conducted in a 358 J capacity impact machine equipped

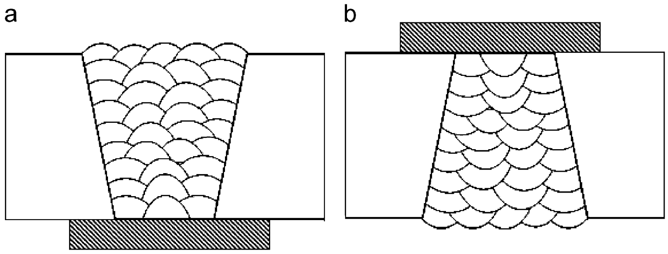

Fig. 1. Schematic representation of (a) 1G weld and (b) 4G weld.