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Weibull analysis of low temperature fracture stress data of 20MnMoNi55 and SA333 (Grade 6) steels

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ABSTRACT

Fracture stress data obtained by tensile testing of circumferentially notched round tensile specimens made of 20MnMoNi55 and SA333 (Grade 6) steels at different subzero temperatures down to −150 °C have been analysed following Weibull statistics. It is observed that between −50 and −100 °C the mean Weibull modulus of 20MnMoNi55 steel obtained by employing linear regression technique over the complete range of data population for every test temperature increases in a perfectly linear manner with lowering of test temperature. A sharp decrease in the modulus value with further decrease of test temperature to −150 °C is observed. The data population for −50 and −70 °C, however, do not agree well with single straight-line relationship of Weibull statistics. In case of SA333 (Grade 6) steel nearly two fold increase in the value of mean Weibull modulus is observed on lowering of test temperature from −100 °C to −150 °C. Scanning electron fractography reveals different failure modes in both the steels depending upon test temperatures.

1. Introduction

The scatter associated with the measurement of a mechanical property, like flow strength or toughness, is of extreme importance as it forms part of the overall probabilistic failure assessment of a structure. Ferritic steels with body centred cubic (bcc) structure show completely two different failure modes under mechanical loading. Structural components made of this steel fail either by transgranular cleavage or by ductile tearing depending upon service temperature. Cleavage failure is brittle in nature and initiates through formation of microcracks either due to inhomogeneous plastic deformation within the grains or due to slip-induced cracking of grain boundary carbide particles and propagation of such cracks into the ferrite matrix [1,2]. On the other side, ductile failure occurs by nucleation, growth and coalescence of microvoids, which nucleate at second phase particles located within the grain body.

Ferritc steels exhibit a ductile to brittle transition behaviour with lowering of temperature in the range of 0 to −100 °C. At very low temperature cleavage becomes the dominant failure mode. In the region of temperature transition between cleavage and ductile tearing, these two failure modes coexist and compete with each other. The brittle mode of failure depends on the stress necessary to propagate the microcrack with very little gross plastic deformation. A salient feature of brittle fracture is the variability of experimental results. Extensive scatter band of measured values is usually observed for the global parameters assessing fracture toughness, e.g. K_{IC}, J_{IC} and COD [3]. The variability in size, shape, distribution and orientation of inclusions, segregations or any other second phase which give rise to incompatible deformations accounts for the scatter in local fracture stress data of ferritic steels determined from fracture load of the specimens at low temperatures [4]. It is, therefore, necessary to describe the scatter in the experimentally measured global parameters through some suitable statistical models. The Weibull stress model, originally proposed by Beremin group [5] based on weakest link theory is widely used for this purpose.

Assessment of structural integrity of nuclear reactor components is of vital concern so to avoid the unpredictable and hazardous consequences. Radiation damage is likely to make the material used for reactor pressure vessels brittle and hence raising the ductile-brittle transition temperature. In such case if there is an accidental loss of coolant the reactor core is flooded. This results in lowering of temperature of the pressure vessel and the material used for fabrication of the vessel may encounter the ductile-brittle transition temperature domain where cleavage fracture of the component may occur. It is, therefore, very much necessary to understand the fracture behaviour of the materials used for reactor pressure vessel and coolant pipes at various low

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temperatures from structural integrity point of view and also for material quality control purpose.

The objective of the present programme of investigation is to study the fracture behaviour of reactor pressure vessel steel and carbon steel used for coolant pipes at various subzero temperatures. In this report the experimental details of testing axisymmetric round notched tensile specimens and scatter associated with true fracture stress data of two nuclear grade steels at different subzero temperatures down to −150 °C have been discussed. The scatter in fracture stress has been analysed according to Weibull statistics.

2. Experimental

2.1. Material and microstructure

In the present investigation two Nuclear Grade steels, 20MnMoNi55 and SA333 (Grade 6) carbon steels were used. While 20MnMoNi55 is pressure vessel steel, SA333 (Grade 6) carbon steel is used for making coolant pipes. Chemistry of the steels is shown in Table 1. Specimens for developing microstructure of the materials were obtained by transverse sectioning of the grip section of broken tensile specimens. After usual grinding and polishing, the specimens were etched with 2% Nital solution. The polished and etched surfaces of the specimens were observed under optical microscope (Leica, DMILM).

2.2. Tensile testing of smooth specimens at subzero temperatures

Cylindrical specimens with gauge length to diameter ratio (L_o/D_o) of 4.00 have been used for tensile tests. Tests were done at −50, −70, −100 and −150 °C in a computer controlled servohydraulic universal testing Machine, Instron 8500R, of ±100 kN load capacity. Three specimens have been tested at each of these temperatures. A cryochamber of Instron make (Model No. 3119/407-22, Serial No. 40568) was mounted on the load frame of the machine for creation of the required environmental condition of −50, −70, −100 and −150 °C. Specimens with threaded ends were tightly secured to the actuator and load cell through a pair of pin loaded pull rods and suitable adaptors. The required subzero test temperatures were attained within an hour by flowing liquid nitrogen (LN2) from a fully automated self-pressurising Dewar flask of 120 l capacity (Wessington, Cryogenics, PV-120). Temperature of the cryochamber was controlled with the help of a Eurotherm controller.

For every desired test temperature, i.e., −50, −70, −100 and −150 °C, specimen temperature was first calibrated with the temperature of cryochamber used to create the low temperature environment by inserting a low temperature sensor inside the specimen through a part way drill hole. After attaining the desired set temperature a soaking time of 30 min were employed for equilibration of test temperature. Every time the specimens were finally loaded once the set temperature stablised. During the tests flow of LN2 was controlled in such a manner that in all cases the specimen temperature never exceeded ±2 °C from the desired set temperatures; while in most of the test duration the specimen temperature was within ±1 °C. Fig. 1 shows the experimental arrangement for testing at subzero temperatures.

All the tensile tests were done under displacement control mode with a ramp rate corresponding to the nominal strain rate of 2×10^{-4}/s. A clip-on axial extensometer of 25 mm gauge length was kept attached to the specimen gauge length for tests at −50, −70 and −100 °C. Test at −150 °C could not be done with extensometer attached to the specimen because of the limitation of the working temperature range over which the extensometer is specified for use. The test programme was controlled and data acquisition was accomplished by using the machine-dedicated software (Instron, Series-IX) for tensile tests.

2.3. Notched tensile testing at subzero temperatures

In the present experimental programme circumferentially notched round tensile specimens with threaded ends have been used. Fig. 2 shows the geometry of the notched round tensile specimen and Fig. 3 is the photograph of the specimens used in the present investigation. In total 180 specimens made of two different steels, 20MnMoNi55 and SA333 (Grade 6) steels, have been tested at different subzero temperatures (−50, −70, −100 and −150 °C). While in case of 20MnMoNi55 steel thirty tests have been done at each of these four temperatures, thirty tests have been done at −100 and also at −150 °C in case of SA333 (Grade 6) steel. Hence a total number of 120 tests were done for 20MnMoNi55 steel and 60 for SA333 (Grade 6) carbon steel. The same experimental setup used for testing of smooth tensile specimens has also been used for testing of notched tensile specimens.

Tests were done under displacement control mode with a ramp rate corresponding to the nominal strain rate of $2\times10^{-4}\,s^{-1}$ in the notch region of the specimens. Before testing the specimens

Fig. 1. Experimental set-up for tensile testing at subzero temperatures.

Table 1
Chemistry of 20MnMoNi55 and SA333 (Grade 6) carbon steels (wt pct).

Material	C	Si	Mn	S	P	Ni	Cr	Mo	V	Al	Fe
20MnMoNi55	0.21	0.21	1.3	0.001	0.009	0.68	0.05	0.494	0.01	0.029	Bal
SA333 (Grade 6)	0.14	0.25	0.90	0.018	0.016	0.25	0.05	–	–	–	Bal