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Rosette fracture of modified 9Cr–1Mo steel in tension

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ABSTRACT

Rosette fracture is a typical mode of tensile fracture with long radial cracks. This type of fracture was observed in the modified 9Cr–1Mo steel in normalized and tempered condition on tensile testing at room temperature (RT). The role of different variables such as temperature, microstructure, strain rate, texture and plastic constraint was studied on the rosette fracture occurring from tensile testing of the modified 9Cr–1Mo steel. Radial cracks were observed on the fracture surface at different angular intervals. These cracks propagated longitudinally and were mostly associated with prior austenite grain boundaries and lath boundaries. Rosette fracture was found to be affected by test temperature, microstructure (in particular the number density, size and distribution of carbide precipitates along the prior austenite grain boundaries/lath boundaries) and the plastic constraint; however, there was no effect of texture. The tendency and severity of rosette fracture were found to be affected by the heat treatment and resulting area fraction of carbides. The process of rosette fracture was found to be associated with void formation at carbide particles, lying at the prior austenite grain boundaries and lath boundaries and their rapid linkage along the boundaries oriented with stress axis.

1. Introduction

Modified 9Cr–1Mo steel is extensively used in fossil-fired power plants as well as in nuclear power plants for supercritical steam tubes, in normalized and tempered condition [1–3]. In general, ductile materials exhibit characteristic cup and cone fracture whereas brittle materials display cleavage fracture under uniaxial tensile loading. The modified 9Cr–1Mo steel was found to exhibit a typical rosette fracture in the normalized and tempered condition under tensile loading at room temperature (RT) [4]. This steel shows lath structure with $M_{23}C_6$ carbides along prior austenite grain boundaries and V and Nb carbides and nitrides within the laths and along the lath boundaries in the normalized and tempered condition [4–6]. Detailed investigation of the typical rosette fracture exhibited by this steel is of much concern in view of its critical applications referred to above.

There have been several studies on longitudinal splitting in ferritic steels and 9Cr–1Mo steel, occurring in Charpy impact test. It was observed that impact toughness and splitting were strongly dependent on tempering temperature and the final rolling temperature [7,8]. Blach et al. [9] reported that severity of longitudinal splitting was increased in the modified 9Cr–1Mo steel in tensile and impact testing from long thermal exposure of the normalized and tempered specimen at different temperatures of 580, 620 and 650 °C. Deterioration in impact toughness with increase in thermal exposure was related mainly to coarsening of secondary phase precipitates and decohesion at precipitate/matrix interface resulting from cracking of the secondary particles during straining [9]. Addition of 0.5–1.5% silicon in the modified 9Cr–1Mo steel was found to cause intergranular cracking with cleavage facets, however, the mode of fracture became ductile at higher content of Si (2%) [10]. Thus, it is essential to understand the process of longitudinal splitting in this steel resulting from tensile loading. The purpose of the present investigation was to examine the role of different variables on the occurrence of rosette fracture from tensile testing of modified 9Cr–1Mo steel and to analyse the process of this typical fracture.

2. Material and methods

The modified 9Cr–1Mo steel was supplied by the IGCAR Kalpakkam, India, in normalized and tempered condition in the form of plate of 25 mm thickness. Normalizing and tempering had been done at 1060 °C for 1 h and at 780 °C for 1 h respectively, followed by cooling in air to RT. Chemical composition of the steel is presented in Table 1. Cylindrical tensile specimens with gage diameter of 4.5 mm and gage length of 15.5 mm were prepared from blanks of 45 mm × 10 mm × 10 mm size along the rolling direction (Fig. 1a). Tensile tests were performed also on the specimens, prepared from blanks oriented at 45° and 90° to the rolling direction. The schematic of

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Table 1
Chemical composition of the modified 9Cr-1Mo steel (wt%).

Elements	C	Si	Mn	P	S	Cr	Mo	Ni	Al	Nb	N	V	Fe
wt%	0.1	0.26	0.41	0.018	0.002	9.27	0.95	0.33	0.013	0.074	0.044	0.21	Balance

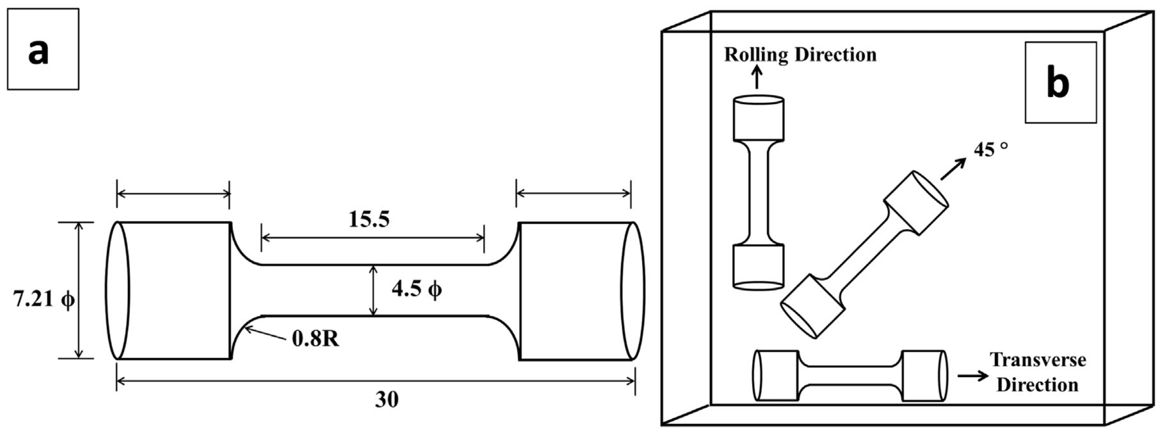

Fig. 1. (a) Schematic of the cylindrical tensile specimen (all dimensions in mm) (b) specimens fabricated at different orientations with respect to rolling direction of the plate.

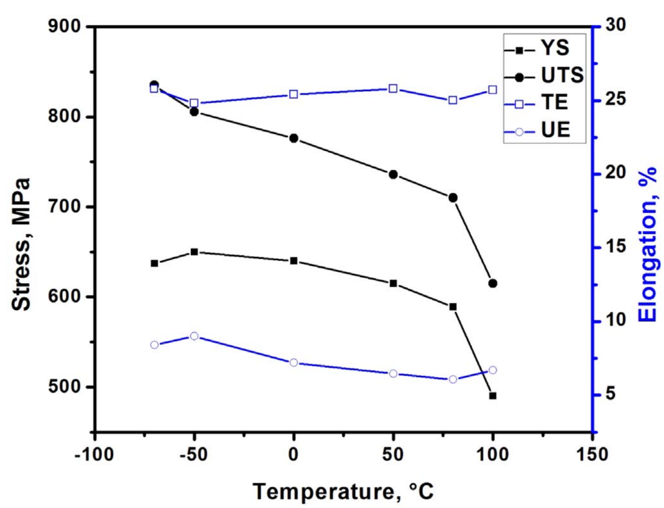

Fig. 2. Effect of temperature on strength and elongation in the specimens parallel to rolling direction in the normalized and tempered (N_1+T) condition.

the specimen orientations is shown in Fig. 1b. Tensile tests were performed at different temperatures in the range −70–100 °C at strain rate of $10^{-4}\,s^{-1}$, using a 100 kN screw driven Universal Testing Machine (Model: INSTRON 4206). Gage portion of the specimens was polished to remove machining marks, if any. Before starting the test, specimens were exposed at respective test temperatures for 15 min to stabilize and homogenise the temperature in gage section. Also, the effect of microstructure and strain rate was studied on rosette fracture of this steel. Fracture surfaces of the tensile tested specimens were examined using scanning electron microscope (Model: FEI Quanta 200 F). Macro-texture measurement was carried out using a PANalytical High Resolution X-Ray Goniometer (Model PW 3040/60).

3. Results

3.1. Effect of temperature

Variation of 0.2% offset yield strength and ultimate tensile strength with temperature is shown in Fig. 2. Both yield as well as tensile strength decreased with increase in temperature and there was relatively faster drop in the strength above 50 °C. The rate of fall in the tensile strength with temperature was relatively higher than that in the yield strength. Variation of total and uniform elongation is shown in Fig. 2. There was no significant variation in the total elongation with temperature, however, the uniform elongation decreased with rise in temperature. The yield strength of the steel in the present investigation is slightly higher than the values reported earlier [11–13]. It may be attributed to relatively higher nitrogen content in this steel in respect of those published earlier [11,12] and also to the lower temperature and shorter duration of its heat treatments as compared to that of the steel used in the earlier investigation [13].

Effect of test temperature on fracture behavior over the temperature range from 100 °C to −70 °C is shown in Fig. 3. There was normal cup and cone fracture with apparent fibrous zone in the central region and double shear lip zone in peripheral region of the specimen tested at 100 °C (Fig. 3a). As the test temperature decreased from 100 °C to RT,