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A TOUGHNESS STUDY OF THE WELD HEAT AFFECTED ZONE OF A MODIFIED 9Cr-1Mo STEEL

A. Moitra, K. Laha, P.R. Sreenivasan and S. L. Mannan

Materials Development Group
Indira Gandhi Centre for Atomic Research
Kalpakkam, Tamilnadu 603 102, India

ABSTRACT

Fracture properties of different microstructural regions of the heat affected zone (HAZ) of modified 9Cr-1Mo steel (tempered base metal, intercritical, fine grained, coarse grained with and without δ-ferrite) have been studied by Charpy impact test. Simulation technique is used to reproduce HAZ microstructures. The fine-grained region shows highest toughness and the coarse grained with δ-ferrite shows the lowest. The results have been analysed in terms of tensile properties and microstructural features. The inter particle distance seems to affect the energy absorbed up to fracture both in the tensile tests and Charpy impact test. The highest toughness is obtained for an optimum inter-particle spacing.

KEYWORDS

Modified 9Cr-1Mo steel, Weld, Microstructure, HAZ, Toughness

1. INTRODUCTION

Modified 9Cr-1Mo (grade T91/P91) steel in tempered martensitic condition is widely used in power plants for headers in steam generators and in tubing for heat exchangers due to excellent high temperature creep strength, high stress corrosion cracking resistance, low oxidation rate and good weldability. The steel is a modified version of the conventional 9Cr-1Mo alloy with controlled addition of niobium, vanadium and nitrogen [1]. It derives its high temperature strength from the complex microstructures consisting of a high dislocation density, sub-boundaries decorated with carbides and Nb-V carbonitride precipitates of the type MX in the matrix [2,3]. However, welding modifies the microstructure of this steel locally (known as the Heat Affected Zone, HAZ) and hence the mechanical properties in this region are altered. Specifically the fracture toughness of the weldment is a matter of concern.

Microstructure in the HAZ is extremely complex and is controlled by interaction of thermal fields produced by heat input from the welding process, the phase transformations and grain growth characteristics of the material being welded [4]. A systematic study by Chandravathi et al. [5] reveals that the HAZ of modified 9Cr-1Mo is composed of coarse prior austenitic grained martensitic region with δ-ferrite (CPAGM-δ) adjacent to fusion line followed by coarse prior austenitic grained martensite (CPAGM), fine prior austenitic grained martensite (FPAGM) and intercritical region (ICR) merging with the tempered base metal (BM). However, the fracture properties of the different structures in the HAZ are difficult to obtain because of practical difficulties of fabricating samples of adequate dimensions with a single microstructure. The simulation of individual microstructure is a powerful method for studying the mechanical behaviour of HAZ [5]. The objective of the present study is to assess the fracture characteristics of the different microstructures likely to be encountered in the HAZ of modified 9Cr-1Mo steel weld joint. This paper reports Charpy impact properties of the steel in different microstructural conditions simulating different parts of HAZ. The results have been analysed in terms of tensile properties and microstructural features.

2. EXPERIMENTAL

Forged rounds (of 70 mm diameter) of a modified 9Cr-1Mo ferritic steel supplied by M/s. Midhani, Hyderabad, India in normalised (1060 ^{o}C/6 hrs/air cooled) and tempered (770 ^{o}C/4 hrs/air cooled) condition were used in this investigation. The chemical composition (in wt %) of the steel is: Cr-8.72, Mo-0.90, C-0.096, Mn-0.46, Si-0.32, V- 0.22, Nb-0.08, N-0.051, S-0.006, P-0.012, Ni-0.1, Fe-balance.

The microstructures of the HAZ have been simulated by isothermal heat treatments in different temperatures representing different phase fields. The details of the simulation technique and microstructures obtained are described in the earlier work by Chandravathi et al [5]. In the present study, the specimens were exposed for five minutes at five different temperatures (800, 850, 950, 1220 and 1350 ^{o}C) followed by oil quenching to reproduce the BM and ICR, FPAGM, CPAGM and CPAGM-δ regions of HAZ respectively. The tempering treatment at 760 ^{o}C/1hr has subsequently been carried out.

Charpy impact tests were carried out on a Tinius-Olsen make 358 J capacity machine using sub-size Charpy V-notch specimens (5x5x55 mm and 1 mm notch depth) in the temperature range of –156 ^{o}C to 61 ^{o}C following ASTM E23 [6] criterion. Scanning electron microscopy (SEM) was carried out on the fracture surfaces of the specimens tested –50 ^{o}C.

Tensile tests were carried out in air at room temperature at a nominal strain rate of $3x10^{-4}$ sec^{-1} on cylindrical tensile specimens of 26 mm gauge length and 4 mm diameter in an Instron 1195 universal testing machine.

3. RESULTS AND DISCUSSION

Charpy impact energies plotted against testing temperatures are shown in Figure 1.

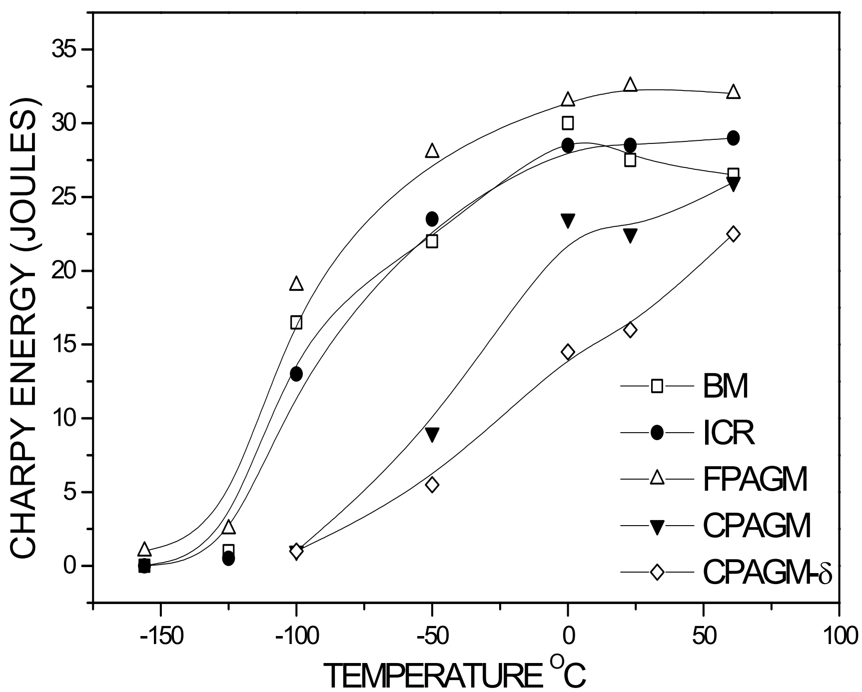

Figure 1: Charpy test results for simulated HAZ samples

Highest toughness in terms of the highest upper shelf energy and the lowest ductile to brittle transition temperature is observed for FPAGM and the lowest toughness is observed for CPAGM-δ. The toughness for BM and ICR are comparable and are higher than the coarse grained region CPAGM.

The results for the SEM study of the fractured surfaces are shown in Figure 2 (a and b). The fibrous appearance of the fracture surface from the FPAGM (fig. 2a) shows the ductile nature of the crack growth in this region. Similar fracture surfaces have been observed for the BM and ICR also. Void growth and coalescence is dominant in these samples. Contrary to the above, brittle cleavage mode of failure features in the fracture surface from CPAGM-δ (fig. 2b). The same has been observed for CPAGM also.

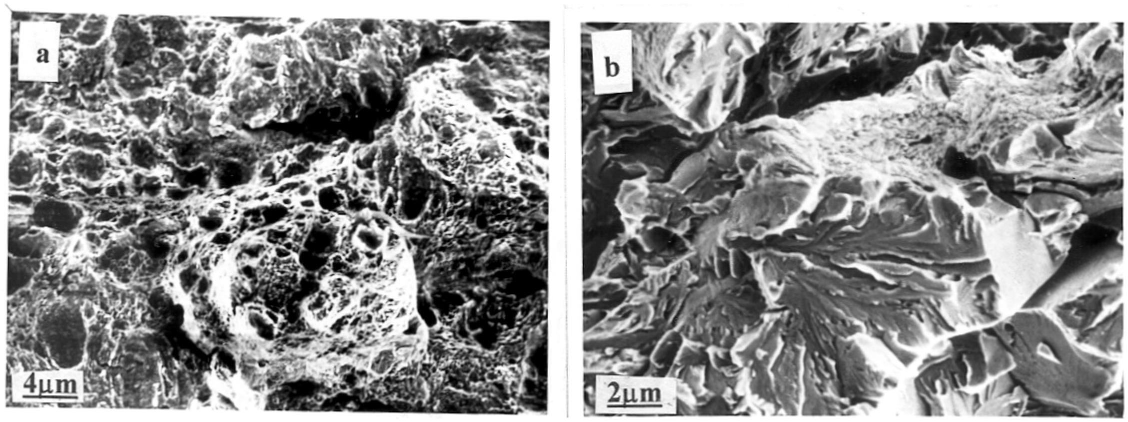

Figure 2 (a-b): The SEM pictures of the fracture surfaces from simulated HAZ samples; FPAGM (a) and CPAGM-δ (b)

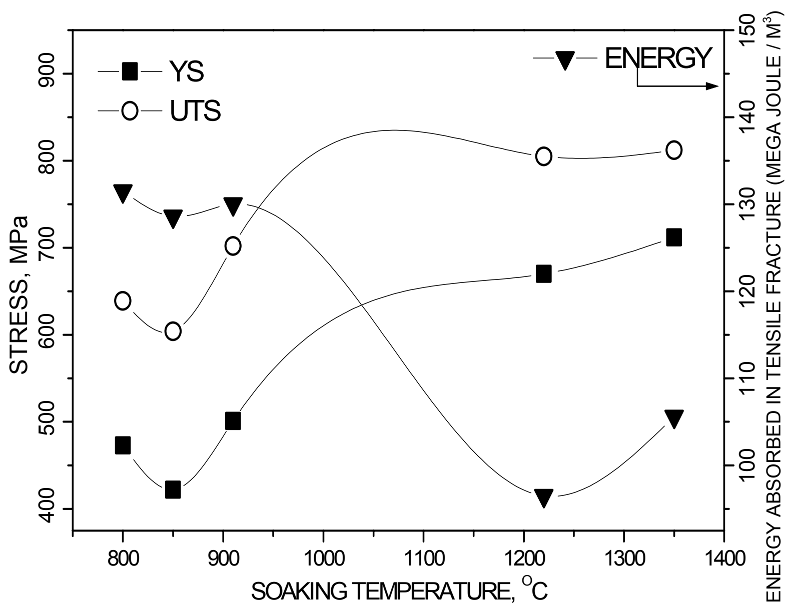

Figure 3: Tensile test results of simulated HAZ samples

The variations of yield stress, ultimate tensile stress and energy absorbed up to fracture (measured from the area under the stress-strain plots) with the heat treatment temperatures are shown in Figure 3.

It is evident that the ICR in the HAZ shows the lowest yield stress and the lowest ultimate tensile stress. The FPAGM shows reasonable combination of low yield stress and high tensile strength. The peak in the energy absorbed up to fracture for the FPAGM confirms highest toughness for this region amongst the HAZ microstructures.

Estrin and Mecking's modified work hardening model [7] has been employed to assess the inter-particle spacing from the tensile curves obtained from different simulated HAZ microstructures. The Charpy upper shelf energies and the total energy absorbed in tensile failure were plotted against the estimated inter particle spacing, Figure. 4.

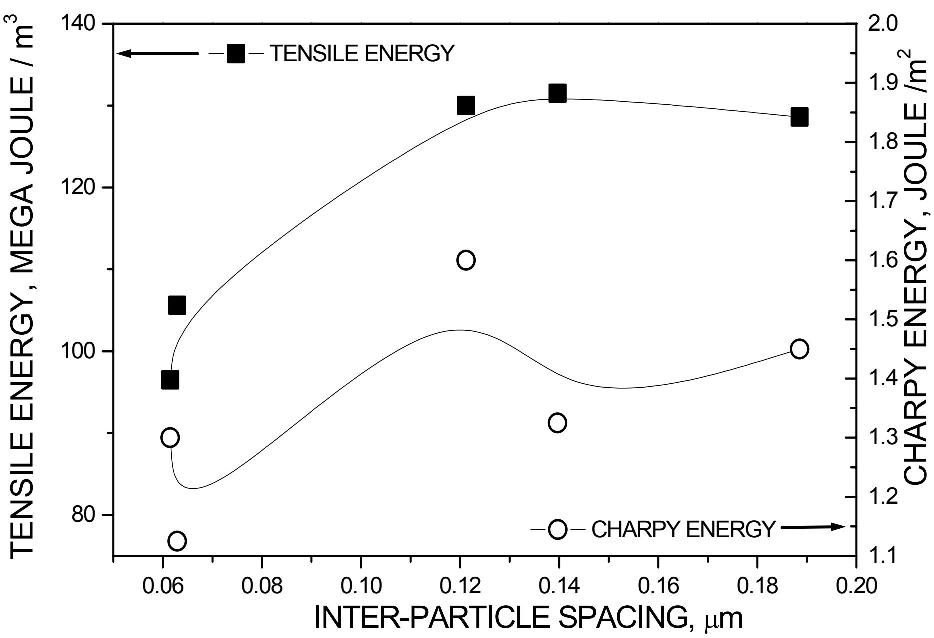

Figure 4. Variation of tensile and Charpy energies with inter-particle spacing

In the HAZ of modified 9Cr-1Mo steel, the general microstructural feature is tempered martensitic with various degrees of prior austenitic grain sizes, except the ICR where martensitic laths starts transforming to ferrites [5]. In these types of microstructures martensitic laths are arranged in packets of the size up to the half of the prior austenitic grain size [8]. The crystallographic orientation of the laths is such that they form low-angle grain boundaries between them [9]. This implies that the crack deviation is small for a crack propagation across the laths. On reaching the high angle packet boundary, a significant deviation of crack path may take place. In the FPAGM, the finer packet sizes contribute to more deviation in crack path, thus leading to the lowest ductile to brittle transition temperature. Also its high strength coupled with reasonably high ductility leads to the highest upper shelf energy (fig. 1). In the CPAGM-δ, slight increase in the energy absorbed (fig.3) during room temperature tensile fracture could be attributed to softer δ-ferrite formation which may blunt the propagating crack tip, initiated at carbide-matrix interfaces in the martensites. But this solute rich δ-ferrite could have lost its ductility more sharply with decreasing temperature and act as a probable crack initiation site (fig.2b), thus leading to the highest ductile to brittle transition temperature.

The inter-particle spacing plays an important role in determining the mechanical properties of steels. The systematic variation of the energy absorbed up to fracture in the tensile tests with the estimated inter-particle spacing indicates the existence of an optimum inter particle spacing for maximum toughness. In the case of Charpy upper shelf region, the same trend is observed with more amount of scatter. The high loading rate, constraints in crack propagation etc. may be contributing to the observed scatter.

CONCLUSIONS

1. The FPAGM is the toughest amongst the other microstructural regions present in the HAZ. This is attributed to its higher strength combined with reasonably higher ductility due to finer martensitic packet sizes.

2. The highest fracture energy is obtained for an optimum inter-particle spacing.

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