Low-Temperature Fracture Toughness of a Heat-Treated Mild Steel

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Specimens from a 0.14% C mild steel were austenitized at 1000 °C for 1 h and thereafter furnace-cooled or isothermally transformed at 700 °C for 0.5, 2, and 8 h. The microconstituents present in the as-received material were ferrite and pearlite and their amounts did not substantially change even after heat treatment. The impact energy of the as-received and the furnace-cooled materials increased from 4 to 89 J and from 4 to 108 J, respectively, when the temperature was changed from -196 to 23 °C. For these materials, the failure mode was by ductile fracture at 0 and 23 °C and by quasi-cleavage fracture at -196 and -40 °C. The fracture toughness did not show any significant change with isothermal transformation time at 700 °C. The failure mode of the isothermally transformed materials was always by quasi-cleavage fracture.

1. Introduction

THE performance of materials at low temperatures has long been of considerable interest because of the anomalous behavior at these conditions especially when strain rates are high. The effect of temperature on fracture behavior has been a subject of previous investigations (Ref 1-4). Most of these investigations have focused on the character of fatigue crack propagation because of the importance of this property. In materials under impact stress, fracture is by ductile rupture or cleavage. These two modes of fracture may sometimes occur concurrently, although different microstructural features are involved in bringing them about (Ref 5).

Cleavage fracture occurs when sections of a material, such as stopped slip band, twin, or dislocation array, undergo shear when the applied stress exceeds the strength. Consider a material with spherical or plate-shaped carbide particles containing crack nuclei (hatched section in Fig. 1a and b) of size \( r \) and \( X \). A crack will propagate across the carbide-ferrite interface if the maximum principal tensile stress, \( \sigma \), acting on the material exceeds the particle fracture strength, \( \sigma_f \) (Ref 6, 7). For a penny-shaped crack, the crack propagation criterion is (Ref 6):

\[
\sigma_f = \left[ \frac{2E\gamma_p}{\pi(1 - \nu^2)r} \right]^{1/2} \tag{Eq 1}
\]

where \( \sigma_f \) is the fracture strength, \( E \) is Young’s modulus, \( \gamma_p \) is the surface energy, \( \nu \) is Poisson’s ratio, and \( r \) is the crack size. For a through-thickness crack, the crack propagation criterion is (Ref 6):

\[
\sigma_f = \left[ \frac{2E\gamma_p}{2(1 - \nu^2)r} \right]^{1/2} \tag{Eq 2}
\]

In the case of a through-thickness crack, \( r = X/2 \) for the Griffith crack propagation criterion to be valid. In steels, cleavage fracture will involve three steps (Ref 7): (1) crack initiation and propagation within carbide particles, (2) crack propagation across the carbide-ferrite interface, and (3) crack propagation across the ferrite-ferrite grain boundary, leading to cleavage fracture. Crack initiation occurs in specific locations such as tips of notches or inclusions, which are stress concentration points. Crack propagation will be more significant across regions of weakness such as grain or phase boundaries. Therefore, cleavage fracture usually occurs by crack propagation along well-defined paths which are grain or phase boundaries, such as the carbide-ferrite or ferrite-ferrite interfaces in Fig. 1.

Ductile fracture arises from the nucleation, growth, and coalescence of voids to form cracks. Void coalescence rate, \( \dot{f} \), can be expressed as (Ref 8):

\[
\dot{f} = \dot{f}_{\text{nucleation}} + \dot{f}_{\text{growth}} \tag{Eq 3}
\]

The void coalescence rate is dependent on both the nucleation rate, \( \dot{f}_{\text{nucleation}} \), and the growth rate, \( \dot{f}_{\text{growth}} \), of individual voids. At elevated temperatures, the mobility of voids is higher, leading to increased coalescence and ductile fracture. The source of most voids are vacancies created by mobile dislocations (Ref 9) or the presence of tensile stresses in a material (Ref 9, 10). A correlation has been found between fracture stress and spacing among these voids (Ref 11). In general, the fracture stress increases with decreasing intervoid spacing. This is attributed to the impediment of dislocation motion by the closely spaced voids.

In iron and iron-binary alloys at very low temperatures, crack propagation rates can be divided into two stages (Ref 12). The initial stage involves a decrease in crack propagation rate at low temperature, which is attributed to lower dislocation velocities that retard striation formation or cyclic cleavage. As the temperature decreases below that of the ductile-brittle transi-
Fig. 2 Charpy impact test specimen (all dimensions are in mm)

\[ \text{ITT} = 63 + 44.1(\%\text{Si}) + 2.2(\%\text{pearlite}) - 258(\%\text{Al}) - 2.3d^{-1/2} \]  

(Eq 4)

where ITT is impact transition temperature and \( d \) is grain size. Equation 4 shows that the transition temperature is dependent on both composition and grain size, parameters that can be controlled by heat treatment. Although other investigators have reported fracture toughness measurements using Charpy impact tests, this article contributes additional information on the subject.

2. Experimental Procedures

The as-received composition of the investigated steel, in wt%, was 0.33 Si, 0.058 Al, 0.74 Mn, 0.019 Cu, 0.017 S, 0.019 P, 0.14 C, bal Fe. Additional investigations were conducted after subjecting specimens of this steel to one of the following heat treatment schemes:

- Austenitizing at 1000 °C for 1 h followed by furnace cooling
- Austenitizing at 1000 °C for 1 h followed by isothermal transformation at 700 °C for 0.5, 2, and 8 h and quenching in cold water

The microstructures were examined in a Neophot 30 optical microscope and quantitative microscopy was conducted in a Leitz CBA 8000 image analyzer. Specimens for fracture toughness measurements by Charpy impact tests were machined to the specifications shown in Fig. 2 before being tested in a Torsce Universal Pendulum Testing Machine TIT-30. The specimens were maintained at 23 °C, 0 °C (ice), –40 °C (dry ice and acetone), and –196 °C (liquid nitrogen) for 2 h prior to the tests. Each specimen was tested within 5 s after removal from the cooling environment. The fractographs from the Charpy impact tests were examined in a JEOL JSM-840A scanning electron microscope operating at 15 KV.