ABSTRACT

Stereographic analyses of fracture surfaces of compact tension specimens were made on three grades of ultra-high strength steels heat-treated to yield strength level between 102-188 kg/mm$^2$. The fracture surface was separated into four regions, namely, a fatigue pre-cracked region, a stretched zone, a ductile fracture band characterized by small dimples, and an over-load fracture region with either cleavage or ductile nature. Plotting of the stretched zone height against the crack tip opening displacement calculated by

$$\text{CTOD} = A \cdot \frac{K_{IC}^2}{E \cdot \sigma_Y}$$

showed that the experimentally obtained stretched zone height was bound by lines with slopes of 0.715 and 0.425, and best correlated with a line calculated by setting $A = (1-v^2)/2$, which indicates that the crack tip opening displacement can be best predicted by Thomason's model. The stretched zone height was correlated well with the fracture strain of the smooth tension bar. But the fracture toughness calculated by Hahn and Rosenfield's equation showed a deviation from the experimentally obtained fracture toughness.

INTRODUCTION

A stretched zone is observed between the fatigue pre-cracked and over-load fracture regions of the fracture toughness specimen [1-6]. A wider stretched zone is observed for a steel with higher fracture toughness as shown in Fig. 1 [1,2,5,7]. This is even observed in ultra-high strength steels, such as maraging and Ni-Cr-Mo steels, with yield strength of 180 kg/mm$^2$ or higher, and in some particular materials tested at $-180^\circ$C [8].

The stretched zone is usually considered the result of crack tip blunting since the calculated crack tip opening displacement (CTOD) from $K_{IC}$ value [9,10] is close to the observed stretched zone width (SZW) [11,12]. This argument, however, is irrelevant. The SZW is the crack tip displacement along the crack propagation direction; CTOD is only the displacement normal to the crack plane.

Therefore, the comparison between SZW and CTOD is unreasonable.

The main purpose of the present study is to make a quantitative comparison between the displacement in the stretched zone normal to the crack plane (stretched zone height, SZH) and the CTOD calculated from $K_{IC}$ value. The SZH was determined by stereographic analysis using a scanning electron microscope.

Several analyses attempt to relate fracture toughness to the fracture ductility of the material [9,10,13-19]. The fact that $K_{IC}$ is correlated with the size of the stretched zone, shown in Fig. 1, indicates the experimental support for these analyses. Therefore, the relation between the size of the stretched zone (SZH) and fracture ductility is also discussed in the study.

**EXPERIMENTAL PROCEDURE**

**Materials and heat treatment**

The chemical compositions of the three grades of steel used in the study are given in Table 1. JIS-SNCM 8 (equivalent to AISI 4340) was sampled from commercial heats, and 18Ni maraging and 10Ni-8Co steels were from 50 kg laboratory heats. Heat treatment conditions of these steels are

- **SNCM 8** --- oil-quenched from 850°C followed by tempering at 500, 550, and 600°C for 1 hour to give yield strength of 123.0-101.6 kg/mm².
- **18Ni maraging** --- solution-treated by air-cooling from 820°C, aged at 400°C for 40 minutes ($\sigma_Y = 122.7$ kg/mm²), and at 480°C for 10 hours ($\sigma_Y = 188.4$ kg/mm²).
- **10Ni-8Co** --- water-quenched from 790°C followed by aging at 500°C for 4 hours to give $\sigma_Y = 118.1$ kg/mm².

**Fracture toughness test**

Fracture toughness tests were conducted according to ASTM designation E399-72. Compact tension specimens were employed. Specimen thickness was 40 mm for SNCM 8, and 20 mm for both 18Ni maraging and 10Ni-8Co steels. All tests were conducted at room temperature. SNCM 8 steel tempered at 500°C was also tested at temperatures down to -175°C.

**Fracture surface observations**

The stereographic analysis method using a scanning electron microscope is proposed by Kimoto et al. [20]. Briefly, the height of the specific point from the fixed point is calculated from the difference in the distance of the specific point from the fixed point on the two photographs with tilt angles of 0° and $\theta°$, respectively. The procedure is schematically depicted in Fig. 2.

The fixed point in this study was set on the fatigue pre-cracked surface far away from the stretched zone. A straight line was drawn through this point to the unstable fracture area along the crack propagation direction. The frac-