J Mater Sci (2008) 43:1910–1913
DOI 10.1007/s10853-007-2430-z

Static fracture toughness of ultra-fine grained steels processed by thermo-mechanical warm rolling

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Received: 13 March 2007 / Accepted: 26 December 2007 / Published online: 31 January 2008

Abstract Ultra-fine grained steels were recently developed by thermo-mechanical warm rolling. Their low-temperature fracture toughness was evaluated in terms of crack tip opening displacement (CTOD) in this paper. Effect of temperature on CTOD and the correlation between CTOD and grain size were investigated, and the experimental results showed that refining ferrite grains can increase the fracture toughness of steel and lower the sensitivity of fracture toughness to temperature. The fracture toughness of the developed ultra-fine grained steels was superior to that of hot-rolled steel SM490B with similar chemical composition.

Introduction

To meet the needs of renovating long-service infrastructure in the future in Japan, attempts have been made to develop new-generation high-strength steels. From the viewpoint of recycling, Si–Mn-based steel was chosen, which is easy to obtain and recycle. By refining ferrite grains, 780 MPa grade structural steels with ultra-fine ferrite grains/cementite particles were successfully manufactured from 400 MPa grade Si–Mn steel (hot-rolled steel SM490) [1].

Adequate toughness as well as strength is generally required for high-strength steel. The mechanical properties of the newly developed Si–Mn steels and their welded joints were investigated in detail elsewhere [2–4], and the results showed that they have good combination of strength and ductility. The characterization of their fracture toughness was the concern of this article.

In this work, the fracture toughness of the ultra-fine grained steels under static loading was evaluated in terms of crack tip opening displacement (CTOD) which was obtained from three-point bending tests. Through the experimental results, the temperature dependence of fracture toughness and the effect of grain size on fracture toughness were discussed. Moreover, the fracture toughness of the ultra-fine grained steels was compared with that of hot-rolled steel SM490B steel with similar chemical composition.

Experimental

Three different chemical compositions (steels D–F) given in Table 1 were selected for producing ultra-fine grained steels. Low values of welding crack sensitivity (P_{cm}) show that steels D–F have strong resistance to cold cracking. For comparison, SM490B steel with thickness 16 mm was used whose chemical composition is also listed in Table 1, which shows that SM490B steel has almost the same chemical composition as steel D.

Steel plates D–F were produced by thermo-mechanical warm rolling with severe plastic deformation. The fabrication processes were described in detail elsewhere [4]. Briefly, the processes were composed of three steps as shown in Fig. 1. In step I, slabs of steels D–F for rolling were prepared by heating in the furnace and then followed by water quenching (WQ). Step II is a rolling process, in which slabs were first rolled 26 passes and then rolled 37

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Table 1 Chemical composition (wt%)

No.	C	Si	Mn	P	S	Sol. Al	N	Nb	Ti	C_{eq}	P_{cm}
D	0.140	0.30	1.46	0.005	0.001	0.032	0.0013			0.38	0.223
E	0.095	0.30	1.45	0.005	0.001	0.032	0.0015			0.34	0.178
F	0.093	0.30	1.45	0.005	0.001	0.033	0.0018	0.016	0.007	0.33	0.176
SM490B	0.16	0.44	1.46	0.004	0.013					0.40	0.248

$C_{eq} = C + Mn/6 + (Cr + Mo + V)/5 + (Cu + Ni)/15$

$P_{cm} = C + Si/30 + (Mn + Cu + Cr)/20 + Ni/60 + Mo/15 + V/10 + 5B$

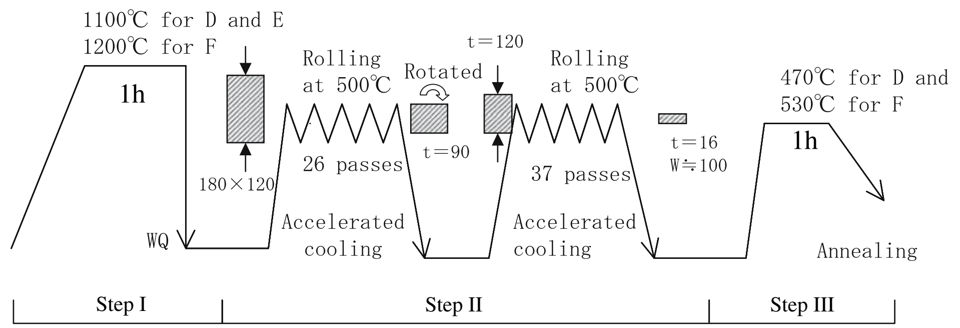

Fig. 1 Schematic illustration of the producing processes

passes again after a 90° rotation. Step III is an annealing process for improving the mechanical properties. The final cross-section size is about 100 mm (width) × 16 mm (thickness). Their mechanical properties are given in Table 2. For comparison, data of SM490B [5, 6] with microstructure of ferrite and pearlite are also listed.

Three-point bend specimens with fatigue pre-crack ($a_0/W \approx 0.5$) were used for measuring the CTOD of steels D–F. L- and T-direction specimens (fatigue pre-crack, respectively, perpendicular and parallel to the rolling direction) were prepared, whose sizes were, respectively, 16 mm (B) × 30 mm (W) × 150 mm (L) and 16 mm (B) × 20 mm (W) × 100 mm (L). Two specimens were used for one condition. CTOD tests were conducted at −40 °C, −140 °C and −196 °C with a span-to-width ratio, S/W, of 4. CTOD was calculated by Eq. 1 proposed by ASTM E1290-99 [7]

$$\mathrm{CTOD} = \frac{K^2(1-\nu^2)}{2\sigma_{ys}E} + \frac{r_p(W-a_0)}{r_p(W-a_0)+a_0+z}V_p \qquad (1)$$

where K is the stress intensity factor; V_p, the plastic component of notch opening displacement; W, the effective width of test specimen; a_0, the average original crack length. In this article, Poisson's ratio ν is taken as 0.3, Young's modulus $E = 206010$ MPa, plastic rotation factor $r_p = 0.44$, distance of knife-edge measurement point from front face on specimen $z = 0$. Yield strength, σ_{ys}, at the temperature of interest was estimated from the yield strength, σ_{ys0}, at room temperature by Eq. 2 for steels [8]

$$\sigma_{ys} = \sigma_{yso} \times \exp\left[\{481.4 - 66.5 \times \ln\sigma_{ys0}\} \times \left\{\frac{1}{T+273} - \frac{1}{293}\right\}\right] \qquad (2)$$

where T is the test temperature in °C.

Table 2 Mechanical properties

Steel	YS (MPa)	TS (MPa)	YR	U.EI (%)
D	714	751	0.951	7.3
E	686	705	0.973	7.8
F	771	787	0.980	7.7
SM490B	340	524	0.649	18

Note: YS, yield strength; TS, tensile strength; YR, YS/TS; U.EI, uniform elongation

Results and discussion

Microstructure

The SEM microstructure of steel D on longitudinal and transverse sections is shown in Fig. 2a and b, respectively. It can be seen that steel D consists of ferrite and cementite particles. Morphology of ferrite grains on longitudinal and transverse sections is apparently different. On the transverse section, ferrite grains are fine (~1 μm) and equiaxial grains are dominant. In contrast, ferrite grains are considerably elongated on the longitudinal section, which indicates that longitudinal section has larger effective ferrite grain size than transverse section. SEM observation showed that steels E and F have similar microstructure as steel D.

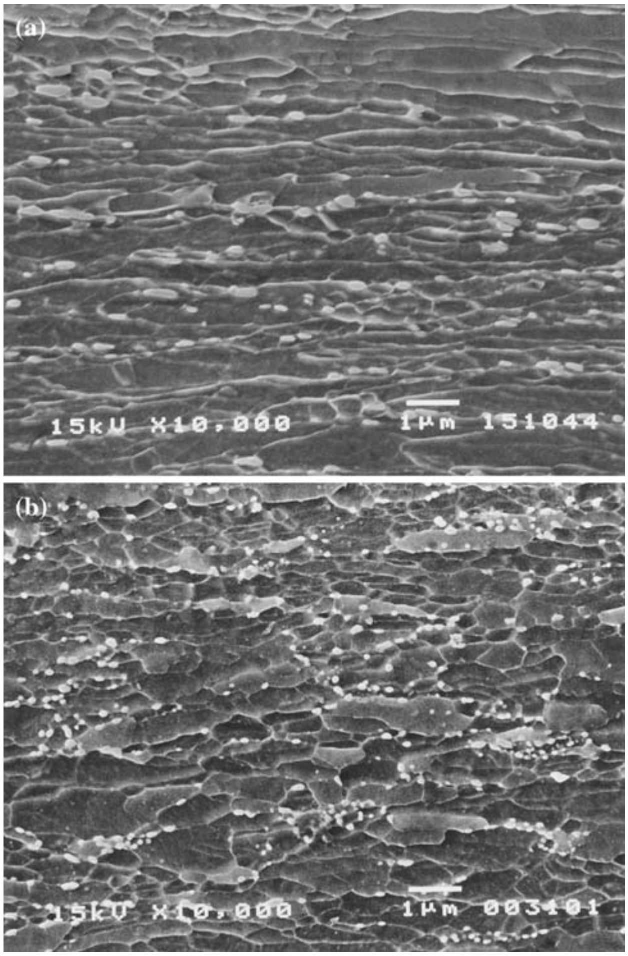

Fig. 2 SEM microstructure of steel D on (**a**) longitudinal and (**b**) transverse sections

Fracture toughness

The CTOD test results at three temperatures are summarized in Fig. 3. The critical CTOD decreases with temperature for the three ultra-fine grained steels irrelevant to L- or T-direction specimens. However, the degrees of the temperature dependence of fracture toughness are different. The critical CTOD of T-direction specimens decreases more strongly with temperature than L-direction specimens for a given steel. Moreover, for a given temperature, the CTOD of L-direction specimens is apparently larger than that of T-direction specimens.

Grain size has been known to strongly affect the toughness of steel. Hanamura et al. [9] researched the toughness of martensite steel, pearlite steel and ferrite steel by Charpy impact tests, and their results showed that the toughness of steels, which was evaluated in terms of ductile-brittle transition temperature, was determined by the effective grain size. The smaller the grain size is, the better the toughness is for steels. As mentioned in section ''Microstructure'', steels D–F are composed of ferrite and

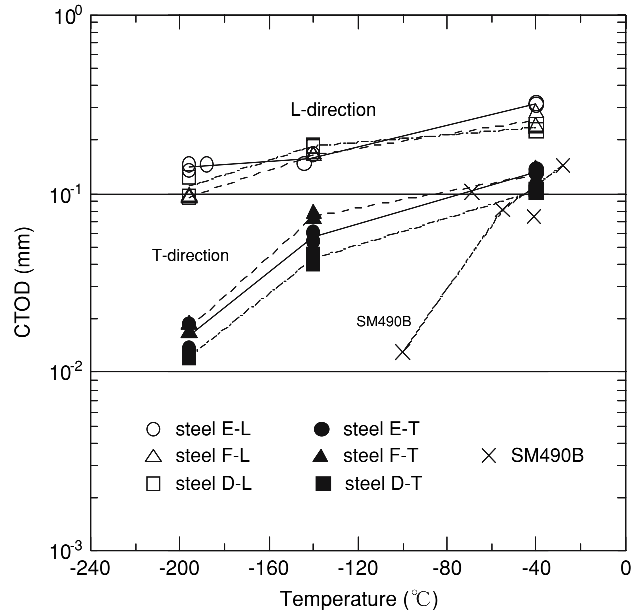

Fig. 3 The dependence of CTOD on temperature

cementite particles. SEM observation showed that there were considerable differences in size and morphology of ferrite grains between transverse and longitudinal sections (see Fig. 2). Obviously, transverse section has much smaller effective grain size than longitudinal section for steels D–F. The difference in grain size accounts for the results in Fig. 3. For warm rolling in this study, serious texture may be caused, and its heterogeneity in L- and T-directions is probably another factor inducing the heterogeneity of fracture toughness in Fig. 3. The effect of texture should be investigated in detail in the future.

In Fig. 3, the CTOD values of SM490B steel are referred, which were obtained from compact tension specimen with $t = 12.7$ mm, $W = 25.4$ mm and $a_0/W = \sim 0.5$ [5, 6]. Obviously, SM490B has the worst low-temperature toughness among all the steels, and its temperature dependence on fracture toughness is much more serious than the ultra-fine grained steels, which indicates that the structure of ferrite/pearlite is more sensitive than that of ultra-fine ferrite.

The effect of temperature is not only reflected in CTOD values, but also in the curves of load against displacement for steels D–F. Figure 4 gives the load vs. clip gage displacement for L- and T-direction specimens of steel D. To clearly distinguish the curves, their zero points are shifted in Fig. 4. It is found that the load vs. displacement curves in both Fig. 4a and b vary with temperature, and the variations in curve shape due to temperature decrease in Fig. 4b are more significant than those in Fig. 4a. This implies that the fracture mode in L- and T-direction specimens changed with temperature, especially in the T-direction specimens.

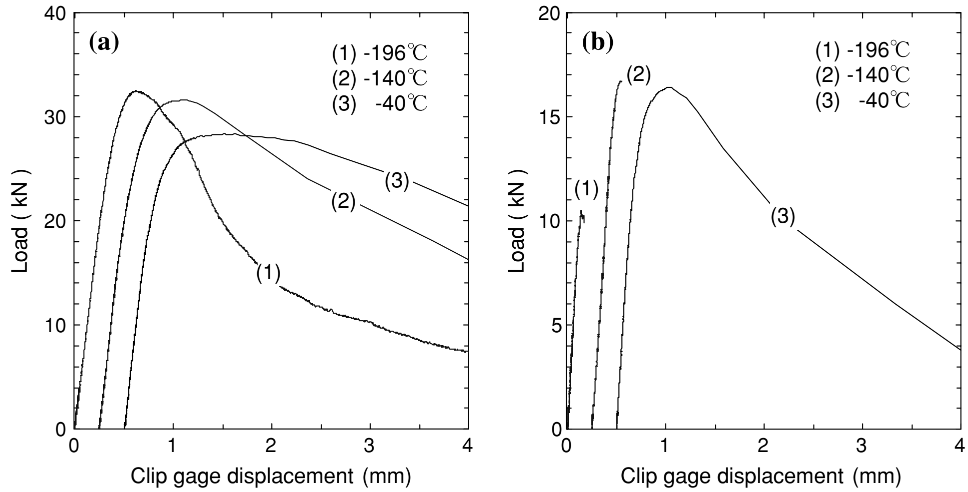

Fig. 4 Load against clip gage displacement of steel D. (**a**) L-direction and (**b**) T-direction specimen

We observed the fracture surfaces of the CTOD specimens of steel D. For L-direction specimens, ductile fracture remained down to −196 °C, and the dimple size decreased with temperature decrease. In T-direction specimens, steel D was fractured in fully ductile mode at −40 °C, and then brittle fracture regions appeared and enlarged with temperature decrease. This result is consistent with the insensitivity of fracture toughness to temperature for L-direction specimens in Figs. 3 and 4.

Conclusions

Refining ferrite grain is an effective means to improve fracture toughness while it can lower the temperature sensitivity of fracture toughness. Ultra-fine grained steel has better low-temperature fracture toughness than hot-rolled steel with the similar chemical composition.

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