Cleavage Fracture of Steels With Fine Grained Ferrite, Coarse Grained Bainitic and Martensitic Microstructures

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ABSTRACT

Tests have been performed to measure the yield stress, the cleavage fracture stress and the fracture toughness of several steels with fine ferrite, coarse grained bainite and martensite. Martensite has extremely high cleavage fracture stress and low fracture toughness at the same testing temperature. Carbon has the additional effect of increasing the cleavage fracture stress and reducing the fracture toughness. The cleavage fracture stress of the ferrite as a function of ferrite grain size, is well on the extension of the curve which is predicted by the grain boundary carbide model. However, for the bainite and the martensite, the results are far from the scatter band for low carbon bainite obtained by others, and it seems to be that lath packet size is not a governing factor in these materials. Quantitative metallographic analysis shows that facet size of the martensite is consistent with the packet size but that of upper bainite is 3 to 4 times the packet size and appears to be associated with the prior austenite grain size. A general correlation between the cleavage fracture stress and the yield stress at -196°C can be found in the steels tested.

KEYWORDS

Cleavage fracture stress; fracture toughness; fine grained ferrite; coarse grained bainite; martensite; grain boundary carbide.

INTRODUCTION

For normalized and annealed mild steels, the micromechanism of the cleavage fracture has been well investigated (McMahon and Cohen,1965; Knott,1966; Smith,1966; Curry and Knott,1976,1978; Curry,1980; Petch,1953,1986,1987). A theoretical model proposed by Smith (1966) assumes that the critical stage in the cleavage fracture process is the propagation of a microcrack, which is nucleated in a grain boundary carbide, into the surrounding ferrite matrix. It has been found that the cleavage fracture of mild steels obeys the critical tensile stress criterion (Knott,1966). According to Smith's model, the tensile stress criterion can be also deduced as an approximation. Though much progress has been made recently in the interpretation of σc in terms of critical events in a metallurgical microstructure, quantitative relationships between σc and microstructural parameters are not yet fully clarified. It seems to be considered that σc is dependent on the ferrite grain size, d (Petch,1953). But Knott and Curry (1977,1978) have emphasized the role of the carbide film in ferrite grain boundary. Recently, Petch (1986,1987) has analysed the energy balance for non-equilibrium carbide crack and showed that the cleavage fracture stress must depend on both the size of the carbide and the ferrite grain. To examine the dependency of σc on the grain size and the carbide film thickness, it is necessary to conduct an experiment for finer grain mild steels (d<15μm).

On the other hand, considerable efforts (for examples, Brozzo *et al.* ,1977; Dolby and Knott,1972; Curry,1982,1984; Hagiwara and Knott,1981; Bowen and Knott,1984) have been made to clarify the cleavage fracture process of other types of microstructure, such as lath martensite and low carbon bainite, and it has been shown that the cleavage fracture of both upper bainite and tempered granular bainitic microstructures in low alloy pressure vessel steels(A508II) also obeys a critical tensile stress criterion(Dolby and Knott,1972). But the factors governing the cleavage fracture in such materials have not been fully clarified. Especially, few data are available concerning coarse grained bainitic and martensitic microstructures.

The aim of the present study is, for three kinds of laboratory-melted steels with fine grained ferrite, coarse grained upper bainite or lath martensite, to investigate the effects of different microstructures on the behaviour of cleavage fracture, and examine the applicability of the proposed theories for the present results and discuss how to feature the cleavage fracture stress in these steels.

EXFERIMENTAL METHOD

Tests were made on three vacuum-melted, hot rolled and normalized steels, with different carbon contents(0.15%, 0.08%). Their chemical compositions are given in Table 1. In order to get fine microstructure, 0.025% Nb was added to one of the 0.08% C steels. These steels(in as-received condition, T3) were austenized at 1,400°C, followed by controlled cooling from 800°C to 500°C in 2 seconds for T1 process and 40 seconds for T2 process. The 0.08%C steel with niobium was tempered at 600°C for 3 hours after the T2 treatment, then air cooled for stress relaxation (T2SR). Tests were made on nine kinds of steels, and their mechanical properties at room temperature are given in Table 2.

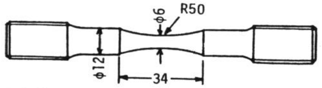
The specimens used in the present work are round bar tensile (unnotched and 1mmR notched) specimens and three-point bend fracture toughness specimens. All test specimens were oriented such that the longitudinal direction of each was parallel to the rolling direction. Specimen configurations are shown in Fig.1. Stress distribution in the minimum cross section was calculated by Bridgman's formula for smooth specimens. For 1mmR-notched specimens, an axisymmetrical finite element analysis (FEM) was performed. The maximum tensile stress at the cleavage fracture was taken as the cleavage fracture stress, σc(smooth) and σc(1R).

The three point bend specimen for the fracture toughness test is shown in Fig.1(c). Tests were performed over a temperature range of -196°C to room temperature. The fracture toughness was evaluated by the J integral from the measurement of load-displacement relation (ASTM E813), except for the values at -196°C, where the toughness was evaluated by the stress intensity factor.

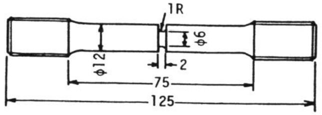
Quantitative measurements of the grain size and the packet size were done by computer aided image analysis(PIAS-II). Fracture surfaces were observed by the SEM and the cleavage facet sizes were measured by PIAS-II.

Table 1. Chemical composition of steels tested, %.

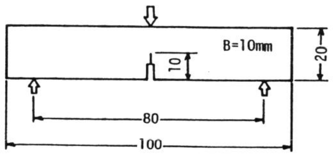
Steel	C	Si	Mn	P	S	Al	N,total	Nb
0.15%C steel	0.147	0.214	1.482	0.0059	0.0037	0.028	0.0029	<0.005
0.08%C steel	0.080	0.195	1.364	0.0048	0.0034	0.025	0.0033	<0.005
0.08%C&Nb st.	0.078	0.196	1.347	0.0051	0.0030	0.024	0.0024	0.024



(a) Smooth round bar specimen.



(b) 1mmR notched round bar specimen.



(c) Three point bend specimen.

Fig. 1. Specimens, mm

Table 2. Mechanical properties of steels tested.

Steel	Thermal cycle	σys (MPa)	σu (MPa)	R.A. (%)	Hv(500)
0.15% C	T1	1,108	1,335	35	404
	T2	482	619	76	196
	T3	326	494	78	137
0.08% C	T1	935	1,086	25	333
	T2	412	538	77	173
	T3	279	432	82	114
0.08%C&Nb	T2	481	588	78	198
	T2SR	489	601	73	198
	T3	301	459	84	131

Table 3. Cleavage fracture stress and yield stress at -196°C, and microstructural parameters.

Steel		σys (MPa)	σc(Smooth) (MPa)	σc(1mmR) (MPa)	d* (μm)	d** (μm)	d*** (μm)
T1(M)	0.15%C	1,453	1,850	2,390	47	35	-
	0.08%C	1,236	1,590	2,060	38	36	-
T2(Bu)	0.15%C	948	1,240	1,720	34	143	174
	0.08%C	889	1,020	1,540	33	137	150
	0.08%C(Nb)	911	1,140	1,520	31	104	132
T2SR(Bu)	0.08%C(Nb)	980	1,090	1,640	30	140	-
T3(F)	0.15%C	838	1,490	1,500	11	8	-
	0.08%C	760	1,350	1,380	15	8	-
	0.08%C(Nb)	818	1,540	1,500	6	7	-

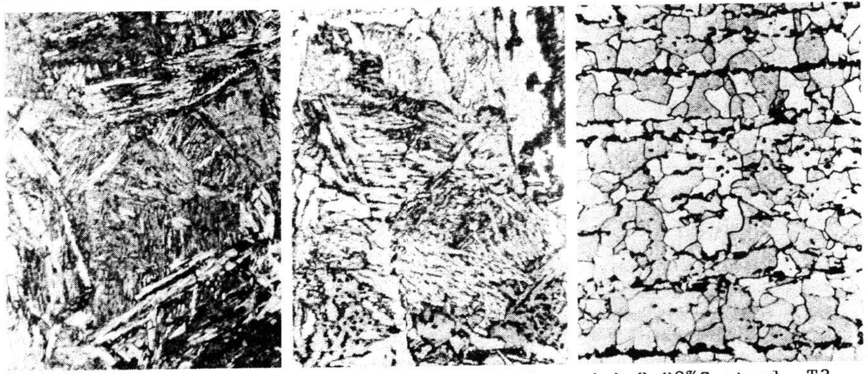
d*=ferrite or packet size, d**=cleavage facet size and d***=austenite grain size.

RESULTS OF EXPERIMENTS

Figure 2 shows the typical microstructures of tested materials. In a normalized condition(T3), the microstructure is composed of ferrite, plate-like grain boundary carbide film and small patches of pearlite, and because of finer grain, the carbide films are so thin as to be less than 0.5-1.5μm in thickness. In an as-transformed condition, the microstructure is mainly coarse grained upper bainite(T2) or coarse grained martensite(T1), which would be expected to be in the heat affected zone of the welds. In both cases, the packet boundary is clearly visible. All data on the ferrite size, packet size, austenite grain size and the cleavage facet size(mean values of measured 400-1,000 grains or packets) are presented in Table 3. There is a consistent view that the facet size is decided by the ferrite grain size in the ferrite microstructure(T3). For the lath martensite, the facet size seems to be related to the packet size. For the upper bainite through T2 process, the facet size is 3 to 4 times larger than the packet size and close to the prior austenite grain size.

The variation of the yield stress (lower yield stress for T3, 0.2% proof stress for others) with temperature is shown in Fig.3. It can be seen that steels which are subjected to thermal cycle T1 show higher strength than other steels. It is also seen that the 0.15% carbon steels show higher yield stress than the 0.08% carbon steels except for steel T2SR.

The values of the cleavage fracture stress at -196 °C for the smooth and notched specimens are presented in Table 3, with the yield stress at -196°C. It should be noted that there is a difference in the cleavage fracture stress between the smooth specimens and the notched specimens for each material. The reason for these differences may be the probabilistic nature of the cleavage fracture. High fracture probability in the smooth specimen, in which the higher stressed region is larger than in the notched specimen, would lead to lower fracture stress as discussed in detail elsewhere (BEREMIN,1983; Miyata *et al.*,1988b). Inaccuracy involved in Bridgman's formula may also lead to some discrepancy(Gilles,1988). For discussion on the relationship with fracture toughness and comparison with other works, the cleavage fracture stress in the notched specimens will be more appropriate, because the effect of notch acuity on σc seems to be relatively small(Miyata *et al.*,1988a). In the present work, the cleavage fracture stress in the notched specimens is adopted for later discussions.



(a) 0.08%C steel, T1 (b) 0.08%C steel, T2 (c) 0.08%C steel, T3

Fig. 2. Typical microstructures of steels tested.

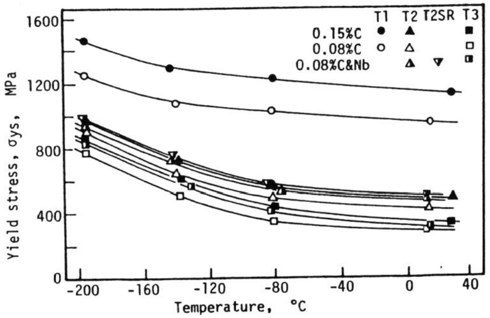


Fig. 3. Variation of yield stress with temperature.

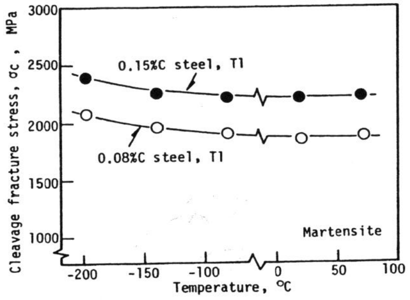


Fig. 4. Effect of temperature on cleavage fracture stress of notched specimens in T1 condition(martensite).

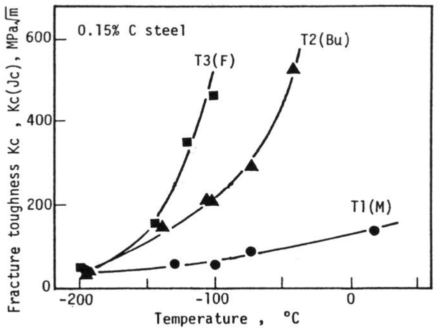


Fig. 5(a). Effect of microstructure on fracture toughness (0.15%C steel).

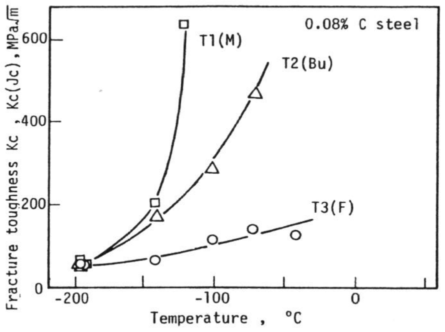


Fig. 5(b). Effect of microstructure on fracture toughness (0.08%C steel).

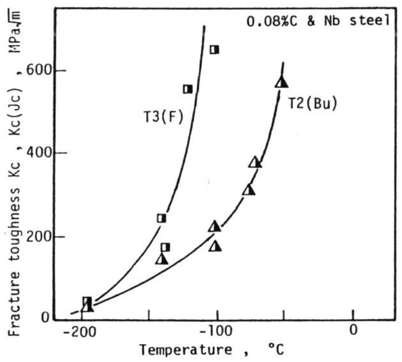


Fig. 5(c). Effect of microstructure on fracture toughness (0.08%C & Nb).

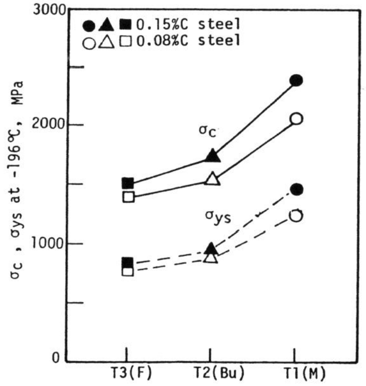


Fig. 6. Effect of microstructure on cleavage fracture stress and yield stress at -196°C.

Figure 4 shows the variations of the cleavage fracture stress of the notched specimens with temperature for the T1 steels of 0.15% and 0.08% carbon. It can be seen that the cleavage fracture stress is almost independent of the testing temperature also for the martensitic microstructure. The same criterion was earlier well justified in mild steels (Knott,1966) and in low carbon bainitic steels by Curry(1982). So, the criterion of a temperature-independent local tensile stress may be accepted as valid for three kinds of common microstructures, ferrite, upper bainite and lath martensite.

Variation of fracture toughness in terms of Kc with temperature for T1,T2 and T3 conditions are shown in Fig.5. The Kc values were converted from the Jc values using the relation of $J= K^2(1-\nu^2)/E$.

DISCUSSIONS

The effect of microstructure on the cleavage fracture stress, $\sigma c(1R)$ and the yield stress, σys at -196°C is shown in Fig.6. Obviously, σ c in the hardened conditions is larger than in the milder conditions. The martensitic steels have extremely high values of cleavage fracture stress. This is consistent with the results by Hagiwara and Knott(1981); Bowen and Knott(1984). The former have studied two-phase microstructure in a combination of the upper bainite and the tempered martensite in HY 80 and found that the cleavage fracture stress σ_c decreases rapidly when a small portion of the bainite is introduced in the martensitic structure. Bowen and Knott(1984) investigated the cleavage fracture of A533B steel in the as-quenched condition and a 3,700 MPa of σ_c in this complex composition steel was obtained for the lath martensite. The fact that hardened structures show a higher σ_c might be related to the difficulty of the dislocation movement and the size of micro-crack nucleus.

Carbon content has an additional contribution to the effect of microstructure on σ_c, as shown in Fig.6. The increase of σ_c with the increase of carbon content for each microstructure is 120-330 MPa, and the ratios of σ_c for 0.15%C steels to those for 0.08%C steels are 1.16 for the martensite(T1), 1.12 for the upper bainite(T2) and 1.09 for the ferrite(T3). Similarly, the ratios of the yield stress are 1.18, 1.07 and 1.10 for T1, T2 and T3, respectively at the same temperature. It is interesting to note that, though the values of σ_c are considerably larger than the yield stress, the value of these ratios of σ_c and of σ_{ys} are about the same for each microstructure.

On the other hand, the value of the fracture toughness and the transition behaviour of the toughness with temperature show an opposite tendency to the cleavage fracture stress as seen in Fig.5. The effect of microstructure on Kc is remarkable compared that of carbon content. The materials having higher yield stress show lower toughness and higher transition temperature. There is a close correspondence between yield stress and toughness. From the mechanical point of view, it can be said that the cleavage fracture toughness is expressed as a function of the yield stress or flow properties and the cleavage fracture stress of the material as shown in the RKR model(Ritchie, Knott and Rice,1973), if the cleavage fracture at the crack tip is controlled by the maximum tensile stress criterion. The correlation between the fracture toughness and flow/fracture properties is discussed elsewhere(Miyata, *et al.*,1988a) in more detail for the present experimental results. Based on the local fracture criterion using the analytical solution for the stress distribution around the crack tip, it has been shown that the cleavage fracture toughness Kc is controlled by the parameter, $\sigma_c(\sigma_c/\sigma_{ys})^m$ where m is a function of the strain hardening coefficient of the material and the value is 4.5 for the materials tested. Denoting this parameter as Q, the relation between Q value obtained from the round bar tensile test and the fracture toughness Kc is shown in Fig.7.

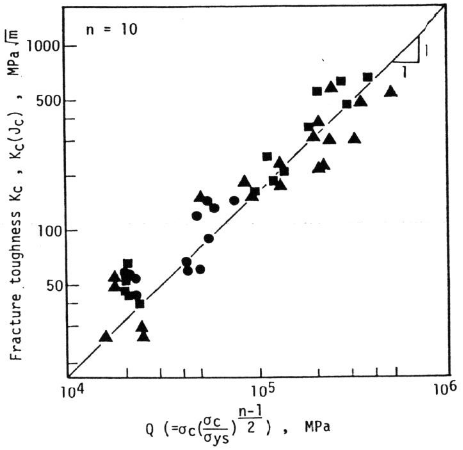


Fig.7. Relation between fracture toughness and cleavage fracture parameter(Miyata et al.,1988).

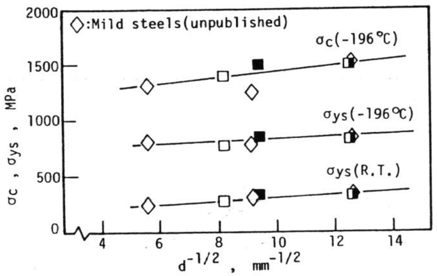


Fig. 8. Variation of cleavage fracture stress and yield stress with $d^{-1/2}$(ferrite).

Figure 8 is a plot of σ_c in the notched specimens and the yield stress, σ_{ys} as a function of $d^{-1/2}$ for steels of T3 condition and other mild steels tested previously by some of the authors, which have fine grained ferrite and pearlite microstructure. Hall-Petch type of relation between σ_c, σ_{ys} and $d^{-1/2}$ can be observed, although the dependency of σ_c on $d^{-1/2}$ is relatively small compared with that in the range of coarser grain(Petch,1953; Knott, 1977). A number of measurements of σ_c in blunt notched specimens of mild steels with different grain sizes by several workers are shown in Fig.9 (Curry,1980) together with the present results. The cleavage fracture in ferrite microstructure seems to be closely related to the grain size. However, it is also obvious that most of the present data are far from the line of σ_c proportional to $d^{-1/2}$, and alternatively, they seem to well fit with Curry's line or to be on the extension of it, which is predicted from the grain boundary carbide model. Knott and Curry (1977,1978) have pointed out that the microstructural parameter governing the cleavage fracture in mild steel is the carbide thickness, Co and the increase of σ_c with $d^{-1/2}$ in fact presents an increase with Co $^{-1/2}$. From experimentally determined relation between d and Co(the coarsest carbide thickness), fracture stress σ_c as a function of $d^{-1/2}$ has been predicted as shown in Fig.9. In the present materials, the thickness of the grain boundary carbide are about 0.3-1.0 μm(average value for each material). These values are consistent with the observation by Curry and Knott(1978) in relation of the ferrite grain size. However, Petch(1986,1987) has shown that the cleavage fracture stress depends on both the carbide thickness and the grain size from the analysis of the energy condition of Stroh(1957) type non-equilibrium carbide crack. Predicted values of the cleavage fracture stress by Petch taking the surface energy γp for the carbide/ferrire boundary as 10J/m^2 are shown in Fig.9. These are also in good agreement with the experimental results. These results indicate that the proposed two grain boundary carbide model, revised Smith model and Petch model appear to be acceptable for the present fine grained ferrite steels, although the observation of the grain boundary carbide film in detail should be required.

The cleavage fracture stress, σ_c in the notched specimen for the steels of T1 and T2 conditions are shown in Fig.9 as a function of the lath packet size. Brozzo *et al.*(1977) have shown the cleavage fracture stress for several bainitic low carbon steels to be proportional to the reciprocal square root of the packet size as also shown in Fig.9. However, Curry(1984) has obtained an experimental result that neither the σ_{ys} nor σ_c decreased systematically with the increase of bainitic packet size in as-transformed materials. Bowen and Knott(1984) examined Brozzo's observation in detail and raised some doubts about the conclusions, discussing together with their own results for A533B pressure vessel steel in the as-quenched martensitic condition. They concluded that the clevage fracture in martensitic condition with the packet size of 3μm to 50μm is not controlled by the prior austenite grain size, the packet size or the lath width in martensitic condition.

The present results, both for the coarse grained bainite and martensite

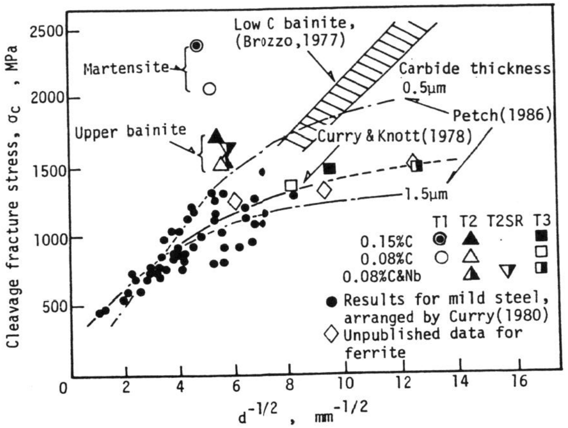


Fig. 9. Correlation between cleavage fracture stress and ferrite grain or packet size.

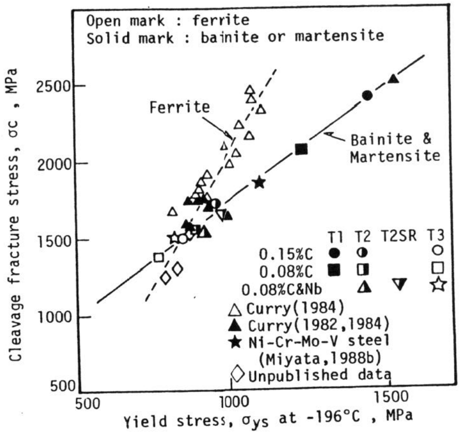


Fig. 10. Correlation between cleavage fracture stress and yield stress at -196°C.

steels with the packet size of 30 to 47μm, also do not support the idea that the critical event in the cleavage fracture of lath microstructural steels is the propagation of packet sized microcracks. It may be more significant that the cleavage fracture stress of martensite with the highest dislocation density shows higher value than other materials at the same $d^{-1/2}$, where d is the ferrite or packet size. Törrönen *et al.*(1981) reported the significance of the dislocation density on the cleavage fracture in Cr-Mo-V steel.

Wallin *et al.*(1984) suggested that the carbide distribution rather than the packet size controls the cleavage fracture in bainitic steels. Another possibility was considered by Khan *et al.*(1982) and Rosenfield *et al.*(1983) that the non-metallic inclusions could be involved in the micro-cracking process in quenched and tempered alloy steels. Bowen and Knott(1984) also favoured an inclusion controlled fracture mechanism in martensitic condition. So, there is no generally agreed model which treats micromechanisms of the cleavage fracture in the bainitic and martensitic microstructure. Probably, several possibilities of the fracture mechanism should be considered from material to material.

From Fig.6 and Fig.8, it can be seen that the same tendency exists in σc and σys, which implies a linear correlation between them. Curry(1984) obtained a linear correlation in several steels involving ferrite and bainitic microstructures. Figure 10 shows all present results of the cleavage fracture stress plotted to corresponding yield stress at the same temperature of -196°C, together with the data obtained by Curry(1982,1984). Open and solid marks show the data for the ferrite and the bainitic or martensitic microstructures, respectively. Present results coincide continuously with the data by Curry, and good correlation between σc and σys can be observed individually for the ferrite and the bainitic/martensitic microstructures. Quantitatively, it may be conceivable that the factors increasing σys by some micromechanisms would have similar effect on σc considering the fact that some amount of yielding is required to nucleate the microcleavage crack. In a certain circumstances, some parameters can only influence σc as shown by McMahon and Cohen(1965). However, more attempt and detailed works to clarify the correlation between σc and σys appear to be worthwhile.

CONCLUSIONS

From the studies of the yield stress and the fracture behaviour of practical microstructures, fine grained ferrite, coarse grained upper bainite and martensite, it may be concluded as follows.

1) There are significant effects of different microstructures on the cleavage fracture. Martensite with high dislocation density and high yield strength has extremely high cleavage fracture stress and low fracture toughness. On the contrary, ferrite shows low σc and high Kc and the upper bainite shows values between them. Carbon content has an additional effect, increasing σc and decreasing Kc.

2) The facet size of the martensite is consistent with the packet size, but that of the upper bainite is 3 to 4 times the packet size and appears to be associated with the prior austenite grain.

3) The results of σc in the ferrite microstructure are well in agreement with the predicted value by Curry and Petch in the relation between σc and $d^{-1/2}$. However, σ_c of the bainitic and martensitic microstructures does not fit the scatter band of results for low carbon bainite obtained by Brozzo *et al.*, and it seems that the packet size is not the only factor governing the cleavage fracture in bainitic and martensitic microstructures.

4) A linear correlation between σc and σys at low temperature of -196°C can be observed differently for ferrite and bainite/martensite.

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