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Fatigue strength of notched specimens having nearly equal sizes of ferrite

N.-A. Noda, H. Nisitani*, S. Harada and Y. Takase

Mechanical Engineering Department, Kyushu Institute of Technology, 1-1 Sensui-cho, Tobata, Kitakyushu 804, Japan
**Mechanical Engineering Department, Kyushu University, Fukuoka 812, Japan*
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In this study, rotating bending fatigue tests were conducted on circumferential notched large and small specimens of three kinds of carbon steel with nearly equal (20 μm) ferrite grain sizes but different volume fractions of pearlite. The effect of microstructures on the fatigue strengths σ_{WS} (the limit stress for slip bands), σ_{W1} (the limit stress for macrocrack initiation), and σ_{W2} (the limit stress for fracture) is discussed by comparing these values in three kinds of carbon steel. The main results newly obtained are as follows. (1) Since σ_{WS} is localized to a highly specified region, variation of $K_t\sigma_{WS}$ (maximum stress repeated at the notch root in the limit stress for slip bands) is small, irrespective of notch root radius. (2) If the grain size of ferrite is nearly equal, variation of σ_{W1} is small irrespective of pearlite under the threshold amount of pearlite. The threshold volume fraction of pearlite is about 50%. (3) In medium-carbon steel, σ_{W2} increases with increasing grain size of ferrite. (4) Notch root radius at the branch point, ρ_0, varies depending on the grain size of ferrite. (5) The values of $K_t\sigma_{w1}$ (maximum stress repeated at the notch root in the limit stress for macrocrack initiation) and $K_t\sigma_{w2}$ (maximum stress repeated at the notch root in the limit stress for fracture) can be determined by the notch root radius ρ alone, independent of geometrical conditions.

(Keywords: fatigue; notch; bending; carbon steel; grain size; fatigue strength; ferrite; pearlite)

It may be regarded as established, by recent investigations, that the fatigue limit of a carbon steel is not the critical stress below which no cracks appear, but the threshold stress where a fatigue crack, developed under the stress level, stops propagating. Thus the fatigue limit of ferritic–pearlitic carbon steels may be considered to be controlled by the propagating condition of a micro fatigue crack induced at the weaker ferrite by repeated stress. From this viewpoint it seems interesting to clarify the effects of the microstructural constituents on the fatigue strength. In previous papers, for example, numerous investigations have been made to find the effects of ferrite grain size on the fatigue strength[1–4]. Then, it has been reported that the limit fatigue stress for plain specimens σ_{W0} increases with decreasing ferrite grain size in the form of the Petch equation:

$$\sigma_{W0} = C_1 + C_2 d_f^{-1/2} \qquad (1)$$

where C_1 and C_2 are constants and d_f is the grain size of ferrite.

A few investigations[5,6] have also been made of the effect of pearlite on the fatigue strength using carbon steels with nearly equal ferrite grain sizes but different amount of pearlite. Yamada *et al.*[5] have indicated that σ_{W0} is almost constant irrespective of the volume fraction of pearlite under equal grain size of ferrite. On the other hand, Nisitani *et al.*[6] have shown that the limit stress for slip bands, σ_{WS}, is almost constant irrespective of pearlite; however, σ_{WO} varies depending on pearlite above a certain amount of pearlite even if the ferrite grain size is equal. In this study, the effect of microstructure on the fatigue strength for notched specimens will be considered because of its importance from the practical point of view.

FATIGUE STRENGTH OF NOTCHED SPECIMENS IN CARBON STEELS

Figure 1 shows the typical relation between the limit stresses σ_{W1} and σ_{W2} and the stress concentration factor K_t, where σ_{W1} is the limit stress for macrocrack initiation and σ_{W2} is the limit stress for final fracture in the range of non-propagating cracks. In the range of no non-propagating cracks, σ_{W1} coincides with the limit stress for fracture; however, it is essential to distinguish σ_{W1} and σ_{W2} when the fatigue strength of notched specimens is discussed.

The critical point where non-propagating cracks appear is called the *branch point*; Nisitani[6] has pointed out that the notch root radius at the branch point is a material constant irrespective of the notch depth t and the diameter of the minimum section, d, unless the notch depth is extremely small. The reason why ρ_0 is a material constant is that the stress distribution near the notch root is controlled by the root radius[7]. Therefore ρ_0 is a controlling parameter of the fatigue limits of notched specimens because they are determined by σ_{W1} when $\rho \geqslant \rho_0$ and by σ_{W2} when $\rho < \rho_0$. Generally, it is well known that σ_W increases with

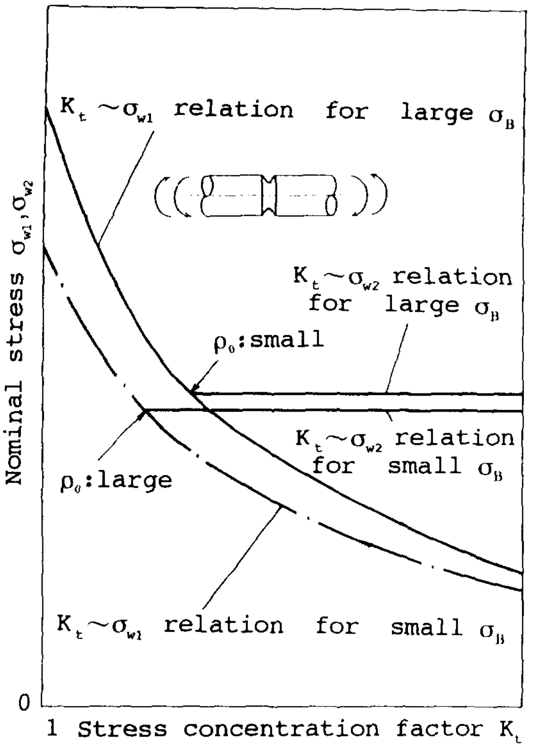

Figure 1 Typical relationships between σ_{W1}, σ_{W2} and K_t

Table 1 Chemical compositions (%)

	C	Si	Mn	P	S	Al
S15C	0.16	0.22	0.50	0.017	0.006	0.037
S35C	0.36	0.23	0.76	0.021	0.022	0.001
S45C	0.46	0.20	0.73	0.029	0.017	0.018

increasing tensile strength σ_B of a material; however, compared with σ_{W0} and σ_{W1}, the limit stress σ_{W2} does not increase very remarkably. As a result, the branch point is shifted to higher stress concentrations with increasing σ_B, and eventually the critical root radius ρ_0 becomes smaller (*Figure 1*). Generally, σ_B increases with increasing carbon content; however, usually this is accompanied by the formation of a pearlite band and the decrease of ferrite grain size. Therefore it has not been clarified yet which microstructural factor controls fatigue parameters such as σ_{W1}, σ_{W2} and ρ_0.

Considering these circumstances, in this study, rotating bending fatigue tests were carried out on plain and notched specimens of three kinds of carbon steel with nearly equal (20 μm) ferrite grain sizes obtained by heat treatment but different volume fractions of pearlite. Fatigue tests were also carried out for 0.16% carbon steel with a ferrite grain size of 50 μm and for 0.46% carbon steel with a ferrite grain size of 5 μm. Through the comparison, the effect of microstructure on the fatigue strengths σ_{WS}, σ_{W1} and σ_{W2} will be discussed.

MATERIALS, SPECIMENS AND TESTING METHOD

The materials used were 0.16%C low-carbon steel (JIS S15C), 0.36%C medium-carbon steel (JIS S35C) and 0.46%C medium-carbon steel (JIS S45C), in rolled cylindrical bars of 20 mm diameter. The chemical compositions are shown in *Table 1*. The specimens were turned after heat treatment shown in *Table 2*. The microstructures, with nearly equal (20 μm) ferrite grain sizes are shown in *Figure 2*. The mechanical properties of the specimens are also shown in *Table 2*. Fatigue tests were also carried out for 0.16% carbon steel with a ferrite grain size of 50 μm and for 0.46% carbon steel with a ferrite grain size of 5 μm.

The principal dimensions of the specimens are shown in *Figures 3* and *4*. The form of the notch was a 60 ° V-shaped circumferential groove (when $t/\rho \geq 0.5$, it was a circular arc). The minimum diameter of each specimen was 5 mm and 10 mm. All specimens were subjected to heat treatment in a vacuum after electropolishing to a depth of about 10 μm, before tests, to eliminate work-hardened layers. The machine used was a rotating fatigue testing machine of uniform bending moment type (Ono-type). The notched surfaces of the specimens were observed by using optical and scanning electron microscopes (SEM).

Here the stress is defined as the nominal bending stress of the minimum section. The crack initiation limit σ_{W1} is defined as the stress required to develop microcracks after 10^7 cycles, where the size of the microcracks is approximately the same as that of a non-propagating microcrack observed at the fatigue limit of a plain specimen. Also, the slip band initiation limit σ_{WS} was observed for 0.16% and 0.46% carbon steel with ferrite grain size of 20 μm. The step of the

Table 2 Heat treatment and mechanical properties of the specimens

Material	Heat treatment	Mechanical properties σ_Y (MPa)	σ_B (MPa)	σ_T (MPa)	ψ (%)	d_f (μm)	V_{fp} (%)
S15C	1000 °C 2 h, air-cooled	231	422	923	68.8	20	19
	1050 °C 2 h, furnace-cooled	187	412	776	60.6	50	19
S35C	900 °C 2 h, furnace-cooled	303	558	906	48.2	20	42
S45C	1000 °C 2 h, furnace-cooled	352	631	979	45.2	20	57
	844 °C 2 h, furnace-cooled	399	653	1088	51.4	5	57

σ_Y, yield stress; σ_B, tensile strength; σ_T, actual stress at fracture; ψ, area contraction; d_f, ferrite grain size; V_{fp}, volume fraction of pearlite

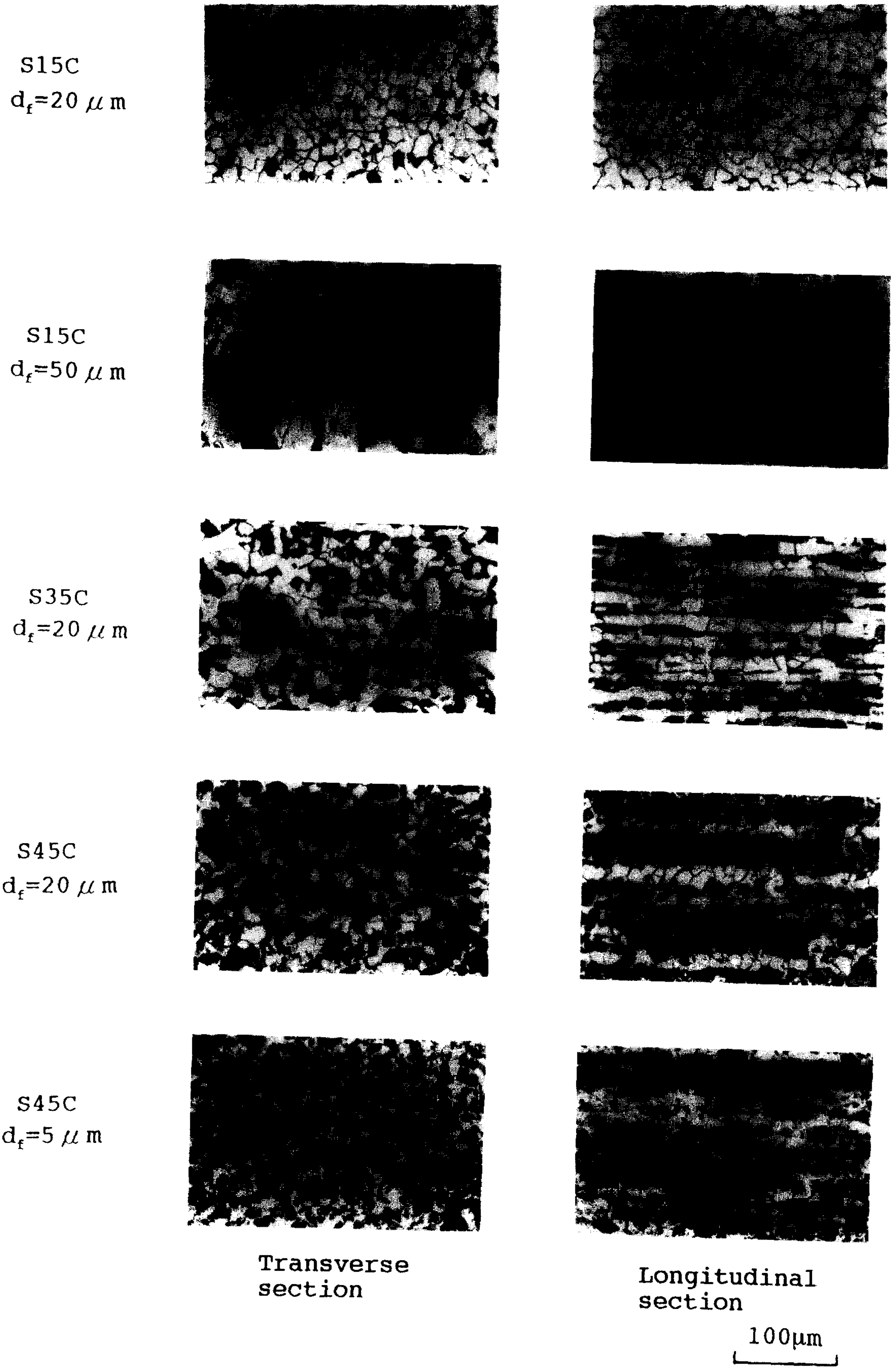

Figure 2 Microstructure of the specimens

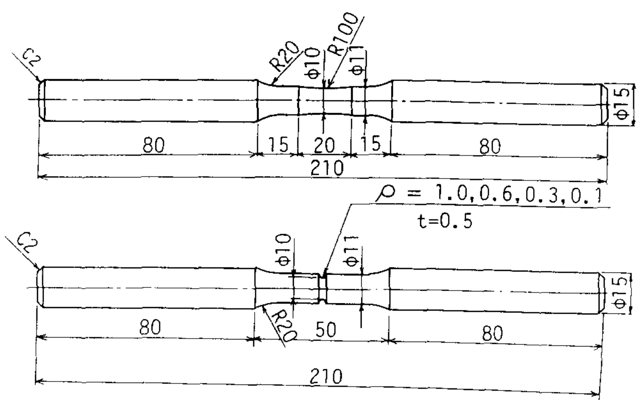

Figure 3 Plain and notched specimens (large type)

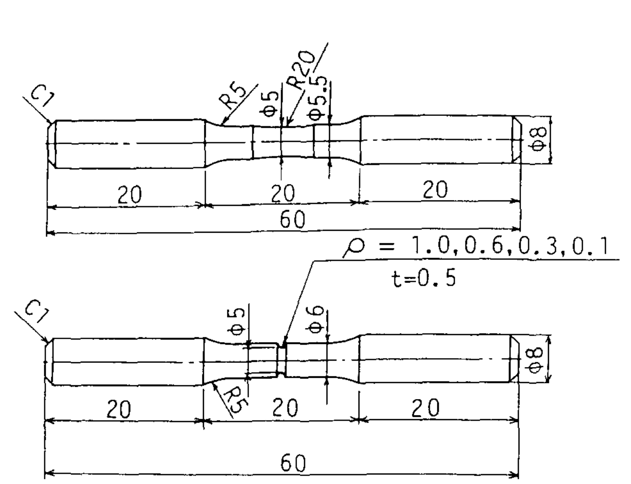

Figure 4 Plain and notched specimens (small type)

stress level used to determine σ_{W1}, σ_{W2} and σ_{WS} was 5 MPa.

EXPERIMENTAL RESULTS AND DISCUSSION

Yield stress σ_Y, tensile strength σ_B and the limit stress σ_{W0} for small plain specimens, with nearly equal ferrite grain size d_f are shown in *Table 3* with the ratios to the results for 0.16% carbon steel. The stresses σ_Y and σ_B increase with increasing amount of pearlite. However, the limit stress σ_{W0} does not vary very much under a specific amount of pearlite and increases with pearlite above that amount. The threshold volume fraction of pearlite is about 50% ($V_{fpth} \cong 50$). The results in *Table 3* are in agreement with those of

Table 3 Yield stress σ_Y, tensile strength σ_B and limit fatigue stress for small plain specimens, σ_{W0}, of nearly equal ferrite grain sizes, d_f, with the ratios to the results for 0.16% carbon steel

	σ_Y (MPa)	σ_B (MPa)	σ_{W0} (MPa) d = 10 mm	σ_{W0} (MPa) d = 5 mm
S15C	231	422	210	215
	(1.00)	(1.00)	(1.00)	(1.00)
S35C	303	558	225	225
	(1.31)	(1.32)	(1.07)	(1.05)
S45C	352	631	255	260
	(1.52)	(1.50)	(1.21)	(1.21)

Table 4 Limit stress for slip bands, σ_{WS}, for 0.16% and 0.46% notched small specimens of nearly equal grain sizes of ferrite

Material	ρ (mm)	K_t	σ_{WS} (MPa)
S15C	∞	1.00	160
	0.3	2.38	70
	0.1	3.77	50
S45C	∞	1.00	175
	0.3	2.38	80
	0.1	3.77	55

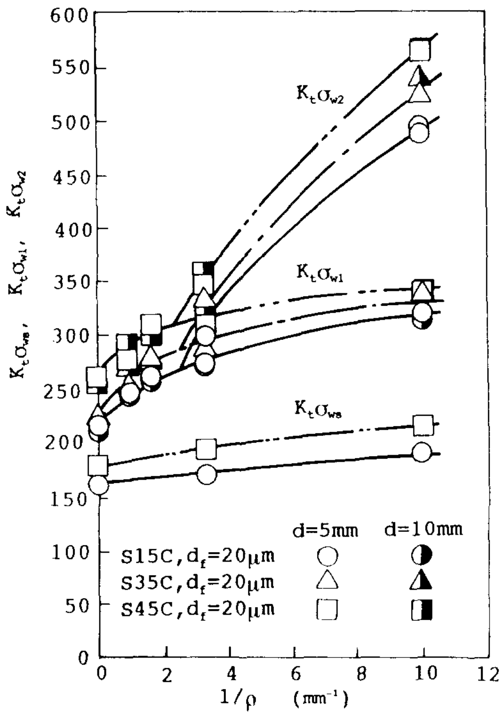

Figure 5 $K_t\sigma_{WS}$ versus $1/\rho$, $K_t\sigma_{W1}$ versus $1/\rho$ and $K_t\sigma_{W2}$ versus $1/\rho$

Table 5 Principal dimensions of large specimens

Material	ρ (mm)	K_t	σ_{W1} (MPa)	σ_{W2} (MPa)	d_f (μm)
S15C	∞	1.00	210	–	20
	1.0	1.87	130	–	20
	0.6	2.21	115	–	20
	0.3	2.86	95	105	20
	0.1	4.53	70	110	20
S35C	∞	1.00	225	–	20
	1.0	1.87	145	–	20
	0.6	2.21	125	–	20
	0.3	2.86	100	115	20
	0.1	4.53	75	120	20
S45C	∞	1.00	255	–	20
	1.0	1.87	155	–	20
	0.6	2.21	135	–	20
	0.3	2.86	110	125	20
	0.1	4.53	75	125	20

σ_{W1}, limit stress for macrocrack initation; σ_{W2}, limit stress for fracture; d = 10 mm

Table 6 Principal dimensions of small specimens

Material	ρ(mm)	K_t	σ_{W1} (MPa)	σ_{W2} (MPa)	d_f (μm)
S15C	∞	1.00	215	-	20
	1.0	1.59	155	-	20
	0.6	1.87	140	-	20
	0.3	2.39	115	125	20
	0.1	3.77	85	130	20
S15C	∞	1.00	180	-	50
	0.3	2.39	100	125	50
	0.1	3.77	70	125	50
S35C	∞	1.00	225	-	20
	1.0	1.59	160	-	20
	0.6	1.87	150	-	20
	0.3	2.39	120	140	20
	0.1	3.77	90	140	20
S45C	∞	1.00	260	-	20
	1.0	1.59	175	-	20
	0.6	1.87	165	-	20
	0.3	2.39	130	145	20
	0.1	3.77	90	150	20
S45C	∞	1.00	280	-	5
	0.3	2.39	145	-	5
	0.1	3.77	100	140	5

d = 5 mm

Nisitani *et al.*[6]. *Table 3* suggests that σ_Y and σ_B depend on the total properties of the microstructure but that σ_{WO} depends on the more localized properties of the microstructure. The reason for this is that σ_{WO} is controlled by the propagating condition of a micro fatigue crack induced at the weaker ferrite.

Table 4 shows the limit stress for slip bands, σ_{WS}, for 0.16% and 0.46% notched small specimens with

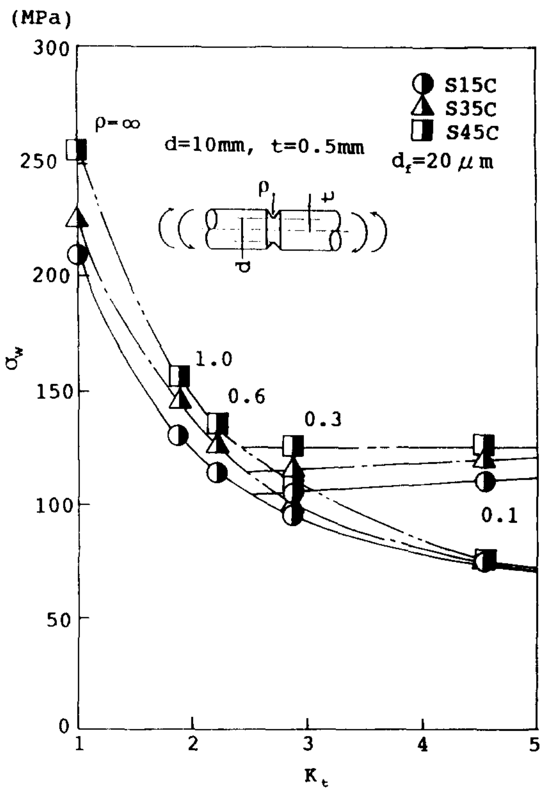

Figure 6 Plots of σ_{W1} and σ_{W2} versus K_t for large specimens

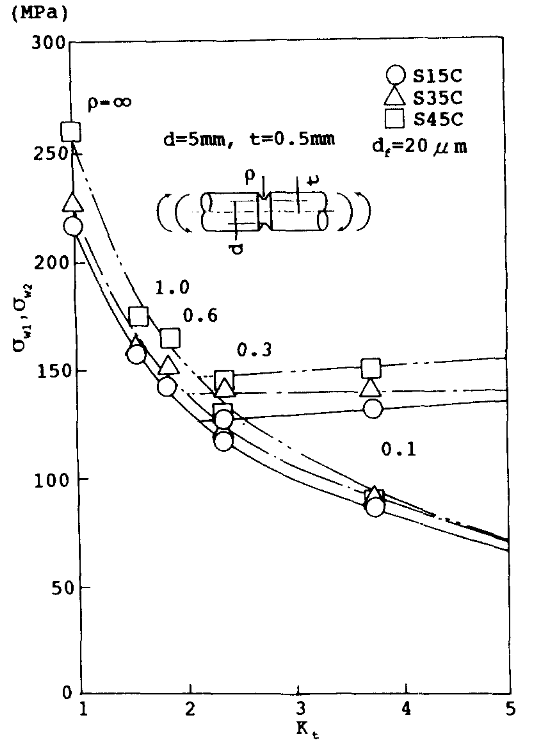

Figure 7 Plots of σ_{W1} and σ_{W2} versus K_t for small specimens

Table 7 Root radius of notches, ρ_0, at the branch point and the ferrite grain size, d_f, compared with the previous result

	Previous result	Present result	
S15C	(d_f = ?) 0.6	(d_f = 20 μm) 0.4	(d_f = 50 μm) 0.6
S35C	(d_f = ?) 0.4	(d_f = 20 μm) 0.4	
S45C	(d_f = ?) 0.25	(d_f = 20 μm) 0.4	(d_f = 5 μm) 0.25

nearly equal grain sizes of ferrite. The relations of $K_t\sigma_{WS}$ versus $1/\rho$ are shown together with the relations $K_t\sigma_{W1}$ versus $1/\rho$ and $K_t\sigma_{W2}$ versus $1/\rho$ in *Figure 5.*, where $K_t\sigma_{WS}$ is the maximum stress repeated at the notch root under the stress σ_{WS}, and $K_t\sigma_{W1}$ and $K_t\sigma_{W2}$ are defined similarly. Comparing the results for 0.16% and 0.46% steels, it is found that the difference due to the pearlite amount is smaller in σ_{WS} and larger in σ_{W1} and σ_{W2}. Moreover, the variation of maximum stress for slip bands, $K_t\sigma_{WS}$, is small irrespective of ρ, compared with $K_t\sigma_{W1}$ and $K_t\sigma_{W2}$. This suggests that the region related to the formation of slip bands, σ_{WS}, is more localized than the region related to σ_{W1} and σ_{W2}; thus the stress gradient controlled by the notch root radius ρ does not have much influence on σ_{WS}.

The results for σ_{W1} and σ_{W2} are shown in *Tables 5* and *6* with accurate stress concentration factors based on analysis using the body force method[8]. The relations of σ_{W1} and σ_{W2} versus K_t for small and large specimens are shown in *Figures 6* and *7* respectively. The limit stresses σ_{W1} and σ_{W2} increase with the increasing amount of pearlite. Compared with previous research where the grain size was not equal (*Figure 1*), *Figure 6* indicates that σ_{W2} increases considerably with the

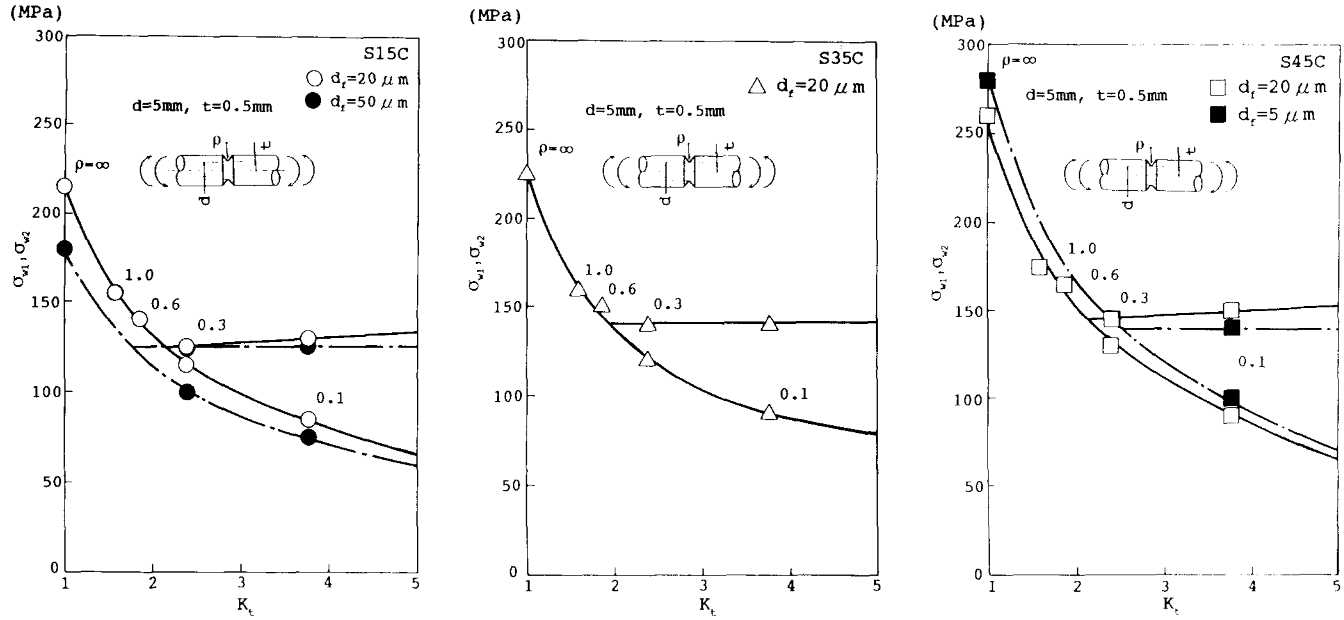

Figure 8 Plots of σ_{W1} and σ_{W2} versus K_t for small specimens

Table 8 Maximum stress repeated at the notch root in the limit stress for macrocrack initiation, $K_t\sigma_{W1}$, and the maximum stress repeated at the notch root in the limit stress for fracture, $K_t\sigma_{W2}$

			$K_t\sigma_{W1}$			$K_t\sigma_{W2}$		
ρ (mm)	d (mm)	K_t	S15C	S35C	S45C	S15C	S35C	S45C
∞	10	1.00	210	225	255	–	–	–
∞	5	1.00	210	225	260	–	–	–
1.0	10	1.87	243	271	290	–	–	–
1.0	5	1.59	246	254	278	–	–	–
0.6	10	2.21	254	276	298	–	–	–
0.6	5	1.87	262	281	309	–	–	–
0.3	10	2.86	272	286	315	300	329	358
0.3	5	2.39	275	287	311	299	335	347
0.1	10	4.53	317	340	340	498	544	566
0.1	5	3.77	320	339	339	490	528	566

t = 0.5 mm

increasing amount of pearlite, and eventually the values of the root radius of notches, ρ_0, at the branch point are about the same (0.4 mm) for the three kinds of carbon steels. In other words, σ_{W2} increases more remarkably with increasing amounts of pearlite when the ferrite grain size is nearly equal. To confirm these findings, fatigue tests were also carried out for 0.16% carbon steel with a ferrite grain size of 50 μm and for 0.46% carbon steel with a ferrite grain size of 5 μm. The results for σ_{W1} and σ_{W2} are also shown in *Table 6* and *Figure 8*. The root radius of notches, ρ_0, at the branch point and the ferrite grain size d_f are shown in *Table 7* and compared with the previous result. The ρ_0 values of 0.16% carbon steel when d_f = 50 μm and of 0.46% carbon steel when d_f = 5 μm coincide with the previous results obtained by Nisitani *et al.*

Table 6 and *Figure 8c* tell us that σ_{W2} increases with increasing ferrite grain size in medium-carbon steels: that is, the effect of grain size on σ_{W2} is completely different from its effect on σ_{W0} and σ_{W1}. To examine the mechanism, the non-propagating cracks after repeating the σ_{W2} stress 10^7 times were observed by optical and scanning electron microscopes. *Figure 9* shows non-propagating cracks in cross-section after annealing at 400 °C and fracture. The depth of the crack when d_f = 20 μm varies remarkably but the depth of the crack when d_f = 5 μm is almost constant along the circumference. *Figure 10* shows cracks observed by SEM in longitudinal section after cutting. Crack deflection can be clearly seen when d_f = 20 μm. From these figures, the increased grain size of ferrite appears to promote the deflection of crack propagation and finally to stop the propagation.

The $K_t\sigma_{W1}$ versus $1/\rho$ relations are shown in *Figure 11*, where $K_t\sigma_{W1}/\sigma_{W0}$ is the normalized maximum stress repeated at the notch root under the fatigue limit σ_{W1}. The previous results using exact K_t are also shown in the figure for comparison with the present results (S10C[11], S20C[7], S30C[12] and S45C[9,10]). In the present results, with nearly equal ferrite grain sizes, the notch sensitivity of 0.16%C steel is similar to that of 0.36%C steel; however the notch sensitivity of 0.46%C steel is greater, owing to the effect of pearlite. Thus the effect of pearlite on the notch sensitivity of

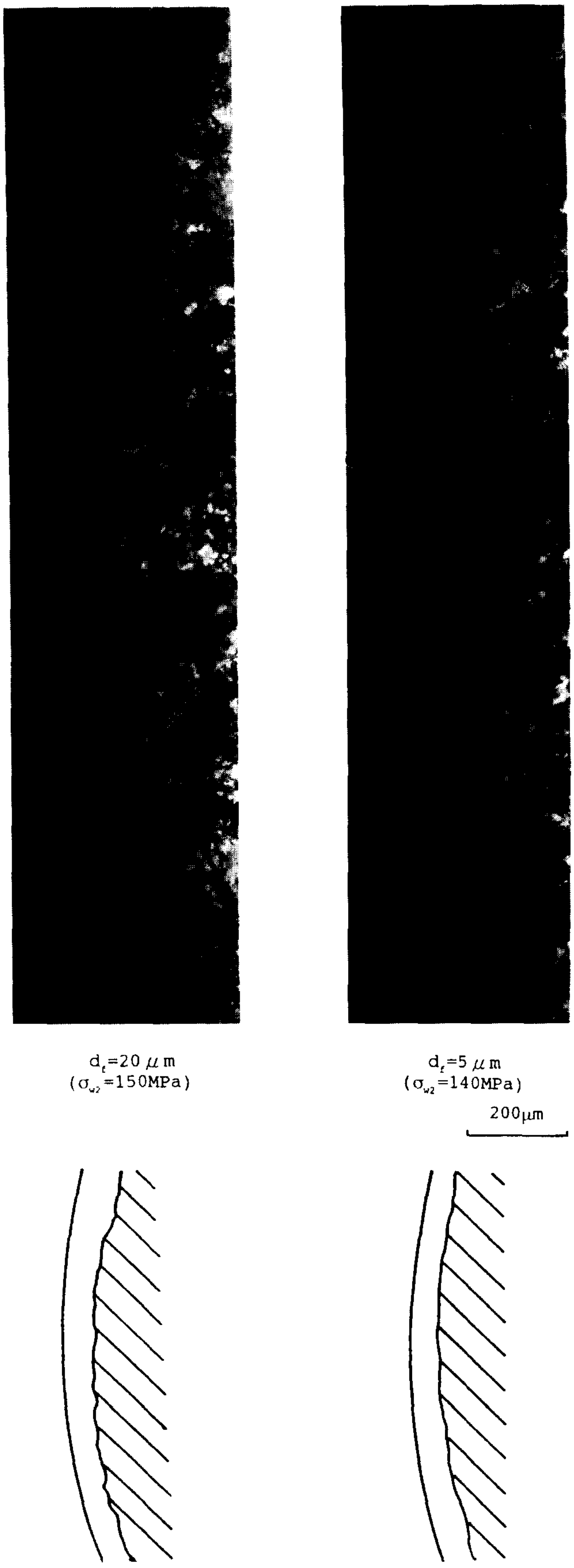

Figure 9 Non-propagating cracks (cross-section, d = 5 mm, t = 0.5 mm, ρ = 0.1)

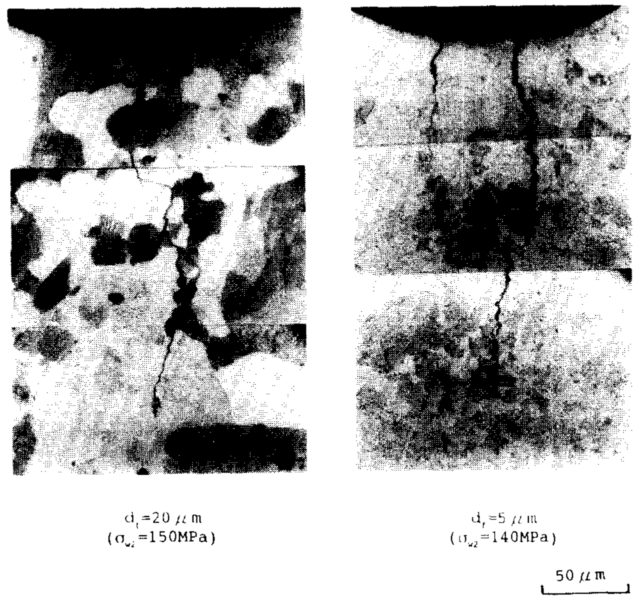

Figure 10 Non-propagating cracks (longitudinal section, d = 5 mm, t = 0.5 mm, ρ = 0.1)

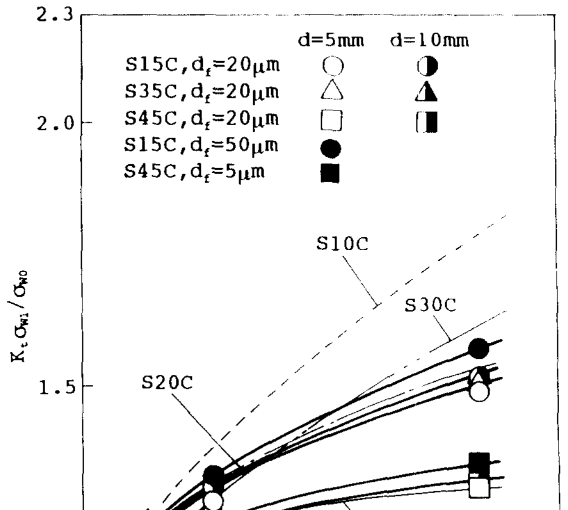

Figure 11 Plot of $K_t\sigma_{W1}$ versus $1/\rho$, where $K_t\sigma_{W1}/\sigma_{W0}$ is the normalized maximum stress repeated at the notch root under the fatigue limit σ_{W1}

σ_{W1} is similar to the effect of pearlite on σ_{W0} (*Table 2*).

The $K_t\sigma_{W2}$ versus $1/\rho$ relations are shown in *Figure 12*, where $K_2\sigma_{W2}/\sigma_{W0}$ is the normalized maximum stress repeated at the notch root under the fatigue limit of σ_{W2}. In *Figures 4*, *10* and *11*, results for both large and small specimens can be plotted on the same curves on the basis of linear notch mechanics proposed by Nisitani[12,13]. *Table 8* shows the values of $K_t\sigma_{W1}$ and $K\sigma_{W2}$ for large and small specimens.

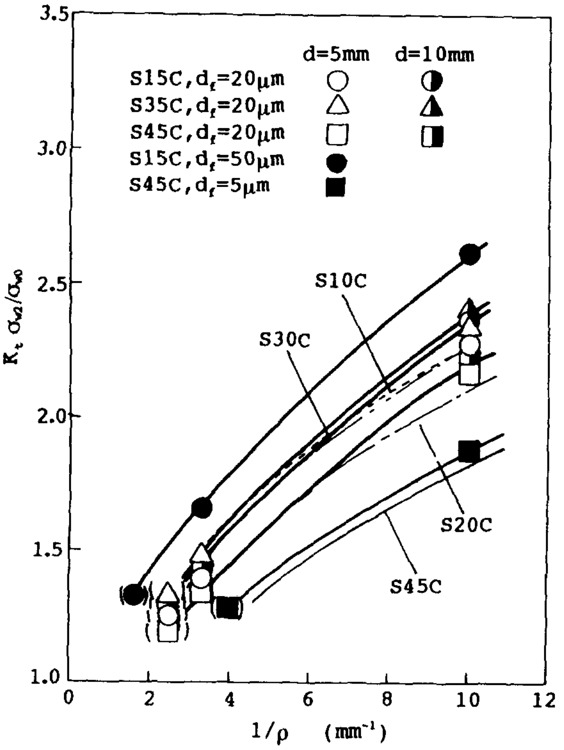

Figure 12 Plot of $K_t\sigma_{W2}$ versus $1/\rho$, where $K_t\sigma_{W2}/\sigma_{W0}$ is the normalized maximum stress repeated at the notch root under the fatigue limit σ_{W2}

CONCLUSIONS

From the results of rotating bending fatigue tests for plain and notched specimens of three kinds of carbon steel with nearly equal (20 μm) ferrite grain sizes, the following conclusions may be drawn.

1. The variation of the maximum stress at the notch root in the limit stress for slip bands, $K_t\sigma_{WS}$, is small irrespective of notch root radius. This suggests that σ_{WS} is localized to a highly specified region compared with the region related to the limit stress for crack initiation, σ_{W1}.
2. If the grain size of ferrite is nearly equal, the variation of σ_{W1} is small irrespective of pearlite under a certain amount; however, σ_{W0} varies depending on pearlite above this threshold value. The threshold volume fraction of pearlite is about 50%.
3. In medium-carbon steel, the limit stress for fracture, σ_{W2}, increases with increasing grain size of ferrite, because the crack deflection caused by the increased grain size of ferrite promotes crack arrest.
4. The notch root radius at the branch point, ρ_0, varies depending on the grain size of ferrite, because σ_{W1} and σ_{W2} have different dependences on the grain size of ferrite.
5. In carbon steels with nearly equal ferrite grain sizes, the values of $K_t\sigma_{W1}$ and $K_t\sigma_{W2}$ can be determined by the notch root radius, ρ, alone, independent of geometrical conditions.

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NOMENCLATURE

D	Outer diameter of specimen
d	Minimum diameter of specimen
d_f	Ferrite grain size
K_t	Stress concentration factor
$K_t\sigma_{W1}$	Maximum stress repeated at notch root in limit stress for macrocrack initiation
$K_t\sigma_{W2}$	Maximum stress repeated at notch root in limit stress for fracture
$K_t\sigma_{WS}$	Maximum stress repeated at notch root in limit stress for slip band
t	Depth of notch
V_{fp}	Volume fraction of pearlite
V_{fpth}	Threshold volume fraction of pearlite when σ_{W0} increases
ρ	Root radius of notch
ρ_0	Root radius of notch at the branch point
σ_B	Tensile strength
σ_T	Actual stress at fracture
σ_{W0}	Limit fatigue stress for plain specimen
σ_{W1}	Limit stress for macrocrack initiation
σ_{W2}	Limit stress for fracture
σ_{WS}	Limit stress for slip band
σ_Y	Yield stress
ψ	Area contraction