

THE SIZE EFFECT ON FATIGUE STRENGTH OF STRUCTURAL STEEL MATERIALS IN HIGH-HUMIDITY ENVIRONMENT

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ABSTRACT

Fatigue tests under rotating bending fatigue testing machine has been carried out to estimate the size effect on fatigue strength of structural steel materials in high-humidity environment. The size and geometry of the specimens were in accordance with specifications of ASTM E-466. The specimen contains a shallow notch to observe crack initiation. The specimen surface and shallow notch were ground with grade 1200 emery paper and then were buff finished. The tests were carried out a variation of diameter size specimens from 8 mm, 2 mm, and 1 mm in humidity environment with 60 % relative humidity, 70 % relative humidity, 80 % relative humidity and 90 % relative humidity. The results show that the fatigue strength increases with decreasing specimen size from diameter of 2 mm and 1 mm of SS400 and S45C steels in high-humidity environment. Ion-exchanged water remarkably reduces the fatigue strength of these steels. The initiation and propagation behaviors of micro cracks were investigated on the specimen surface. Cracks were observed by a scanning electron microscope (SEM).

Keywords : *Fatigue strength, structural steel, high-humidity environment, crack length, fatigue test.*

1.0 INTRODUCTION

In the previous studies, the effect of high-humidity environment on fatigue strength of metal materials such as structure steel and aluminum alloys has been reported [1, 2]. The results show that high-humidity environment with ranges from 70 to 90 % RH reduces remarkably in fatigue strength. Thus, a transition of environmental fatigue strength was found with increasing humidity for those metal materials. Concerning the effect of specimen size on corrosion fatigue in salt water and sea water was investigated. The result found that the fatigue strength decreases with decreasing diameter and the fatigue strength increases in tap water [3]. Due to salt water and sea water are severe corrosion behaviour environment compared with in tap water the crack occurs very fast. However corrosion and crack very difficult to occur in tap water compared with in salt water. The smallest size of specimen is failure in short time than biggest size of specimen [4]. The shear stress of the smallest size will become higher than that of the largest size which is volume of surface decrease. Thus, the effect of specimen size on fatigue strength in high-humidity environment has not been clarified completely.

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The aim of this study is first to reveal the size effect on fatigue strength of structural steel materials in high-humidity environment, and then to clarify the crack initiation mechanisms.

2.0 EXPERIMENTAL

The materials used in this study are two kinds of carbon steels SS400 and S45C. Chemical compositions and mechanical properties of the materials are listed in Table I and 2, respectively. The specimen diameter of 8 mm was machined from bar with diameter of 12 mm and the specimens diameter of 2 mm and 1 mm were machined from bar with diameter of 3 mm. The shape and dimension of the specimen diameter of 8 mm, 2 mm, and 1 mm are shown in Figure 1, 2, 3, respectively. The fatigue tests were performed in the high-humid environment between 60 and 90 % relative humidity (referred to as 60 and 90 % RH hereinafter) using a humidifying unit. The test temperature was room temperature. The temperature was kept constant by a combination of heating lamp and a thermo-couple controller. For the solution test, the specimens were fully immersed in ion-exchanged water, which was circulated at 0.4 l/min between a test chamber and a reservoir, but the dissolved oxygen was not controlled. Cracks were observed by a scanning electron microscope (SEM).

Table 1: Chemical Composition on Materials (%WT)

Material	C	S _i	Mn	P	S
SS400*	0.12	0.14	0.54	0.016	0.028
SS400**	0.17	0.26	0.76	0.033	0.026
S45C*	0.45	0.25	0.79	0.011	0.010
S45C**	0.46	0.27	0.50	0.011	0.023

* Specimen 8 mm

** Specimen 1 and 2 mm

Table 2: Mechanical Properties

Material	Yield Strength σ_y (N/mm ²)	Ultimate Strength σ_{ut} (N/mm ²)	δ (%)	Hv
SS400*	455	657	40	190
SS400**	368	648	25	216
S45C*	514	781	36	226
S45C**	928	1160	49	306

* Specimen 8 mm

** Specimen 1 and 2 mm

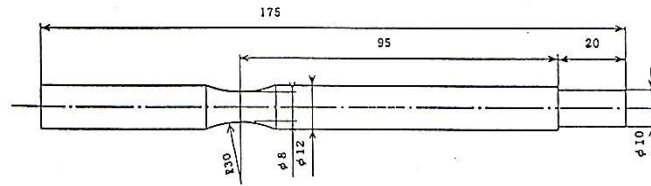


Figure 1: Shape and dimension of the specimen diameter of 8 mm

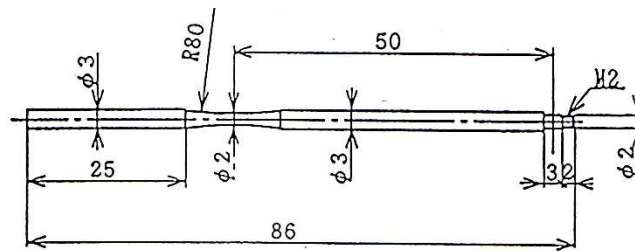


Figure 2 : Shape and dimension of the specimen diameter of 2 mm

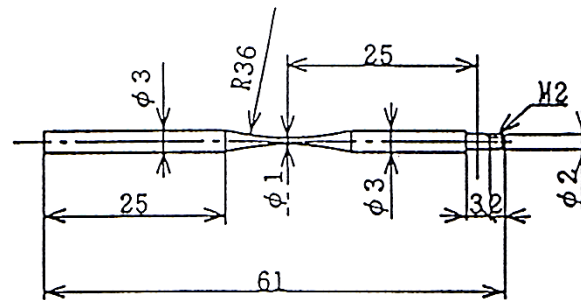


Figure 3 : Shape and dimension of the specimen diameter of 1 mm

3.0 EXPERIMENTAL RESULTS AND DISCUSSION

3.1 A Effect of High-Humidity Environment on Fatigue Strength

Figure 4, 5, and 6 show the S – N curves of SS400 steel for diameter of 8 mm, 2 mm, and 1mm. The tests were carried out in laboratory air, in humid air and in ion-exchanged water. It can be seen from these figures that fatigue strength (σ) of SS400 steel is 400 MPa in laboratory air (60 % RH) which is the same as obtained at 70 % RH. Fatigue strength is number of cycles of stress of a material which can withstand before failure. The fatigue strength of 1 mm is higher than that of 2 mm and 8 mm in laboratory air with 60 % RH. Fatigue strength decreases at 85 and 90 % RH, and the fatigue strength of 8 mm is lower than that of 2 mm and 1 mm, which is decrease sharply in ion-exchanged water. For diameter of 8 mm, 2 mm, and 1 mm of S45C steel are shown in Figure 7, 8, and 9, the same result as SS400 steel that in high-humidity environment reduces the fatigue strength of S45C steels for diameter of 8 mm, 2 mm, and 1 mm, and then in ion-exchanged water remarkably reduces the fatigue strength of this steel. Thus, the effect of high-humidity environment reduces fatigue strength for both SS400 and S45C steels.

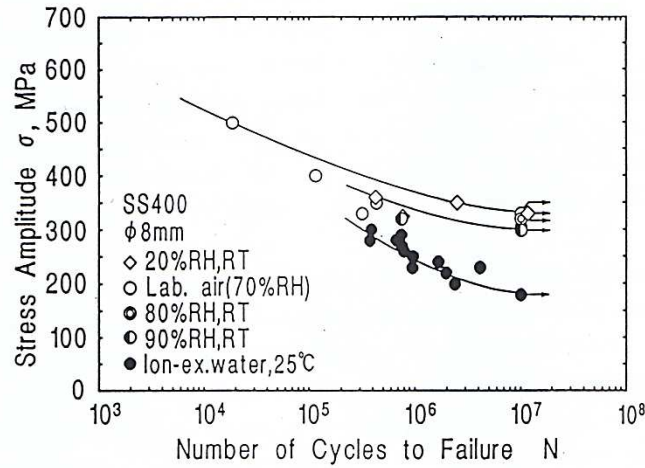


Figure 4 : S - N curves of SS400 steel for diameter of 8 mm

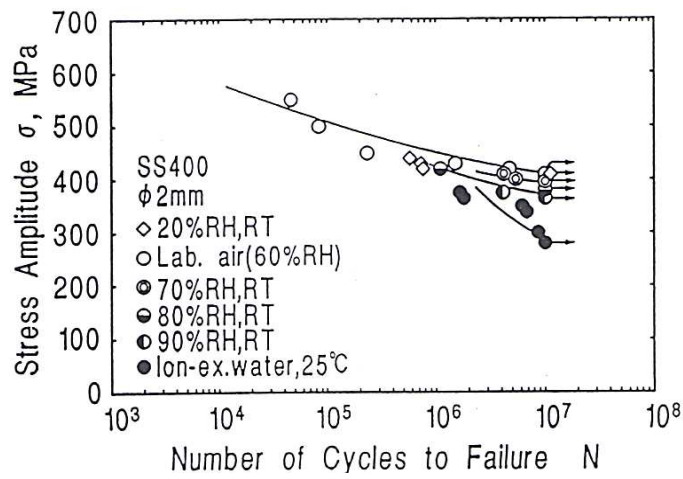


Figure 5 : S - N curves of SS400 steel for diameter of 2 mm

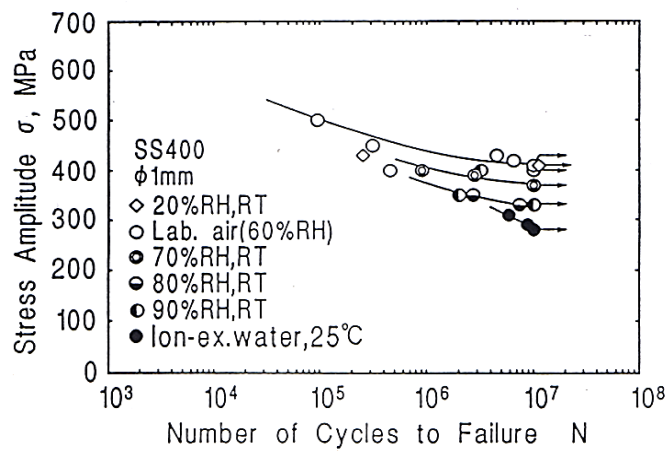


Figure 6 : S - N curves of SS400 steel for diameter of 1 mm

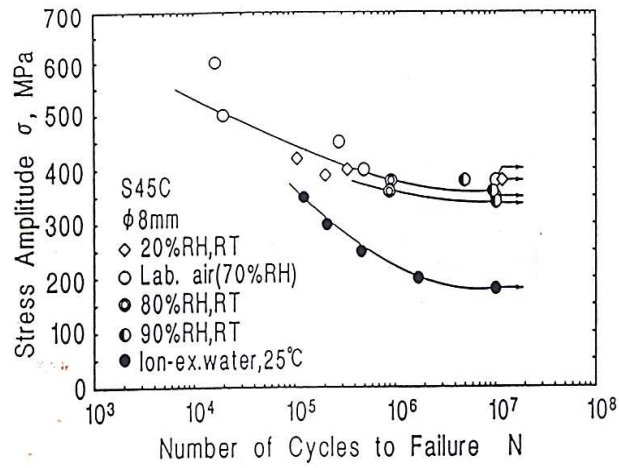


Figure 7 : S - N curves of S45C steel for diameter of 8 mm

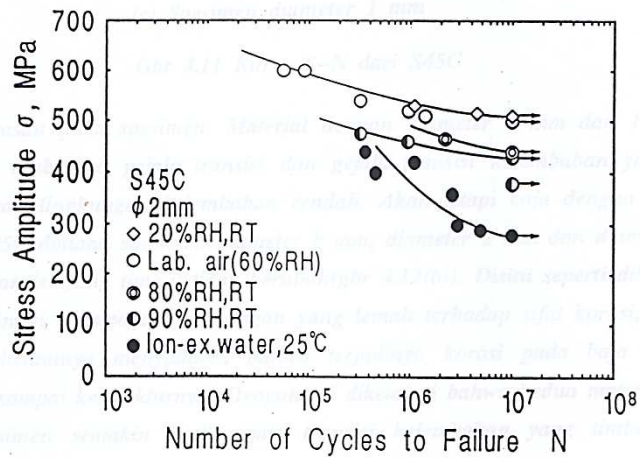


Figure 8 : S - N curves of S45C steel for diameter of 2 mm

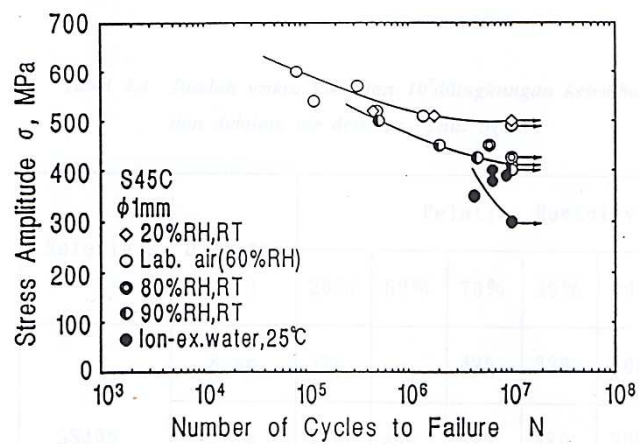


Figure 9 : S - N curves of S45C steel for diameter of 1 mm

Figure 10 and 11 summarize the results obtained when experiment is conducted in humidity environment between 20 % RH and 90 % RH for specimen diameter of 8 mm, 2 mm and 1 mm. As seen from these figures, the transition of fatigue strength occurs on the fatigue strength of SS400 and S45C steels at 10^7 cycles under rotating bending load fatigue test in high-humidity environment between 60 % RH and 80 % RH for diameter of 2 mm and 1 mm, and then the transition of fatigue strength occurs in high-humidity environment between 70 % RH and 80 % RH for diameter of 8 mm. In the previous study, fatigue strength reduce remarkably and a the transition of fatigue strength occurs in high-humidity environment between 70 % RH and 80 % RH for axial loading fatigue test [1]. Generally, one would expect that high-humidity environment would reduce fatigue strength in both SS400 and S45C steels. Therefore, it is clear that in high-humidity environment a transition of fatigue strength of SS400 and S45C steels for diameter of 8 mm, 2mm, and 1 mm is present. In high-humidity environment crack growth seems to occur on the surface specimen.

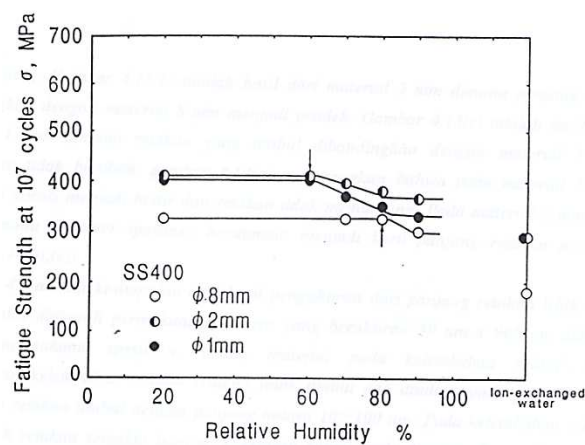


Figure 10 : Relation between fatigue strength at 10^7 cycles and relative humidity of SS400 steel

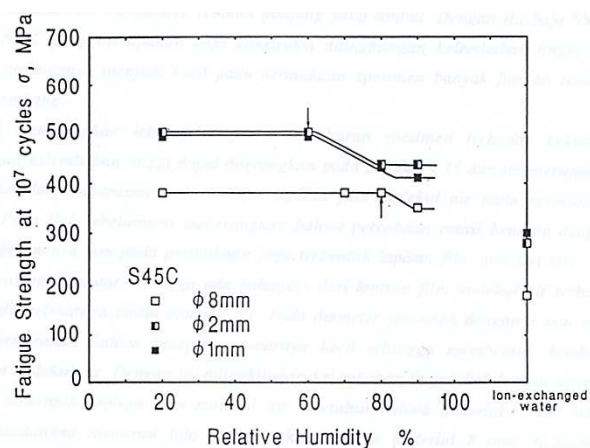
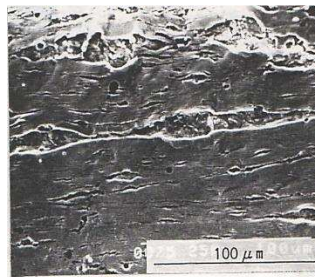


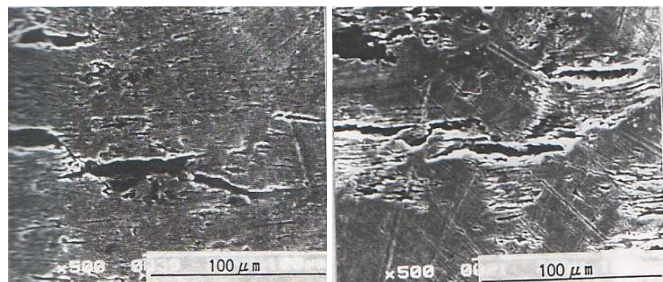
Figure 11 : Relation between fatigue strength at 10^7 cycles and relative humidity of S45C steel

3.2 Crack Initiation in High-Humidity Environment

Figure 12 and 13 show the photographs of surface cracks for SS400 steel in high-humidity environment in the vicinity of a pioneer crack on the shallow notch of the specimen, which was fatigued at 10^7 cycles. The loading direction has been maintained perpendicular to the axis of specimen. It can be seen that Figure 12(a), (b), and (c) show crack initiation and pit corrosion on the surface specimen of SS400 steel. For specimen diameter of 8 mm, the length crack occurs on the surface and many cracks initiate and some of them were joined together to form a long crack on the surface specimen diameter of 2 mm. The photograph for diameter of 1 mm is the same as diameter of 2 mm many crack initiate and they were joined together to form a long crack. Furthermore, for specimen diameter of 8 mm of S45C steel crack initiates shorter than that of SS400 steel in high-humidity environment and the same results as specimen diameter of 2 mm and 1 mm that the crack length initiates more shorter than that of SS400 steel. The length of cracks was measured in the area close to the final fracture on the fatigue surface specimen and the crack length was $20\mu\text{m}$. The results are summarized in Table III. The distribution of the length is different depending on humidity and material. The crack length is in the range from $10\mu\text{m}$ to $1000\mu\text{m}$. In high-humidity environment at 90 % RH, both SS400 and S45C steels, the number of cracks on the specimen diameter of 8 mm is higher than that of the specimen diameter of 2 mm and 1 mm. Therefore, the fatigue strength increases with decreasing the specimen size to diameter of 2 mm to 1 mm in high-humidity environment.

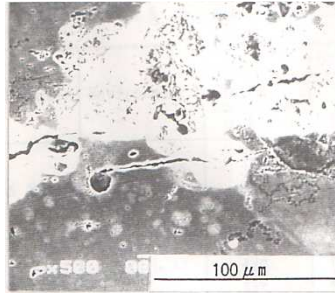


$\sigma = 350\text{ MPa}$, $N = 6.742 \times 10^5$ cycles
(a) Diameter specimen of 8 mm

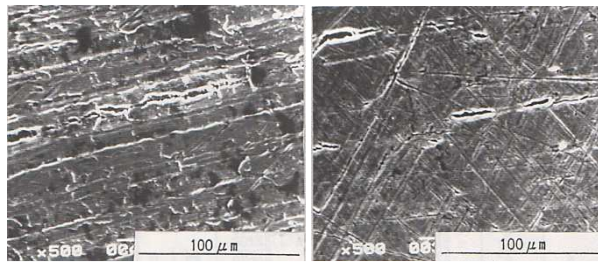


$\sigma = 375\text{ MPa}$, $N = 4.1 \times 10^6$ cycles $\sigma = 350\text{ MPa}$, $N = 6.4 \times 10^6$ cycles
(b) Diameter specimen of 2 mm (c) Diameter specimen of 1 mm

Figure 12 : Surface cracks of SS400 steel in high-humidity environment



$\sigma = 360$ MPa, $N = 9.24 \times 10^6$ cycles
 (a) Diameter specimen of 8 mm



$\sigma = 440$ MPa, $N = 5.8 \times 10^6$ cycles
 (b) Diameter specimen of 2 mm

$\sigma = 425$ MPa, $N = 4.6 \times 10^6$ cycles
 (c) Diameter specimen of 1 mm

Figure 13 : Surface cracks of S45C steel in high-humidity environment

Table 3 : Number of Crack (Area 50 x 50μm)

Material	Diameter Ø (mm)	Environment % Relative Humidity (RH)	Fatigue Strength σ (MPa)	Number of cracks		
				Crack Length (μm)	Crack Length (μm)	Crack Length (μm)
				10 -100	101-500	501-1000
SS400	8	20	350	0	0	0
		70 (LA)	350	24	0	0
		80	325	34	0	0
		90	350	52	9	3
		IEW	200	36	11	5
	2	20	440	0	0	0
		60 (LA)	420	24	0	0
		70	410	26	1	0
		80	390	30	1	0
		90	375	37	3	0
		IEW	340	15	4	1
	1	20	400	0	0	0
		60 (LA)	400	18	0	0
		70	390	31	2	0
		80	330	48	2	0
90		350	52	2	0	
IEW		300	28	2	1	

S45C	8	20	400	0	0	0
		70 (LA)	400	25	0	0
		80	380	27	0	0
		90	360	60	8	2
		IEW	200	22	5	10
	2	20	515	0	0	0
		60 (LA)	510	8	0	0
		80	465	69	2	0
		90	440	87	3	0
		IEW	300	76	3	1
	1	20	510	0	0	0
		60 (LA)	500	16	0	0
		80	450	23	0	0
		90	425	60	2	0
		IEW	350	22	4	3

LA: Laboratory Air
 IEW: Ion-Exchanged Water

Figure 14 shows mechanisms of molecule water forming on the surface specimen. For specimen diameter of 8 mm at rotating bending load fatigue test, molecule water forming on the surface occurs such as water droplet because water molecule is difficult to stick at surface of specimen and due to diameter specimen is to bigger than that of diameter of 2 mm and 1 mm. On the contrary, for specimen diameter of 2 mm and 1 mm molecule water very easy to stick at surface so that molecule water is form water film. Thus, water droplet indicates crack create easy to grow if compared with water film at the surface of specimen.

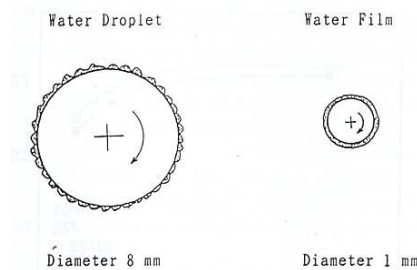


Figure 14 : Mechanisms of molecule water forming on the surface specimen

3.3 The Size Effect on the Fatigue Strength in High-Humidity Environment.

As described above, the fatigue strength increases with decreasing the specimen size Figure 15 shows the relationship between fatigue strength at 10^7 cycles and diameter of specimen. Both SS400 and S45C steels in laboratory air with 70 % RH, fatigue strength specimen diameter of 8 mm is lower than that for specimen diameter of 2 mm and the fatigue strength of 1 mm is slightly lower than that of 2 mm. The curves in high-humidity environment with 90 % RH shows the same trend as that observed in laboratory air. The curve becomes peak for specimen diameter of 2 mm in high-humidity environment.

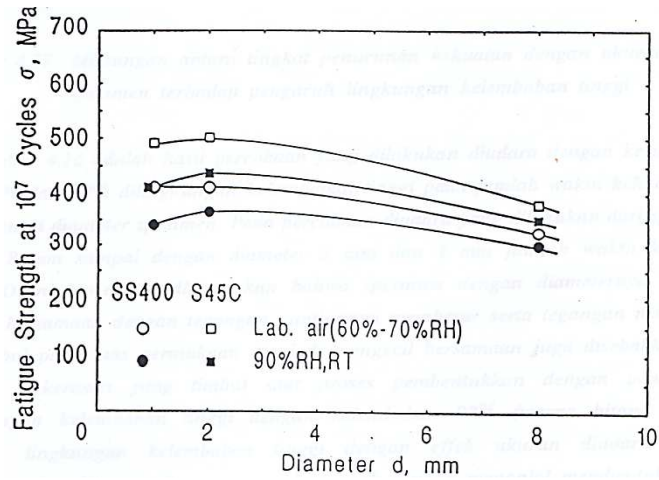


Figure 15 : Relationship between fatigue strength at 10⁷ cycles and diameter of specimen

Figure 16 shows relationship between reduction ratio of fatigue strength and diameter of specimen. Reduction ratio is referred here as the ratio of fatigue strength in laboratory air environment to fatigue strength in high-humidity environment. It can be seen this figure that both of condition in laboratory air and in high-humidity environment the specimen diameter of 8 mm the reduction ratio of fatigue strength due to humidity is slightly reduced and the reduction ratio of fatigue strength for specimen diameter of 2 mm and 1 mm is much lower than the specimen diameter of 8 mm. The reduction of fatigue strength of S45C steel is larger than that of S400 steel, since S45C steel is susceptible to corrosion. Therefore In high-humidity environment the specimen size decreases with increasing the fatigue strength. From the above observations, it can be concluded that the size effect of specimen reflect on the fatigue strength of structural in high-humidity, presumably depending the following reasons; an under rotating bending load fatigue test molecule water forming on the surface specimen diameter of 8 mm occurs such as water droplet due to molecule water which is difficult to stick on the surface that the many cracks and pit corrosion are easy to grow and some of them were joint together to form a long crack than that of diameter of 2 mm and 1 mm.

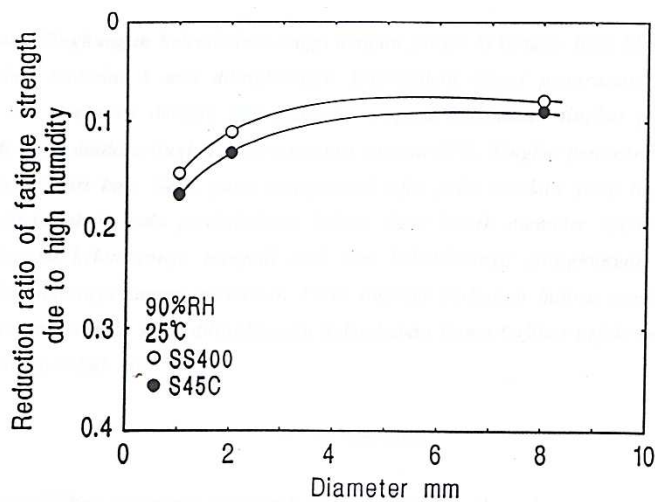


Figure 16 : Relationship between reduction ratio of fatigue strength and diameter of specimen

4.0 CONCLUSIONS

The size effect on fatigue strength of structural steel materials in high-humidity environment has been studied. The results obtained can be summarized as follows:

- i. The fatigue strength of SS400 and S45C steels increases with decreasing the specimen size to diameter of 2 mm and 1 mm in high-humidity environment. In ion-exchanged water, the fatigue strength remarkably reduces the fatigue strength of these steels.
- ii. In high-humidity environment a transition of fatigue strength occurs between 70 % RH and 80 % RH. The specimen diameter becomes small a transition of fatigue strength makes a move towards to low-humidity environment.
- iii. The fatigue strength increases with decreasing the specimen size in high-humidity environment. This indicates that the smaller specimen diameter molecule water very easy to stick at surface so that molecule water is form water film. Water droplet form indicates pit corrosion and crack create easy to grow if compared with water film at the surface of specimen.

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