The Size Effect on Fatigue Strength of Structural Steel Materials in High-humidity Environment

Haftirman
School of Mechatronic Engineering, Mechanical Engineering Program
Universiti Malaysia Perlis (UniMAP), Malaysia.
haftirman@unimap.edu.my

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 pct Relative Humidity, 70 pct Relative Humidity, 80 pct Relative Humidity, and 90 pct Relative Humidity. The results show that the fatigue strength increases with decreasing the specimen size to diameter of 2 mm and 1 mm of SS400 and S45C steels in high-humidity environment. In 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 microscopy (SEM).

***Keywords* - Fatigue Strength, Structural Steel, High-humidity Environment, Crack length, Fatigue Test.**

I. 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.

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.

II. 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 II, respectively. Table 1 shows almost different properties of SS400* and SS400**.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. These materials have been investigated for the effect of high-humidity on fatigue strength with different sizes of specimens. The shape and dimension of the specimen diameter of 8 mm, 2 mm, and 1 mm are shown in Fig. 1, 2, 3, respectively. The fatigue tests were performed in the high-humidity between 60 and 90 pct Relative Humidity (referred to as 60 and 90 pct 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 microscopy (SEM).

TABLE I
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 2 mm

TABLE II
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 2 mm

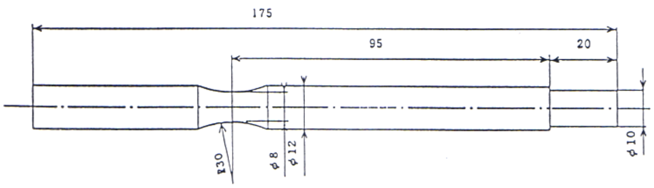


Fig. 1. Shape and dimension of the specimen diameter of 8 mm

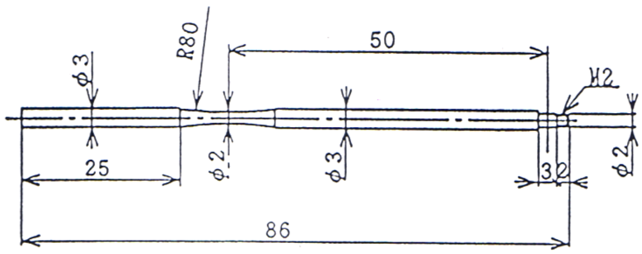


Fig.2. Shape and dimension of the specimen diameter of 2 mm

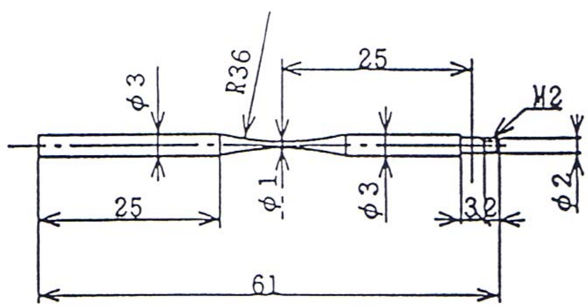


Fig.3. Shape and dimension of the specimen diameter of 1 mm

III. EXPERIMENTAL RESULTS AND DISCUSSION

A. Effect of high-humidity environment on fatigue strength

Figs. 4, 5, and 6 show the S – N curves of SS400 steel for diameter of 8 mm, 2 mm, and 1 mm. 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 of SS400 steel in laboratory air (60 pct RH) is as high as 400 MPa, which is the same as obtained at 70 pct RH. The fatigue strength of 1 mm is higher than that of 2 mm and 8 mm in laboratory air with 60 pct RH. Fatigue strength decreases at 85 and 90 pct 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 Figs 7, 8, and 9, the same result as

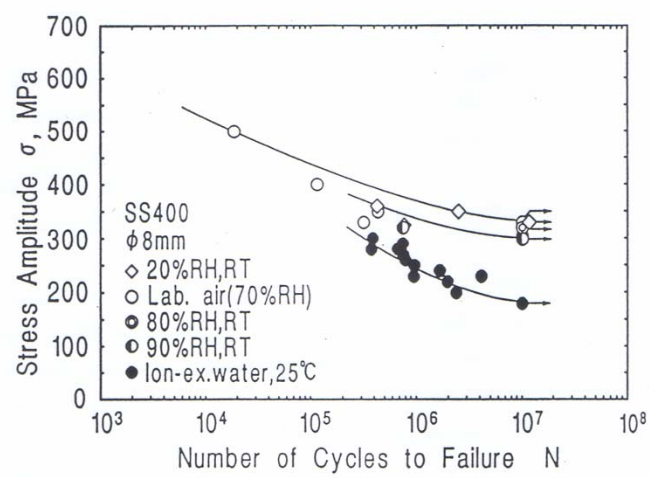


Fig.4. S - N curves of SS400 steel for diameter of 8 mm

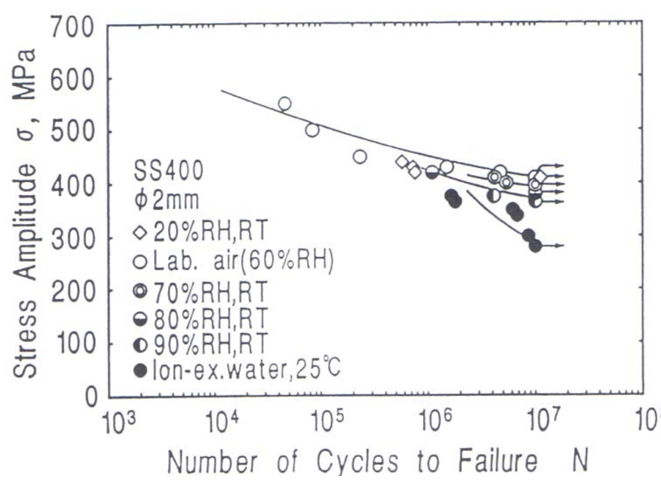


Fig.5. S - N curves of SS400 steel for diameter of 2 mm

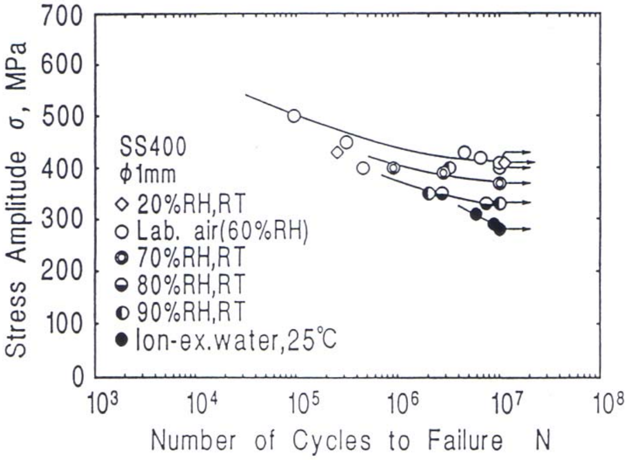


Fig.6. S - N curves of SS400 steel for diameter of 1 mm

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

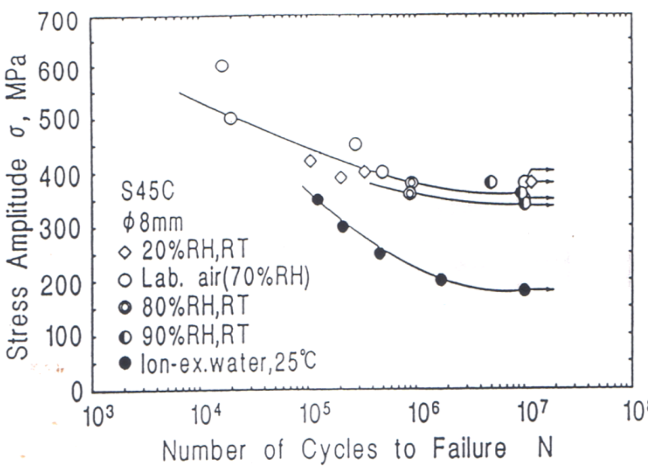


Fig.7. S - N curves of S45C steel for diameter of 8 mm

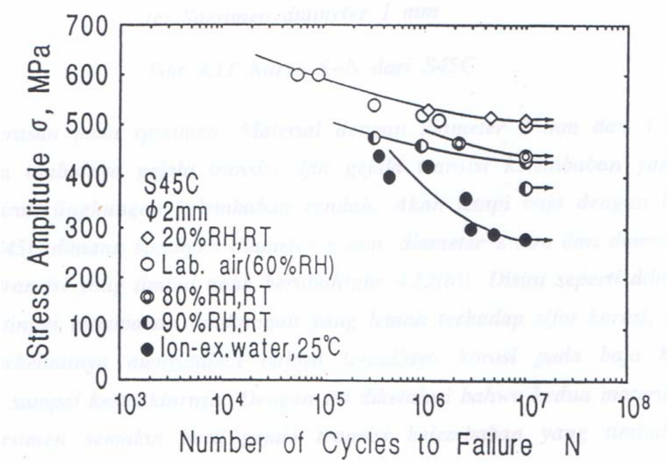


Fig.8. S - N curves of S45C steel for diameter of 2 mm

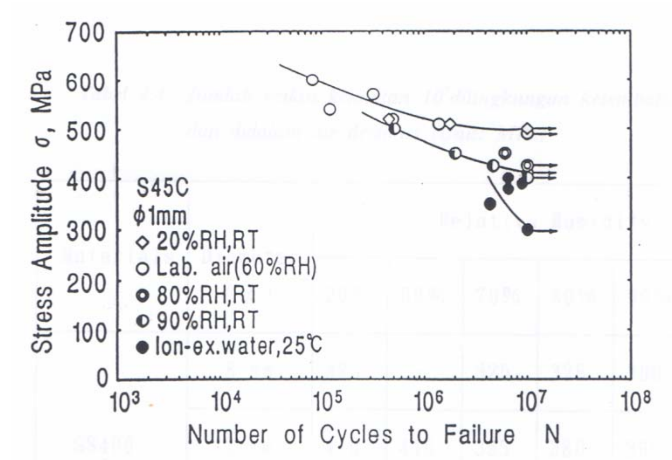


Fig.9. S - N curves of S45C steel for diameter of 1 mm

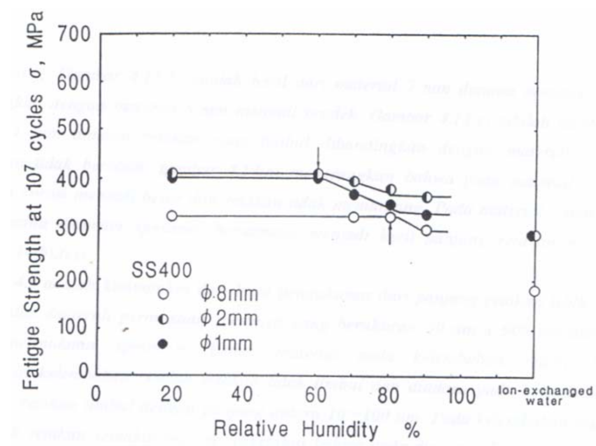


Fig.10. Relation between fatigue strength at 10^7 cycles and relative humidity of SS400 steel

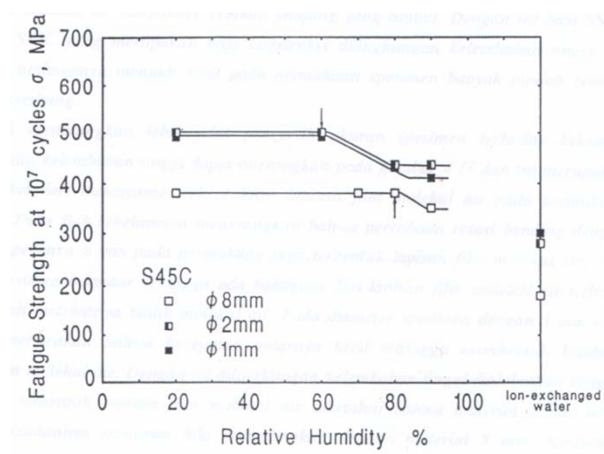
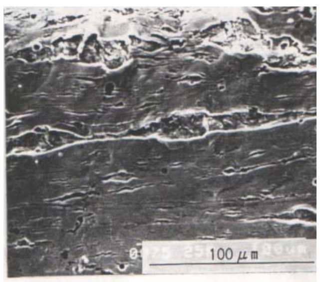


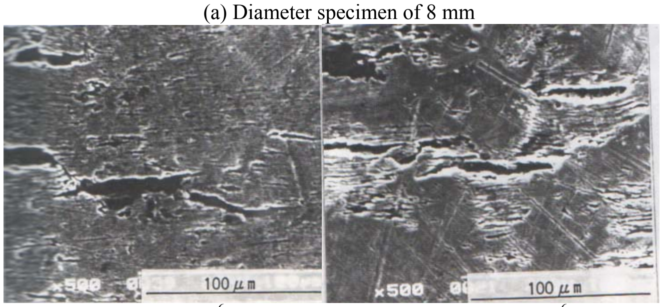
Fig.11. Relation between fatigue strength at 10^7 cycles and relative humidity of S45C steel.

reduces the fatigue strength of this steel. Thus, the effect of high-humidity environment reduces fatigue strength for both SS400 and S45C steels.

Figs 10 and 11 summaries the results obtained when experiment conducting in humidity environment between 20 pct RH and 90 pct RH for specimen diameter of 8 mm, 2 mm, and 1 mm. As seen from these figure, the transition humidity 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 pct RH and 80 pct RH for diameter of 2 mm and 1 mm, and then the transition of fatigue strength occurs in high-humidity environment between 70 pct RH and 80 pct 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 pct RH and 80 pct RH for axial loading fatigue test [1].

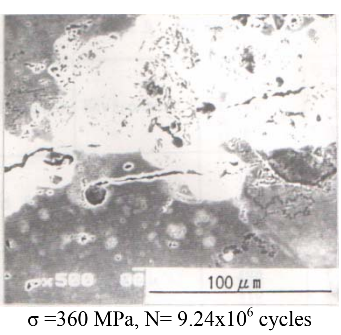


σ =350 MPa, N= 6.742x10^5 cycles
(a) Diameter specimen of 8 mm

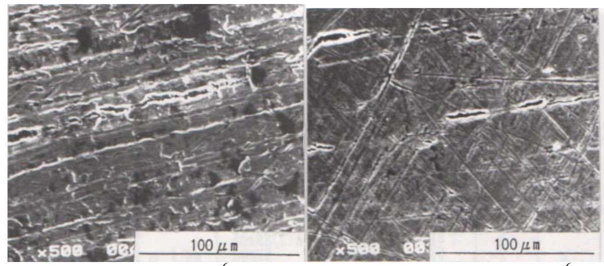


σ = 375 MPa, N= 4.1x10^6 cycles σ = 350 MPa, N= 6.4x10^6 cycles
(b) Diameter specimen of 2 mm (c) Diameter specimen of 1 mm

Fig.12. Surface cracks of SS400 steel in high-humidity environment



σ =360 MPa, N= 9.24x10^6 cycles
(a) Diameter specimen of 8 mm



σ = 440 MPa, N= 5.8x10^6 cycles σ = 425 MPa, N= 4.6x10^6 cycles
(b) Diameter specimen of 2 mm (c) Diameter specimen of 1 mm

Fig.13. Surface cracks of S45C steel in high-humidity environment

Generally, one would expect the effect of high- humidity environment reduces fatigue strength both SS400 and S45C steels. The results show that the fatigue strength of specimen diameter of 2 mm is higher than that of specimen diameter of 8 mm; the properties of material do not influence on the fatigue strength.

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. In high-humidity environment crack growth seems to occur on the surface specimen.

TABLE III
NUMBER OF CRACK (AREA 50X50μm)

Material	Diameter Ø (mm)	Environment % Relative Humidity (RH)	Fatigue Strength σ (MPa)	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

B. Crack Initiation in High-humidity Environment

Fig. 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. It can be seen that fig. 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 joint 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 of measurement was 20µm. 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 20 to 1000 µm. In high-humidity environment at 90 pct RH, both SS400 and S45C steels, the number of cracks on the specimen diameter of 8 mm is more 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.

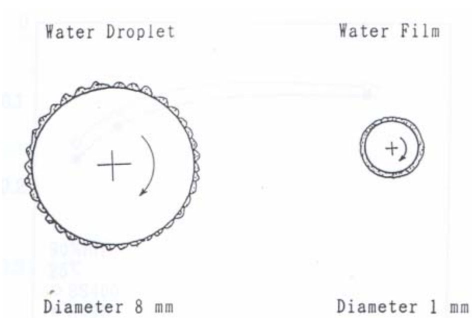


Fig.14. Mechanisms of molecule water forming on the surface specimen

Fig. 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 due to molecule water 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.

C. The size effect on the fatigue strength in high-humidity environment.

As described above, the fatigue strength increases with decreasing the specimen size. Fig. 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 pct 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 pct 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.

Fig. 16 shows relationship between reduction ratio of fatigue strength and diameter of specimen. It can be seen this figure that both of condition in laboratory air and high-humidity environment the specimen diameter of 8 mm the reduction ratio of fatigue strength due to humidity is slightly reduce 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

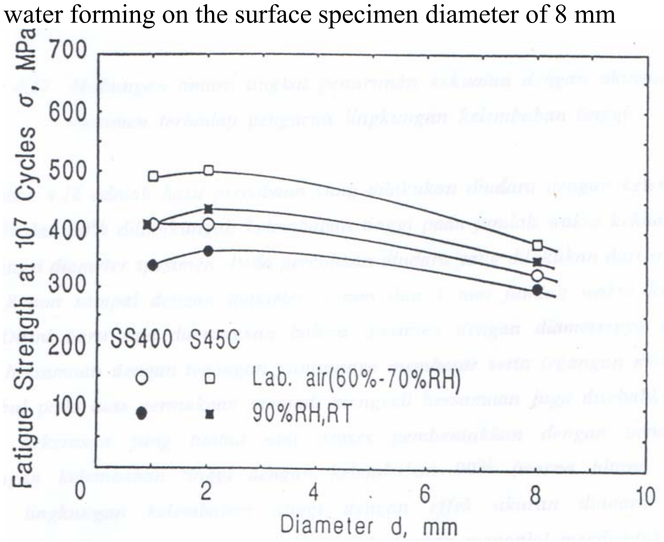


Fig.15. Relationship between fatigue strength at 10^7 cycles and diameter of specimen

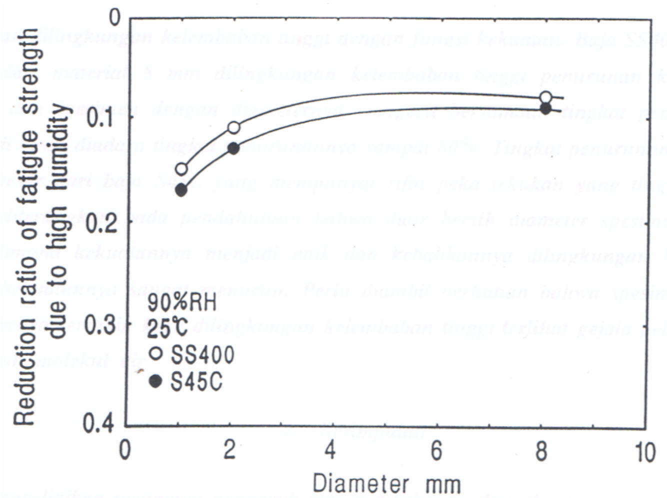


Fig.16. Relationship between reduction ratio of fatigue strength and diameter of specimen

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.

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:

(1).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. This result is applied to a small component on component element machine especially used in the shaft of robot driver. The other component is used in humidity environment.

(2).In high-humidity environment a transition of fatigue strength occurs between 70 pct RH and 80 pct RH. The specimen diameter becomes small a transition of fatigue strength makes a move towards to low-humidity environment.

(3).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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