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Size Effect on Fatigue Strength of Machined Carbon Steel* (X-Ray Detection of Fatigue Damage in Machine Parts)

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An X-ray observation was made during the fatigue process of 100 mm, 20 mm and 10 mm dia. rotating bending fatigue specimens machined by a lathe.

The results obtained from this experiment are as follows:

(1) It became clear that there exists a thin surface layer which has been work hardened by machining and is sensitive to repeating stress. This surface layer yields throughout the specimen surface fairly uniformly before crack initiation.

(2) When the reduction rate of surface residual stress at the number of cycles $N=10^4$ and $N=10^5$, $\Delta\sigma_R/\sigma_{R0}$ (where $\Delta\sigma_R$ is the changed value of residual stress and σ_{R0} is the residual stress of initial state), was plotted as a function of number of cycles to failure, all the points lie close to a single line. Thus, the change in residual stress during the fatigue process depends mainly on fatigue life itself irrespective of specimen size.

1. Introduction

The size effect of fatigue strength should be taken into consideration when large machine parts are designed. But there are still many difficult problems unsolved for the design of large machines such as the difficulty of testing and a vibration problem or financial problems. The breakdown accident of large machines has serious influence on the society. Thus, it is very important to detect the fatigue damage of the real machine parts before failure in order to prevent the breakdown accident of large machines. However, as there are no detection methods of the fatigue damage before the crack initiation of the real machine parts, the periodical inspection of these large machine parts is usually made to relieve look for cracks.

On the other hand, an X-ray study on the fatigue mechanism⁽¹⁾ has been developed for small laboratory sized specimens. But it seems that there have not been enough results to support application of X-ray to damage detection of large machine parts. For example, the X-ray microbeam technique and electron microscopic observations suggest that the fatigue damage phenomena are microscopically localized, but if we are to observe such a localized phenomena that

might be detected only by the X-ray microbeam technique or the electron microscope, we must give up the fatigue detection of large machine parts because of their size. Also the X-ray powder diffraction method can detect submicroscopic phenomena, even though the resolution might be inferior to that of the X-ray microbeam method or the electron microscope method. The former report⁽²⁾ shows the basis for the size effect detection of the annealed carbon steel by the powder photographing method. In this report, the size effect detection of machined carbon steel is described, namely surface finishing of the real machine parts such as locomotive shafts was chosen for specimen finishing. The employed methods were X-ray powder photographing and X-ray stress measurement. The surface damage distribution has been especially observed. The merit of these method is that the fatigue damage of the specimen as a whole can be detected only by surface (which is work hardened by surface finishing) observations.

2. Test method

2.1 Specimen

The specimens were taken from SFA55(JIS), 180 mm diameter steel. The mechanical properties and the chemical compositions of the original material are listed in Table 1. The hardness distribution across the section is uniform (H_V 161~3), and there are no irregularities in the optical microscopic structure. The average grain size is about 20 μ , JIS

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No. 8. The specimen sizes and dimensions are shown in Fig. 1. All specimens are rotating bending type fatigue specimens. The specimens of 100 mm, 20 mm and 10 mm in diameter are named large, medium and small specimens, respectively. The medium and small specimens were taken at the position being circumscribed by the 100 mm diameter in the section

Fig. 1 Specimen sizes and dimensions

Table 1 Mechanical properties and chemical compositions

Steel	Mechanical properties kg/mm ² , %, kg m/cm ²				
	Yielding point	Tensile strength	Elongation	Reduction of area	V-notch impact value
JIS SFA55	38.3	60.1	28.8	45.9	6.3

Steel	Chemical compositions %							
	C	Si	Mn	P	S	Ni	Cr	Cu
JIS SFA55	0.36	0.26	0.71	0.007	0.010	0.06	0.05	0.10

Table 2 Condition of X-ray diffraction

Conditions	Stress measurement	Photographing	
		For large specimens	For small and medium specimens
Characteristic X-ray	CrK α	CoK α	CoK α
Exposed area (mm ²)	2 $\times$ 2	1 ϕ	1 ϕ
Tube voltage (kV)	25	25	50
Tube current (mA)	8	8	60
Filter (foil)	V	Fe	Fe
Film specimen distance (mm)	—	70	70
Exposed time (min)	—	40	5
Count range (c/sec)	200	—	—
Time constant (sec)	16	—	—
Measuring method	Half-value method	—	—
Apparatus	Parallel beam type auto recording X-ray stress measuring apparatus	Portable back reflection camera with the tube	Back reflection desk camera with the rotating anode X-ray generator

of the original steel. The surface finishing conditions of the small and medium specimens on the lathe are 630 rpm, 0.307 mm/rev pitch and 0.15 mm cutting depth, and these of large specimens 40 rpm, 0.15 mm/rev pitch and 0.03 mm cutting depth. Then all specimens were machined with the finishing tool (High Speed Steel: SKE 3 JIS). The surface roughnesses of all the specimens were about 1.5 μ . The X-ray observation and fatigue tests were made on the specimens as machined condition.

2.2 Fatigue testing

A large uniform rotating bending fatigue machine (7.8 t $\cdot$ m capacity, 800 rpm), a cantilever type rotating bending fatigue machine (50 kg m capacity, 1 400 rpm) and a small uniform rotating bending fatigue machine (8 kg m capacity, 2 000 rpm) were used for the large, medium and small specimens respectively. The X-ray observation was made several times during the fatigue testing. It was assumed that this interruption of the fatigue testing has not so large effect on the fatigue strength.

2.3 The X-ray measurement

2.3.1 The X-ray diffraction photographing

CoK α was used for the (310) reflection of iron as shown in Table 2. The blackness intensity curves of the diffraction pattern on the film were drawn by the microphotometer and the half-values breadth was measured for each curve. In the case of large sized specimens, four points were measured under the same conditions to make the deviation of the damage clear as shown in Table 3, two points being taken at the center of the specimen and the other two at 50 mm apart from the specimen center.

2.3.2 X-ray stress measurement

CrK α was used for the stress measurement as shown in Table 2. The stress measurement was made using a portable X-ray unit on the specimen in the fatigue testing machine.

3. The test results and discussions

3.1 Fatigue testing results

An S - N curve for each test specimen was obtained as shown in Fig. 2. It is clear that there is a size effect on fatigue strength, i.e. the fatigue limits of large, medium and small specimens are 22, 25.5 and 26.5 kg/mm² respectively. These value are only 1~2 kg/mm² higher than the previous results of annealed carbon steel (SFA 55), i.e. the fatigue limits are 21,

Table 3 Deviation and distribution of the residual stresses

The results of residual stress measurement kg/mm²

No.	Size	Small	Medium	Large	Purpose
A		-26.8	-43.0	-31.0	Deviation of X-ray stress measurement
A		-29.1	-45.3	-30.7	
A		-31.6	-43.7	-30.5	
1		—	—	-36.7	Residual stress distribution along the axis
2		-27.5	—	-29.1	
3		-28.5	-43.0	-30.5	
4		-31.2	—	-30.5	
5		—	—	-36.0	
A		-27.2	-43.1	-31.4	Residual stress distribution along the circumference
B		-35.1	-49.5	-28.0	
C		-28.5	-47.7	-33.7	
D		—	-48.0	-28.4	

Fig. 2 S - N curves of machined specimens

24 and 26 kg/mm² for large, medium and small annealed specimens respectively. No clear difference in the increment value is observed between the different sized specimens. This small increment of the strength might be caused by the existence of a surface work hardened layer. But the residual stress on the surface caused by lathe machining ($-37 \sim -47$ kg/mm²) does not affect directly the strength as the mean stress does. The reason for the small effect of the residual stress is not that the residual stress is reduced during the fatigue process because a compressive residual stress of about -30 kg/mm² was also observed after 10^7 cycles at the fatigue limit amplitude, but that the residual stress distribution along the depth, i.e. at tens of microns below the surface, the residual stress was sharply reduced to zero.

3.2 Changes in half-value breadth

The diffraction patterns of the large specimens are shown in Fig. 3. Figure 3(a) shows the initial state of the surface machined specimen. The diffraction ring is very broad and $K\alpha$ doublet cannot be distinguished. This means that the high dislocation density caused by the large plastic deformation during the surface finishing process, exists on the surface layer crystals as a whole. Figure 3(b) and (c) show the diffraction patterns after $N=10^4$ and $N=7.784 \times 10^5$ (failure) cycles respectively with the amplitude of $\sigma_b=26$ kg/mm². It is clearly shown that the diffraction ring became sharper during the fatigue process.

Figure 4 shows the changes in half-value breadth of large specimens as a function of the number of cycles. There by b is the half-value breadth and B is the half-value breadth of the initial state specimen.

Fig. 4 Changes in half-value breadth of large specimen as a function of number of cycles

Fig. 3 Changes of X-ray diffraction patterns during fatigue process of large sized machined specimen

The deviation of the measurement at the four different points is shown as a vertical segment. The half-value breadth ratio (b/B) decreases constantly during the fatigue process. The reduction rate of the ratio b/B is larger when the stress amplitude is larger and the fatigue life is shorter. This phenomenon might be caused by the same mechanism as described for the material work hardened by rolling i.e. the development of the substructure, i.e. the rearrangement of the dislocations to a very limited boundaries called subgrain boundaries⁽⁴⁾⁽⁵⁾. The half-value breadth distribution is relatively uniform throughout the parallel testing part of the specimen compared with its changed value before the crack initiation. This means that the fatigue damage was developed relatively uniform on the specimen surface as a whole. The observed change of the half-value breadth after macroscopic crack initiation is the largest at the crack initiation point, followed by crack propagation parts and it is not so much at more than 3 mm apart from the crack. Figure 5 shows the half-value breadth changes during the fatigue process of the medium and small specimens. The tendency of the half-value breadth change is the same as that of Fig. 4.

Figure 6 shows the changes in half-value breadth as a function of cycle ratio (N/N_f : where N is the number of cycles and N_f is the number of cycles to

Fig. 5 Changes in half-value breadth of medium and small specimens as a function of number of cycles

Fig. 6 Changes in half-value breadth of machined specimens as a function of cycle ratio

failure). In the case of the half-value breadth change of the fatigue limit amplitude (i.e., $\sigma_i = 22$ kg/mm² for the large specimen) N/N_f is calculated by $N/10^7$. As shown in this figure, the fatigue damage which may be proportional to N/N_f can be evaluated by the changes in half-value breadth. It can be clearly distinguished if the applied stress is more or less than the fatigue limit of that machine part on the basis of the half-value breadth $b/B = 0.955$. It is also shown that even if the fatigue limit stress was applied, the surface yielding still occurred and it reduced the half-value breadth ratio b/B up to 0.955 after 10^7 cycles.

3.3 Changes in residual stress

The deviation of the measured stresses and the distribution of the residual stress on the specimen surface are shown in Table 3. The deviation (i.e., re-appearance of the measured stress) of the stress measurement is 2.5 kg/mm² for the small specimen and 1 kg/mm² for the medium and large specimens. The surface residual stress distribution is within the error of the stress measurement. This suggests that the uniform surface finishing was done on the specimen. However, several kg/mm² difference was observed between the different sized specimens caused by the slight difference of the surface finishing conditions. Since such a difference might occur in the real machine parts, the test was continued.

Figure 7 shows the distribution of the half-value breadth along the depth from the surface of each sized specimen. The tendency of the distribution of each sized specimen is almost the same and the work hardened layer is found to be about 50 microns in thickness. As a reference, one example of the half-value breadth distribution after fatigue is also shown in this figure. The half-value breadth decreased, as a whole, up to 50 microns depth.

Figures 8 to 10 show the changes in residual stress during the fatigue process of each sized specimen⁽⁸⁾. In the case of large specimens (Fig. 8) the

Fig. 7 Half-value breadth distribution as a function of the depth from the surface

plotted points are the average of the four different measuring points and the deviation is shown as the vertical segment in this figure. Before crack initiation the changes in residual stress are relatively uniform throughout the parallel testing part (100 mm in diameter and 200 mm testing part). The deviation was unexpectedly small with a similar tendency to the half-value breadth. Figures 8 and 10 show the residual stress changes for the medium and small specimens respectively. When the changes of residual stress of the different sized specimens are compared at the same stress amplitude, the larger the size is, the greater and the earlier the change is Fig. 11 shows the reduction rate of the residual stress ($\Delta\sigma_R/\sigma_{R0}$) after $N=10^4$ and 10^5 cycles as a function of stress amplitude. Where, σ_{R0} is the initial residual stress, $\Delta\sigma_R$ is the residual stress change after N cycles (i.e. $\Delta\sigma_R = \sigma_{R0} - \sigma_R$ is the residual stress after N

cycles. The reduction rate of the residual stress ($\Delta\sigma_R/\sigma_R$) is large with respect to the large, medium and small specimens, as shown in this figure.

Figure 12 shows the residual stress reduction rate as a function of number of cycles to failure. It is shown that all the plotted points lie on a single line for each N cycle. This means that the surface residual stress change (i.e. the relative plastic flow of the surface work hardened layer to the internal part of the specimen) is one of the important fatigue damage factors, whatever the specimen size. This fact and the value of the half-value breadth show directly that the yielding of a tens of microns work hardened surface layer is an important reason for the size effect on the fatigue strength. This yielding should be emphasized by the difference of the stress gradient⁽⁵⁾ and by the increase of the yielding possibility with an increase of the surface area. The proof of this

Fig. 8 Changes in residual stress of large specimen (100φ) as a function of number of cycles

Fig. 9 Changes in residual stress of medium specimen (20φ) as a function of number of cycles

Fig. 10 Changes in residual stress of small specimen (10φ) as a function of number of cycles

Fig. 11 Reduction rate of residual stress after N cycles as a function of stress amplitude

Fig. 12 Reduction rate of residual stress after N cycles as a function of number of cycles to failure

mechanism will be reported in the near future. Figure 12 shows also that even though there exists the deviation of the surface residual stress at the initial state (i.e. about 10 kg/mm² difference) the reduction rate of the residual stress ($\Delta\sigma_R/\sigma_{R0}$) can possibly be the damage factor.

From the above results, the changes in residual stress that can be measured by the X-ray method can show the fatigue damage itself, whatever the specimen size. Thus, the fatigue strength of any sized machine part can be measured in the early stage of the fatigue life. It is also shown that the data obtained from the small sized specimen can be useful enough for the fatigue detection of the large machine parts.

4. Discussions

4.1 The effect of the mechanically work hardened surface layer on the fatigue strength

The compressive residual stress of about -30 kg/mm² was retained after 10⁷ cycles at the stress amplitude of fatigue limit for each sized specimen. If the fatigue strength depended mainly on the strength of the mechanically work hardened layer (about 50 microns), this compressive residual stress should be considered as a mean stress. But the increment of the fatigue strength is only 1 kg/mm² to 2 kg/mm² compared with the previous results⁽²⁾ on annealed carbon steel (SFA55). On the other hand, the results of this report show that the changes in half-value breadth and residual stress can be measured by the X-ray method, i.e. the phenomena of very thin surface layer can represent the fatigue damage of the specimen itself. Here, the problem is now to interpret the relationship between the residual stress that can be measured by the X-ray method and the residual stress that can influence the fatigue strength increment. The hypothesis which states that because the residual stress which was caused by mechanical finishing might be reduced to zero by repeating stress, the residual stress on the surface layer would not influence the fatigue strength, is denied by the fact that there exists about -30 kg/mm² residual stress even after 10⁷ cycles at the amplitude of fatigue limit.

It was confirmed that the microscopic plastic flow occurs even at the fatigue limit stress amplitude by the fact that the residual stress decreased about 20% and the half-value breadth decreased also up to $b/B=0.955$. It may be considered that there occurs a microscopic crack initiation (for example persistent slip line) by this microscopic plastic flow. Therefore, a new mechanism for the residual stress effect on fatigue strength can be proposed, i.e. the residual stress would work as a resistance force to the propagation of this microscopic crack and this causes an increase of the fatigue strength. Many results showing that

the mean stress (or residual stress) would not work for the crack initiation but work for the crack propagation, also support the above hypothesis. Now it is important that the residual stress which would work as a resistant force to the crack propagation (even though it is a microscopic crack) should exist not only on the surface (there exists the maximum residual stress very close to the surface in the case of the specimen machined by the lathe) but also in the interior portion that includes the crack tips. However, the residual stress of this report sharply decreases to zero at about 50 microns below the surface (Fig. 7). For this reason, there is only a little residual stress that would work as a resistance force to the microscopic crack propagation, and the fatigue strength of the mechanically finished specimen is only 1 kg/mm² to 2 kg/mm² higher than that of the annealed one. Thus, it is suggested that the residual stress that would influence the fatigue strength of the large machine parts should be distributed more than 100 microns deep even though the microscopic crack would initiate from the surface and the surface phenomena are important for the fatigue damage detection. There still remains the problem of what the effective depth should be when the influence of the residual stress on fatigue strength is taken into consideration.

4.2 The detection of the size effect on fatigue strength

One of the mechanisms of the size effect on fatigue strength which have been proposed only on the results of *S-N* curves was directly proven to be a difference of the surface yielding by the X-ray observation. It is also confirmed that there exists a thin surface layer⁽⁵⁾ which sensitively yields by repeating stress and this yielding is very important for the fatigue strength regardless of the size. The yielding mechanism of the surface as a whole ruling the fatigue strength gives great support for the X-ray detection of the large machine parts. Since the size effect is caused mainly by the increase of flaws, it might be very difficult to detect the fatigue damage of the large machine parts, unless the X-ray exposure is made near the flaws.

5. Conclusions

From the X-ray observation during the rotating bending fatigue process of the large (100 mm in diameter), medium (20 mm in diameter) and small (10 mm in diameter) specimens as machined, the following conclusions were obtained:

(1) The changes in half-value breadth are relatively uniform along the parallel part of the large specimen during the fatigue process before the macroscopic crack initiation. After crack initiation, the reduction of half-value breadth at the crack tip is very sharp and large but this sharp reduction is not

observed at more than 3 mm apart from the crack. When the changes in half-value breadth of all specimens (b/B) are plotted as a function of cycle ratio (N/N_f) all the spots lie close to a single line. This is clearly seen if the applied load is more or less than the fatigue limit of the machine part itself in the early stage of the fatigue process by the measurement of half-value breadth ratio ($b/B \leq 0.955$).

(2) The changes in residual stress during the fatigue do not depend on stress amplitude itself, but on the fatigue damage i.e., the larger the specimen size is, the larger the changes in residual stress even though the stress amplitudes are the same (Fig. 11). On the other hand, the change ratio $\Delta\sigma_R/\sigma_{R0}$ in residual stress after a certain stress cycles (N) follows a single curve when it is plotted as a function of number of cycles to failure, whatever size the specimens are (Fig. 12). Thus the evaluation of fatigue life of a certain machine part (which has been tempered and mechanically finished) in the early stages of fatigue is possible by the X-ray stress measurement only on the surface, whatever size the machine part is.

(3) The surface residual stress of the large specimens changes relatively uniformly throughout the parallel part of the specimen before macroscopic crack initiation, just the same as the half-value breadth does. A residual stress of $-15 \sim -20 \text{ kg/mm}^2$ was still measured after failure when the number of cycles to failure was about 10^6 . After crack initiation a sharp reduction of residual stress occurred in the limited area near the crack.

(4) The initial compressive residual stresses are $-37 \sim -47 \text{ kg/mm}^2$. And even after 10^7 stress cycles at the fatigue limit amplitude, a compressive residual stress of about -30 kg/mm^2 was observed, but the increment of the fatigue limit of these machined specimens was only 1 kg/mm^2 to 2 kg/mm^2 compared with the annealed ones. The increment of the fatigue strength might be caused by the surface work hardened layer, but this increment of the fatigue limit was not large enough compared with a mean stress effect when the residual stress was considered a mean stress. No clear difference in the incremental value

is observed between the different sized specimens. This might be caused by the fact that the compressive residual stress sharply decreased at a depth of tens microns. From this fact, it is suggested that the average residual stress up to more than 100 microns depth from the surface should be taken into consideration for the comparison of the residual stress effect on fatigue strength with the mean stress effect on it.

(5) It is found that a yielding (i.e. the dislocation re-arrangement) occurs on the surface layer which was work hardened by mechanical finishing. Thus, there exists a surface effect in the mechanical finished work-hardened layer which is very sensitive to the repeating stress. It is guessed that the size effect on fatigue strength might be caused by the difference of the stress gradient and by the different yielding possibility because of the surface area difference.

(6) From the above results it is concluded that the surface observation by the X-ray diffraction method is a very useful method for the detection of the fatigue damage in any sized mechanically finished machine parts. The X-ray data obtained from the small specimen are useful for the fatigue damage detection of large machine parts.

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Discussion

H. NISITANI (Kyushu University):

(1) You have commented that the decrease in yield strength due to the increase in surface area seems to be a cause of the size effect. Does this also mean that under axial loading, yield strength of a surface area as small as 1 mm^2 is dependent on size?

(2) I suppose there are actually many cases when fatigue fracture is initiated from the defect on surface. May we suppose that even in such cases X-ray analysis is applicable to the study of size effect?

K. NISHIOKA (Sumitomo Metal Ind. Co., Ltd.):

(3) I think that a considerable temperature-

rise might occur in fatigue tests of large-scale specimens, especially at high testing speed of 800 rpm and at a stress over the fatigue limit. Such temperature-rise might result in a reduction of half-value breadth owing to tempering of the material. Did you take the influence into consideration?

(4) It is reported that the half-value breadth within a thin layer of $50\ \mu$ below the surface in Fig. 7 was generally found to decrease after fatigue tests. However, the layer in which the half-value breadth was measured was a work-hardened layer by turning. If there is no such a worked layer, what will be the result?

Authors' closure

(1) As even under axial loadings the surface layer is considered to yield first, it is not unreasonable to consider that fatigue strength is dependent on the cyclic plastic strain in the whole surface area. It will not be so salient as in the case when there is stress gradient due to bending, even though the decrease of yield strength due to the volumetric increase of surface layer can be detected by the X-ray observation.

(2) Fatigue fracture is sometimes initiated from surface defects as you have mentioned. In the case of defects being rather larger sizes and widely scattered in S - N diagrams, this method alone will not be adequate. However the recent development of non-destructive testing makes careful testing of dangerous parts safe thus if combined with this technique this

X-ray method will be applicable. As in the tests using these test pieces, deviations of S - N curves were small, and as the same results were obtained from the tests using annealed carbon steel as in the previous report, we presume that this X-ray method is practically usable.

(3) Even with large test pieces of 100 mm diameter, there was almost no temperature rise, and the maximum temperature of the test pieces in the high stress range was around 40 to 50°C. The reason for this small temperature rise is considered to be due to the short operating time of about 10 minutes for 10^4 cycles of the primary half-value breadth measurements. Generally it is well known that there occurs a temperature rise in the primary stage of high stress loading test of specimens, and again before the breakdown. However, in present tests these phenomena were not observed. Therefore, the change of half-value breadth due to the temperature rise is not considered in the results.

(4) As a fatigue damaged zone is generally said to occur very near the surface, we have guessed that it had coincided with the lathe worked layer. If there is no worked layer as in a completely annealed material, half-value breadth of the initial state will be evenly distributed up to the surface, and as the half-value breadth of only the damaged layer due to stress cycles will increase, the detection of the fatigue damage will be possible by the X-ray observation.