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Studies on Impact Fatigue*
(part II, Inelastic Behavior of S50C Steel
under Impact Fatigue Loads)

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Using plain specimens of annealed S50C carbon steel, fatigue tests were conducted under fully reversed sinusoidal axial stress and under repeated impact stress. Inelastic behavior of specimens was observed using strain gauges mounted on the specimens.

Under the impact fatigue stress, fractures occurred at the stress levels lower than the ordinary fatigue limit and in the region of a larger number of stress cycles than 10^7 . The inelastic strains accompanied with a fracture were unexpectedly small comparing with those under sinusoidal stress. And the amount of hysteresis energy accumulated in the specimen during the impact fatigue test was also less than the corresponding value under sinusoidal stress.

1. Introduction

In the previous investigation, the authors had conducted a series of impact and ordinary fatigue tests on plain and U-notched specimens of 0.11%C steel and found the impact fatigue characteristics such that the impact fatigue failure occurred at the stress level below the ordinary fatigue limit and in the range of a number of cycles exceeding the critical value of stress cycles for sinusoidal stress pattern, in other words, the knee point of the ordinary S-N curve.

The investigation reported here was planned to study whether the above impact fatigue characteristics found with 0.11%C carbon steel would be observed with the other steel. Moreover the inelastic behaviors of the material during the ordinary and impact fatigue tests were observed by the aid of the strain gauges mounted on the specimen.

In a series of experiments, the same impact fatigue characteristic in strength aspect was also observed on a 0.53%C carbon steel, and moreover, the impact fatigue characteristic in the aspect of inelastic be-

haviors was found such that the smaller inelastic strain amplitude and the less accumulation of hysteresis energy were needed for the impact fatigue failure than those needed for the ordinary fatigue failure, by analyzing the observed data of the inelastic strain and the hysteresis energy under the ordinary and impact fatigue loads.

2. Material

The material used in this experiment was a 0.53%C carbon steel supplied as hot rolled bars of 19mm diameter. Chemical composition of the material is listed in Table 1, and the heat treatment and mechanical properties in static tension test are listed in Table 2. Specimens were machine finished after annealing to the shape indicated in Fig.1.

3. Testing machine and testing procedure

The push-pull type impact fatigue testing machine introduced in the previous report was used in this experiment. The capacity of the testing machine and the method of adjusting the testing condition were previously described in detail, so that only a brief description is made here.

The principle of the testing machine is shown in Fig.2. A full reversed sinusoidal stress pattern can be obtained when the clearance adjusting rod is pressed so tightly to the rigid wall as not to allow any clearance between them during

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Table 1 Chemical composition of the material

Material	Chemical composition (%)							
	C	Mn	Si	P	S	Cu	Ni	Cr
0.53%C carbon steel	0.53	0.79	0.32	0.024	0.023	0.04	0.02	0.10

Table 2 Heat treatment and mechanical properties of the material

Heat treatment	Upper yield point	Lower yield point	Ultimate strength	Breaking strength on final area	Elongation	Reduction of area
	σ_{so} kg/mm ²	σ_{su} kg/mm ²	σ_B kg/mm ²	σ_T kg/mm ²	ϕ %	ψ %
820C, 1hr., F.C.	37.8	32.8	65.2	107.6	32.0	48.6

Fig. 1 Specimen

Fig. 2 Principle of impact fatigue testing machine

the fatigue test. The alternating load is produced by the vibro-motor and applied to the left end of the specimen. The compressive force of 600kg ($P_c=600\text{kg}$) was adopted here for the ordinary fatigue test with the sinusoidal stress pattern. The stress pattern obtained under this condition is shown in the left hand side of Fig. 3(a).

On the other hand, by releasing the clearance adjusting rod to allow a little clearance between the rod and the rigid wall, an impact fatigue load is generated by repeated collisions between the two parts with the vibration excited by the vibro-motor. In this study, the impact fatigue tests were conducted by setting the clearance at 0.02mm ($CL=0.02\text{mm}$). The impact stress patterns obtained with this clearance are shown in Fig. 3(b), (c), and, at the bottom of

Fig. 3(c), those patterns detected on both impact rods of tension and compression sides are also indicated. Some absorption of the higher harmonic components of the impact load is observed, when the comparison is done between these load patterns detected on the impact rods and that on the load-cell.

The results of the harmonic analysis of the impact stress patterns are presented in Fig. 4. The odd number harmonic components up to the 9th order are superposed on the fundamental sinusoidal wave of 57.5Hz, and these harmonic components are due to the vibration characteristics.

All the stress patterns produced on the specimen were detected by means of the strain gauges mounted on the load-cell, and were observed and measured by the cathode-ray synchronized oscilloscope after preamplification. The stress amplitude σ_a was determined as a half value of the observed stress range. No mean stress was applied to the specimen, since the specimen was free from the static constraint as was shown in Fig. 2. The stability of the load during the testing period is the most important in this study, since the major purpose of the study is to clarify the fatigue characteristics in the long life range under impact load. Therefore, the observation of the stress patterns and their magnitude was done continuously during the experiment, and adjustment was made if necessary to keep the testing condition constant.

4. Experimental results and discussion

4-1. Fatigue strengths

The stress amplitude σ_a and the number of stress cycles to failure N obtained in a series of experiments made on 0.53%C carbon steel are listed in the 2nd and 3rd columns of Table 3, respectively. And these data are represented on an S-N diagram as shown in Fig. 6. The hollow circles are results of the ordinary fatigue test with the test condition of $P_c=600\text{kg}$, and curve drawn smoothly through these points is treated hereafter as the fundamental S-N curve, from which the ordinary fatigue limit σ_w is about 23kg/mm^2 . The solid circles indicate, on the other hand, the results of the impact fatigue test under $CL=0.02\text{mm}$.

Now, from the comparison of the

(a) $\sigma_a = 26.3$, $N = 0.463 \times 10^5$
($P_c = 600\text{kg}$)

(b) $\sigma_a = 24.7$, $N = 1.24 \times 10^5$
($CL = 0.02\text{mm}$)

⇒ Load pattern on the impact rod
of tension side

⇒ Load pattern on the impact rod
of compression side

(c) $\sigma_a = 21.7$, $N = 9.06 \times 10^5$
($CL = 0.02\text{mm}$)

Fig.3 The stress patterns and the shapes of the hysteresis loop under the ordinary and the impact fatigue tests

Fig.4 Results of harmonic analysis of the impact stress patterns

Fig.5 Illustration of the hysteresis loop

Table 3 Experimental results

Test condition	Stress amplitude σ_a kg/mm ²	Number of stress cycles to failure N	Inelastic strain amplitude at $n/N = 50\%$ $\Delta\epsilon_{i50}$ μ strain	Hysteresis energy ΔW kg-mm/mm ²	Cumulative hysteresis energy for failure W kg-mm/mm ²	Remark
Fc=600kg	21.7	0.293×10^5				
	26.3	0.483	1024.0	108.0×10^3	4.64×10^3	
	25.4	2.69				
	24.6	1.47	440.0	43.3	6.45	
	24.4	3.24	385.0	37.6	11.41	
	23.8	7.73				
	23.3	6.56				
	23.3	1.3×10^7				Unbroken
	23.2	6.21×10^5				
	23.2	8.75				
	22.6	2.5×10^7	115.0	10.4	319.01	Unbroken
	22.0	1.1×10^7				Unbroken
	22.0	1.4×10^7				Unbroken
	21.2	1.0×10^7				Unbroken
	21.2	5.0×10^7				Unbroken
	21.1	4.5×10^7	55.0	4.6	233.70	Unbroken
CL=0.02 mm	24.7	1.24×10^5	419.0	41.4×10^3	5.22×10^3	
	24.3	1.91				
	23.3	4.35	43.0	4.0	1.98	
	21.7	9.06	85.0	7.4	6.97	
	21.0	281.47	59.0	5.1	9.02	
	19.2	136.70	33.0	2.5	35.29	
	17.0	10.0×10^7	14.0	1.0	113.27	Unbroken

results under these two fatigue tests conducted up to 10^8 stress cycles, it can be observed that there exists only a little difference between the results at the stress level above the fatigue limit σ_w , provided that the fatigue lives under the impact load take slightly shorter values. A distinct difference, however, appears at the stress level lower than the ordinary fatigue limit σ_w , that is, the impact fatigue failures occur in the range of a number of stress cycles longer than 10^7 , and no fatigue limit is attained in the impact fatigue test, in the range of a number of cycles up to 10^8 . Consequently, in the figure, the S-N curve for the impact fatigue was drawn showing a trend of a smooth decline. From this

trend of the S-N curves, the difference in the fatigue strengths between two load conditions reaches about 5 kg/mm^2 at 10^8 stress cycles.

The above tendency shown on the S-N diagram is the same as that observed in the previous study with 0.11% C carbon steel, and, therefore, this is considered one of the impact fatigue characteristics of carbon steel. That is to say, a distinct difference between the ordinary fatigue strength and the impact fatigue strength appears at the stress level below the ordinary fatigue limit. In other words, it appears in the range of stress cycles beyond the critical number of cycles of the ordinary S-N curve, and, in this range, the S-N curve for impact fa-

Fig.6 S-N curves

tigue does not become horizontal but shows a continuous decrease. The impact fatigue characteristics thus appear in the long life region sometimes beyond 10^7 cycles, and, this is one of the reasons why this feature could not be disclosed so far by many past studies, where the long life impact fatigue test was difficult from the limitation of the testing speed of equipment.

The stress patterns in the impact fatigue test are shown in Fig.3(b),(c); they are similar to the superposed stress pattern composed of two sinusoidal stresses of different frequencies. Therefore, the impact-superimposed stresses obtained in this experiment are simplified and rearranged by the method of plotting the fatigue data under the composite stress consisting of the fundamental stress wave σ_1 of the frequency $f_1 = 57.5\text{Hz}$ and the secondary stress wave σ_2 of the frequency f_2 as is shown in Fig.7. As the result of the measurement done in the neighbourhood of the peak of stress pattern, the frequency of the secondary stress wave was determined as about 655.3Hz, the ratio σ_2/σ_1 lying in the range of 0.04~0.11.

According to the experimental results about the fatigue strength under composite stress, the fatigue life becomes shorter generally when the ratio σ_2/σ_1 becomes larger; furthermore, even a lowering of endurance

Fig.7 Representation of the impact stress pattern as the superposed stress

limit can occur in the case of a relatively large ratio of σ_2/σ_1 . On the other hand, in the case of the ratio $\sigma_2/\sigma_1 < 0.11$ as was given in this experiment, secondary stress wave σ_2 seems to have no effect or have an effect to increase fatigue life.

Therefore, as was mentioned above, the impact fatigue failure which occurred at the stress level below the ordinary fatigue limit can't be explained from the view point of the fatigue failure under the composite stress, and a further study would be needed.

4-2. Inelastic strain amplitude and fatigue strength

In order to discuss the impact fatigue behavior of carbon steel from the standpoint of its inelastic behavior during the fatigue test, an observation was made on hysteresis loops with the aid of the strain gauges mounted on the specimen as was mentioned before.

At first, the variations of the inelastic strain amplitude $\Delta\epsilon_i$ during the ordinary and the impact fatigue tests are shown in Figs.8 and 9 respectively. The inelastic strain amplitude taken on the ordinate of these figures was defined as a half of the maximum width of the hysteresis

Fig.8 Variation of the inelastic strain amplitude ($P_c=600\text{kg}$) Fig.9 Variation of the inelastic strain amplitude ($CL=0.02\text{mm}$)

esis loop. And these data are replotted in Figs.10 and 11 by replacing the abscissa of Figs.8 and 9 with the stress cycles ratio $n/N(\%)$, where n is the number of stress cycles when the observation was done and N is the number of stress cycles to failure or the final number of stress cycles for runout specimens.

The variation of $\Delta\epsilon_i$ over the whole life of the specimens especially of low fatigue lives could not be clarified, because the inelastic behavior before 10^4 stress cycles was not detected in this experiment; however, the inelastic strain amplitude $\Delta\epsilon_i$ in the ordinary fatigue test shows a trend of fatigue softening-hardening in an early stage of the life, followed by a stable stage except in the results obtained at high stress amplitude, as shown in Fig.10.

As to the behavior under the impact fatigue load, shown in Fig.11 a similar trend is observed in the range of cycle ratios within 50%, but the value increased gradually toward fatigue failure after 50% of cycle ratio. Nearly the same trend as that under the ordinary fatigue test can be observed for the unbroken specimen.

In the second place, as for the value of inelastic strain amplitude $\Delta\epsilon_i$ itself, the difference between the inelastic behaviors under the two test conditions becomes more evident. Referring to Figs.8 and 10, it can reasonably be said that the ordi-

nary fatigue failure may not occur in the range of inelastic strain amplitudes below about $120\mu\text{strain}$ estimated at least in its stable stage. But, the impact fatigue failure does occur with a less value of inelastic strain amplitude than $120\mu\text{strain}$ as is seen in Figs.9 and 11.

In order to discuss this point in detail, the value of inelastic strain amplitude at the cycle ratio $n/N=50\%$ was adopted as the representative value and denoted by $\Delta\epsilon_{i50}$ under each stress condition, referring to Figs.10, 11. These values are listed in the 4th column of Table3. The relation between this representative value $\Delta\epsilon_{i50}$ and the number of stress cycles to failure N is represented on log-log paper in Fig.12. It is obvious in Fig.12 that the impact fatigue failure takes place for a small value of $\Delta\epsilon_{i50}$ at which the ordinary fatigue failure does not occur. The lowest value of $\Delta\epsilon_i$ is about 33 strain in the case of the impact fatigue failure, and this corresponds to about a fourth of the endurance inelastic strain limit $\Delta\epsilon_{iw}$ of $120\mu\text{strain}$ where $\Delta\epsilon_{iw}$ was defined as the magnitude below which no failure occurred in the ordinary fatigue test.

The above fact suggests that, in the range of small inelastic strain amplitudes $\Delta\epsilon_i$, there exists a difference in the relation between the observed inelastic strain amplitude $\Delta\epsilon_i$ and fatigue life N in accordance with the pattern of applied stress.

But, at a relatively high stress level over the fatigue limit, there exists no distinct difference between the values of $\Delta\epsilon_{i50}$ under both test conditions, as is recognized by

Fig.10 Variation of the inelastic strain amplitude ($P_c=600\text{kg}$)

Fig.11 Variation of the inelastic strain amplitude ($CL=0.02\text{mm}$)

Fig.12 $\Delta\epsilon_{i50}$ -N curve

Fig.13 Relation between the inelastic strain amplitude and the stress amplitude

comparing the inelastic behavior at the stress level of $\sigma_a = 24.6 \text{ kg/mm}^2$ (⊙) in Fig.8 with that at the stress level of $\sigma_a = 24.7 \text{ kg/mm}^2$ (⊖) in Fig.9. And, in this stress range, there exists no distinct difference of the fatigue strengths also as was mentioned before.

The relation between the representative inelastic strain amplitude $\Delta\epsilon_{i50}$ and the stress amplitude σ_a is presented on log-log paper in Fig.13. In this figure, it is found that this relation under the ordinary fatigue test can be reduced to a straight line, and expressed by an appropriate formula (1)

$$\Delta\epsilon_{i50} = 9.7 \times 10^{-18} \sigma_a^{14.1} \dots (1)$$

But results of the impact fatigue test show a little discrepancy with this relation, especially in the low stress range, and, in this range the inelastic strain amplitude $\Delta\epsilon_{i50}$ under the impact fatigue load is larger than that under the ordinary fatigue test because of the disturbance of stress pattern as shown in Fig.3 (b) and (c).

Now, the following is thought to be a typical process of the fatigue failure: Crystal lattice

strains, which grow up into the nuclei of the fatigue damage, are accumulated in a material during the early stage of stress cycles, and then, a fatigue failure occurs in the growing process of these nuclei from micro-cracks to macro-cracks. Besides, the accumulation of lattice strains is mainly caused by micro-slips in a crystal, and the total amount of the plastic strain due to these slips and the anelastic strain due to the pre-existing slip bands and the grain boundaries constitute the inelastic strain, the average value of which on the gauge length of strain gauge is observed. Furthermore, according to the past investigations, the anelastic strain component included in the inelastic strain did not contribute to the fatigue failure.

In this investigation, it seems to be obvious that the nuclei of the fatigue damage, which lead the specimen to failure, exist even at a considerably low stress level, since the impact fatigue failure occurred at the stress level well below the ordinary fatigue limit σ_w . Furthermore, the result shows that the observed inelastic strain amplitude $\Delta\epsilon_i$ in these cases measured as an average on the gauge length is far less than the endurance inelastic strain amplitude $\Delta\epsilon_{iw}$ defined in the ordinary fatigue test.

As an explanation for this phenomenon, it would reasonably be supposed that, in spite of the limited number of the nuclei of fatigue damage resulting from the low stress amplitude below σ_w , the growth of these nuclei is promoted by somewhat different mechanism under the impact load condition, and then, the failure occurs.

It is also supposed that a concentrated localization of inelastic strain actually occurs under the impact fatigue load, and if this is the case, the significance of $\Delta\epsilon_i$ measured as the mean value becomes ambiguous, depending on the degree of localization of the inelastic strain. The larger scattering of the experimental results of the impact fatigue test in the long life range shown in Fig.12 seems to be caused mainly by this reason, though the accuracy of the strain measurement may, of course, be another reason.

In order to verify the above reasonings, it is necessary to clarify the mechanism of the growth of the nuclei of fatigue damage being promoted under impact fatigue load in connection with the mechanism of occurrence of plastic and anelastic strains, and it is also necessary to examine the degree of

localization of inelastic strain at least experimentally. The authors are planning to pursue these problems in near future.

4-3. Hysteresis energy and fatigue strength

The relation between the inelastic strain amplitude $\Delta \epsilon_i$ and fatigue strength was discussed in the preceding article. It is also important to examine the difference in the shapes of hysteresis loops and its variation during the test period, in order to establish the relation between the stress-strain behaviors and fatigue strengths under the two fatigue load conditions

Fig.14 The hysteresis loop at low stress level in the impact fatigue test

Fig.15 Correlation between the hysteresis loop obtained at the low stress amplitude and the impact stress pattern

more precisely, since there exists a disturbance on hysteresis loop under the impact fatigue load which was not observed under the sinusoidal fatigue load.

Referring to the observational results of the hysteresis loops represented in Fig.3, it is found that the hysteresis loop in ordinary fatigue test becomes smooth according to the smooth variation of sinusoidal stress as shown in Fig.3(a); on the other hand, there exists a disturbance on hysteresis loop corresponding to the disturbance of stress pattern in the case of the impact fatigue test as shown in Fig.3(b) and (c). The hysteresis loop obtained at the stress level above or near the ordinary fatigue limit σ_w is composed of a large loop corresponding to the stress amplitude and a superimposed small loop corresponding to the disturbance of impact stress pattern. But, in the impact fatigue test with much lower stress amplitude than σ_w , the large loop corresponding to the stress amplitude almost diminishes, as shown in Fig.14, and the disturbance of the loop due to the disturbance of stress pattern becomes rather conspicuous.

Though the hysteresis energy absorbed in the unit volume of a material during a stress cycle is given as an area surrounded by this hysteresis loop, the hysteresis energy ΔW used in this report was defined as an area of the parallelogram ABCD enveloping the actual loop as a first approximation. This definition of the hysteresis energy ΔW brings about a problem of what is the ratio of the area surrounded by the actual loop to that of the parallelogram ABCD. But, the measurement of

Fig.16 W-N curve

the area of actual loop for sinusoidal stress gave the correcting factor K_s , the ratio of actual area to the area of the parallelogram, of about 0.74, which was nearly equal to that obtained by Halford, namely $K_s=0.75$. On the other hand, the same measurement of the hysteresis loops for impact fatigue stress gave the value of K_i , the correcting factor in the case of impact fatigue, about 0.75 for the medium stress level, and, therefore, it does not differ from that for the sinusoidal stress. The calculation of K_i was made, in this case, by considering that the real area was composed of the area of a large loop and those of the superimposed small loops as recognized from Fig.3(b),(c). However, since the shape of the hysteresis loop obtained at a considerably low stress level ($\sigma_a=19.2\text{kg/mm}^2$) was a very complicated one as shown in Fig.14, the measurement was made by dividing the loop into several parts and by correlating with the variation of the stress pattern. The value of K_i thus obtained was about 0.38 which was obviously less than the value of K_s . Consequently, the value of K_i does not exceed that of K_s in the over all stress range. Fig.15 represents the correlation between the impact stress pattern and the hysteresis loop shown in Fig.14.

The representative values of the hysteresis energy ΔW , which are the values at the cycle ratio $n/N=50\%$, are listed in the 5th column of Table 3. And the relation between this hysteresis energy ΔW and the number of stress cycles to failure N is presented on log-log paper in Fig.16, which shows nearly the same trend as the relation of $\Delta \epsilon_f$ and N shown in Fig.12. Also, the relation between the hysteresis energy ΔW and the stress amplitude σ_a is presented on log-log paper in Fig.17.

Fig.17 Relation between the hysteresis energy and the stress amplitude

A straight line can be drawn appropriately linking the plotting points for the ordinary fatigue test, and the relation is expressed by the following formula.

$$\Delta W = 6.8 \times 10^{-23} \sigma_a^{14.9} \dots (2)$$

But the results of the impact fatigue test show some discrepancies in this straight line, especially at a low stress level, which means that the quantity of work done on the material is larger under the impact fatigue test than under the ordinary fatigue test at such a low stress level, as a first approximation. It is, however, expected that the relation between the real value of the hysteresis energy and the stress amplitude will be reduced to a straight line, because the value of K_i at the low stress level is considerably small comparing to the value of K_s as was described above.

As a further discussion, the accumulated value of the hysteresis energy until failure, that is, the cumulative hysteresis energy, is plotted against the number of stress cycles in Fig.18, where a broken line is the boundary curve for ordinary fatigue failure and a chain line for impact fatigue failure, that is, the fatigue failure occurs when the amount of the cumulative hysteresis energy W reaches the value of these curves. It is obvious that there exists no distinct difference in the trends of the energy accumulation under both test conditions, but, a difference is observed in the values of cumulative

Fig.18 Accumulation of the hysteresis energy

hysteresis energy for fatigue failure, and, the value of cumulative hysteresis energy needed for the impact fatigue failure is always smaller than that needed for the ordinary fatigue failure.

In connection with the accumulation of the hysteresis energy, in order to explain the existence of the fatigue limit from the view point of inelastic strain behavior C.E. Feltner and J.D. Morrow pointed out that the inelastic strain energy obtained at the stress level below the fatigue limit was mainly composed of the anelastic strain energy and that the latter did not contribute to the fatigue failure. But, to explain the experimental results in this study, it must be taken into consideration that the ratio of anelastic strain energy in the whole inelastic strain energy never holds a constant value even at the same stress level and may vary with the stress pattern.

5. Conclusions

As the second part of a series of investigations on the impact fatigue, 0.53%C carbon steel was tested under ordinary and impact fatigue loads, and the inelastic behavior of this steel was observed with the strain gauges mounted on the specimen. Based on the results, discussions were made on the two major aspects of fatigue characteristics under impact load: the fatigue strength and the inelastic behavior of material.

Major conclusions obtained are as follows

(1) Though there existed a distinct fatigue limit on the fundamental S-N curve obtained under sinusoidal stress, the impact fatigue failure occurred at the stress level below the ordinary fatigue limit $\bar{\sigma}_w$, and the S-N curve for impact fatigue failure showed no fatigue limit in the range of a number of stress cycles up to 10^8 . This fatigue behavior under the impact fatigue test is the same as that found in the previous report, and consequently this is considered one of the impact fatigue characteristics of carbon steel.

(2) The impact fatigue failures occurred with the inelastic strain

amplitude below the endurance inelastic strain amplitude $\Delta \epsilon_w$ defined in the ordinary fatigue test. Consequently, it is thought that there may exist a difference in the relations between the inelastic strain amplitude and the fatigue strength depending on the mode of the stress variation.

(3) By comparing the impact fatigue failure with the ordinary fatigue failure from the view point of the relation between the cumulative hysteresis energy W and the number of stress cycles to failure N , it was found that the cumulative energy needed for the impact fatigue failure was smaller than that needed for ordinary fatigue failure.

(4) Based on the preceding conclusion, it is reasonably thought that the limited number of the nuclei of fatigue damage, which lead the material to failure, initiated under the impact load even at the stress level below the ordinary fatigue limit $\bar{\sigma}_w$. In connection with such a consideration as mentioned above, the problems on the localization of the inelastic strain and on the ratio of anelastic strain to total inelastic strain still remain unclarified and will be examined in near future.

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