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# REVIEW ON THE IMPACT FATIGUE STRENGTH OF METALLIC MATERIALS*

by

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## 1. INTRODUCTION

To prevent the unfortunate or unexpected fatigue failure of metallic mechanical structural elements, it is important to survey and to analyse the load conditions on the critical location of the mechanical structure carefully at first, and then, to obtain the precise knowledge on the fatigue strength or the fatigue life of the corresponding material through an appropriate fatigue study.

Types of the fatigue investigations having been conducted hitherto can be classified into two categories essentially as follows: One is the fundamental study conducted under the sinusoidally varying load condition to investigate the metallurgical feature of fatigue process, another is the fatigue experiment under the several sorts of the varying load conditions to obtain the method for predicting the fatigue life under the service load. The load patterns for the latter study are non-sinusoidal load[1], composite load[2], program load[3], random load[4] and impact load[5] for example. In the load patterns listed above, those except for impact load are to be classified as non-impact load. As for the fatigue study under program load which belongs to non-impact load, about twenty reports having been published in a year. On the other hand, the reports concerning the impact fatigue behavior amount to only about five in a year[6]. A fundation for the impact fatigue investigation seems still to be shallow as matters stand.

Since the impact load is considered as that induced by a collision of two bodies in a sence of phenomenlogical definition, the impact load is necessarily accompanied with transmission and reflection of the stress wave[7], which makes it difficult to measure the stress produced on the specimen.

Consequently, evaluation of the results of the impact fatigue tests has been made, mainly, from the viewpoint of the impact energy value obtainable from the load generating mechanism. In such a case, the experimental results are represented on an $E$-$N$ diagram, and the main purpose is to research the relative impact toughness or to make a comparison of the impact fatigue resistances among the several sorts of the metallic materials. Furthermore, such an evaluation method of the results as mentioned above makes it impossible to compare with

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those of the ordinary fatigue test results represented on an *S-N* diagram.

Of cource, a few investigations on the relationship between the impact energy and impact load in impact tests have been carried out to overcome such a difficulty accompanying the impact fatigue test. However the general theory for this relationship has not been established because this relationship differed owing to the diffence in the impact testing conditions such as the rigidity of the chucking device, the shape and dimensions of the specimen used and the characteristics of the load-time curve[8·9].

But recently, it has become possible for the rapid varying load to be measured so easily by means of new technical procedures, for example with the aid of the wire resistance strain gages, that the impact load is now determined in most cases in this way[10·11].

Now, loads acting on the many mechanical systems and elements, such as gear teeth[12], roller-chains[13-16] and the printing hammer of a mechanical printer[17] are well known as impact loads. As the other examples, wheels and shafts of railway trains are said to be subjected to impact load when they run over switching points or when tires are flattened by the braking action[18-21], and also the gears in the power plants of earthmoving equipment[22].

The practical example of the impact load pattern measured on the printing hammer of a mechanical printer is shown in Fig.1[17], and examples of load patterns acting on the gear teeth and on the shafts of the railway train are represented schematically in Figs.2 and 3, respectively.

Referring to the experimental results on impact fatigue carried out so far, the general characteristics of the impact fatigue behavior of metallic materials are examined below.

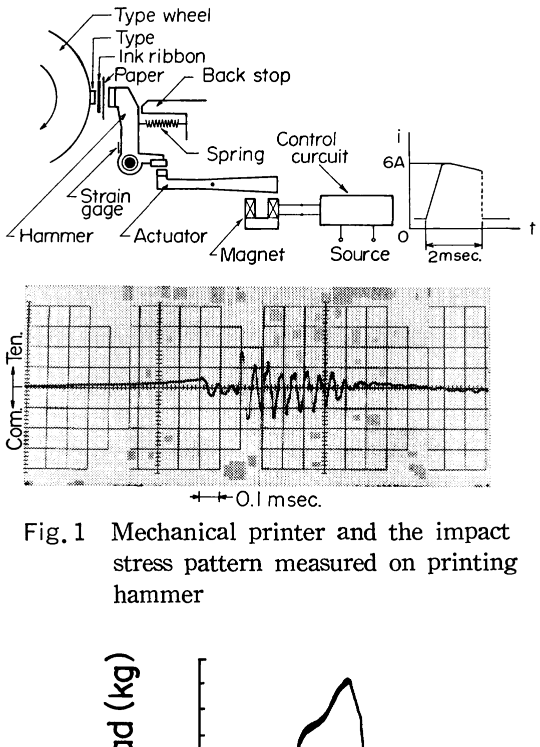


Fig. 1 Mechanical printer and the impact stress pattern measured on printing hammer

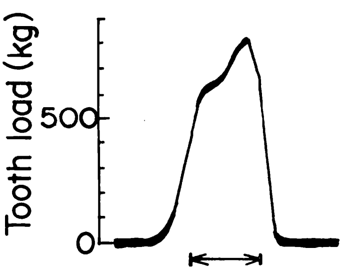


Fig. 2 Impact load pattern on gear tooth

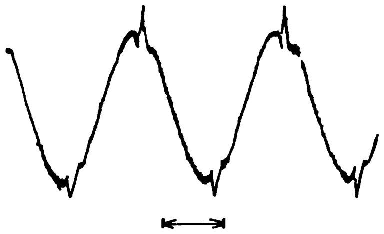
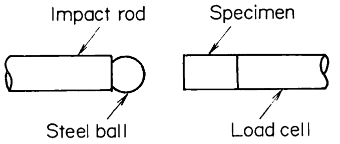


Fig. 3 Stress pattern involving the impact stress measured on the shaft of railway train when tires are flattened

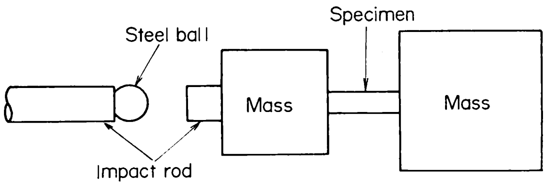
## 2. TWO TYPES OF IMPACT FATIGUE TESTS, EXPERIMENTAL APPARATUS FOR IMPACT FATIGUE INVESTIGATION AND DEFINITION OF IMPACT LOAD

In glancing at the impact fatigue tests so far carried out, the types of impact fatigue tests are to be divided mainly into two groups for the purposes involved: One is the experiment to investigate the plastic deformation and the fatigue damage on the colliding surface, and another is that to investigate those at the weakest location under the load condition caused by the collosion of two bodies. So to say, the former type of the investigaton is named as a direct impact fatigue test and the latter as an indirect impact fatigue test. Illustrations for these two types of the experiments are represented in Fig. 4.

First, the experiment to observe the failure process of the specimen surface under the colliding condition of the steel ball[23] or the plain surface[24,25] with the specimen surface, and furthermore, that to study the surface failure under impact load in connection with wear[26] are cited as examples of the direct impact fatigue test.



(a) Schematic representation of apparatus for direct impact fatigue test



(b) Schematic representation of apparatus for indirect impact fatigue test

Fig. 4 Two types of impact fatigue tests

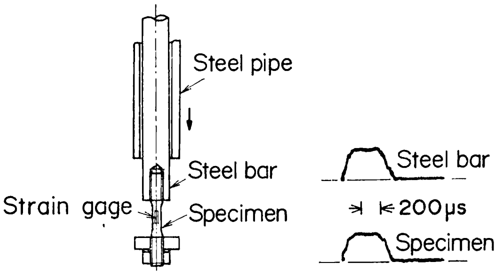
Next, as for the indirect impact fatigue test, considerably extensive studies have been made to research the following subjects, the fatigue strength of the several sorts of metallic materials under the impact load[27-33], propagation of the fatigue crack[34-37], hysteresis phenomenon[38-42], the residual compressive stress variation under impact fatigue load by the X-ray diffraction method[43], the fractographic observation[44,45], the effect of the ultimate tensile strength and the deformation resistance[46], the effect of notch[47-50], microscopical structure[51] and crystal grain size[52,53] on the impact fatigue strength, the relation with the low temperature brittleness[35,38,54], the effect of the crystal grain size on the propagation of the impact fatigue crack[55-57], the effect of the shock absorption on the tensile impact fatigue strength[58], the effect of the magnitude and the holding time of the impact stress pattern[50,59-61] and of the stress ratio[62] on the plastic deformation and the fatigue failure, and the effect of the transitional load vibration induced by the impact loading on the fatigue strength and the crack propagation behavior[63-65].

Besides, impact fatigue experiments on the actual structural elements have been carried out over a long period[12-16,66-68].

The experimental devices used in the impact fatigue tests are as follows; Amsler type universal tensile impact fatigue testing machine[9], Fujii type universal impact fatigue testing machine[27], drop-weight type tensile impact fatigue testing machine[60], rotating disk type impact fatigue testing machine[51], drop-weight type compressive impact fatigue testing machine[59], Matsumura type bending impact fatigue testing machine[34], push-pull impact fatigue testing machine[5] and rotating bending impact fatigue testing machine[63].

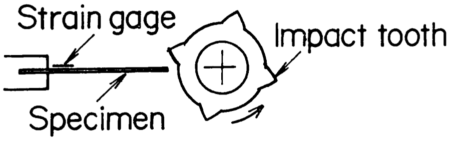
As for the impact load generating mechanism of the devices cited above, it can be said that the impact load is in all cases obtained by the collision of two bodies, which characterizes the impact fatigue testing machine. Accordingly the definition of the impact load described in the preceding chapter is appropriate to discuss the results of impact fatigue behavior obtained up to date as a whole.

As the last of this chapter, the principles of some impact fatigue testing machines and the typical stress patterns obtained with these machines are shown in Figs. 5[60], 6[69] and 7[5] for the purpose of reference, while the experimental results are given in the following chapter. It is noted that the impact stress patterns are more or less inherent to the testing machine used, and are selected in connection with the purpose of the study.

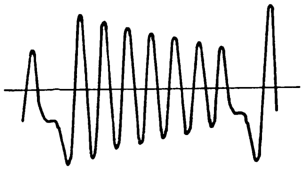


(a) Testing appratus for tensile impact
(b) Impact stress patterns

Fig. 5 Tensile impact testing machine and stress patterns

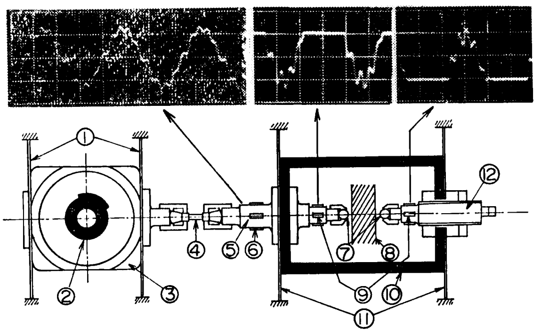


(a) Testing apparatus for bending impact



(b) Impact stress pattern

Fig. 6 Bending impact testing machine and stress pattern



① Plate spring
② Eccentric mass
③ Vibro motor
④ Specimen
⑤ Load cell
⑥ Strain gage
⑦ Impact ball
⑧ Rigid wall
⑨ Strain gage
⑩ Rigid frame
⑪ Plate spring
⑫ Clearance adjusting rod

Fig. 7 Push-pull impact fatigue testing machine and stress patterns

## 3. GENERAL CHARACTERISTICS OF IMPACT FATIGUE

The description of the general characteristics of the impact fatigue is to be done by taking notice of the indirect impact fatigue test because the numerical studies on the impact fatigue belong to this type of test.

As mentioned in Chaps. 1 and 2, the impact fatigue tests have been conducted by generating the load with the collision of two bodies. Therefore, in many cases, the load frequency or the repetition rate can not be so high as that of the ordinary fatigue test because of its load generating mechanism. For this reason, most of the studies on the impact fatigue are restricted to the experiments in low stress cycles range, for exemple $10^5$ stress cycles at most.

However, endeavors have been made to increase the load frequency by several investigators whose purpose is, mainly, to evaluate the impact fatigue characteristic in comparison with that under the ordinary fatigue load condition.

Some typical impact fatigue testing machines and the load frequency of these are listed in the review on this subject by A. Chatani[70].

In this chapter, the impact fatigue studies in which the experimental range of the number of stress cycles lies below $10^5$ stress cycles are treated as the low cycle impact fatigue test and those over $10^5$ stress cycles as high cycle impact fatigue test.

### 3-1. *General Characteristics of Low Cycle Impact Fatigue*

Bsaed on the experimental results obtained in the fatigue tests whose run-out number is about $10^5$ stress cycles, the characteristics from the strength aspect can be described as follows.

In Fig. 8 the typical impact load pattern measured in such a low cycle impact fatigue test is shown, and the approximation of this practical stress pattern to the rectangular one is illustrated schematically in Fig. 9. Some studies have been conducted to examine the effects of the impact stress $\sigma$ and the hold time T on impact fatigue failure[44,59-61,71]. One of the results obtained by A.Chatani *et al.* for 0.01%C carbon steel is shown in Fig. 10[60]. It is observed that the impact fatigue life is affected not only by the magnitude of the impact stress $\sigma$ but also by the hold time T. And, the strength characteristic can be formulated by the equation (1).

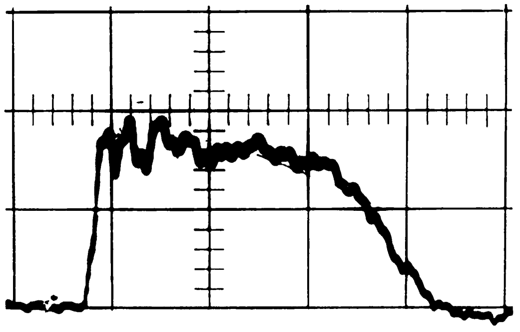


Fig. 8 Example of impact stress pattern in low cycle impact fatigue test

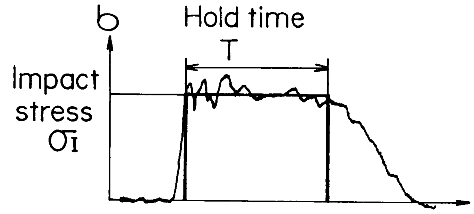


Fig. 9 Approximation of impact stress pattern to rectangular stess

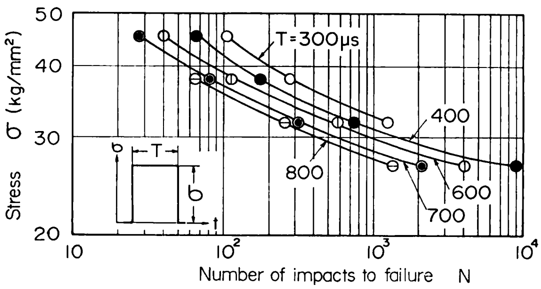


Fig. 10 *S-N* curves with parameter T

$$\sigma N^m T^n = C \cdots\cdots (1),$$

where m, n and C are material constants. But, since m is nearly equal to n, the above equation can be rewritten as

$$\sigma (NT)^m = C \cdots\cdots (1)'.$$

This relationship is also recognized for several sorts of carbon steels[72] and alloy steels[70]. Futhermore, the constant C is well correlated with the static tensile strength $\sigma_B$ and the reduction of area $\phi$, as is represented by the following equation;

$$C = (0.8+0.002\phi)\ \sigma_B \cdots\cdots (2).$$

It may be considered that such a phenomenological relationship as is formulated in Eqs. (1) and (1)′ can be reduced to the general problem on the stress holding time in connection with the stress frequency effect in the ordinary high cycle fatigue test.

Besides, M. Arii *et al.* demonstrate that the low cycle impact fatigue life is well predicted, when the stress ratio is taken into account, by means of the linear damage rule[73].

Next, the results obtained through the experiments made from viewpoints of the hysteresis energy and the transition tempetature are reviewed briefly. Hitherto, the magnitude of the impact energy value obtained in the single impact test *e.g.* Charpy impact test has been taken as a measure to estimate the material toughness in connection with the existence of the ductile-brittle transition temperature. As to the transition temperature, it must be noticed that the Charpy impact energy value consists of the sum of the energies for initiating and propagating cracks, and the transition behavior takes place by the fact that the lower the ambient temperature, the smaller the energy expended in crack propagation[74]. Though the single impact value seems to be correlated with the static tensile strength to a certain extent[75], the relation with the impact fatigue strength has not been established yet.

In impact fatigue test conducted in the low cycles range, the transition behavior of the fatigue strength can be treated as an extension of the single impact test, since the impact fracture mechanism seems to be dominant rather than the fatigue failure mechanism in considerably low stress cycles range. An example of such invesigations carried out by K• Nagai is represented in Fig. 11[38]. It is observed that the effect of the low temperature on the impact fatigue failure gradually vanishes with the increase in the number of stress cycles[54], and then the fatigue strength in low temperature ambiance is increased, since the fatigue failure mechanism becomes dominant rather than the impact fracture mechanism in the range of the stress cycles exceeding $10^3$ *vice versa*[76-79].

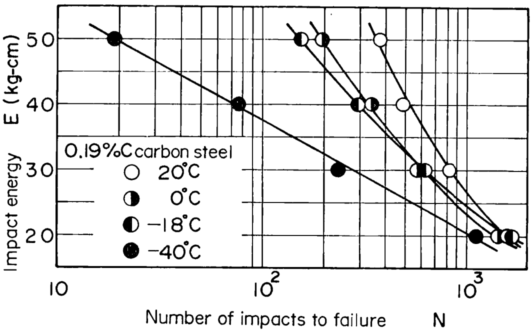


Fig. 11 *E-N* curves for several testing temperatures

Another example obtained by K. Nagai, which demonstrates the temperature effect on the hysteresis energy behavior in impact fatigue test, is represented on log-log paper in Fig. 12 by taking the hysteresis energy △W at the life fraction n/N = 50% as the ordinate and the number of impacts to failure as the abscissa[38]. This figure reveals that the impact fatigue failures occur with much less hysteresis energy at the ambient temperature ot -40°C due to the reduced residual strain retained in the specimen. And the fracture surtace obtained under this temperature condition is of the cleavage type. On the other hand, the fracture surfaces under the other three temperature conditions show those of the ordinary fatigue

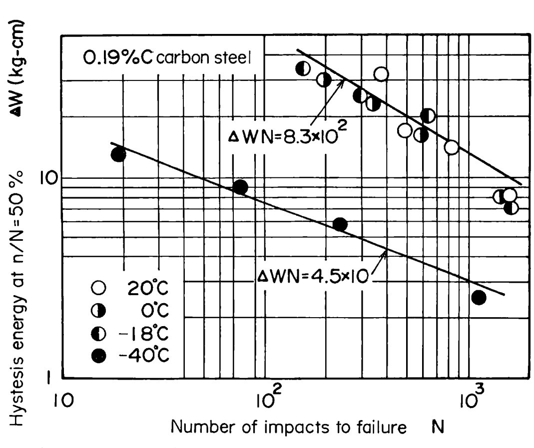


Fig. 12 △*W-N* curves for testing seueral temperatures failure, and, therefore, it is recognized that the accumulation of the hysteresis energy plays the role of the fatigue failure criterion because a regression line for these results can be drawn suitably. Beisdes, the discrepancy lying between two lines shown in this figure seems to decrease gradually with the increase in the number of impacts.

Results of some studies on the crack intiation and propagation behavior under the impact fatigue load would be described below in connection with the evaluation from the stress intensity factor and the fractographic aspect. Though the fundamental study on the fatigue crack initiation and propagation behavior has been made for a long time to research the whole fatigue process systematically[80], study from such a viewpoint has come to be carried out vigorously with the development of the electron microscopic technique and with the difussion of the Fracture Mechanics concept in this country.

In the ordinary fatigue load condition, it is well known emprically that the fatigue crack propagation rate da/dN can be correlated to the crack length a[81], and to the stress intensity factor range $\triangle K$[82] with a power law as are written down in the following equations*;

$$da/dN = Ba = A\sigma^{l}a \cdots\cdots (3)$$

$$da/dN = (\triangle K)^{m} \cdots\cdots (4)$$

where B, A, $l$ in Eq. (3) and C, m in Eq. (4) are constants depending on the material used or on the experimental condition. The index $l$ in Eq. (3) takes the value of 2[83] or 3[84], and though the index m in Eq. (4) takes the value ranging from 0.5 to 8.0[85], the value of $m=4$ is adopted in considering the long range characteristic as is demonstrated by P. C. Paris and F. Erdogan[82].

In impact fatigue tests, the values of $l=1.9$[56] $m=1.7$[45] and 2.2[44] having been obtained, peculiarity of the crack propagation behavior has not been observed. Besides, according to the impact fatigue test carried out in the low temperature ambiance of −40°C, it is revealed that fatigue cracks initiate with smaller number of impacts in the low temper ature ambiance than that needed in room temperature at the rel atively high impact energy level, but this relation is reversed at the relatively low impact energy level[35].

Referring the results of the fractographic observation done with the aid of the electron microscope, Laird's fatigue crack propagation model[86] seems to be also available to interpret the fracture surface configuration in impact fatigue test, and the final stage of the crack propagation shows the river pattern due to cleavage fracture[44·45·46].

Finally, though it seems to be important to compare the impact fatigue strength with the ordinary one in evaluating the effect of the impact load pattern on the fatigue strength quantitatively, only a few studies are made from such a point of view. Results of these studies reveal that the impact fatigue strength shows lowering trend in comparison with the ordinary fatigue strength for three sorts of metallic materials, *i.e.*, carbon steels (JIS. S25C, JIS. SK5)[61] and a pure aluminum of commercial base[87]. Such a strength trend in low cycle impact fatigue test coincides with the impact fatigue characteristic from the strength aspect demonstrated by the present authors through a series of studies on the impact fatigue in high stress cycles range[88].

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* Historical review on the treatise of the fatigue crack propagation is described in details in "Introduction to Fracture Mechanics", ed. by H. Murakami and M. Ohnami, Ohmsha, (1979), P. 130.

### 3-2. *General Characteristics of High Cycle Impact Fatigue*

In this chapter, the high cycle impact fatigue characteristics composed of several aspects would be reviewed. Though there exist some results of impact fatigue tests without the comparative fatigue test result sunder the ordinery load condition, *e.g.*, that to research the relative strength of the defected materials[89], the quantitative comparison with the results of the ordinary fatigue tests would be intended if possible.

To begin with, discussion on the impact fatigue characteristics from the strength aspect is to be done. The results of the experiment conducted by K. Akizono *et al.* for 0.21%C carbon steel to research the effect of crystal grain size on the impact fatigue strength are represented in Fig.13, where the impact load pattern measured is also illustrated and the letters A, B and C mean the crystal grain size respectively[52]. In this study, the comparative fatigue tests under the sinusoidal load pattern are also conducted. And, results obtained by the present authors with the impact fatigue testing machine shown in Fig. 7 are represented in Figs. 14[39] and 15[32]. The former results are for 0.53%C carbon steel, the latter for SCM 4 alloy, where Pc= 500kg and 800kg mean the experimental conditions for the ordinary fatigue test and CL.= 0.02mm for the impact fatigue test respectively.

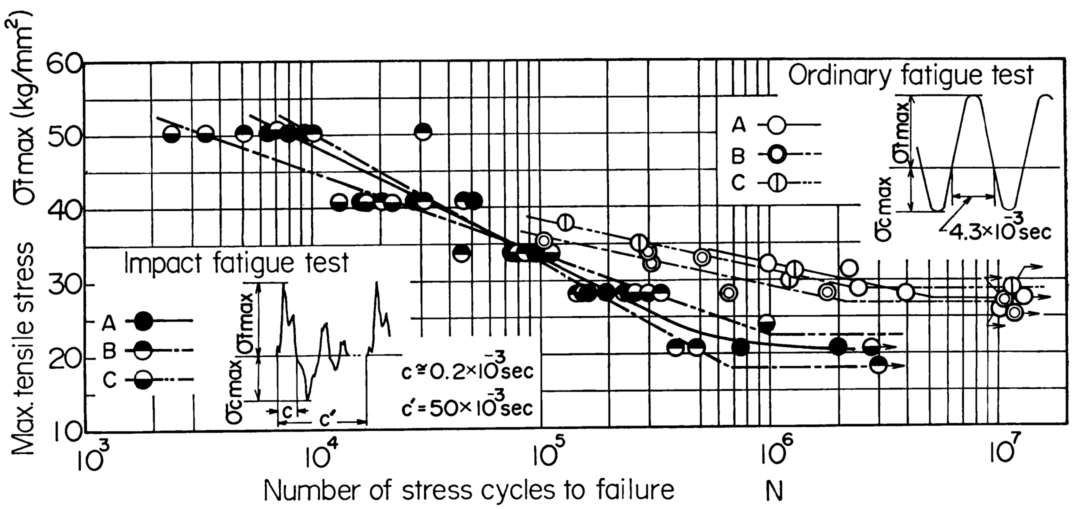

Fig. 13 *S-N* curves for 0.21%C carbon steel

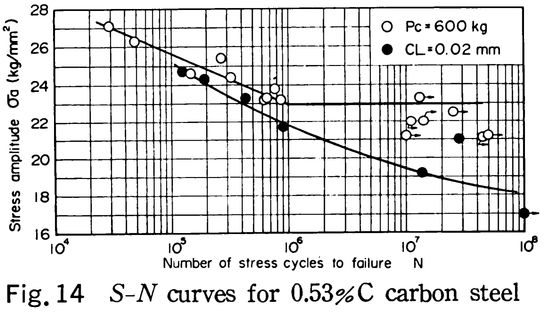

Fig. 14 *S-N* curves for 0.53%C carbon steel

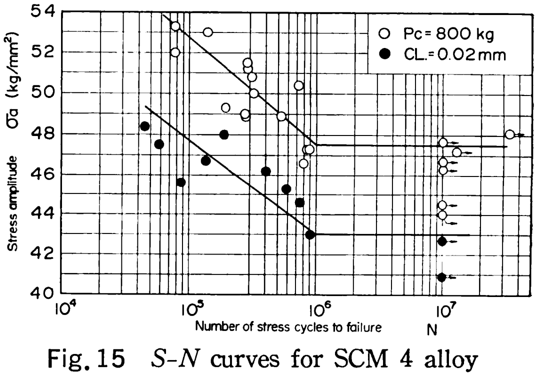

Fig. 15 *S-N* curves for SCM 4 alloy

From the results shown in above three figures, it can be observed as a common trend that the impact fatigue strength is lower than the ordinary one in the relatively high stress cycles range. But, the whole feature of the fatigue strength differs from one another. In the first place, the strength behavior in the low stress cycles range of SCM 4 alloy is somewhat different from those of two sorts of the carbon steels. That is, in the case of SCM 4 alloy, the lowering trend of impact fatigue strength is observed over the whole stress cycles range, while the results of the carbon steels do not show such a strength trend. In the second place, though it seems to be a matter of more importance to obtain a experimental knowledge on the existence of the fatigue limit in the impact fatigue test in a practical meaning, there does not exist a definite opinion as is seen from these three figures. But the lowering trend of the impact fatigue strength in high stress cycles range must be noticed.

The results of the impact fatigue test obtained S. Kondo *et al.* are introduced here[9 0], which shows the opposite strength trend to those described above. That is, though the ordinary fatigue tests are conducted only in the narrow range of stress cycles, it is observd that the fatigue strengths under the impact load are higher than those under the ordinary load condition in the stress cycles range lower than $10^6$ stress cycles.

However, the study on this subject by S. Taira *et al.* suggests that such a strength trend in impact fatigue test depends on the shape of the specimen, *i. e.*, theoretical stress concentration factor Kt[9 1], so the effect of notch shape on the impact fatigue must be investigated hereafter systematically.

As the stress pattern obtained with the testing machine shown in Fig. 7 well resembles the composite stress pattern, the lowering trend under the impact load is examined quantitatively by means of the comparison with the strength characteristic under the composite load condition referring the results obtained by the present authors shown in Fig. 14. So, the impact stress pattern is characterized as the composite stress pattern to make the correspondence possible as is shown in Fig. 16 schematically. Thus, the *S-N* relations represented in Fig. 14 can be rewritten as in Fig.17, where the impact stress pattern is supposed to be composed of the primary stress wave $\sigma_1$ of the frequency $f_1 = 57.5$Hz and the secondary stress wave $\sigma_2$ whose magnitude and the frequency are determined referring to the neighbourhood of the maximum stress level in the impact stress pattern. Besides, results of the impact fatigue test are divided

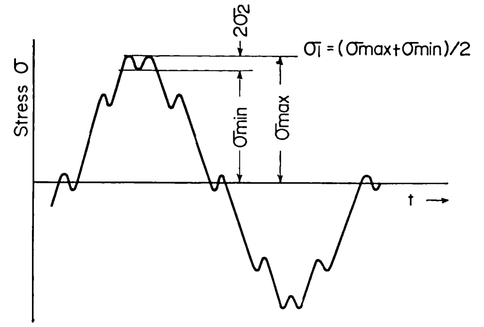

Fig. 16 Approximation of impact stress pattern to composite stress pattern

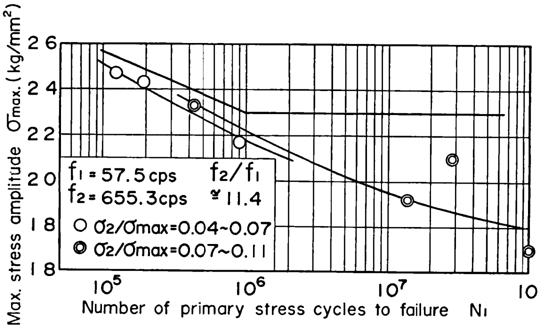

Fig. 17 Relation between $\sigma_{\max}$ and $N_1$ for 0.53%C carbon steel

into two groups because the value of the ratio $\sigma_2/\sigma_{\max}$, taking as a parameter, is spreading in the wide range.

According to the general concept on the fatigue strength characteristics under the composite load condition, it can be said that, though the decrease in the fatigue life and furthermore the lowering of the fatigue limit take place when the value of the ratio $\sigma_2/\sigma_{\max}$ is considerably large[2,92-96], the effect of the secondary component is negligible or acts even as a strengthening factor when this ratio takes such a small value, *e.g.* $\sigma_2/\sigma_{\max}<0.1$, as in the case of this experiment[2]. Therefore, it seems to be almost impossible to explain the lowering trend in the impact fatigue tests, observed in the results except for those by S. Kondo *et al.*, with the aid of the previous studies on fatigue under composite stress.

S.Tanaka approves that the linear damage rule can be applied to predict the impact fatigue life in his experiments done with the apparatus shown in Fig. 6[69] But, the scattering of the experimental results from the theoretically predicted line is observed to be large in the unconservative side rather than in the conservatiue side.

Then, the impact fatigue characteristic from the inelastic strain behavior aspect is to be described below depending largely on the results obtained by the present authors.

The following is thought to be a typical process of fatigue failure: Crystal lattice strains, which grow into the nuclei of fatigue damage, accmulate in a material during the early stage of stress cycling, and then, a fatigue failure occures in the growing process of these nuclei from micro-cracks to macro-craks. Such a fatigue process described above can be measured as a hytseresis loop shown in Fig. 18 schematically with the aid of the strain gages mounted on the specimen. There, it is well known that the values extracted from this hysteresis loop, *i. e.*, the inelastic strain amplitude Δεi and the hysteresis energy ΔW are the key parameters to estimate the fatigue life of the metallic materials even in the high stress cycles range[97] despite that this Δεi-N relation was advocated in the studies on thermal fatigue and low cycle fatigue individually.

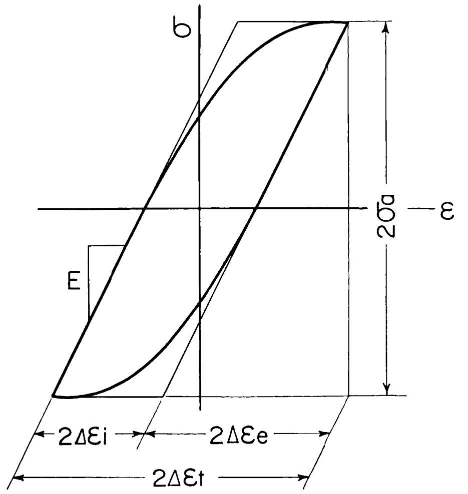

Fig. 18 Illustration of hysteresis loop

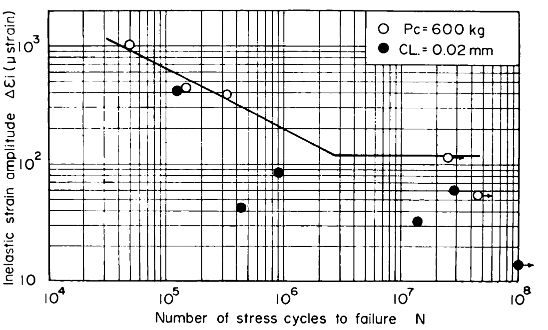

Fig. 19 $\Delta\varepsilon_i$-$N$ curve for 0.53%C carbon steel

One of the results obtained for 0.53%C carbon steel by the present authors is represented in Fig. 19, where the ordinate is taken as the representative value of inelastic strain amplitude at the life fraction n/N=50% and the abscissa as the number of stress cycles to failure[39]. It is obvious in Fig. 19 that the impact fatigue failures take place with a small value of $\Delta\varepsilon_i$ at which the ordinary fatigue failures do not occur. The lowest value of $\Delta\varepsilon_i$ is about $33\mu$ strain in the case of the impact fatigue failure, and this corresponds to about a fourth of the endurance inelastic strain limit $\Delta\varepsilon_{iw}$ of $120\mu$ strain, where $\Delta\varepsilon_{iw}$ is defined as the magnitude below which no failures occur in the ordinary fatigue test[98,99].

The speculation on such a inelastic strain behavior in impact fatigue test is tried in the previous paper in detals by the present authors, in which the distinct localization of the inelastic strain and the fatigue failure process based on this localised inelastic strain under the impact load are supposed[39]. Describing briefly, the slip bands, whose visco-elastic and plastic behavior according to stress cycling appear as the inelastic strain, distributing with low density on the specimen surface grow into the fatigue damage nuclei even under low impact stress, while such a small plastic strain strengthen the material with the combined effect of the strain aging[100] and work hardening[101] under the ordinary load condition.

From the description done above, the lowering trend of impact fatigue strength seems to be explained from the view point of the peculiar inelastic strain behavior in impact fatigue test. However, it is a matter of more importance to clarify why this peculiarity is allowed under the impact load, and it must be studied hereafter.

On the other hand, it is impossible to try such a discussion for the some sorts of hardened metallic materials, *e.g.*, duralumin and SCM 4 alloy and so forth, because the imformative hysteresis behavior can not be obtained for these sorts of the materials[32,40].

Here, as is reviewed by H. Matsumoto and H. Nakazawa, the stress concentration factor under the dynamic load takes somewhat higher value than under the static load[102], and it is well known that the inclusions lying near the specimen surface play a role as crack starter in the case of the hardened material[103]. So, the lowering trend for these materials, as one of the example is represented in Fig. 15, is to be explained by considering the fatigue damage nucleation around the inclusions.

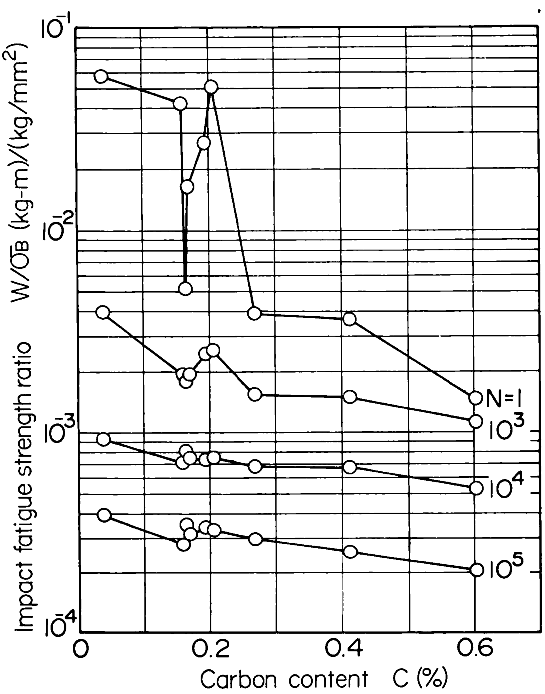

Fig. 20 Relation between the impact fatigue strength ratio and carbon content

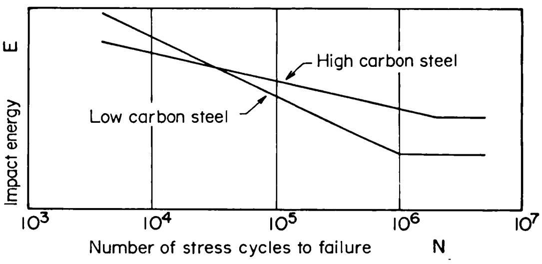

Fig. 21 Impact fatigue behavior of low and high carbon steels on *E-N* diagram

Miscellaneous aspects concerning the high cycle impact fatigue would reviewed briefly. Single impact-high cycle impact fatigue transition behavior is represented in Figs. 20 and 21. From Fig. 20 obtianed through rearrangement of the experimental results by T.E. Stantton, *et al.*,[104] it can be said that the single impact characteristic under N=1 vanishes gradually according to the increase in the number of stress cycles to failure, and finally, the values of the ratio $w/\sigma_B$ come to take the stable value neverthless the difference of the carbon content, which corresponds to a common trend in the ordinary fatigue test that the values of the fatigue strength ratio $\sigma_W/\sigma_B$ are almost constant[105], where W, $\sigma_B$ and $\sigma_W$ are the impact energy, ultimate strength and fatigue limit respectively. Other examples are represented in the previous review on this subject[88].

The existence of the transitional number of stress cycles in impact fatigue test is seen in Fig. 21[46], that is, though the single impact characteristic is still retained in low cycle range, ordinary fatigue property come to appear in high cycle range exceeding the transitional number of stress cycles.

The relationship between the theoretical stress concentration factor $K_t$ and the notch factor $\beta$ in impact fatigue test is examined by M. Kawamoto, *et al.*,[46] and F. Hamayoshi, *et al*[49]. And they demonstrate that there does not exist any peculiarity in this relation in comparison with that in ordinary fatigue test[106.107].

## 4. CLOSING REMARKS FOR FURTHER DEVELOPMENT

In a series of the impact fatigue tests in low temperature ambiance conducted by the authors, it is revealed that, as is represented in Fig. 22, the fatigue strength under the impact load(●) is higher than that under the ordinary load(○) at -100°C low tempetature[42] contrary to the strength behavior in room temperature. Such a strength trend suggests that the impact fatigue characteristics must be considered from the metallurgical point of view, for example, from the viewpoint that how behave the solute atoms as carbon and nitrogen atoms, which constitute the interaction with the movable dislocations, under the impact load condition.

Then, as is seen in this paper, importance of the impact fatigue characteristics is essentially, its lowering trend in high cycle range. So, from the standpoint of the practical design engineering, some amount of the experimental results must be accumulated with the analytical representation of the impact stress patterns to discuss the strength trend more precisely.

Most peculiar aspect to impact fatigue is in the problem of the elastic wave propagation. This problem is dwarfed to that of the one-dimensional elastic wave propagation by longitudinal wave as matters stand. So, endeavor must be paid to study such a subject considering conceptual extension to Dynamic Fracture Mechanics.

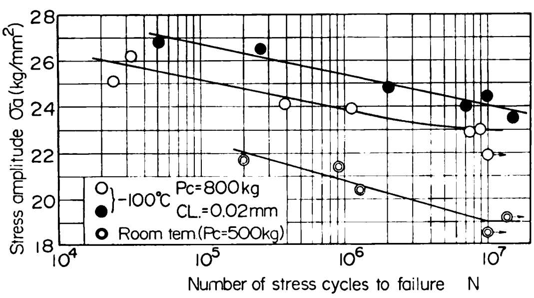

Fig. 22 *S-N* curves for 0.21%C carbon steel in low temperature ambiance of −100°C

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