HIGH STRAIN RATE FRACTURE AND IMPACT MECHANICS

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ABSTRACT

According to previous studies, the dynamic yield strength increases but the dynamic fracture toughness decreases with increasing loading rate. The dynamic stress concentration behavior of a strip with a shoulder fillet and the stress distribution in a bar subjected to an impact force are investigated. In these results, size dependence of the impact stress caused by the superposition of stress waves was observed. The impact fatigue life and impact fracture toughness also exhibit size dependence. In addition, disadvantageous aspects of conventional evaluation method for the impact strength of materials and a new simple practical method are described.

KEYWORDS

Stress wave, dynamic stress concentration, impact fracture toughness,impact fatigue, strain rate, dynamic stress strain diagram, impact testing method.

INTRODUCTION

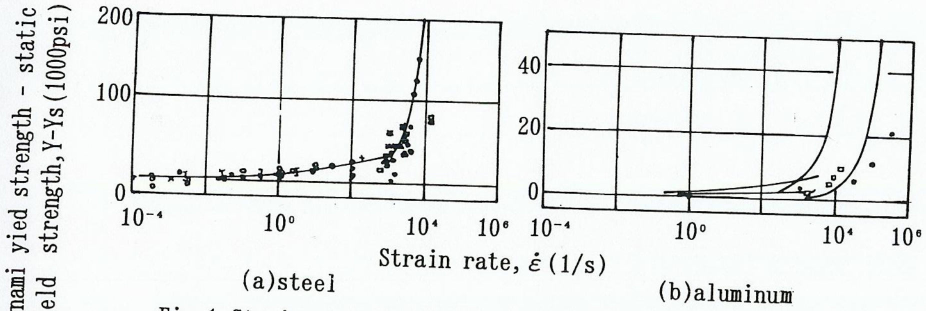
Now, impact fracture of vehicles in traffic accidents is a serious social problem. In future,the occurence of fracture under a high loading rate will increase as the numbers of high speed machines increases. Damage caused by high speed collision of small pitchs with blades in gas turbines and penetration of cosmic dust with space craft will also be an important problem. Thus,investigations on the impact fracture behavior of structures and materials are important. It is well known that impact forces are dangerous for structures and so large safety factors are incorporated into the design,if impact forces are presumed to act on the structure.

Regarding car or aircraft crashes,structural improvements based on the concept of energy absorption have been effective (Jones, 1993). More fundamental studies on the characteristic properties of the dynamic stress distribution in a structural element subjected to an impact force (Maekawa et al.,1988a),the dynamic yield strength of materials (Kanninen *et al.*, 1967; Harding,1987) and dynamic fracture toughness (Klepaczko, 1990) have also been performed. According to these results,the dynamic fracture behavior is often quite different from the static behavior.This may be due to the characteristic properties of the dynamic stress distribution in a specimen subjected to an impact force and the material behavior under such mechanical conditions. In this work,discussion is forcussed mainly on the former.

At the same time,the development of a strength evaluation method cannot be neglected. Since impact fracture is a very high speed phenomenon,the measurement of fracture behavior is not easy. The development of a method of measuring impact strength is also important. Therefore,some disadvantageous aspect of the conventional evaluation method for the impact strength of materials are pointed out and a new method is proposed.

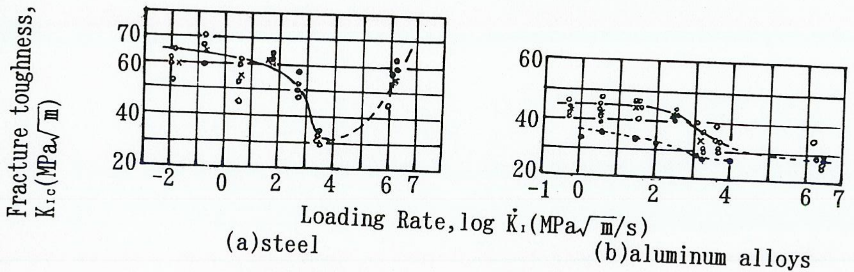
STRENGTH OF MATERIALS UNDER A HIGH STRAIN RATE

Extensive studies concerned with the strain rate dependence of the yield strength of materials have been performed,some of which are summarized in Figs.1(a) and 1(b) (Kanninen *et al.*, 1967). According to these results,the dynamic strength increases with increasing strain rate. In the case of composite materials, the stress strain relationship fluctuates, and so the strain rate dependence of the tensile modulus is shown. The modulus increases slowly below a strain rate of log 10^1 and increases remarkably above it with increasing strain rate (Harding, 1987).



(a)steel (b)aluminum

Fig.1 Strain rate dependence of yield strength (at RT).



(a)steel (b)aluminum alloys

Fig.2 Fracture toughness spectrum.

If a small particle collides with the surface of a material, a crater and ring cracks around it are produced at the collision site. Radial cracks, conical cracks and lateral cracks were observed in cross sections through the craters (Maekawa *et al.*,1991), and ductile voids and adiabatic shear bands were also observed beneath the craters (Shockey *et al.*,1983). These damages reduce the residual strength, which is evaluated by bending tests performed after the particle collision experiments (Maekawa *et al.*,1991).

When a cracked structural element is subjected to an impact force, the dynamic fracture toughness decreases with increasing loading rate, as shown in Figs.2(a) and 2(b)(Klepaczko, 1982). In the case of ceramics,the loading rate dependence of dynamic fracture toughness K_{Id} is different for different materials (Kishi *et al.*,1989). The characteristic properties of the dynamic stress concentration factor are discussed in the next section.

DYNAMIC STRESS CONCENTRATION

As a typical example, the stress concentration factor for a strip with a shoulder fillet was experimentally investigated (Maekawa and Yoshikawa,1996b). When impact tension was applied to the narrow end of the strip, the magnitude of the dynamic stress concentration factor α_d is larger than that when the same impact force was applied to the wide end. Where,influence of the difference in the widths of the loaded ends on the nominal stress was took into account by considering the width ratio.

Moreover,the value of α_d for a full-length specimen was the same as that for a half-length specimen, although the maximum and the nominal stresses (strains) for the half-specimen were increased due to the size dependence of the impact stress, which is described later. In addition, the maximum strain amplitude amplified by the superposition of waves reflected from both ends of the specimen was recorded after the first peak in the strain history. These dynamic behavior are also different from the static stress concentration.

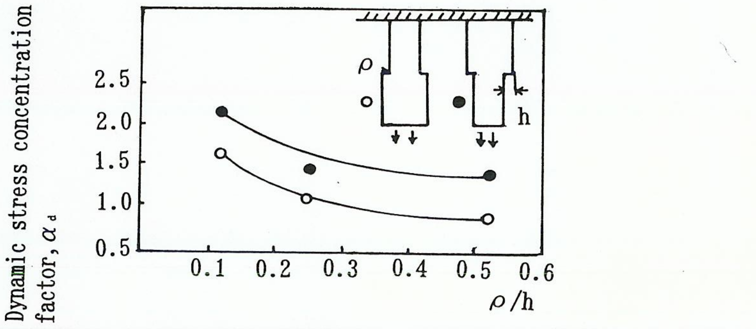


Fig.3 Characteristics of dynamic stress concentration factor.

CHARACTERISTIC PROPERTIES OF IMPACT STRESS

irst,the dynamic stress distribution in a bar supported by an elastic wall considered to investigate the behavior of reflected stress waves when a bar is subjected to an impact compression using an impactor with mass M and velocity V_0 as shown in Fig.4(a). The equation of motion of the impacted d of the bar is

$$\frac{M}{\sqrt{E\rho}}\frac{d\sigma}{d\,t}+\sigma=0 \tag{1}$$

is solution is given as

$$\sigma=\sigma_0\cdot\exp\{-t\sqrt{E\cdot\rho}/M\}, \tag{2}$$

ere $\sigma_0=V_0\sqrt{E\cdot\rho}$ is the initial stress produced at the impacted end,and and ρ are the elastic modulus and the density of the bar (Timoshenko and Goodier, 1951). Taking into account the influences of reduction in stress plitude due to the imperfect reflections at the left and right ends of e bar by the coefficients of reflection β_1 and β_2, and considering the tenuation in amplitude during propagation by the function $f(x)$ of the distance x wave propagated,the resultant stress can be expressed as follows,

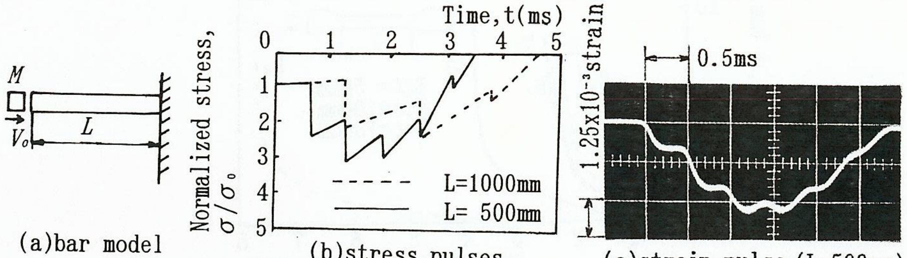
$$\sigma=P_n(t)+P_{n-1}(t-T) \tag{3}$$

for the time interval $nT<t<(n+1)T$,after n reflections at the left end of the bar. Here

$$P_n(t)=P_{n-1}(t)+\sigma_0\exp\{-2\alpha[(t/T)-n]\}$$
$$\times\{(\beta_1\beta_2)^n f(2nL)+\sum_{r=0}^{n-1}\frac{Q_{r,n}}{r!}[4\alpha(n-(t/T))]^r+\frac{1}{n!}[4\alpha(n-(t/T))]^n\}, \tag{4}$$

re L = length of bar
C = wave velocity
$Q_{0,n}=0$
$Q_{1,n}=\sum_{p=0}^{n-1}(\beta_1\beta_2)^p f(2pL)$ $(n\geqq 2)$
$Q_{n-1,n}=(n-1)+\beta_1\beta_2 f(x)$ $(n\geqq 2)$
$Q_{r,n}=Q_{r,n-1}+Q_{r-1,n-1}$ $(r\geqq 2, n\geqq 4, r\neq n-1)$
$\alpha=L\rho/M$

S stituting appropriate material constants into Eqs.(3) and (4),the theoretical stress pulse shown in Fig.4(b) was obtained for a polymethyl metharylate (PMMA) specimen. The strain pulse produced in a PMMA bar subjected impact compression was measured as shown in Fig.4(c). Qualitatively good eement can be seen between the results in Figs.4(b) and 4(c) (Maekawa *et al.*,1988a). According to these results,the magnitude of the stress produced n a short bar is larger than that produced in a long bar. The size depende of impact stress influences the fracture strength of specimen. Similar problem was shown by computer simulation for the fracture initiation of a rectangular block (Zukas *et al.*, 1992).



(a)bar model (b)stress pulses (c)strain pulse (L=500mm)

Fig.4 Theoretical stress pulse and experimental strain pulse (PMMA).

SIZE DEPENDENCE OF IMPACT STRENGTH

Impact Fatigue Experiments

According to the above results,an impact force with comparatively small amplitude can cause fracture due to the amplified amplitude resulting from the superposition of reflected stress waves. The degree of amplification depends on the number of reflections and therefore on the length of the specimen. Impact fatigue experiments were carried out using short and long specimens under a pulsation of comparatively small stress amplitude.

First, impact tension pulses were generated in a notched specimen made of carbon steel. Crack growth curves for two series of steel are shown in Fig. 5. In this figure,the fatigue life of the shorter specimen is shorter than that of the longer one for both series of specimens (Maekawa, 1996a). Next, impact force pulses were applied to the upper cross-sectional surfaces of specimens with three different lengths using a falling weight. In Fig.6,the relationships between the pitting life L_p, defined as the number of pulses required to initiate pitting on the upper surface of the specimen,and specimen length are shown for two series of carbon steels. This figure shows that the pitting life of the shorter specimen is also shorter than that of the longer specimen (Maekawa and Hida, 1980; Maekawa, 1996a). Thirdly,the results of impact torsional fatigue experiments carried out using steel specimens with a shoulder fillet are shown in Fig.7, which shows a similar dependence of impact fatigue life on specimen length (Maekawa *et al.*,1982). The size dependence of impact fatigue life corresponds to that of impact stress described above.

However,the size dependence described above is opposite to the well known

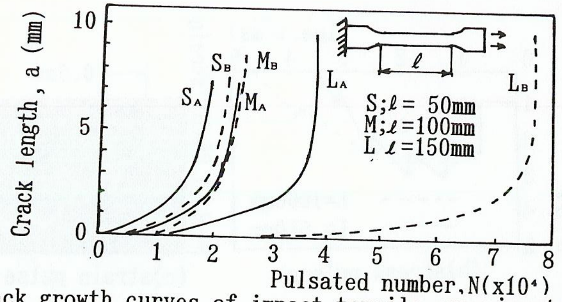


Fig.5 Crack growth curves of impact tensile experiments (steel).

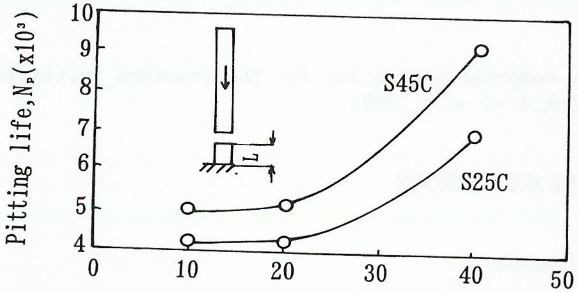


Fig.6 Pitting lives vs. specimen length (steel).

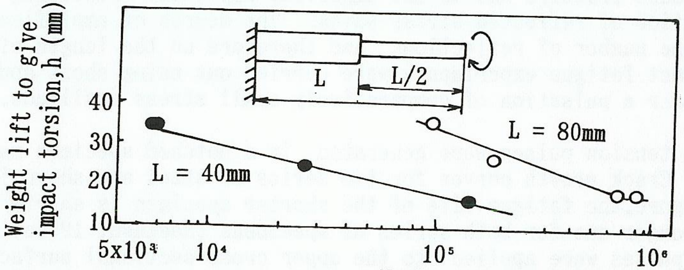


Fig.7 Impact torsional fdatigue experiments (steel).

size dependence of materials, i.e., small specimens are stronger than large specimens under similar static loading conditions. This is explained by considering that the probability of the exisence of weak defects in a large specimen is higher than that in a small specimen. That is, the size dependence results from a qualitative effect. On the other hand, the size dependence of the impact fatigue life described above result from mechanical effect. Therefore, these are called the qualitative size dependence and the mechanical size dependence, respectively (Maekawa, 1992a). Since experimental results include the qualitative size dependence, it can be said that the mechanical size dependence is remarkable compared with qualitative one for common engineering materials (Maekawa, 1996a). However, graphite did not show a clear mechanical size dependence, due to the considerable attenuation of the stress amplitude during wave propagation (Maekawa, 1988b).

Impact Fracture Toughness

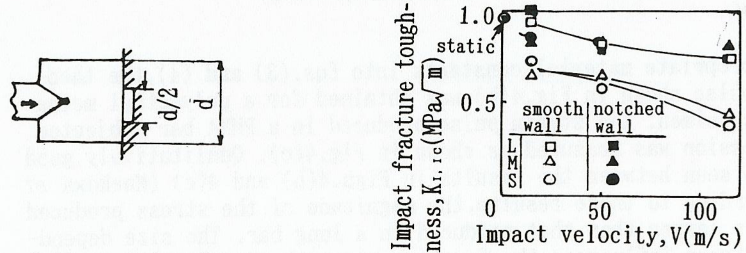
The size dependence of the impact fracture toughness $K_{I,Ic}$ was investigated using three Compact type specimens of different sizes made of PMMA. Impact tearing was produced using a steel wedge as shown in Fig.8(a). The specimens were supported by a smooth or notched steel wall. The value of $K_{I,Ic}$ was evaluated from the fracture stress σ_f, which was estimated from the fracture strain multiplied by the dynamic elastic modulus of PMMA, using the following expression, where γ is a nondimensional factor.

$$K_{I,Ic} = \sigma_f \ \gamma \sqrt{\pi a} \qquad (5)$$

In Fig.8(b), the large specimen shows a large $K_{I,Ic}$ value compared with that of the small specimen (Maekawa and Shibata, 1995). Even though the fracture toughness is a material constant, the value of $K_{I,Ic}$ depends on the size of the specimen because the impact stress depends on the size of the specimen. The impact fracture toughness $K_{I,Ic}$ is related to the onset of crack growth and therefore is not always the same as the dynamic fracture toughness K_{Id}, which is sometimes used to describe the behavior of running crack. The density of the parabola pattern, which was produced by the interference between stress waves from a running crack and an applied stress wave and observed on a fracture surface, increased with increasing $K_{I,Ic}$ (Maekawa, 1992b).

Improvement of Impact Strength by the Reversed Phase Method

Since the mechanical size dependence is due to the superposition of stress waves, the magnitude of a stress pulse is reduced if some of the superposed waves have a negative phase. Thus, the impact fatigue life was improved by using holed specimen (Maekawa, 1996a). The impact fracture toughness was also improved as shown in Fig.8(b) when the specimen was supported by a notched wall as shown in Fig.8(a) (Maekawa and Shibata, 1995).



(a)impact tearing (b)experimental results

Fig.8 Size dependence of impact fracture toughness.

NEW CONVENIENT METHOD OF EVALUATING IMPACT STRENGTH

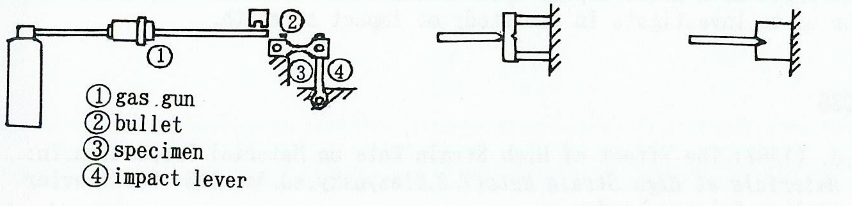
me Problems with Conventional Methods

The impact strength of materials is usually evaluated using pendulum tester ch as a Charpy or Izod tester. These methods are very simple and conven- nt,but they have the follwing disadvantages.

(1)The result is not convenient for structural design,because it is expressed in units of energy.
(The influences of the mass and velocity of the impactor cannot be evaluated separately using results expressed in terms of impact energy, which is the product of these factors.
(The impact velocity is low and is not determined theoretically.
(The testing velocity cannot be varied over a wide range and so data obtained using this method cannot be used for structural design,if the strength strongly depends on the impact velocity.
(5)The use of optional equipment such as cooling boxes for low temperature tests or electric furnaces for high temperature tests is difficult.
(Direct observation of the fracture behavior of a specimen is difficult, especially in the case of a Charpy test,because the specimen is placed in a narrow space.
(These testers are used for impact bending tests. However,the dynamic bending stress distribution produced by an impact force is more complicated than that produced by an impact tension. In order to compare experimental and theoretical results, it is desirable to perform the ex- periment using a stress distribution which is as simple as possible. herefore,an impact tension test is preferable.

Ne Evaluation Method for Impact Strength of Materials

e proposed a new practical method in order to overcome the problems in- volved in conventional methods (Maekawa and Shoda,1993;Maekawa, 1992a). The te ing apparatus is composed of a gas gun and a loading mechanism as shown in ig.9.The loading mechanism is different for impact tension,impact bend- ing,impact fracture toughness and particle collision tests (Maekawa, 1992a;



(a) impact tension (b)impact bending (c)impact tearing

Fig.9 Set up of versatile impact experiment.

Maekawa, 1994).Therefore, this method is versatile and convenient for comparative studies of impact strength under different loading condition. In the case of impact tensile tests, a bullet is shot from the gas gun and strikes the tip of the impact lever. This imposes an impact tension on a specimen the ends of which are connected to the lever and frame using a pin, respectively. According to the experimental results,the plastic deformation around the fracture surface was so small that the influence of bending due to the rotation of the impact lever on the strength was negligible. The fracture strain ε_f was measured using a strain gage cemented onto each specimen. The fracture stress was evaluated from ε_f using a dynamic stress strain diagram.

In order to obtain the dynamic stress-strain diagram for a material,usually Split Hopkinson Bar Method is used. However,in this work,the diagram was obtained directly from each specimen using two strain gages cemented at positions A and B on a specimen as shown in Fig.10 to perform the experiment under a possibly simple stress distribution. Since the cross-sectional area of the specimen was designed to be large at position A,the stress amplitude does not exceed the yield strength. The dynamic stress can be estimated for position A by multiplying by the elasic modulus. Then,the stress history $\sigma_B(t)$ at position B was estimated as

$$\sigma_B(t) = (S_A/S_B)\cdot E\cdot \varepsilon_A(t-\tau) \tag{6}$$

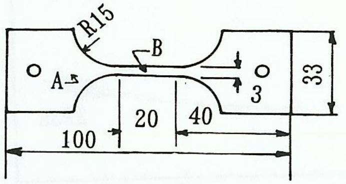
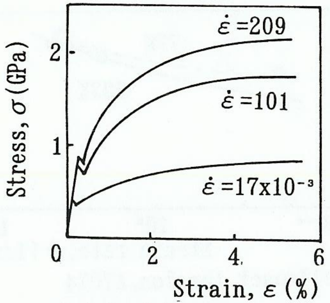
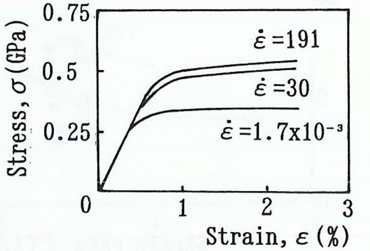


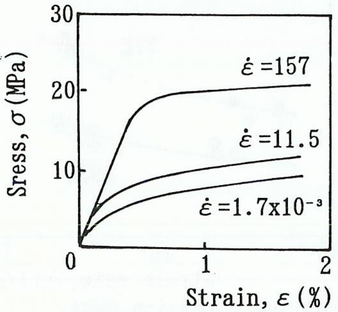
Fig.10 Geometry of specimen (PMMA).



(a)steel(S45C)



(b)aluminum alloy(A7045)

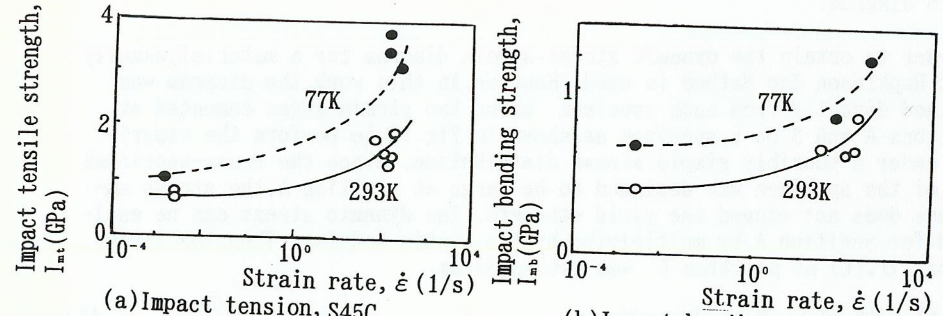


(c)plastics(PMMA)

Fig.11 Dynamic stress-strain diagrams.

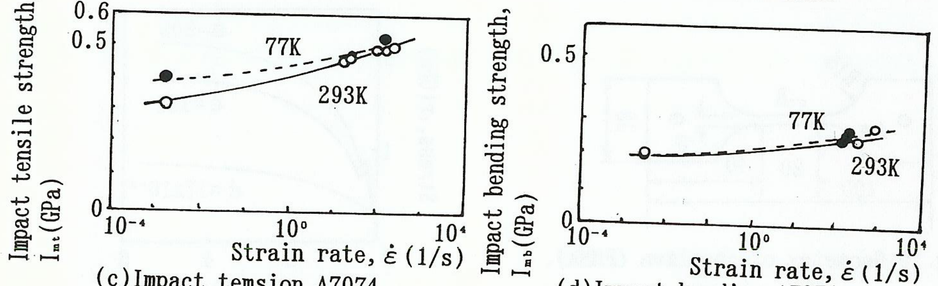
using the strain history $\varepsilon_A(t-\tau)$ at position A, taking into account the time lag τ which is necessary for an elastic wave to propagate between positions A and B. Here S_A and S_B are the cross-sectional areas at positions A and B. The strain was measured over elastic and plastic range at position B. Thus, the synchronized relationship between stress $\sigma_B(t)$ and strain $\varepsilon_B(t)$ at position B can be obtained. Typical examples are shown in Figs.11(a) to 11(c) for carbon steel, aluminum alloy and PMMA.

Using these stress-strain diagrams, the impact fracture strength I_m corresponding to the onset of fracture can be evaluated using the fracture



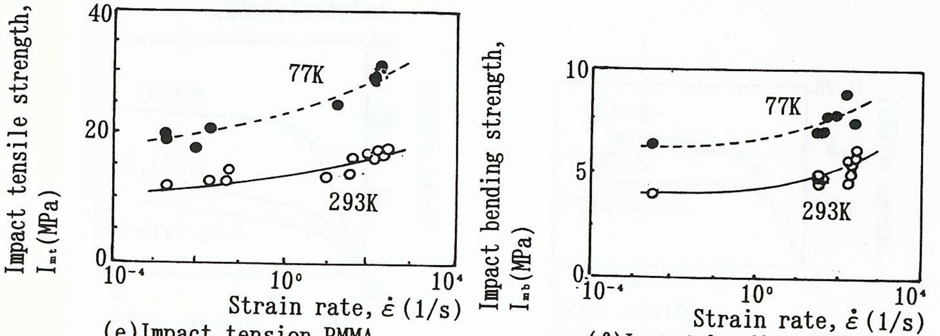
(a) Impact tension, S45C

(b) Impact bending, S45C



(c) Impact temsion, A7074

(d) Impact bending, A7074



(e) Impact tension, PMMA

(f) Impact bending, PMMA

Fig.12 Strain rate dependence of impact strength.

strain ε_f measured above. These results are shown in Figs.12(a) to 12(f). In these figures, the impact strength I_m is expressed in stress units. In all cases, the impact strength increases with increasing strain rate and I_m evaluated at lower temperatures is larger than that at room temperature, except in the case of aluminum alloy. The impact bending strength I_{mb} is lower than the impact tensile strength I_{mt} in contrast to the static case.

SUMMARY

In this work, it was shown that the fracture behavior of materials under a high strain rate is very different from the static or quasi-static behavior. The strength of materials increases but the fracture toughness is reduced with increasing loading rate. The dynamic stress concentration factor α_d is not defined uniquely for a given geometry. In the case of a strip with a shoulder fillet, α_d depended on the loading site, the specimen length and the type of support. Moreover, the maximum strain was obtained after the first peak in the strain history.

The amplitude of the stress pulse produced in a short specimen subjected to an impact force is larger than that in a long specimen. This dependence on specimen size also influences the impact fatigue life and the impact fracture toughness. Based on these considerations, a possible method to improve the impact strength of a structural member, called reversed phase method, was proposed. In this method, the influence of neighboring structures should also be taken into account in order to determine the dynamic stress distribution in a structural member.

Some disadvantages of the conventional method for testing the impact strength of materials were pointed out, and a new practical and versatile method which can be used to measure the impact strength in units of stress instead of units of energy was proposed. The dynamic stress-strain relationship for steel, aluminum alloy and plastics were measured directly using plate specimens. Cooperative work is desirable to device a practical standard method for evaluating the impact strength of materials.

The microscopic mechanism of the dynamic fracture behavior of materials is also interesting problem. It is well known that the strain rate dependence of the strength of a metal depend upon the crystal structure. Thus, much remains for us to investigate in the study of impact strength.

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