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Effect of Multi-Impacts on a PMMA Sheet Material

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Abstract

When a specimen or component is subjected to repeated impacts it may eventually crack and fracture. A multi-impacts/impact fatigue study has been made for the first time on acrylic type PMMA (polymethylmethacrylate) sheet material with different type of notches and loading conditions. The study is conducted using a pendulum type repeated impact apparatus specially designed and instrumented for determining single and repeated impact strengths. Well defined impact fatigue (S-N) behaviour, having progressive endurance below the threshold single cycle impact fracture strength, with a limit, has been demonstrated.

Keywords: Impact fatigue; Testing apparatus; PMMA; Impact velocity; Endurance limit

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1. Introduction

Repeated impact loads are considered to be one of the service loads acting on gear teeth and roller chains are well known as impact loads. Wheels and shafts of rail road train are said to be subjected to impact load when they run over switching points or when tires are flattened by braking action. Fatigue failures caused by repeated impact loading have frequently been reported. The increasing use of PMMA type acrylic sheet and rod materials for various structural and electrical applications have demanded with greatly improved performance to withstand repeated impact stresses under various notch and loading conditions. Failure of PMMA type acrylic materials under single and repeated impacts analogous to fatigue are of concern to the designer and users of various structural applications. For applicability in structure where PMMA sheets are subjected to repeated impact loading conditions it is necessary to predict the probable lifetime of such acrylic structures.

Studies on effect of repeated impacts/multi-impacts/impact fatigue began concurrently with those on conventional fluctuating stress fatigue, but the volume of work on multi-impacts reported in the literature has been small. Some preliminary studies on metallic materials revealed that the impact-fatigue strength is lower than the non impact-fatigue strength, except for a few cases. In some cases, the impact-fatigue limit is not clearly defined. The impact-fatigue loading gives strength values on the non-conservative side when compared to the values obtained in non-impact fatigue tests. However, the impact fatigue of materials remains less investigated, and a systematic theory and a sound database have not been established for machine parts design and materials selection. This is mainly due to the difficulties associated with impact- fatigue experiments and the complexity of impact-fatigue test results. The impact-fatigue behaviour obtained by different authors [1-24] presents typical fatigue-fracture characteristics. The experimental results of the impact fatigue of materials are usually expressed by the impact energy and impact-fatigue life curve (S-N curve).

The impact studies on acrylic type PMMA sheet materials have been limited to single impact and a full S-N type curve with an endurance limit has not been demonstrated so far. A multi-impacts/impact fatigue study has, therefore, been designed to assess the behavior of these type of materials under repeated impacts are to demonstrate the existence of a fatigue curve with an endurance limit. Effects of different type of notches and loading conditions on multi-impact behavior are also examined.

2. Experimental

2.1 Material

The material used in the present investigation was a hard transparent and clear acrylic type PMMA sheet. This type of sheet materials are now widely used in the workshop because it can be used to make precision engineering components for both domestic and industrial products. Typical applications include signs, glazing, safety screening, roof lighting, furniture, lighting fittings and a great many industrial parts for the medical and chemical industries. This type acrylic sheet is manufactured in two forms; cell cast and extruded sheet and available in a wide range of thickness and colors, including blocks, and surface patterns. In our all experiments extruded clear acrylic sheets (properties are listed in Table 1) are used. Authors feel worth to mention that the basic purpose of the present work is to study the mechanical behavior of these materials to multi-impacts without going detail about its chemical composition.

2.2 Test equipment

A special swinging pendulum type impact fatigue tester (Resil Impactor^{TM}) is used (Fig.1) for all the experiments. It consists of a pendulum hammer arm (R) with an instrumented striker (I) attached at one end. Other end of the hammer arm is connected to the horizontal shaft of the reducing motor (M), which is controlled by the pneumatic system (P) and compressed air is supplied by an air compressor (A) attached to the system. The pneumatic system consists of pneumatic actuators for hammer release and braking, the pneumatic distributors and solenoid valves controlling the actuators, the reducer motor for raising and angular positioning of the hammer, the encoder for measuring the drop and rise angle of the hammer and the electronic circuit board with microprocessor for function control and calculation of the test results. The impactor has an instrumented hammer (I) for Izod type test condition and an instrumented vice (V) for Tensile type test condition, which are connected to a data acquisition system (D), connected to a PC (P), permits display of the test results in graphic format. The D8EXTWIN™ program is able to control and operate the movements of the apparatus through the PC. The multi-impactor is made of a robust steel structure, on which the components intended for conduction of the test are mounted. In the Izod type test condition (Fig.2(a)), the specimen (S_2) is supported as an embedded beam and is broken by a single or multiple oscillation of the pendulum at a fixed distance from the specimen clamp and from the center line of the impact. In this case the striker is equipped with strain-gauge type sensor, which is connected to the analog input connector for strain-gauge sensor of the data acquisition system (D). In the Tensile type test condition (Fig.2(b)), the two ends of the specimen (S_1) are supported between a traction terminal (movable) and a clamping bracket and is broken by a single or multiple oscillation of the pendulum on the traction end. In this case the vice is equipped with piezo-electric type sensor, which is connected to the analog input connector for piezo sensor of the data acquisition system(D). The measuring method is based on determining the amount of energy, expressed in Joules, needed to break the specimen under specified conditions, such as: location of the specimen, shape of the notch and speed of impact of the hammer on the specimen. As the maximum potential energy of the pendulum is known, and is in relation to the weight of the hammer used and the drop height, the latter in turn being in relation to the starting angle, it results that the energy absorbed by the specimen in order to break it can be determined by measuring the hammer rise angle after impact.

There are also other parameters that affect this value, such as for example vibrations of the arm and its structure, friction between the various moving members, aerodynamic friction, etc. In order to make the measurements repeatable, these disturbance factors must be kept under control and to within determined tolerances established by the international standards (ISO 180, ISO 8256). The energy range of the impactor is from 1 to 50 Joules.

2.3 Specimen preparation

Specimens of standard dimensions (4×10×80 for Izod & 4×15×80 for Tensile multi-impact tests, Fig.3) of acrylic type PMMA sheet with different type of notch are used to know the behaviors of these materials towards the repeated impacts. The used acrylic type PMMA sheet will soften if heated above 80°C. Considerable heat can be generated by machining, causing stress, so suitable coolants with light machining cuts are used to maintain a cool stress-free machining temperature and to remove the produced swarf from the machining zone. To achieve a good finish sharp cutting tools of HSS tool bits designed for use with wood and soft metals are used. For small length cuts fine-toothed powered saw (band saw) with blades having alternative teeth beveled, as for aluminum, are used with light pressure after securing work perfectly on the vice.

2.4 Impact test procedure

The multi-impactor can be configured to perform different types of test in accordance with the Izod and Tensile-Impact methods described by the main international standards (ISO 8256, DIN 53448). As per the requirements of the standard being used, the instrumented hammer (for Izod test) and vice (for tensile-impact test) with an appropriate energy value, are selected. Before starting of the tests proper calibration of the hammer and correction for the energy lost due to mechanical friction and air resistance is done. The experiments are conducted, using the hammers of mass 0.951 kg. and pendulum effective arm of 0.2297 m. for tensile type tests & those are of 0.334 kg. and 0.3268 m. respectively for Izod type multi impacts tests. Initially the single impact fracture energy (critical) value was obtained by reducing the angle of swing starting from a high angle to a value where the sample sustained the impact without fracture. Four to five samples were tested at each impact. The critical angles at which the specimens broke in a single blow were near 30^o and 20^o for tensile type and Izod type loading conditions respectively. The angles were then reduced progressively by a few degrees at a time and the number of impacts sustained at each angle (impact energy were noted to determine the fatigue (S-N type) curve. The tests were terminated at around 10^4 impacts cycles at an impact energy level of 0.0163 J where the samples withstood without fracture. Impact frequency was set at 4 impacts/ min demonstrated schematically in Fig. 4.

3. Results and discussion

Two types of specimen geometries (Fig. 3) are used with two types of settings (Izod and Tensile type multi impact tests) with different type of notches (Fig. 5). During the first set of impact fatigue tests, the impact frequency, the impact load and the effective neck width (6mm) are kept constant. The impact-fatigue results obtained for the both cases are depicted in Fig.6 in a log-log scale for C type notch. A typical S-N type curve is evident having progressive endurance with decreasing applied impact energy (decrease in critical multi impact strength with the number of impacts). Also it is clear that the critical multi-impact strength is better for tensile type tests (along rolling direction of the PMMA material) than the Izod type bending tests (force is perpendicular to the rolling direction). It may be due to the fact that the applied load produces a much lager stress in Izod bending specimen than in the tensile specimen. Also there is a steep fall of multi-impact strength when impact force causes bending than causes simple tensile elongation, which indicates fast damage accumulation for the former case.

Fig. 7 shows the progressive endurance with decreasing applied nominal stress. It is seen from linear regression analysis of the impact fatigue data (between nominal impact stress and number of impacts) that fatigue failure under the conditions of impact stress could be satisfactorily explained by a simple power law $\sigma = AN^{-n}$, where N is the number of impacts to failure under nominal repeated impact stress of σ. For Izod type and tensile type of repeated impact loading the present material under prevailing conditions follow the equations $\sigma = 4.973N^{-0.0962}$ and $\sigma = 36.68N^{-0.0686}$ respectively. The higher coefficient A indicates higher impact fatigue resistance of PMMA under tensile type loading than Izod type loading. Similarly, higher value of exponent n indicates there is a steeper fall of nominal stress for same number of impacts in Izod type loading to tensile type loading.

The irregular behaviors of force (Fig. 8) during first impacts may be attributed to the clearances at clamping surfaces and marginal deformation at impact points. Visible variation of force at fracture & earlier impact (Fig.8 & Table 2) indicates that damage/accumulation of micro-cracks has already started at the minimum cross-section before final fracture. Typical load-deformation/displacement curves (Fig.9) shows a straight line relationship between them until the maximum load was reached, followed by a sudden drop. There are some irregularities for tensile type multi-impact tests, which may be due to the prior damage and ductility of the material. It is to be noted that the force is measured by the instrumented striker/vice and the other parameters are determined by the angle of the striker with a reference. The term deformation or displacement, which is expressed in millimeters, is the deformation undergo by the specimen from the impact instant up to the break.

Effects of notch geometry and eccentricity on multi-impact behavior of PMMA are also studied (Fig.10 and Table 3 respectively). It is evident from figure that as the severity of the notch increases (round notch to a notch with sharp cut), with the increase of stress concentration the multi impact strength of the material decreases and also it is steeper.

Table 3 summarizes the results of experiments carried out to understand the notch eccentricity effect on multi-impact strength of the PMMA specimens under tensile type loading. Although the obtained experimental data (number of impacts to failure) are to some extent scattered, it seems (Fig.11) that as eccentricity increases the strength against multi-impact increases and approaches to that with a single notch (eccentricity is very high).

The present impact loading frequency is relatively low compared with those of fluctuating stresses by other techniques. There is a sudden imposition of maximum stress at the moment of impact; the stress was then allowed to relax between impacts. The applied stress was not completely relaxed; it retained some residual stress on each cycle, which was largely dependent on the applied impact energy. It is necessary of the cumulative residual stress factor leading to ultimate failure. As shown (typical appearances of the fractured surfaces are shown in Fig.12) the predominant micro mechanism of failure in the present cases is craze formation, indicating brittle failure. Clamshell marking radiating from the initiation zone characterizes this type of rupture. The image of the failed surface of the PMMA indicated that the fracture had initiated from a crack at or near the corner of the notch. The final rupture took place when the initial crack had grown to critical size resulting in a brittle failure by a combination of rapid propagation of the initial crack and/or the initiation of multiple secondary cracks at crazes.

4. Conclusions

Impact fatigue failure curves for PMMA have been determined at different conditions. The tested material showed progressive endurance with decreasing applied impact energy. It is seen that the impact fatigue failure resistance can be satisfactorily explained by a simple power law between numbers of impacts to failure and nominal impact stress. The coefficient and exponent will give the impact fatigue resistance of the material under different conditions. It is also evident that impact fatigue resistance decrease with increase of notch severity.

Microstructure study of the fractured surface indicates that the failure is predominantly by crazing. The accumulations of residual stress lead to ultimate instantaneous failure. Authors feel that to arrive at an established conclusion it requires standardization of the impact-fatigue test method, equipment, specimen, and working conditions.

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Legend of the Figures

Caption of the Tables

Table 1	Properties of acrylic sheet used for the tests
Table 2	Variation of force for fracture and force at earlier impacts (Tensile type tests)
Table 3	Effect of notch eccentricity (Tensile type multi impact tests)

Tables

Table 1
Properties of acrylic sheet used for the tests

Relative Density	Rockwell Hardness	Tensile Strength	Elongation at Break	Flexural Strength	Flexural Modulus	Vicat Softening Point	Co. of Thermal Expansion
1.19	101	70 MPa	4 %	107 MPa	3030 MPa	>105°C	$7.8\times10^{-5}K^{-1}$

Table 2

Variation of force for fracture and force at earlier impacts (Tensile type tests)

Sl. No.	Hammer Energy (J)	No. of Impacts	Absorbed energy at break (J)	Notch type	Max. Force at Fracture (N)	Force at previous impacts
1	0.39	1618	0.343	A	727.16	739.43
2	0.27	628	0.204	B	686.89	689.13
3	0.20	415	0.180	C	731.64	735.21
4	0.29	423	0.231	D	653.33	731.64
5	0.20	415	0.168	E	559.36	619.77

Table 3

Effect of notch eccentricity (Tensile type multi impact tests)

Sl. No.	Eccentricity (mm.)	Hammer Energy (J)	No. of Impacts	Notch type	Max. Force at Fracture (N)	Impact Energy to Fracture (J)
1	0	0.33	35	E	559.36	0.15
2	1	0.39	105	E	633.19	0.15
3	3	0.20	27	E	653.33	0.187
4	5	0.20	415	E	698.08	0.168
5	10	0.20	49	E	758.49	0.164
6	Very high	0.29	64	E	809.95	0.179

Figures

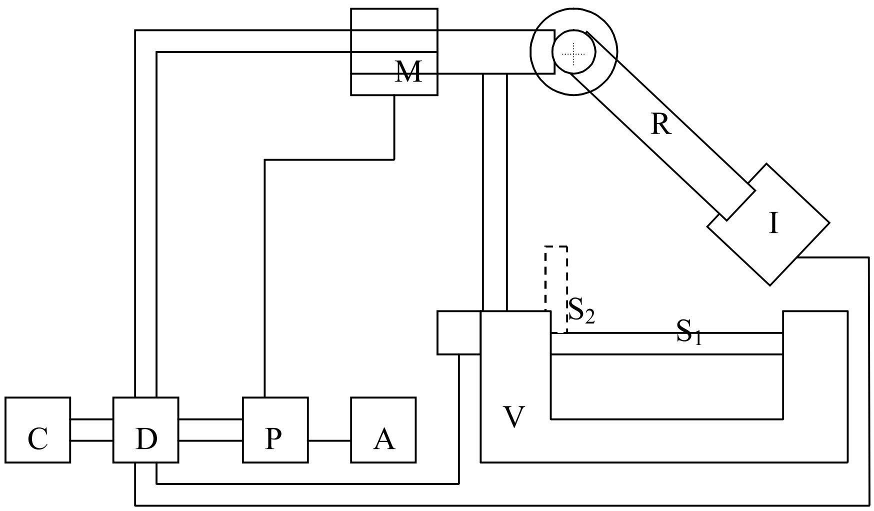


Fig. 1 Schematic diagram of repeated impact fatigue apparatus.

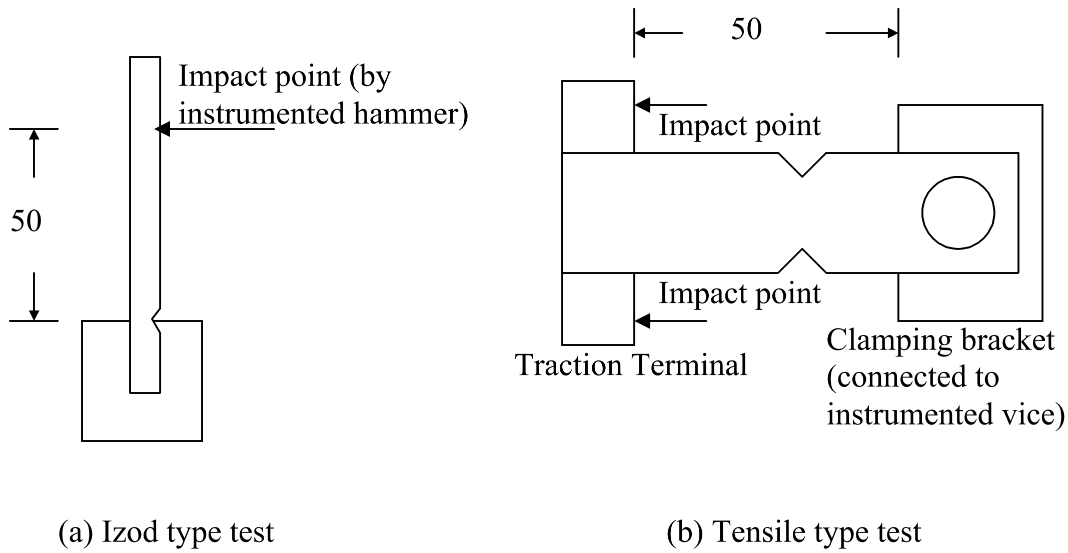
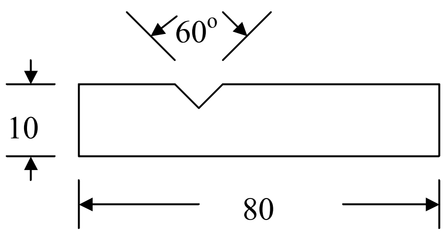
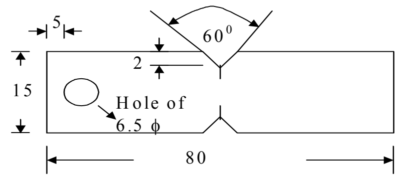


Fig. 2 Repeated impact test conditions



(a) Izod type test



(b) Tensile type test

Fig. 3 Specimens used for repeated impact tests

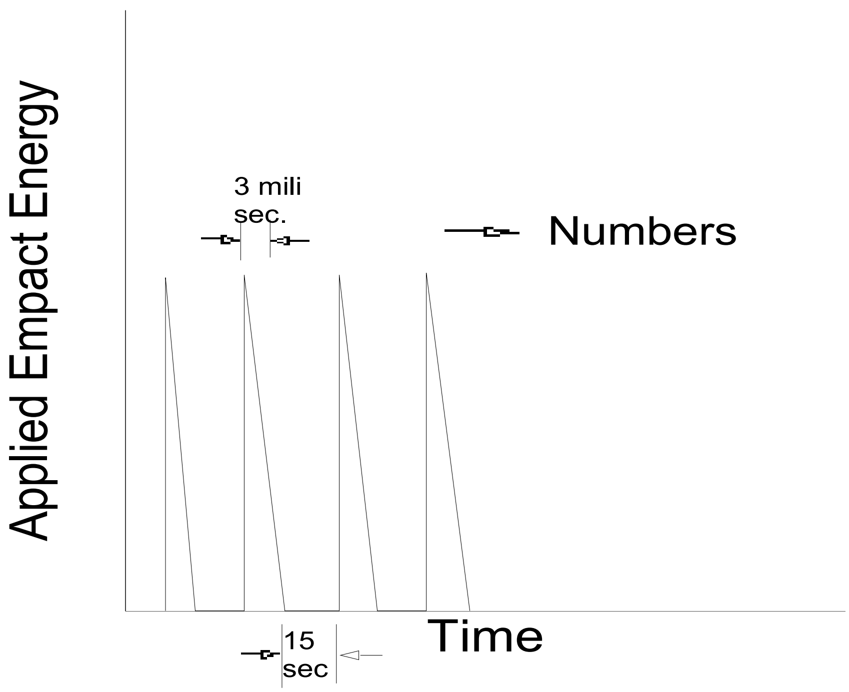


Fig.4 Schematic representation of the frequency of applied impact energy with time

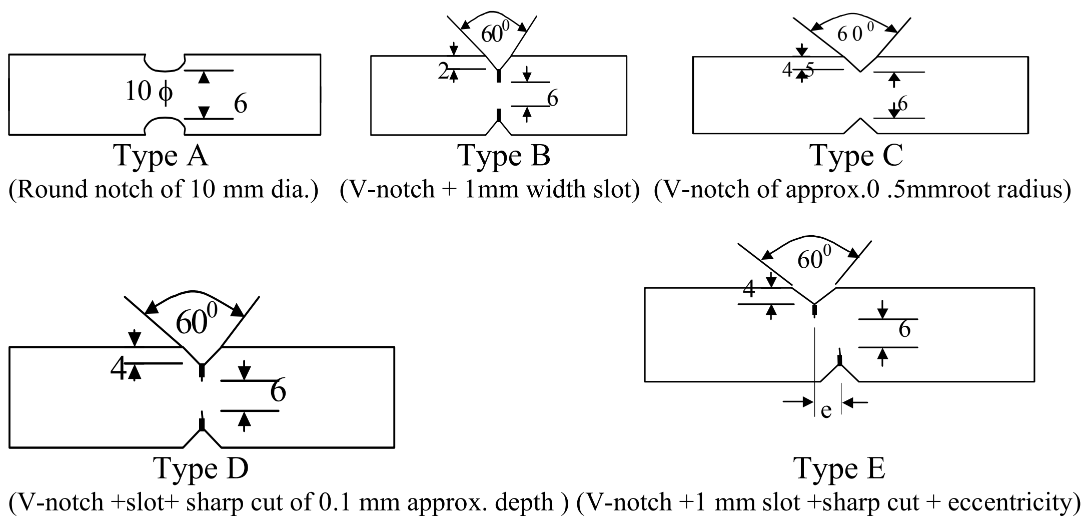


Fig.5 Different type of notches used for the tensile type multi impact tests

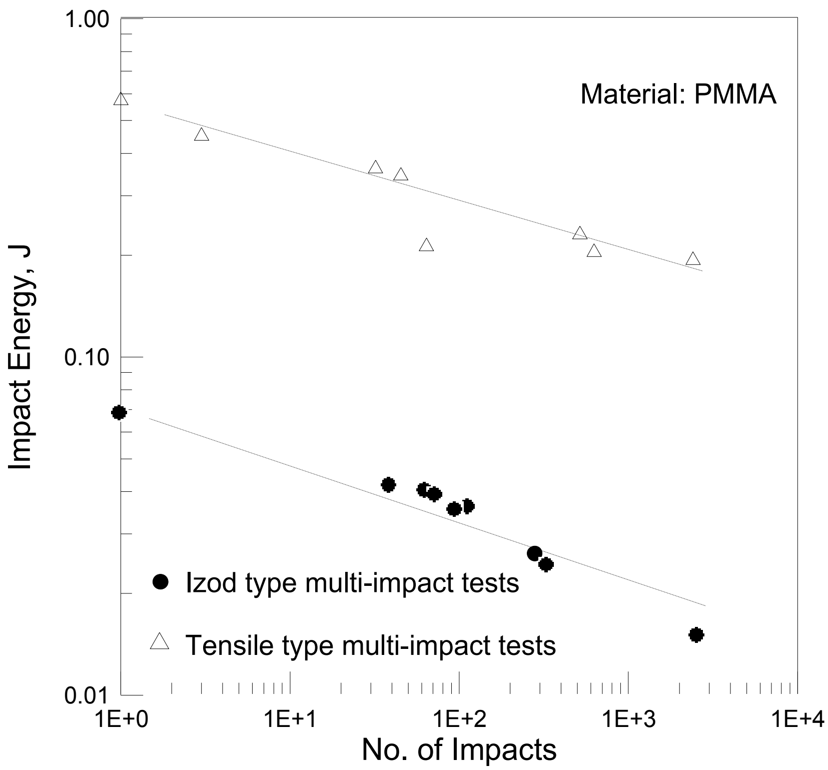


Fig. 6 Variation of impact energy with number of impacts

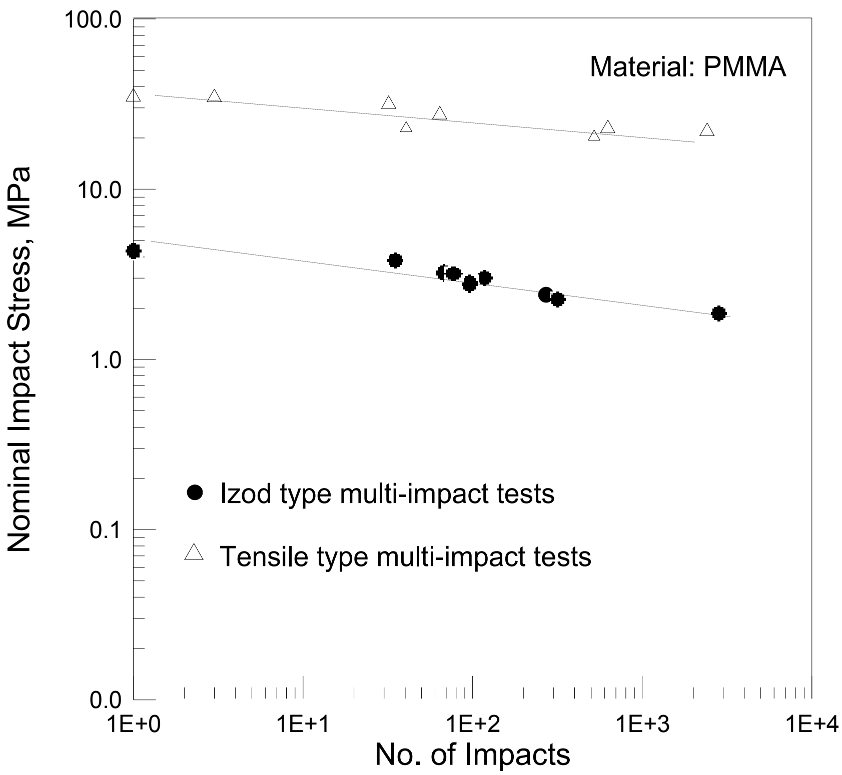


Fig. 7 Variation of nominal impact stress with number of impacts

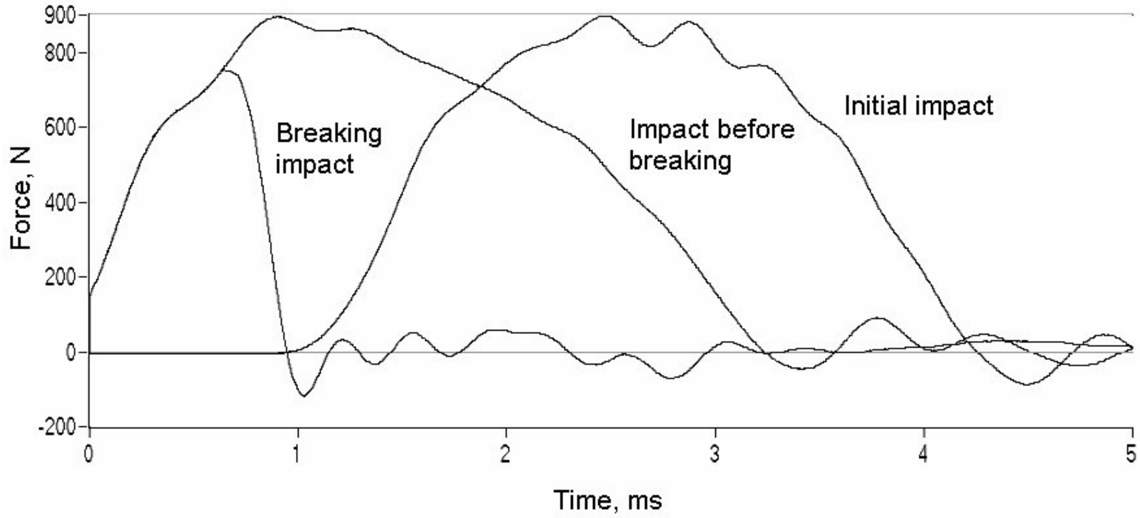
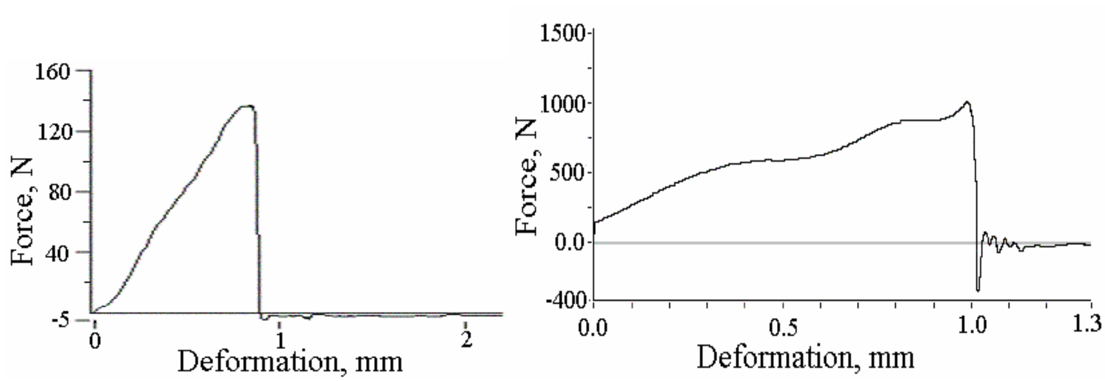


Fig. 8 Typical curves showing variation of impact force with time



a) Izod type multi-impact tests b) Tensile type multi-impact tests

Fig. 9 Force–deformation/displacement curves

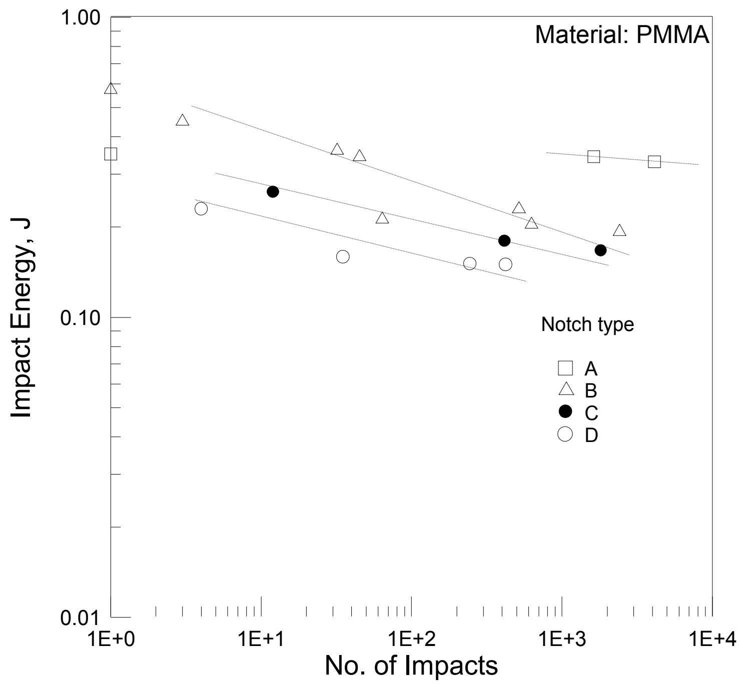


Fig. 10 Effect of notch geometry (For tensile-type multi impact tests)

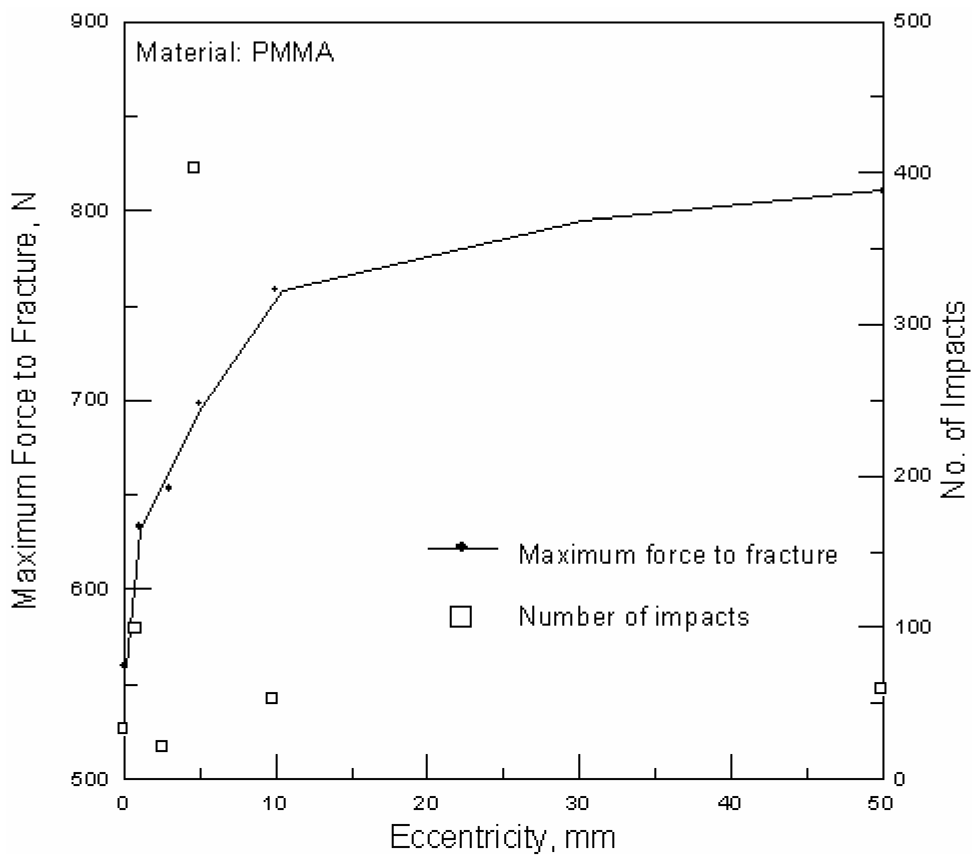
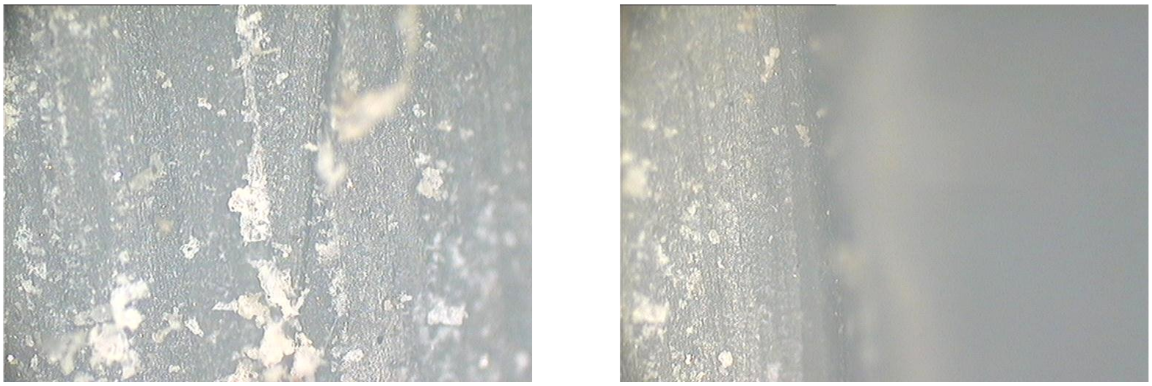


Fig. 11 Effect of notch eccentricity (For tensile-type multi impact tests)



(a) Initial craze area

(b) Transition area between craze and sudden rupture

Fig. 12 Fracture surface (Normal optical Microscopy ×200)