IMPACT TEST

1 – Impact properties

The impact properties of polymers are directly related to the overall toughness of the material. Toughness is defined as the ability of the polymer to absorb the applied energy. By analysing a stress-strain curve, it is possible to estimate the toughness of the material because it is directly proportional to the area under the curve. In this sense, impact energy is a measure of the toughness of the material. The higher the impact energy, the higher the toughness. Now, it is possible to define the impact resistance, the ability of the material to resist breaking under an impulsive load, or the ability to resist the fracture under stress applied at high velocity.

The molecular flexibility plays an important role in determining the toughness and the brittleness of a material. For example, flexible polymers have an high-impact behaviour due to the fact that the large segments of molecules can disentangle very easily and can respond rapidly to mechanical stress while, on the contrary, in stiff polymers the molecular segments are unable to disentangle and respond so fast to mechanical stress, and the impact produces brittle failure. This part will be discussed into details in another chapter of this handbook.

Impact properties of a polymer can be improved by adding a structure modifier, such as rubber or plasticizer, by changing the orientation of the molecules or by using fibrous fillers.

Most polymers, when subjected to impact load, seem to fracture in a well defined way. Due to the impact load, impulse, the crack starts to propagate on the polymer surface. The energy that is necessary to initiate the crack on the surface is called the crack initiation energy. If the load applied give enough energy to exceed the crack initiation energy, the crack will continue to propagate along the polymer. A complete failure occurs when the load energy has exceeded the crack propagation energy. Both terms, crack initiation and crack propagation energy, contribute to the measured impact energy. It exists basically four different types of failure mechanism due to impact load, but they will be shown and described later. For the moment, could be interesting to know that the distinction amongst the four different kind of failure is not very clear even if impact behaviour is one of the most specified mechanical properties. Predicting the impact properties of a polymeric material is still one of the most troublesome areas of product designer. As anticipated in the first part of the handbook, the problem arise to the fact that impact test on plastic were adopted from metallurgist, and the principles of impact mechanism as applied to metals do not seems to work satisfactory with plastics, because the structures of the materials are completely different.

In the following will be presented the most common impact test on plastic material with the apparatus and the test specimens too.

1.1 - Pendulum Impact Test

The most common configuration for pendulum impact test are Izod and Charpy ones. The scope of these impact test is to measure the answer of a standard test specimen to the pendulum-type impact load. The result is expressed in term of kinetic energy consumed by the pendulum in order to break the specimen. The energy required to break a standard specimen (which dimension are in according to standard adopted) is actually the sum of different contributes: the energy to deform the specimen, to initiate the fracture, to propagate the fracture across specimen and the energy spent in order to toss the broken ends of the specimen. The energy lost through the friction and vibration of the apparatus is usually very small for all practical purpose and it is usually neglected. A photo of a Instron impact pendulum is in the following reported.

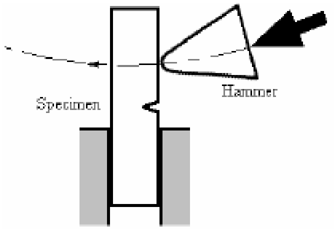
The notch.

The specimen used in these kinds of tests have usually to be notched. The reason for notching the specimen is to provide a stress concentration area that promotes a brittle rather than a ductile failure. A plastic deformation is also prevented by such type of notch in the specimen. The impact values are seriously affected because of the notch sensitivity of certain type of plastic material. The effect of the notch will be discussed in detail in the notch chapter.

The Izod test requires a specimen that have to be clamped vertically. This specimen is struck by means of a single swing of a pendulum released by a fixed distance from the specimen clamp point. On the contrary, in Charpy method the specimen is supported horizontally as a simple beam and fractured by a hit delivered in the middle of the specimen by a pendulum. The advantage of Charpy test over the Izod one is, obviously, that the specimen does not have to be clamped and it is free of variations in clamping process.

Izod test procedures.

The test specimen is clamped into the vice in a position so that the notched end of the specimen is facing the striking edge of the pendulum. A properly positioned test specimen is showed in the following figure.

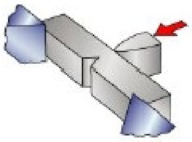


Once the pendulum is released, it strikes the specimen and swing through. If the specimen does not break, an higher energy hammer have to be used and the test should be repeated until failure is observed. The impact strength (resilience) is calculated directly by dividing the impact value obtained from the measure by the thickness of the specimen (dimension J/m) or by the residual area under the notch (dimension kJ/m2).

The reversed notch impact resistance technique is obtained by reversing the specimen in the position of a notched specimen in the vice. Here, the notch is subjected to compressive load rather than tensile stress during the impact. As a final remarks on these technique it is possible to assert that: notching of the test specimen drastically reduces the energy loss due to deformation. Tough notched plastic materials (which Izod impact strength is higher than 27 J/m) seem to spend very low energy in tossing the broken end of the specimen. For relative brittle material (which Izod impact strength is less than 27 J/m), the energy loss due to toss factor represents a major portion of the total energy.

Charpy test procedures.

The only difference with the previous kind of test is the positioning of the specimen. The following figure illustrates one such example.



In this test the specimen is placed horizontally and supported unclamped at both ends. Only the specimens that are completely broken can be accepted as a results. The impact strength (resilience), as in the previous test, is calculated directly by dividing the impact value obtained from the measure by the thickness of the specimen (dimension J/m) or by the residual area under the notch (dimension kJ/m2).

Chip impact test procedures.

The chip impact test was originally developed in order to measuring the effect of surface microcracking caused by the weathering. The toughness of the material is measured in this test as opposed to the material notch sensitivity in an Izod measure, this method is in fact a variation of the Izod method previously described. The specimen is relatively thin and it is struck on the broad surface, so that the test results is sensitive to the condition of the surface. The retained toughness is proportional to the energy adsorbed during impact, which is measured by the angle of travel of the pendulum after impact.

Tensile impact test procedures.

The tensile impact strength test was originally developed to overcome the deficiencies of flexural (both Izod and Charpy) impact test. All the test variables that have a high effect on the results, such as notch sensitivity, toss factor and specimen thickness, are eliminated in the tensile impact test. This test, on the contrary of Izod and Charpy types, which are limited to thick specimen only, allows to determine the impact strength of very thin and flexible specimens. Not only, many other characteristics of polymers, such as the anisotropy and the orientation can be studied by means of tensile impact test.

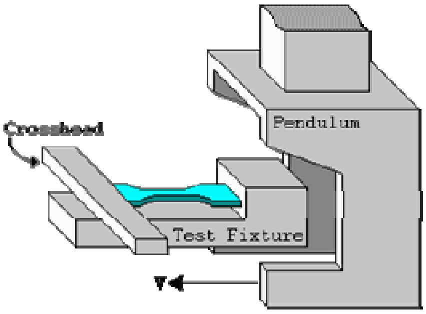
It exist two different test configurations. One consists in a specimen-in-head kind of setup (method B), where the specimen is mounted in the pendulum and achieves full kinetic energy at the point of impact, eliminating the problem of toss correction. The energy to break by impact is determined by the kinetic energy value extracted by the pendulum in the process of breaking the specimen. The test setup requires to mount one end of the specimen on the hammer and the other end have to be gripped inside a crosshead member, which travels together with the pendulum until the impact instant. As long as the machine bas is rigid enough to prevent vibrations, the energy lost by the bounce of the crosshead in the opposite direction can be easily calculated.

The second test configuration is very similar to the previous one but it is a specimen-in-base setup (method A). The specimen is now clamped in a vice supported by the frame of the pendulum and it is broken by the impact between pendulum and crosshead member, which is always clamped on the other extremity of the specimen.

The tensile impact test introduces strain rate as an important test variable and many researchers have demonstrated that the tensile impact test results correlate better with the actual field failures than Izod or

Charpy impact test analysis. Even if this is still a uniaxial test and most impact events are multi-axial in the real-life situations.

As far as concerns the testing machine, the pendulum is specially designed to hold a dumb-bell shaped specimen so that the specimen is not under stress up to the moment of impact. In the following figure it is instead reported the most common specimen-in-base impact configuration.



The corrected tensile impact energy, Ec, is in the following reported for both the methods:

$$E_c = E_s - E_q \quad \text{(method A)}$$

where Es is the impact energy absorbed during the test as measured by the instrument, and Eq is the toss energy due to plastic deformation and kinetic energy of the crosshead.

$$E_c = E_s + E_b \quad \text{(method B)}$$

where Es is the impact energy measured by the instrument, and Eb is the cross-head bounce energy as determined from the measured value of Es. The correction factors are in the following specified:

$$E_q \approx \frac{3}{2} \cdot E_{max} \cdot \mu$$

and Emax is the maximum impact energy of the pendulum, while μ is the mass of crosshead divided by the reduced mass of the pendulum.

As far as concerns the method B the correction term is:

$$E_b = \frac{1}{2} \cdot m \cdot \left\{ v_1^2 - \left[v_1 - \frac{M}{m} \cdot \left(V - \sqrt{V^2 - \frac{2 \cdot E_s}{M}} \right)^2 \right] \right\}$$

where m is the mass of the crosshead, v1 is the crosshead velocity immediately after bounce, M is the pendulum mass and V is the maximum velocity of the centre of impact of the crosshead.

2 – Non-Instrumented Impact Test

When products made from polymers are used in industrial practice, impact loading often occurs in addition to static loading. Some practical examples of that include traffic accidents, stone impact on frontal surfaces of automotive and railroad rolling stock, accidents involving motorcycles or bicycles helmets, demolding, …

It was already discussed as impact loading results as a function of increased strain rate, significantly altering the strength and the break behaviour of most plastic material. Moreover, factors contributing to brittle fracture include also low temperatures and multiaxial stress states, including the residual stress. The stress concentration at notch of the specimen contribute to the formation of brittle fracture, so that test are often performed on notched specimens.

The test mostly adopted in order to evaluate the toughness of polymers under impact loading are the Charpy, the Izod and the biaxial free-falling dart test (all are described in the previous chapter), due to their simple applicability.

The Charpy impact test has gained the greatest importance in the quality control in the last years because of its easily applicability, short testing time and low consumption of materials during the test. But, on the other side, its applicability is very limited in the area of material development and optimization and the shift to instrumented measure must be done if this is the main area of interest.

When thermoplastic material are tested, injection molded specimens are preferred due to their simple production technology. At the same time, internal states related to manufacturing process, which can affect the final test result, have to be taken in account. The orientation influence can be reduced by using different manufacturing process, such as sheet molding.

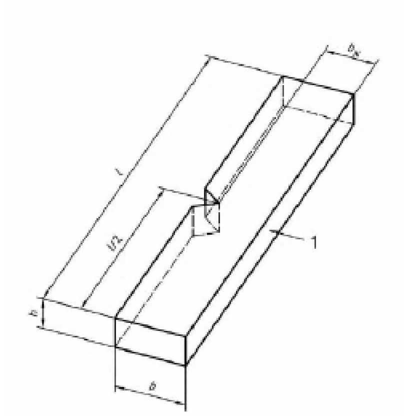
2.1 - Pendulum Impact test

Three different configuration can be distinguished for impact loading with the pendulum impact tester. The specimen either lies with its notched side centrally between two support (carpy configuration) or it is clamped on notch side (Izod configuration). The third configuration which allow to determine the impact strength is the tensile impact one.

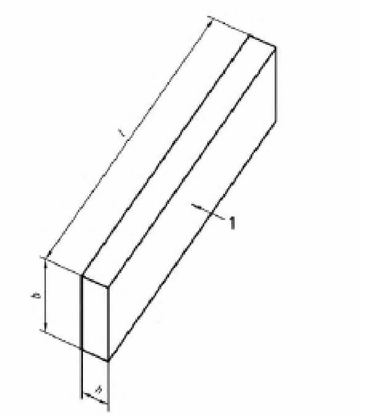
The Charpy impact test is performed on both notched or unnotched specimens by means of three-point support and is used to evaluate the toughness behaviour under impact load. It is standardized in ISO 179 and ASTM D6110 (the most commons). Prismatic specimens have to be produced in according to the corresponding molding material standard. The specimens can be obtained directly by injection molding or by cutting from sheet. Also Izod impact test can be performed on both notched or unnotched specimens by the support and the test method is rather different, as can be seen in the previous chapter. It is standardized in the ISO 180 and ASTM D256.

In the notched impact test, a notch is cut into the specimen. By notching, a stress concentration as well an increase in crack propagation rate is achieved at the front of the crack tip. In this way, it is possible to break tough materials too, also if they do not break when unnotched specimens are tested. When notch is cut on the specimen, a great care must be taken in the preparation of the specimens (it will be described in the notch chapter).

The Charpy test standard distinguish between a configuration in which the direction of impact is parallel to dimension b with impact on the narrow longitudinal surface h*l of the specimen (edegewise) and one in which the direction of impact is parallel to dimension h with impact on the broad longitudinal surface b*l (flatwise), as shown in the figure below.



Charpy edgewise impact specimen with single notch, as usually used.

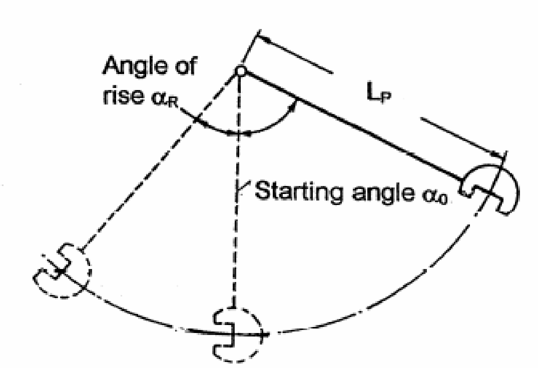


Charpy flatwise impact specimen unnotched, as common used for this test method.

Here, notch shape defined as A is used with notch base radius rn= 0.25±0.05 mm and the remaining width bn at notch base of the specimen of 8.0±0.2 mm (it is ISO 179/1eA, bn is equal to 10.2 mm and specimens dimension are different if standard ASTM is adopted). There exist additional notch types (B and C) whose radius are respectively rn= 1.00±0.05 and rn= 0.10±0.05 mm defined in the ISO standard. Specimens shape, dimensions and notch radius (types A and B) have the same definition in ISO 180 for Izod impact test.

For the test, pendulum hammers in according to standard ISO 13802 are used with a nominal impact energy range from 0.5 un to 50 Jand impact velocities of 2.9 m/s and 3.8 m/s, in Charpy configuration, and 3.5 m/s in Izod one.

When a test is performed, the energy W absorbed by the specimen (but it is more true call it the energy looses by the pendulum during the impact) is calculated from the difference between the pendulum hammer height over specimen before and after impact and the mass mp of the pendulum hammer itself.



tarting from the previous figure it is possible to define, respect to the vertical, the starting angle α0 and the raising angle αr. The absorbed energy is from that calculated:

$$W = W_{before\ impact} - W_{after\ impact} = m_p\, g\, L_p\, (\cos \alpha_r - \cos \alpha_0).$$

To determine Charpy (or Izod) impact strength of an unnotched specimen acU, also known as Resilience of the material, the energy Wc used in order to break the specimen is related to the initial cross-section area of the specimen, by the following formula:

$$a_{cU} = \frac{W_c}{b \cdot h}.$$

To determine notched Charpy (but also Izod one) impact strength, the notched specimen is positioned centrally on the supports and with the notch on its tension surface. Thus, impact occurs on the side opposite to the notch (the side of the notch if it is a Izod test). Notched Charpy resilience acN, is calculated from the energy absorbed during the impact Wc related to the smallest initial cross-section area of the specimen at notch base:

$$a_{cN} = \frac{W_c}{b_n \cdot h}.$$

It is usually expressed in kJ/m2 but ASTM standard prefers to indicate it in J/m, dividing the total energy to the specimen thickness. It is also interesting to notice that the difference between unnotched and notched impact strength indicates how sensitive a plastic material is to external notches. In this way, notch sensitivity can be calculated as a percent from the ratio:

$$k_Z = \frac{a_{cN}}{a_{cU}} \cdot 100.$$

In the next chapters it will be illustrated how the impact strength is influenced by the notch radius and the notching procedures.

In the following it is presented a list of typical values for Charpy impact strength, both notch and unnotch, of a selected number of polymers (these value are courtesy taken from Campus web; N is without fracture):

Thermoplastics unreinforced	a_{cU} (kJ/m^2)	a_{cN} (kJ/m^2)		Thermoplastics reinforced	a_{cU} (kJ/m^2)	a_{cN} (kJ/m^2)
PE-HD	N	4.9		PP + Glass Fibres	45	15
PP	100	10		PA6 + GF	85	19
PS	21.5	2.8		PA + Carbon Fibres	70	15
SAN	19	2.5		PP + talc	40	3.5
ABS	120	20		PP + chalk	40	3.5
PC	N	18		PVC + chalk		9
PMMA	25	2.9		**Thermosets unreinforced**		
PVC-U	80	3.2		PF resin	8.5	2.9
PVC-P	N	50		UF resin	6.3	1.3
PA	N	50		MF resin	4.3	1.8
POM	N	12		UP resin	11	3
PET	N	3.9		Ep resin	22	1.5
PTFE	N	16				

The only disadvantage of impact energy measured by the notched impact test is due to the fact that, due to the relation:

$$E_c = \int_{f=0}^{f=f_c} F \cdot df$$

with f means deflection, fc deflection at break and F is the load force. From this relation, that relate the forces acting during the impact to the total energy, it is clear that impact energy consists of both a strength and a deformation component. This means that the same impact energy is obtained from very different load and deflection values. For this reason, is impossible to use the non instrumented results as a dimensioning parameters for impact loaded components. If the dimension parameters are the main goal of the research, this problem will be bypassed by using the instrumented impact test. It allow to measure directly the load-deflection diagram. An example of this diagram is reported in the following figure, that allow also to understand the possibility to have comparable impact strengths but different force-deflection behaviours.

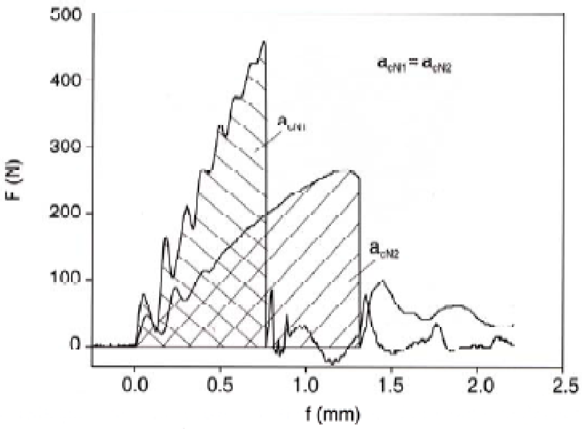


Figure: in this figure two different curves with different force value but with the same absorbed energy are presented. (F_1 is different from F_2 but a_{Cn1} is equal to a_{Cn2}).

Although any conclusions about the behaviour of component part under impact can be drawn, this kind of tests continue to be used in production monitoring and in development laboratories. Furthermore, the non instrumented impact test is useful if the temperature dependence of the impact strength has to be evaluated.

Tensile Impact test

The conventional tensile-impact test is standardized in the ISO 8256 standard. It is the uniaxial tensile test with a relative high strain rate which is generally used for that polymers that are too flexible or too thin for Charpy or Izod impact test.

The pendulum that allow to perform this kind of test was presented and discussed in the previous chapter. Inside the standard, two different procedures are reported, and both are used for determining the energy required to break plastic specimens under uniaxial impact loading. In procedure A, the specimen lies horizontally and is held at one end in a specimen clamp while the other one end in a cross-head. The cross-head is separated from the specimen clamp support. The bifurcate arm impacts the cross-head at the lowest point of pendulum motion, on the vertical respect to the frame of the instrument. In procedure B, the cross-head moves together with the striker because the specimen is clamped on the hammer and not on the vice. The correction that have to be applied in both methods are described in the paragraph 3.2.

Five different specimen shapes for the aforementioned test exist, the most common one is very similar to a notched Charpy/Izod specimen but with a notch on both side. Others common specimens are the dumb-bell unnotched ones, specially used in the method B. It must be here taken in consideration that the specimen with molded-in notches tend to provide different results than specimens with the notch made mechanically. Nevertheless, these procedures are both suitable for production monitoring as well as for quality assurance.

Tensile-impact strength atU, or the notched tensile-impact strength atN, is calculated from this test by the following formula:

$$a_{tU}\,(\text{or } a_{tN}) = \frac{E_c}{x \cdot h}$$

where Ec is the corrected impact energy, x is the width of the narrow parallel side-section of the specimen or the distance between notches and h is the total specimen thickness. It is usually expressed in kJ/m2. By analogy, permanent strain εbl can be measured with the tensile test. The change in length is measured by fitting the two part of the specimen after the test and the strain is obtained in the following way:

$$\varepsilon_{bl} = \frac{l_{bl} - l_0}{l_0} \cdot 100\ (\%)$$

where lbl is the final and l0 the initial length.

The test results obtained from specimens with different dimensions do not have to be identical and also the experimental results coming from A and B methods do not necessarily have to be comparable. It appears clear that tensile-impact data are not suitable for calculating design parts and components. On the contrary, non instrumented tensile-impact test is a suitable test for material developing even if the amount of information obtained can be improved by means of the instrumented test.

3 – Instrumented Impact Test

In the previous chapter it was explained what is a non instrumented impact test. It is immediately clear that one of the biggest drawbacks of this kind of impact test methods is that it provides only one value: the impact strength (resilience), or better, the total impact energy. It was also demonstrated that the total energy is a sum of many components which affects the results and a certain numbers of that are a parasitic terms (vibrations, frictions, ecc.). Additional information on the ductility, dynamic toughness, yield or the behaviour of the specimen during the whole impact event cannot be provided by such a test.

This fact effectively limits the application of non-instrumented impact test methods to quality control and/or material ranking. On the contrary, instrumented impact testers are generally suited for research and development as well as advance quality control.

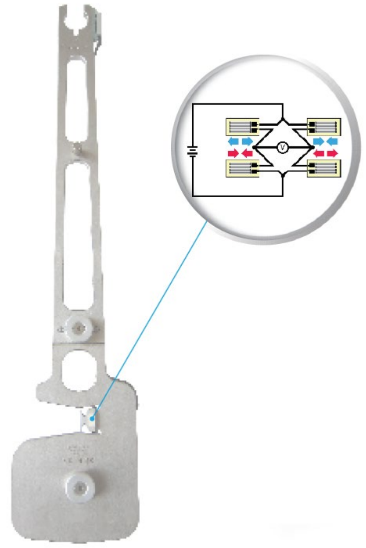
Strain-gauge instrumentation

In order to measure the deformations (and the force in the case of an impact test), a series of transducers named extensometers are used. These sensors are able to convert a deformation signal into an analog one, which is different in according to the kind of extensometer adopted. It exists different families of extensometers: mechanical, optical, acoustical and electrical. The last category comprises the electrical resistances sensors, the most used and useful for the purpose to measure the force acting on a specimen during an impact event. They can be made with different dimensions, with an high degree of accuracy and with an easy circuit able to acquire the signal. The desired characteristics of an extensometer are the following:

- The calibration constant must be stable and do not change during time, due to the effect of the temperature or environmental factors;
- It must measure the local deformation and not the mean vale (that given by two point very close to each others);
- It must have a good answer in frequency.

The extensometers are based on the physical principle that the elongation of a wire is directly proportional to its internal resistance. This extensometer are made by one or more grid, made by a wire, disposed on a support which is glued into the striker. Once the extensometer is glued it is connected to the read circuit and covered with a protective layer. Let's note that the extensometer always read a mean deformation relative at the length of the grid. In the pictures below an example of extensometer is reported.

Usually, if high deformation gradients are present a reduced length sensor will be employed as a sensor. In the picture below a striker for a pendulum test and the strain gauge circuit inserted inside are schematized.



In this picture a pendulum striker is shown. The blue line individuates the zone where the strain gauge sensors are placed (inside the striker) and in the lower right part the circuit that connect all the sensors is shown. They will be discussed in detail in the following.

For a wire conductor the electric resistance is given by the formula:

$$R = \rho \cdot \frac{l}{A}$$

where ρ is the resistivity of the material, l is the length of the wire and A the section. It is possible to define also, starting to the previous formula, a parameter which represents the sensibility of the extensometer or gauge factor K:

$$K = \frac{\delta\rho}{\rho \cdot \varepsilon_a} + (1 + 2\nu)$$

the first term is the piezoresistive sensitivity while the second one is the geometric sensitivity. This formula is also known as the first fundamental law of the extensometers. An axial sensor extensometer has a linear characteristic behaviour, so that the formula which allows to measure the strength is the following:

$$\frac{\Delta R}{R} = K \cdot \varepsilon_a$$

ε a is the strength along the axis of deformation.
The resistance of the extensometer is measured in a Wheatstone's bridge circuit. In the picture below this kind of circuit is represented:

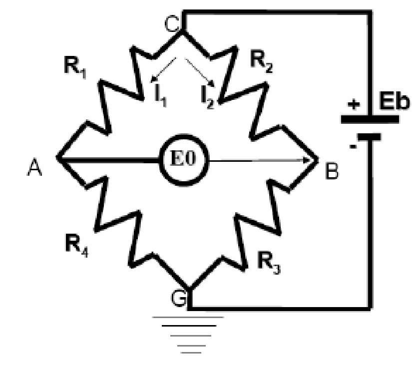


Figure: the Wheatstone's bridge circuit.

By solving the system it is possible to obtain the ratio:

$$\frac{E_0}{E_b} = \frac{R_1R_3 - R_2R_4}{(R_1+R_4)(R_2+R_3)}$$

If the bridge becomes unbalanced, this value is directly proportional at the resistance variation. The formula previously reported can be generalized to the case that all the resistance can vary:

$$\frac{\Delta E_0}{E_b} \approx \frac{1}{4}\left(\frac{\Delta R_1}{R_1} - \frac{\Delta R_2}{R_2} + \frac{\Delta R_3}{R_3} - \frac{\Delta R_4}{R_4}\right)$$

and from that it is possible to explain the second fundamental law of the extensometers:

$$\frac{\Delta E_0}{E_b} \approx \frac{1}{4}K(\varepsilon_1 - \varepsilon_2 + \varepsilon_3 - \varepsilon_4)$$

It is possible to place up to four exetensometers in a Wheatstone's bridge and to calculate the deformation by means of the disequilibrium of the bridge. This is the physical principle which allow to measure the deformation of the striker during the impact and to relate it to the force acting on the striker during the whole impact event.

Naturally, this simplify formula can be varied because of some external effects which takes place. The temperature, for example, is a noise signal either interferential than modifying, which is add to the measure. The temperature causes a direct variation on the resistance because it changes: the reistivity of the wire (it is a function of the temperature), the length of the grid, the resistance of the wire among the sides of the bridge. In order to reduce and minimize this effect it is important to chose in a correct way the thermal dilatation coefficients of both the extensometer and the grid. By means of a correct choice it is possible to compensate the resistivity variations. Even if strain gauges are not self-temperature compensated (such as isoelastic alloy), by using a Wheatstone bridge arrangement it is possible to compensate the temperature variation in the specimen under test and in the strain gauge.

If the lead wires are long, the temperature can have a not negligible effect on them too. These effects can be both signal-modificant (it vaeies the sensitivity of the brige) than interferences (but

they are compensed if a four-wires bridge is used).
It is very important that both the support and the glue are effectively an electric isolant in order to prevent the possibility that an external resistance is added to the circuit.

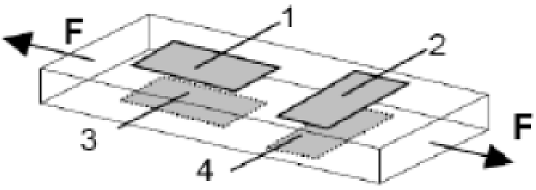


Figure: the extensometer arrangement in the full bridge configuration.

In this figure an example of the extensometer arrangement is showed. By means of this configuration it is possible to:

- Have the maximum sensitivity to the deformation;
- Compensate for the temperature variation;
- Delay the possibly presence of a component of flexural momentum, which can affect the final result if not delayed.

It also exist another big family of extensometers: the semiconductor one. In spite of a grid of wires these sensor are made by means of a semiconductive film (n or p). They have a great piezoresistive sensitivity, or most generally speaking, a higher sensitivity respect to wire extensometers, but they are very sensitive to temperature and they also are very brittle.

Instrumented data

This kind of test allows to measure the force continuously as the specimen is broken by the striker. The resulting data can be used in order to determine the type of failure and the maximum load exercised, in addition to the calculus of the amount of energy required to fracture the specimen. One of the most common kind of failure occurring from brittle to ductile transition at low temperature can only be studied and observed by studying the load (energy) – time curves. The fracture mode of polymers is sensitive to the changes of temperature and can change abruptly at, or immediately close, the transition temperature of the material. For example, test which involves manufactures of plastic for the automotive field are usually tested at low temperature in order to ensure that they will not become brittle in cold weather conditions. By studying the shape of the of the load-time or load deflection curve, the type of failure can be analyzed, and important information about the performance in service can be obtained.

All standard impact tester can be instrumented to provide a complete load and energy history of the specimen. This kind of system monitors and records, by means of an electronic system, the whole impact event, starting form the acceleration to the initial impact and plastic bending to fracture initiation and propagation to the complete failure. This instrumentation is done by inserting a straingauge or a load cell into striking edge in the case of pendulum or in the tup in the case of falling weight instrument. The new piezoelectric-equipped strikers are able to offer an increased sensitivity, and open the door to the testing of new families of materials. application involving light weight products or ultra-thin films can now be significantly tested.

By using this technique, the apparent total energy absorbed by the specimen can be calculated an plotted against time. The specimen displacement can be also calculate by double integration of the load-time curve and the load-deflection can be plotted.

In the following it will be explained the procedure which allow to calculate and plot the force or the energy as a function of the displacement. First of all, what is obtained from an impact test is the force-time curve, as reported in the following figure.

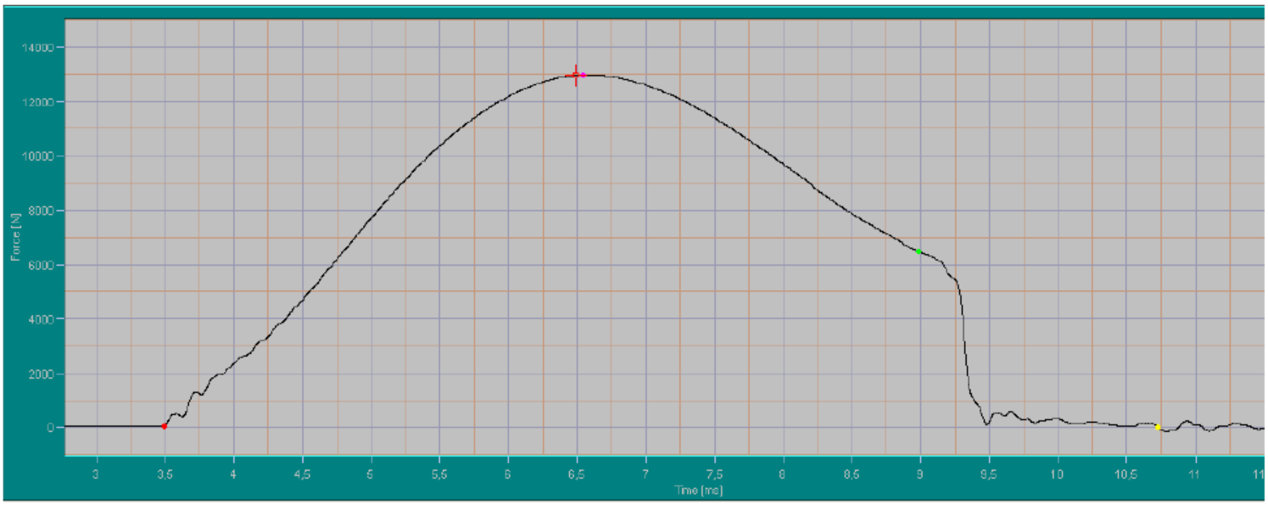


Figure: the force-time curve acquired during a test.

Once the curve is acquired a first integration point by point allow to calculate and plot the velocity as a function of the time:

$$v(t) = v_0 - \frac{1}{m} \cdot \int_0^t F(t) \cdot dt$$

where v_0 is the starting velocity, m is the mass of the striker and the integral of F(t) is the impulse given by the striker to the specimens. It can be graphically seen as the area under the force-time curve. It is now possible to plot the velocity-time graph (shown below) or plot the load-velocity graph because now it is possible to know exactly which is the velocity at each instant.

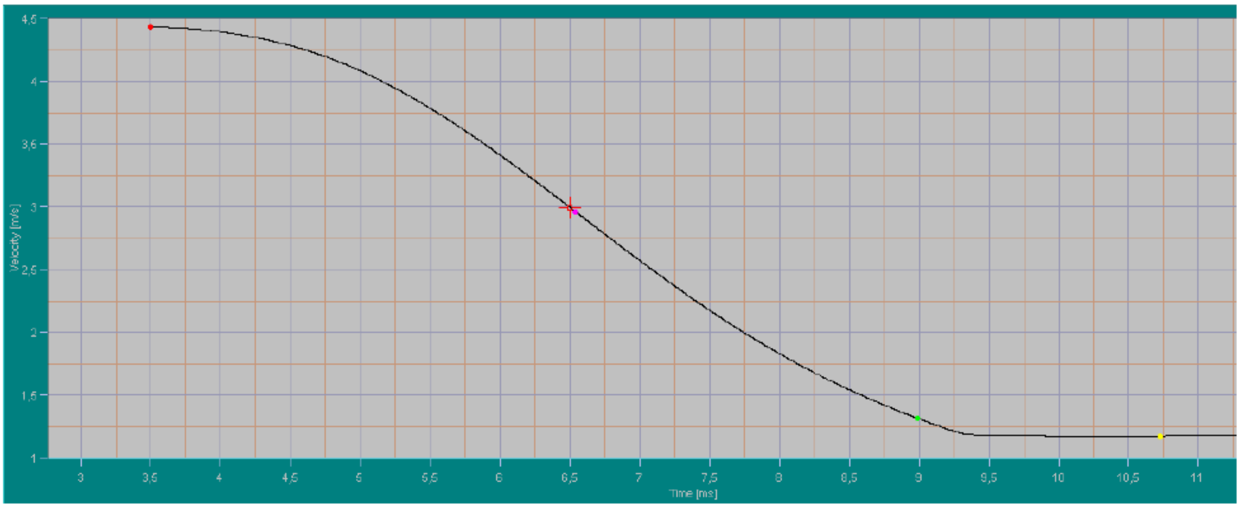


Figure: the velocity-time curve obtained by calculation.

Now, by means of a second integration it is possible to obtain the deformation of the specimen at each instant and plot it as a function of the time or, more interesting, plot the load-deflection graph, as reported in the next figure:

$$d(t) = v_0 \cdot t - \frac{1}{m} \cdot \int_0^{t'}\int_0^{t} F(t) \cdot dt \cdot dt' .$$

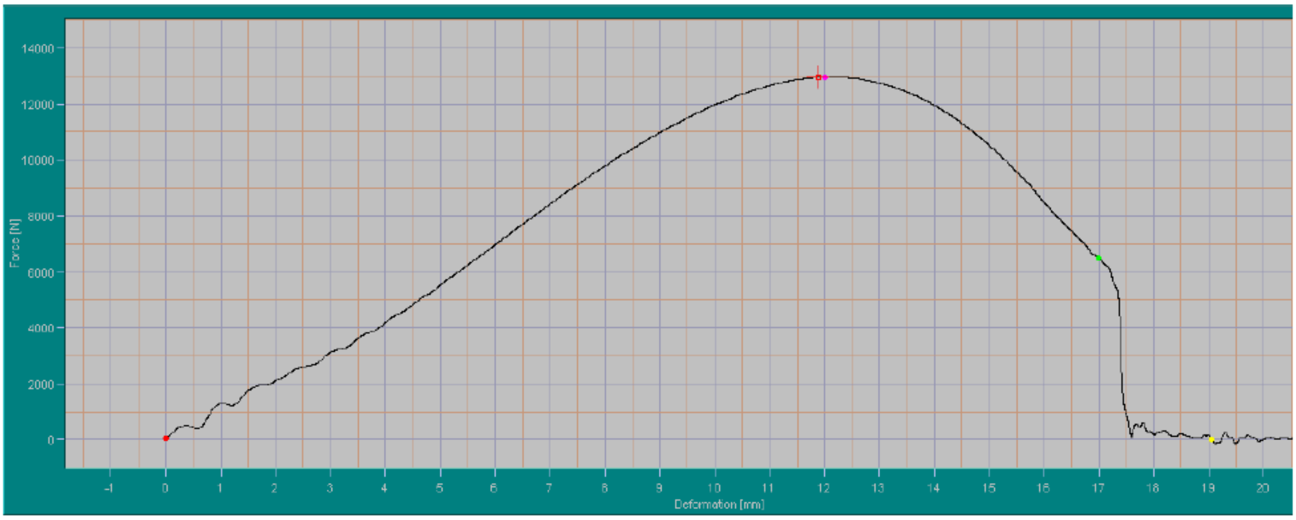


Figure: the force-deformation curve obtained from the test data.

Once the deflection is calculated, it is also possible to evaluate the total energy absorbed by the specimen during the test, the total area under the load-displacement curve, by using the following formula:

$$E_{tot} = v_0 \cdot \int_0^{t_{max}} F(t) \cdot dt - \frac{\left(\int_0^{t_{max}} F(t) \cdot dt \right)^2}{2m}$$

and by integrating point by point it is possible to plot energy-deformation graph:

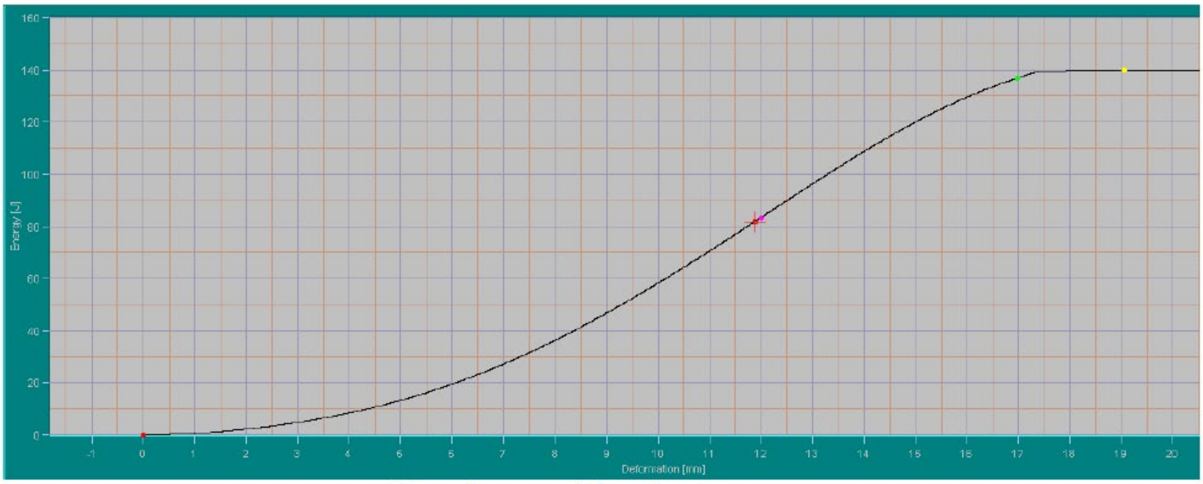


Figure: the energy-deformation curve.

3.1 - Pendulum instrumented impact test

To evaluate the toughness of the polymer under impact load conditions, suitable sensors and electronic hardware is applied nowadays. In the next paragraphs it will be shown and discussed in details the different kinds of sensors used to acquire forces during the impact. The working principle of the instrumentation for recording load-deflection diagram is equal for all the tests. The load signal is picked up by a sensor (semiconductor strain gauge or piezoelectric cell) mounted on the striker more close is possible to the impact point. The signal is amplified by a power amplifier with integrated operational amplifiers. A PC allows to manage all these information and the plot directly load as a function of time. Below, a typical force versus time measured curve is reported:

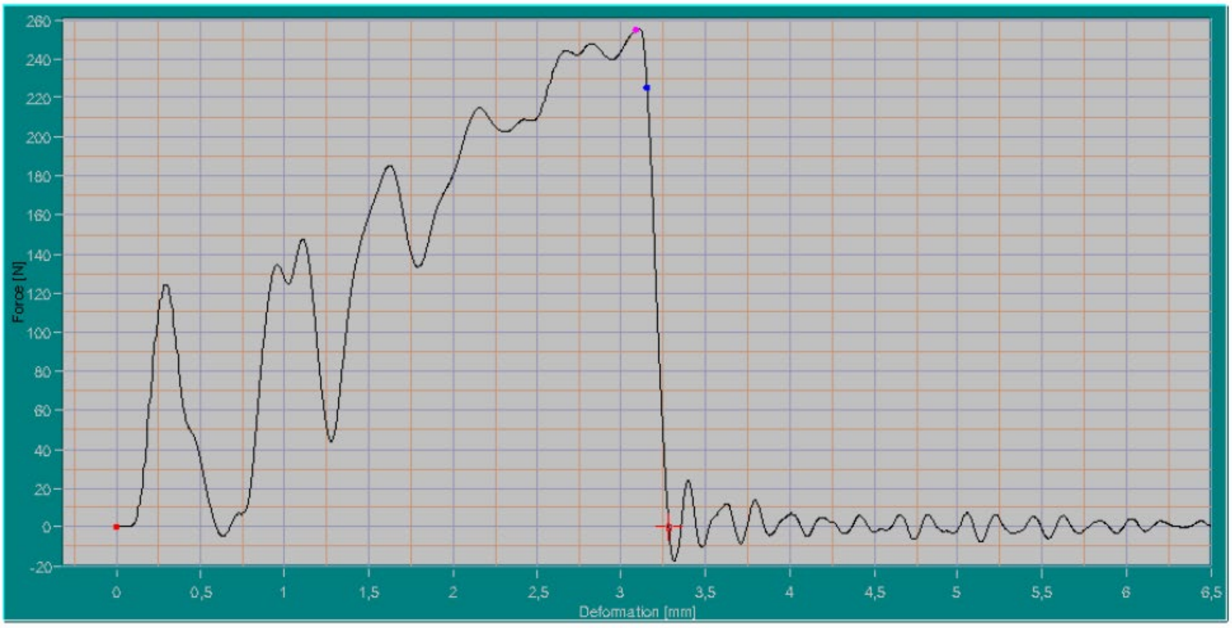


Figure: the force-deformation curve obtained from a test.

It has been shown that modern instrumented impact test machines generate a complete record of force applied to the specimen versus time, and it is possible from that to calculate the displacement of the striker versus time or force versus displacement, velocity of the striker versus time and energy absorbed by the specimen versus time. Once they were plotted, many details of the impact event become clearly visible in the data. Results coming from instrumented test are interpreted differently and they depend on the kind of material being tested and the failure criteria.

For most homogeneous materials, four values are critical: the maximum load, the energy at maximum load, the total absorbed energy and the deflection at maximum load.

Maximum load is the highest point on the load-time curve before failure. Often the maximum corresponds to the onset of complete failure. However, it exists some cases, e.g. polymers reinforced with fillers, where the peak load can be higher than the maximum load.

Energy to maximum load is the energy absorbed by the specimen up to the point of maximum load. When the maximum corresponds to failure, this is the amount of energy that specimen can absorb before failing.

Total energy is the amount of energy the specimen the specimen absorb during the complete test. Deflection to maximum load is the distance the striker travelled from the point of impact to the point of maximum load.

All these points can be very easily recognized in the graph previously reported.
In addition, on a force-time graph it is possible to distinguish some characteristic behaviour. The first part of the curve (one example is reported below) is the so called inertial part.

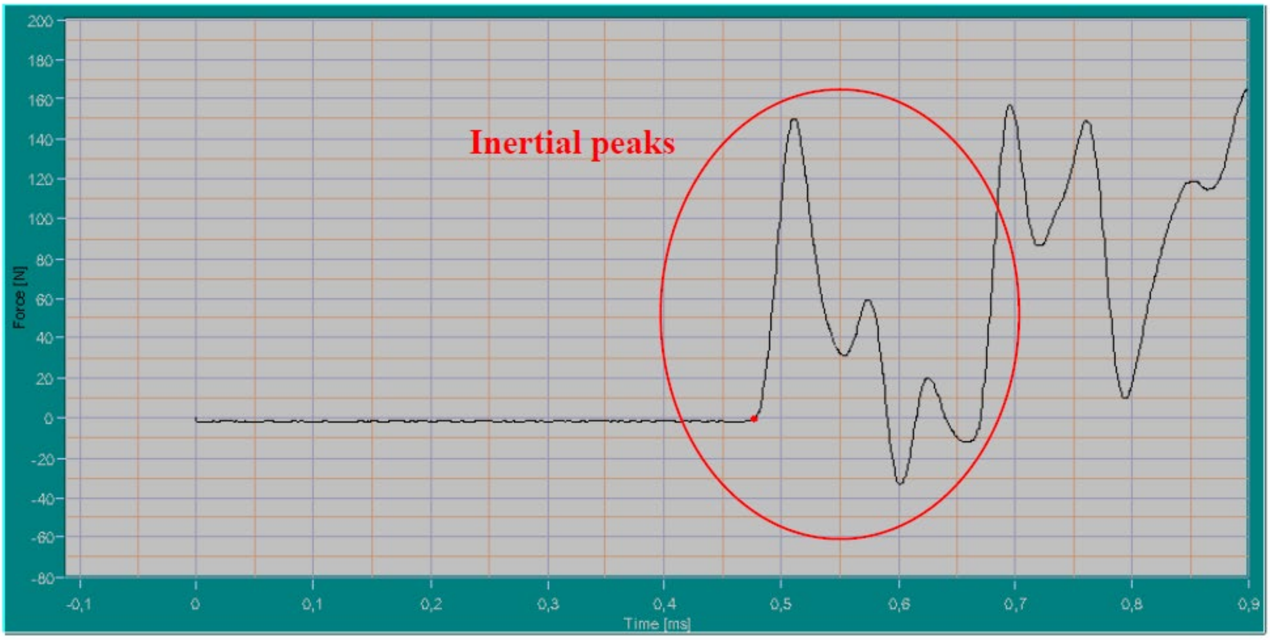


Figure: the typical inertial peaks zone.

It is caused by the inertia of that part of the specimen which is accelerated after the inertial contact with the striker. The peak force and the peak duration depend on the contact mass and stiffness. Due to the elastic components of the impact event, “bouncing” generally occurs. This means that specimen is accelerated at a speed higher than the impact velocity, so that contact is momentarily lost between specimen and striker, and it is reflected in a series of oscillations in the graph.

Another important information that is possible to obtain from an instrumented test is the modulus of elasticity. It is the ratio of stress to corresponding strain below the proportional limit of material, the zone where the curve is linear. This is also known as Young’s modulus and can be estimated as the angle from x axis to the linear part of the curve. A modulus is a measure of the stiffness of the material.

It is also possible to estimate the yield point (and the yield region), the first point on the stress-strain curve at which an increase in strain occurs without an increase in stress. It can be interpreted as the point where the curve deviates from linearity. A plastic strain of 0.2% is usually used to define the offset yield stress, although other values may be used depending on the material and the application. Once the yield point is passed some fraction of the deformation will be permanent and nonreversible.

4 – Factors affecting the measure

In the following chapter, the most important parameters which have an important effect on the impact strength properties of a polymeric material, will be presented.

Temperature

The impact behaviour of plastic materials is strongly dependent upon the temperature. At lower temperatures the impact resistance is reduced drastically. This reduction in impact is even more dramatic near the glass transition temperature. For an amorphous material glass transition temperature has the same meaning than the fusion temperature for a crystalline polymer. On the contrary at higher test temperatures, the resistance is significantly improved.

Orientation

The manner in which the polymer molecules are oriented will have a major effect on the impact behaviour of polymer. Molecular orientation introduced into drawn films and fibres may give an extra strength and toughness over the isotropic material. However, this directional orientation of polymer molecules can be very fatal in a moulded part since the impact stress is usually multiaxial. The impact strength is usually higher in the direction of flow.

Degree of crystallinity

Increasing the percentage of cristallinity decreases the impact resistance and increases the probability of the brittle failure. A reduction of the average molecular weight tends to reduce the impact behaviour, and vice-versa.

Processing conditions

Processing conditions play an absolute key role in determining the impact behaviour of a material. Inadequate processing conditions can cause the material to lose part of its toughness. Voids which act as stress concentrators are created by poor processing conditions. High processing temperatures can also cause thermal degradation and therefore reduced the impact property. Improper processing conditions also create a weak weld line that reduces overall the impact energy. The compression-moulded specimens usually show a lower impact resistance than the injection moulded ones.

Rate of loading

The speed at which the specimen or part of it is struck with a striker has a significant effect on the behaviour of a polymer under impact loading. At low rates of impact, relatively stiff materials can still have good impact strength. However, at high impact rates, even rubber may exhibit brittle failure. All materials seems to have a critical velocity above which they appear as glassy and brittle materials. This point is very important because sometimes the tests were performed at a velocity that is quite distant from that encountered in the end-used object.

Method of loading

The manner in which the specimen is impacted with the impact loading device significantly affects the impact results. A pendulum type of impact loading will produce a different results respect to the one obtained by means of a falling weight instrument or an high-speed ball impact loading. In the previous chapter has been shown, as example, that the inertial peak is present only in the pendulum impact loading.

Specimen clamping

Excessive clamping (when necessary) force can pre-stress the specimen, particularly behind the notch. Such kind of stress tend to reduce Izod test results.

Notch sensitivity

A notch in a test specimen, or a sharp corner in a fabricated part drastically lowers the impact energy. A notch is used in order to create a localized stress concentration and, as a consequence, the part failure under impact loading. All plastic material are notch sensitive and the level of sensitivity varies with the type of plastics. Both notch depth and notch radius have an effect on the impact behaviour of the material, this argument will be described into details in the next chapter. For example, generally speaking, a larger radius of curvature at the base of the notch will have a lower stress concentration and, therefore, a higher impact energy of the base material. It is obvious from the above discussion that all the factors that act as a stress concentrators should be avoided while designing a plastic part or component.

5 - Effects of test variables on pendulum impact test

In the previous part it was described the most general factors which affect the impact strength value. Now, the test variables and the limitations for each kind of test are presented in a more specific way.

Temperature

As previously reported the temperature has a high effect on the result obtained. The impact value increase with the increasing temperature and vice versa.

Specimen preparation

Injection-moulded specimens seem to usually have higher impact strength values than compression-moulded ones. This is due to the molecular orientation caused by the injection process.
The gate location has also a significant effect on the test results, especially in the fibre-reinforced specimens.

Fillers and additives

Fillers and reinforcements have naturally a great effect on the impact test results. The effect can go in different directions and not always is easy to predict the behaviour of the reinforced material. For example, a reinforced (with 30% of glass fibres) polycarbonate specimen has an Izod impact strength about four time lower than the un-reinforced one. In contrast, reinforced polystyrene (with 30% of glass fibres) has more than double impact strength value respect to unreinforced material. Fillers and pigments generally lower the impact strength value.

Specimen thickness

Although the impact values reported are on the basis of 4 mm (ISO) thickness specimens, the actual value of thickness used in the test influence the result.

Notch

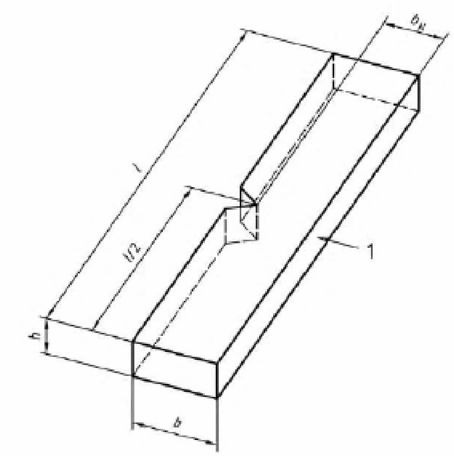
This parameter has a great influence on the results and it will be discussed in the next chapter because of its importance.

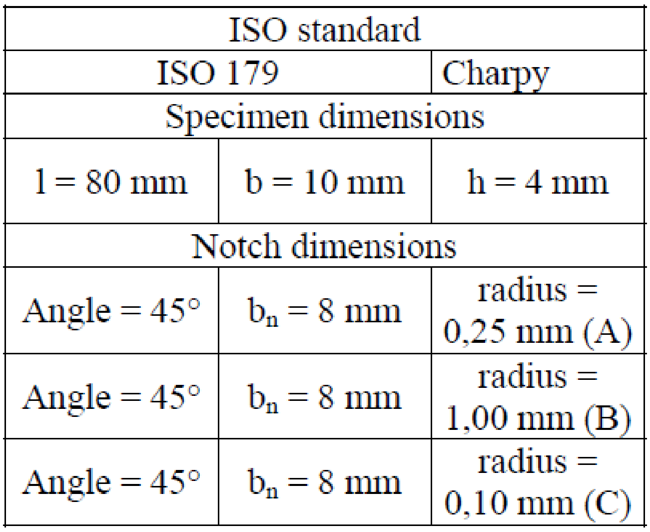
Limitations

The results obtained from the Charpy or Izod impact test cannot be directly applied to design. This is due to the fact that these tests do not measure the true energy required to break the specimen. The notched Izod impact test measure in fact the notch sensitivity of the different materials and not the toughness.

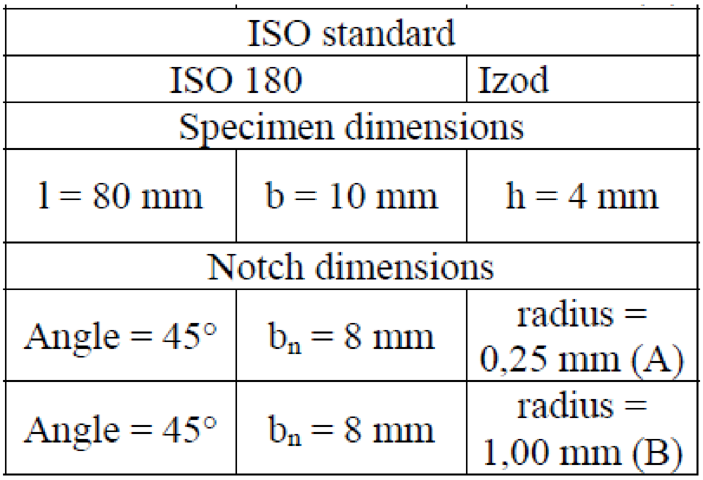
6 – Influence of the Notch

The notch is one of the factor that affect very much the impact strength of a polymer. In particular it acts in order to lower the impact strength of the specimen. It is created, as recommended by the most common international standards, in order to concentrate and localize the stress and hence it allows the failure of the sample under impact loading. All the most important standards define the geometric dimensions of both specimens and notchs, here in the following they ware resumed for both ISO and ASTM standard and for both Izod and Charpy test. In the following a figure which can help to recognize the dimensions is reported.

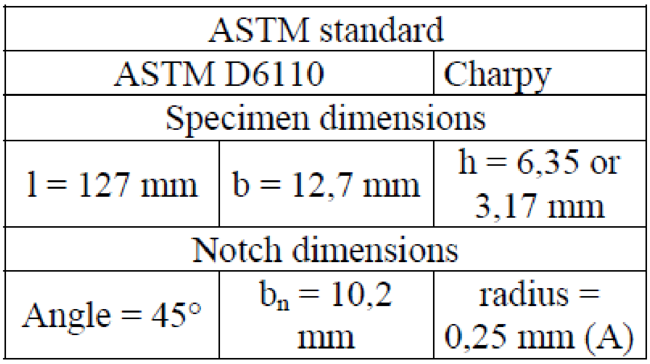




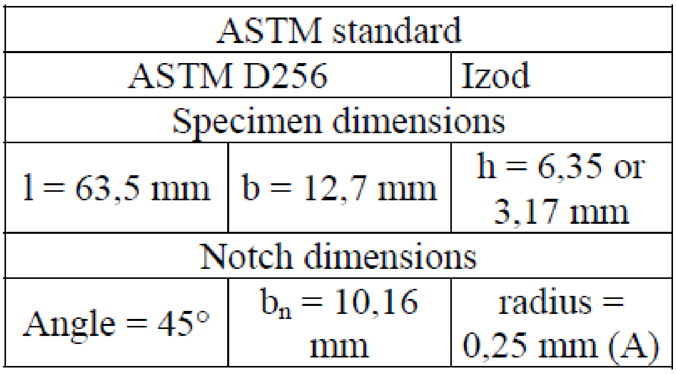
ISO standard		
ISO 179		Charpy
Specimen dimensions		
l = 80 mm	b = 10 mm	h = 4 mm
Notch dimensions		
Angle = 45°	b_n = 8 mm	radius = 0,25 mm (A)
Angle = 45°	b_n = 8 mm	radius = 1,00 mm (B)
Angle = 45°	b_n = 8 mm	radius = 0,10 mm (C)



ISO standard		
ISO 180		Izod
Specimen dimensions		
l = 80 mm	b = 10 mm	h = 4 mm
Notch dimensions		
Angle = 45°	b_n = 8 mm	radius = 0,25 mm (A)
Angle = 45°	b_n = 8 mm	radius = 1,00 mm (B)



ASTM standard		
ASTM D6110		Charpy
Specimen dimensions		
l = 127 mm	b = 12,7 mm	h = 6,35 or 3,17 mm
Notch dimensions		
Angle = 45°	b_n = 10,2 mm	radius = 0,25 mm (A)

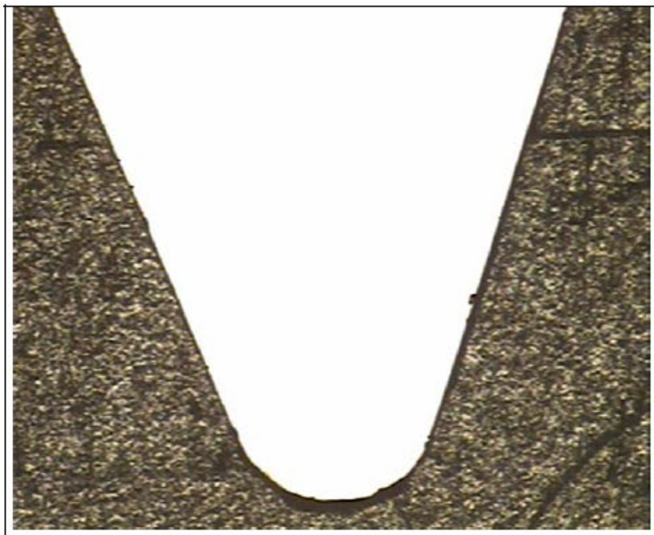
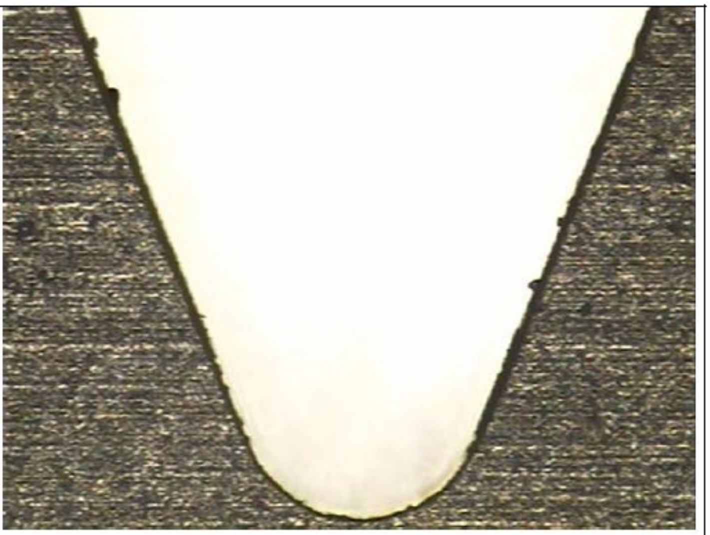


ASTM standard		
ASTM D256		Izod
Specimen dimensions		
l = 63,5 mm	b = 12,7 mm	h = 6,35 or 3,17 mm
Notch dimensions		
Angle = 45°	b_n = 10,16 mm	radius = 0,25 mm (A)

The test specimens can be prepared either by moulding or cutting them from a plate, while the specified geometry of the notch is cut into the specimen very carefully by means of a milling machine or a lathe. It exists also different kind of instruments able to cut the notch into the specimen: the linear motion cutting machine and the rotating one.

Instron is one of the worldwide leaders in the sector of the linear motion cutting machine (broaching procedure). A constant profile knife moves through the specimens and pass after pass, with a selected velocity, is able to cut the specimens in according to the method adopted for the test.

Nevertheless, an accurate study on the reproducibility of the data obtained by using a single-tooth rotating device during the preparation of the notch is at the present moment studied in the Instron laboratory. Without going into details, it can be point out that the notch obtained by means of a rotating instruments presents a quite good aspect but the impact strength obtained from the test is in general higher than that obtained from the reference value. This fact seems to be due to a residual stress that this kind of operation leaves on the specimen during the notch cutting. In the pictures below an example of the notch obtained from the both the procedures are reported.

	
Notch obtained by means of a linear-cutting machine.	Notch obtained by means of a rotating single-tooth device machine.

The notch parameters

Since the impact test is a kind of destructive test, the accuracy during the notch preparation is extremely important. This is one of the critical aspect that precede the test and each imperfection obtained from a non correct notch operation is reflected in an increase of the scattering of the data. If the non correct parameters are used during the preparation of the notch it is possible to have a residual stress or a localized increase of the toughness around the apex of the notch that will be reflected in an increase of the apparent impact strength value.

It is important to remark that all plastic are notch sensitive and the rate of sensitivity unfortunately vary from material to material, thus it is impossible to generalize this effect. From a geometric point of view both notch depth in the specimen and notch radius have an effect on the impact behaviour of the material.

For example, a larger radius of curvature at the base of the notch will have a lower stress concentration factor and, as a consequence, an higher impact energy of the base material is expected. A slight variation of this parameter, or a different value of notch depth, affects the impact strength results of some percent. The tolerance defined by the standard for the notch radius is 0,1 mm and lead to conclude that even if the notches obtained are inside the range aforementioned the impact strength values can vary sensibly.

Many other variables as the cutting speed, the depth pass, the sharpness of the cutting tooth, the feed rate, the type of plastic used (all the previous variables are parameters of this function) and, obviously, the quality of the cutting equipment seem to have a significant effect on the results too.
Is not easy in this case try to distinguish the effect of each parameter on the impact strength separately because they all seem to be related. Nevertheless, it can be pointed out that usually the effect of these parameters is secondary to those of the notch radius and notch depth. Actually, such variations are difficult to control and non-uniformity among lots are quite common while the notch radius can be measured very well by means of a microscope.

Certain heat-sensitive polymers are also affected by the high cutter speed which seems to contribute to the thermal degradation of the material. In this case can be useful refrigerate the knife during the cutting process.

It has been said that the notch in the specimen tends to create a stress concentration area. This fact produces unrealistically low impact values especially in crystalline plastics.

The profiles of the knives have to be checked regularly and the standard recommend to re-sharp and check the profile after five hundred operations. It is also recommended to wait a lot of time between notching preparation and testing. Usually it can be adopted an interval of about 40 hours after notching and before testing.

7 – Failure Analysis

In the previous chapters it was briefly described the different kind of impact measurements. After that it was analysed how to measure and how collect data by means of instrumented striker. It was shown which are the most common shapes of impact curves for each kind of test and the different zone which constituted the whole curve. After that the parameters which affect the final results were presented and the effect of the notch on the impact strength of a pendulum impact test was described into details. Now, it remains to analyse the different kind of failure and the most common behaviours of the force-deformation curves.

Impact test

The impact properties of the polymeric materials are directly related to the overall toughness of the material. The toughness is defined as the ability of a material to resist to an impulsive load. It has been previously shown that the area under the force-deflection curve is directly related to the material toughness. On the other side it was also introduced the fact that some materials under some conditions exhibit a brittle behaviour. What does it means?

The theory behind brittleness and toughness of the polymer is very complex and not trivial to understand. The molecular flexibility plays a very important role, from a microscopic point of view, in determining the relative brittleness or toughness of the material.

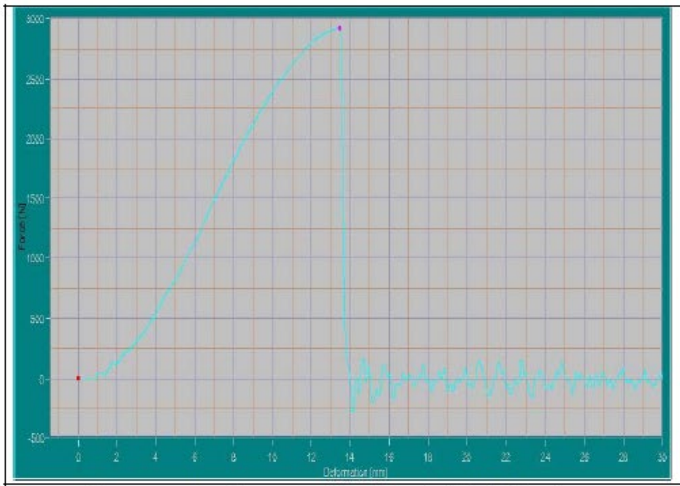
Most polymers, when subjected to impact loading, seem to fracture in a characteristic way and the crack is initiated on a polymer surface due to the impact loading. This amount of energy necessary to initiate such a crack is called the crack initiation energy. If impact energy value is higher than crack initiation value the crack continues to propagate. A complete failure occurs when the load when impact energy is higher than crack propagation contribute. Usually, it exist four different kinds of failures due to the impact load.

Brittle: In this kind of failure, the part are fractured extensively but without yielding. A catastrophic mechanical failure is observed.

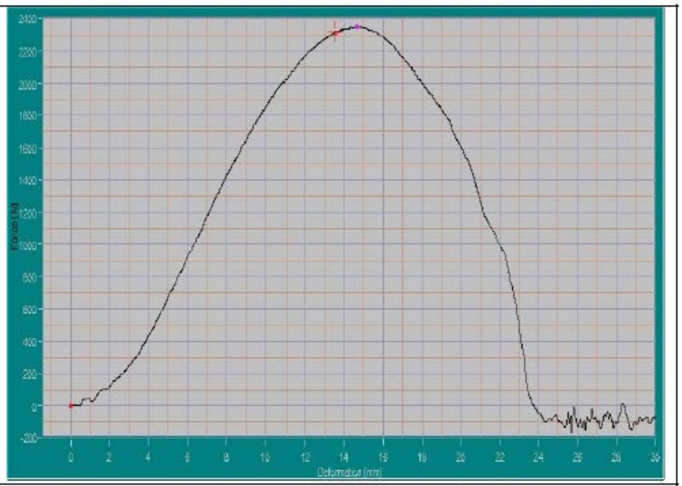
Slight cracking: The specimen shows here evidence of slight cracking and yielding but without losing its shape integrity after the test.

Yielding: The specimen actually yields showing deformation and stress whitening but the crack is not propagated along all the surface.

Ductile: This type of failure is characterized by a complete yielding of material along with cracking. The differences amongst the four types of failure are sometimes not very clear and some overlapping are absolutely possible. In the figures below some examples are reported.



An example of a material with a brittle behaviour.



An example of a material with a ductile behaviour.

Nevertheless, each international standard try to define the types of failure. In a Charpy non-instrumented test (ISO 179-1), for example, by analysing the specimen after the test it is possible to define:

Complete break: a break in which the specimen separates into two or more pieces.

Hinge break: an incomplete break such that both parts are held together only by a thin peripheral layer in the form of a hinge having very low residual stiffness.

Partial break: an incomplete break that does not meet the definition for hinge break.

Non-break: there is no break, the specimen is only bent and pushed through the support blocks (pull-through effect), possibly combined with stress whitening.

In a Charpy instrumented test (ISO 179-2) the type of failures are defined by analysing the force as a function of time deformation:

No break: there is no break, yielding is followed by plastic deformation up to the deflection limit. The deflection limit is the beginning of pull-through which is determined by the length and the width of the specimen and the span between the support.

Partial: yielding followed by stable cracking, resulting in a force at the deflection limit which is greater than 5% of the maximum force.

Tough: yielding followed by stable cracking, resulting in a force at the deflection limit which is less than or equal to 5% of the maximum force.

Brittle: yielding followed by unstable cracking.

Splintering: unstable cracking followed by yielding.

Linear Elastic Fracture Mechanics

Up to now it was shown that, in order to increase the understanding of the mechanical properties, instrumented tests were introduced. These measures allow to study the toughness and failure properties of the material.

The failure analysis is based on the analysis of the appearance of the specimen after the test or on the study of the force-deformation curve. Obviously, this arguments can be applied in a satisfactory manner to a specimen but it is very difficult generalize the behaviour to a manufacture.

The products made from polymers are subject to innumerable types of mechanical loading in use conditions. Numerous influencing factors (design-related notches, multiaxial stress states, …) induced defects increase susceptibility to brittle fracture. These are some reasons for developing testing and measuring methods with the established parameters of material science.

The polymers producing and processing industries are currently using very limited methods for evaluating toughness properties. Due to geometry dependence, conventional parameters cannot be converted from each other.

Fracture mechanics assumes that fracture in a component, and thus in the material too, occurs in consequence of crack propagation. It investigates the conditions for crack propagation and it allow to establish quantitative relations between external load acting on the specimen or on the component (nominal stress) and the shape of cracks, as well as the resistance of materials to crack propagation. The LEFM theory express the stress state near the crack tip as a stress intensity factor K. It was introduced first time by Irwin and it is expressed as:

$$K = \sigma_N (\pi\, a)^{1/2}$$

with σ_N nominal stress value and a crack length.
Allowance is made for the finite geometry of each component and specimen, as well as for crack geometry by introducing a geometry correction function f(a/W), where W is the length of the specimen:

$$K = \sigma_N (\pi\, a)^{1/2} f(a/W)$$

This function f(a/W) is calculated for a great amount of fracture mechanics specimens.
At the start of unstable crack propagation, the stress intensity factor reaches the critical value K_{IC}, also called fracture or crack toughness. Index I refers to mode I of opening crack in which load acts perpendicular to the crack surface, as shown in the figure below.

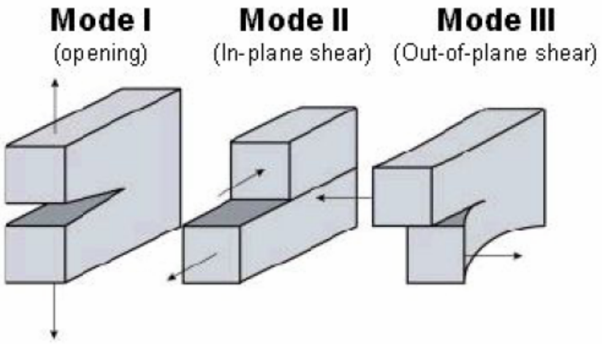


Figure: the different mode of crack opening on tne specimens.

For this first mode, the technically most important case of loading, the fracture criterion is:

$$K_I \leq K_{IC}$$

where the component safety against fracture propagation is ensured as long as the critical value is not exceeded.
The mode II and III occur in case of shear or torsional loading. Depending on specimen geometry, many different multiaxial stress state are formed in the front of the crack tip. The observable macroscopic increase in normal stress fracture results from the transition from plane stress to plane strain state. In all the cases where crack tip is under plane strain, fracture toughness is dependent on specimen geometry. It reflects the influence of material structure, loading rate and environmental temperature on toughness.

Nevertheless, this powerful theory has some limitations. A first constraint is that LEFM requires linear elastic materials, in which plasticity is confined to a small region around the crack tip. A second constraint concerns high speed fracture mechanics: since the present theory is based on a quasi-static approximation (waves propagation into the material is neglected), the evaluation of K_C becomes troublesome once that velocity is high (more than 1 m/s).

It must be remember that the great impulse to the introduction of Linear Elastic Fracture Mechanics was due to the contribution of George Rankin Irwin. He introduced this theory that is able to explain and predict the crack propagation along the liberty boat body, made of a single piece, that was one of the common problem during the '50s. The basic concepts are now used world wide for fracture control of aircraft, nuclear-reactor vessels and other fracture-critical applications.

Crack-Tip-Opening displacement (CTOD) concept

This method is based on the assumption that, in cases of ductile material behaviour, the fracture process is determined by critical plastic deformation of the crack opening (named δ) or Crack-Tip-Opening Displacement (CTOD).

Formation of the plastic zone depends on microstructure and thus cannot be illustrated in a generally valid form.

Calculation of critical CTOD was reduced to the whole region at the notch tip by subtracting the amount of deflection of an un-notched specimen from the maximum deflection f_{max} of a notched specimen.

To the LEFM concept there exists the simple relation:

$$K_{IC}^{CTOD} = \left(m\sigma_y \delta E\right)^{1/2}.$$

The constraint factor m is material dependent and was determined experimentally.

J-integral concept

The J-integral has achieved its dominant significance for polymers due to its energy-based approach to the fracture process. The path-independent contour integral envelops the plastically deformed region and its closed path of integration circles in the elastically deformed region around the crack tip.

Curve integration is used to determine deformation energy A_G from the acquired load versus loadline displacement curves with different crack lengths. The A_G/B (B is the thickness of the specimen) relation is presented as a function of *a* parameter. By using graphic differentiation:

$$J = \frac{1}{B} \cdot \frac{\partial A_G}{\partial a}$$

and the J results as a function of load-line displacement or deflection.

In cases of elastic material behaviour, the J-integral is identical with the energy release rate G (introduced by LEFM):

$$J_I = G_I = \frac{K_I^2}{E} \text{ for plane stress state or}$$

$$J_I = G_I = \frac{K_I^2}{E}\left(1-\upsilon^2\right) \text{ for plane strain state.}$$

υ is the Poisson's ratio of the material. These equations are used in order to extrapolate K_{J} $_{IC}$ values from J_{IC} values.

It exists also a relation between the J-integral and CTOD concept:

$$J = m \cdot \sigma_y \cdot \delta_{IC} .$$