

INSTRUMENTED IMPACT TESTS: POTENTIAL AND BENEFITS

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ABSTRAKT

Tato bakalářská práce pojednává o instrumentovaném rázovém testu.

První část popisuje některé mechanické zkoušky jako tahovou zkoušku, reologii, relaxační a creepový test.

Druhá část je zaměřena na rázový test jako takový, na jeho jednotlivé zkoušky např. Izod a Charpy test, tahový rázový test a padostroje.

Třetí část se zabývá instrumentovanou zkouškou a lomovou mechanikou a také faktory, které ji ovlivňují.

This Bachelor thesis is dedicated to instrumented impact test.

The first part describes some of the mechanical test as tensile test, rheology, relaxation and creep test.

The second part concentrates on the impact test in common, its individual tests, for example Izod and Charpy test, tensile impact test and falling-weight impact test.

The third and the last part is interested in instrumented test and fracture mechanics and also in factors that effect fracture parameters.

I declare I worked on this Bachelor thesis by myself and I have mentioned all the used literature.

Zlín, datum

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INTRODUCTION

Chemists normally seek to understand the physical properties of materials in terms of molecular features, for example, in terms of molecular shape, conformational mobility, crystal packing forces, and bond energies. On the other hand, the engineer or technologist, while being aware of such fundamental matters, is usually much more interested in the question: What are the special properties of this material that would favor its use in this particular application? At this moment, an important aspect of polymer technology is the mechanical testing, because it is right the mechanical tests providing engineering-type evaluations of polymers and determining the advantages and disadvantages of polymeric materials in specific applications.

Mechanical tests are routinely performed in materials laboratories and in industrial research laboratories. However, it should be kept in mind that since the most of the tests result in destruction of the sample, and because such tests do not have a high degree of reproducibility, multiple tests on similar samples are needed before valid results can be obtained. Also it is important that for the ultimate test of any polymer this need to be fabricated into a suitable object and tested under the same operating conditions that it would encounter in normal use. [1] The commonly used mechanical tests are rheological measurements, creep and relaxation tests, tensile and impact tests.

1 MECHANICAL TESTS

1.1 Rheology

Rheology is science about flowing of various materials. Very often rheological measurements follow the dependence of stress in the material on the deformation or rate of deformation.

Two basic physical laws describing deformation of an elastic solid (Hooke's) and linear viscous fluid (Newton's) in shear can be regarded two theoretical extremes of material response: a non-deformable body on the one hand, and an inviscid fluid on the other hand. Nevertheless, the behaviour of real materials falls between these limits – they show viscoelastic response.

Newton and Hooke's laws considered viscoelastic behaviour as linear, but the range of stresses over which materials behave linearly is invariably limited. Thus materials properties, such as rigidity, modulus and viscosity (defined as resistance to flow) can change with the applied stress. The change can occur either instantaneously or over a long time. In other words, it depends on the stress and the duration of stress application.

For various materials viscosities can significantly differ. At constant temperature and pressure viscosity is constant and materials have following characteristics:

- viscosity is independent of shear rate and time of shearing
- viscosities measured under different types of deformation are always in simple proportion to one another
- the only stress generated in simple shear flow is the shear stress,
- the stress in liquid falls to zero immediately if the shearing is stopped

Nevertheless, viscosity of most real materials shows some deviation from the behaviour described above. Viscosity is also significantly affected by experimental conditions, such as temperature, pressure, time of shearing and material structure.

1.2 Creep and relaxation measurements

Creep tests are carried out on cylindrical or flat test pieces under constant load; the time for a test can be anything from a few hours to several years, according to the application. The results are given as a time deformation curve (*Fig.1*).

The test is characterized by initial value of the axial stress:

$$\varepsilon_0 = F/S_0$$

where F is applied force and S_0 the initial cross-section of the test piece. There are three main stages in the response to the load:

- *primary creep* – during which the strain rate falls; this corresponds to an increase in the resistance of material
- *secondary creep* – in which the strain rate remains constant
- *tertiary creep* – when the rate increases; significant mechanical damage appears in this stage, related to cavitation for example, or to a softening of the material.

At low temperatures it is usually the primary and secondary creep that dominates; as the temperature rises the secondary phase becomes established sooner, and tertiary creep becomes more important. To the extent that the load is usually applied as a dead weight, the stress is not constant throughout the test but this is usually ignored.

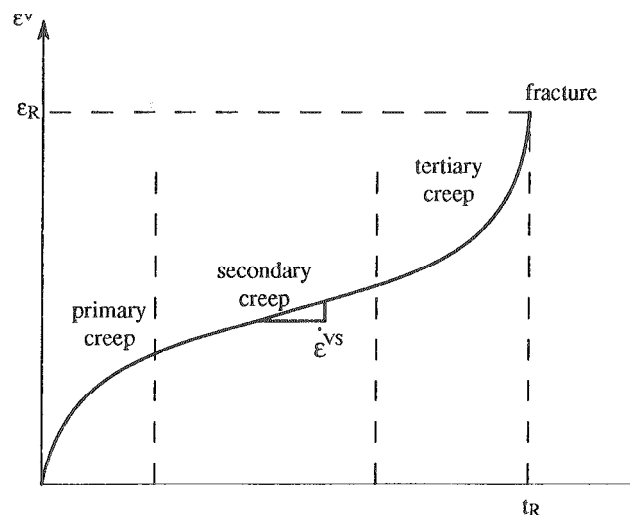


Fig.1. Three phases in a creep test.

In *relaxation tests* a load is applied, generally at a controlled strain rate, followed by holding the deformation constant, see *Fig.2*. During the relaxation the rates of change of stress and viscoplastic deformation are related by:

$$\dot{\sigma} = -E\dot{\epsilon}^v$$

where E is Young's modulus in the direction of the traction. It is often more difficult here than in case of creep to carry out tests of very long duration, mainly because of the difficulty with controlling the temperature. Even so, relaxation tests have the advantage of enabling a wide range of viscoplastic strain rates to be covered. In most cases simple laws, that do not involve internal stresses, are not able to describe both creep and relaxation simultaneously [2].

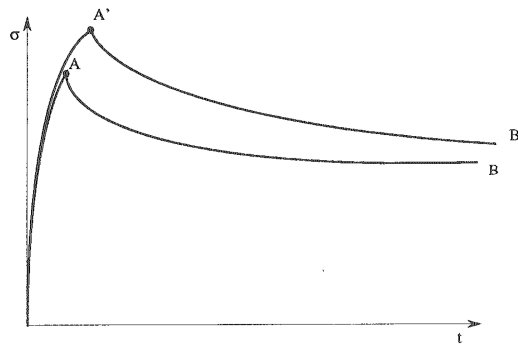
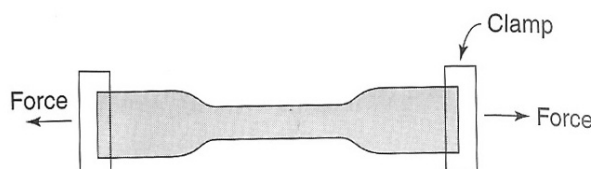


Fig.2. Relaxation test

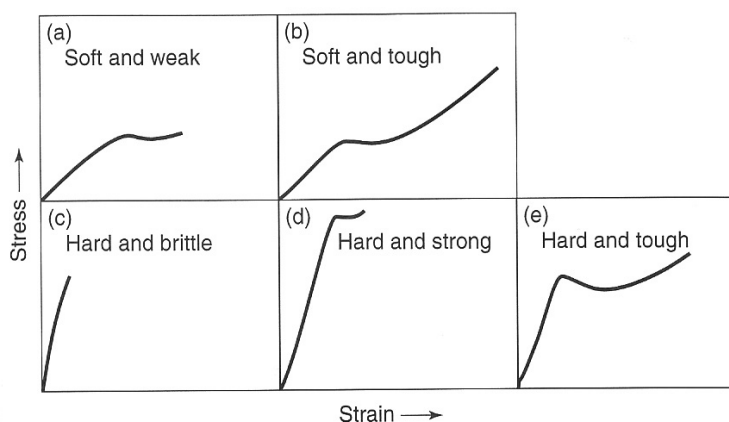
1.3 Tensile tests

The tensile strength of a material provides a measure of its resistance to elongation of breaking when stretching forces are applied to it. Because the stress-strain behaviour of most materials is time-dependent, the speed at which the stress is applied must also be taken into account. In practice, stress-strain experiments are often carried out on a flat sample that has been shaped into the form shown in *Fig 3*.



*Fig. 3. Typical shape of a flat polymer sample used
for stress-strain tests*

The ends of the sample are clamped into the jaws of a testing machine and the jaws are separated by the application of a known mechanical force. The test material usually elongates or breaks in the narrower, central region of the specimen. Both the stress and the strain can be read from the dials on the machine, or the data may be provided directly on chart paper or computer [1]. The result of this test is suspension between force and elongation [3].



*Fig.4. Characteristics stress-strain curves for five different
types of polymeric materials*

1.4 Impact tests

Impact testing is viewed as covering the high strain-rate end of the strain-rate spectrum. Because some polymers that are quite tough under actual operating condition (nylon, for example) could perform poorly in standard impact tests, the impact tests complete a series of mechanical tests, which seek to assess the performance of plastics and other materials. The standard impact test involves two types of experiments. Either a swinging pendulum is allowed to strike the sample from different displacements or a falling weight is dropped on to the sample from various heights. The impact force is increased until the sample breaks [1].

Impact test will be discussed in more details in chapter below.

2 IMPACT TESTS

Impact tests are employed to measure the ability of a specimen or a finished component to withstand a sudden blow. In many applications a satisfactory resistance to impact loading is an important performance requirement and impact toughness is often the deciding factor in materials selection. Impact testing and the impact performance of plastics has therefore been the subject of several reviews.

The importance of impact testing consists in fact that these tests frequently indicate that many polymers which appear to exhibit tough, ductile failures when tested by tensile loading at a low or moderate strain rate may suffer brittle fracture under impact loading when the strain rate is relatively high. Brittle fracture, which is accompanied by relatively low energy absorption by the material, is obviously a mode of failure that the design engineer generally wishes to avoid. A transition from ductile to brittle behaviour is particularly likely to be observed if the impact tests are conducted at relatively low temperatures or if the specimen contains a stress concentration. [4]

Impact testing is conducted with several objectives in view. The primary aim of impact studies on plastics materials is to give a basic understanding of the behaviour of such materials under impact loading and hence provide a reliable guide to their impact performance [5]. Impact tests have the advantage of being easily and rapidly performed, and provide a relatively simple means of observing fracture phenomena of considerable practical importance that cannot be readily studied by other means. These tests are therefore best regarded as providing valuable information for ranking materials in order of impact toughness, especially when the tests are conducted with specimens containing no notch or notches of various tip radii, and are performed over a range of test temperatures. Because it must be kept in mind that the ranking order may change with factors such as test method, specimen geometry and temperature [4].

However, impact tests, although simple to perform, are difficult to analyze in detailed scientific terms, since they involve the dynamic response of structures, stress waves in solids and non-equilibrium situations. Problems with impact testing and the application of impact test results to practical situations are no unique to plastics. The same problems face the metallurgist and engineer using metals and understanding in that area is probably not greatly more advanced than in polymers. However, in contrast to many commonly used

metals, polymeric materials are generally highly sensitive to strain rate and temperature in the zone of use. Brittle behaviour can often occur with minor increases in strain rate or modest decreases in temperature. Since the impact test serves to highlight the possibility of brittle behaviour in service, the test takes on more significance in the case of polymeric materials. [5]

2.1 Experimental methods

The impact strength is defined either in terms of energy per unit width of notch or energy per unit area under the notch. Taking the width (B), depth (D) and notch length (a) of the specimen shown in *Fig.5*.

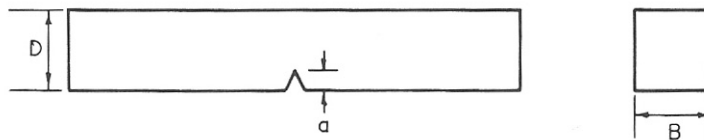


Fig.5. Proportion of the specimen

The impact strengths are specified as either:

$$U/B \text{ (kJ.m}^{-1}\text{)} \quad \text{or} \quad U/B(D - a) \text{ (kJ.m}^{-2}\text{)}$$

The two methods of expressing the impact strength are not convertible unless it is assumed that the energy-to-break is proportional to the ligament length under the notch. Then assuming $(D - a) = 10.16\text{mm}$

$$1 \text{ kJ.m}^{-1} \equiv 100 \text{ kJ.m}^{-2}$$

Turner [6] has classified experimental methods for measuring impact strength into three basic categories:

- Flexed-beam impact
- Falling-weight impact
- High-speed tensile impact

This classification covers most of the experimental methods which have been employed as basic impact tests and includes all those called for in British Standards (BS), American

Society for Testing and Materials (ASTM) and International Standard Organization (ISO) specifications for material assessment [4]. However, it possibly excludes certain high strain-rate tests, which may be considered as adjuncts to impact testing if not actually classified as impact tests themselves. There are also acceptance impact tests on polymeric components covered by the Standards. It is difficult to set a boundary to the subject of impact testing, in contrast to other mechanical tests. To some the term is synonymous with notched-bar testing, to others it implies high strain-rate testing. Probably all would agree that it involves impact loading of the specimen or component. Turner makes the point that current impact tests are designed specifically to measure the ability of a specimen to withstand a sudden blow, drawing a clear distinction between specimen and sample (a specimen is taken from a sample, a sample in turn being taken from a population) [5].

Two flexed-beam impact tests, the Charpy and the Izod methods, are the most commonly used methods and a standard test procedure is described in ISO 179, ISO 180, BS 2782 and ASTM-D 256. In both the Charpy and the Izod tests the specimen is usually notched and the specimen geometry and support arrangements are shown in *Fig 6*. [4]

2.1.1 Izod and Charpy impact tests

The Izod and Charpy tests are both swinging pendulum techniques in which a pendulum is released from a fixed height, swings down to strike and break the specimen at the bottom of the swing and then continues to a measured maximum height at the end of the first half-oscillation [5]. The energy absorbed from the pendulum is deduced from the difference between the release height and the maximum height [4]. These two tests differ mainly in the manner in which specimens are held. In the Charpy test, the test-piece is a simply supported by rectangular beam, struck at mid-span as shown in *Fig 6a*.

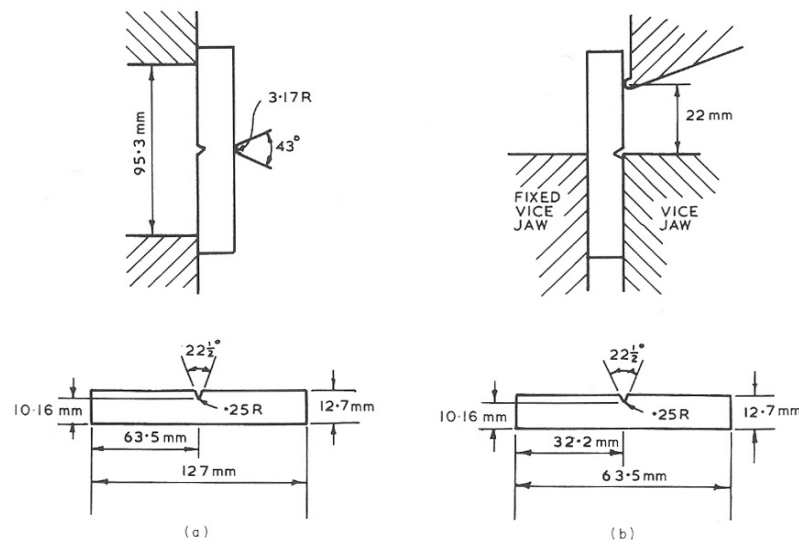


Fig.6. Geometry of testing and specimen support arrangement for Charpy (Fig.6a) and Izod (Fig.6b) tests.

In the Izod test the specimen is a notched cantilever beam which is held in a vice and struck by the pendulum bob just above the notch, as shown in *Fig.6b* [5]. Variations in the clamping force may cause significant differences in the measured energy absorption but use of a standard clamping force may help in minimising this source of variability [4]. The different Standard specifications state exact dimensions for the specimens but give only broad requirements for the machine. For example:

- BS 2782 for the Izod test requires the specimen to be struck with a striker of nose radius 3.2mm at a velocity of 2.44m.s^{-1} ;
- the center of percussion of the pendulum is to coincide with the center of the striking edge;
- For the Charpy test, the relationship required between the energy available in the machine and the strike velocity is as follows:

Maximum energy (J)	Strike velocity (m.s^{-1})
0.5	2.9
1	2.9
4	2.9
15	3.8

- d) the energy required to fracture the specimen has to be within 10-80% of the blow energy.

The lack of precise specification of the machine to be used has led to the production of many different devices, some commercially available, others privately built. However, the variables machine which are permitted by the various standards lead to a situation where different values of impact strength are obtained for the same material from Izod and Charpy tests and from different machines using the same test.

In both the Izod and Charpy test, the parameter measured is the energy absorbed from the pendulum during its first half-oscillation. This impact energy, as it is sometimes termed, may be defined as

$$U = 1/2 I(v_0^2 - v_f^2)$$

where I is the moment of inertia of the pendulum and v_0 and v_f respectively the velocities of the pendulum bob just before and just after striking the specimen. Assuming no windage of friction losses on the pendulum, $v_0^2 = 2gh_0$ and $v_f^2 = 2gh_f$. Then

$$U = gI(h_0 - h_f)$$

or more realistically, $U = K(h_0 - h_f)$, where K is a machine constant for a given system.

In both the Izod and Charpy test, failure initiates in the vicinity of the notch tip and propagates through the ligament of the specimen in line with the notch. The types of failure that can occur are listed as:

- a) the specimen yields without cracking and the specimen deforms sufficiently to allow passage of the pendulum without separation of the specimen into 2 parts;
- b) the specimen yields and cracks but the entire fracture surface exhibits ductile failure;
- c) the specimen initially cracks in a brittle manner but then changes to a ductile mode of behaviour;
- d) the specimen yields first and then changes to brittle behaviour;
- e) the fracture surfaces appear entirely brittle.

With this variety of behaviour, it has been suggested that information on the mode of failure as well as the impact energy or impact strength should be quoted following any test.[5]

The flexed-beam impact tests are the most popular methods for determining impact strength but where these are inappropriate, because, for example, the specimen is too thin or too flexible, then the falling-weight tests are useful alternative [4].

2.1.2 Falling-weight impact testing

Impact testing of sheet or film is difficult by means of conventional notched-bar tests, and falling-weight tests are then employed. In both tests, a hemispherically nosed metal dart of variable weight is released from a fixed height and falls freely to strike the centre of the sheet specimen. The specimen is a circular disc, which is supported and clamped at its periphery. The dart is released so that no rotational movement is imparted to it, often from an electromagnet.

Knowing the weight of the dart and the height through which it falls, it is easy to calculate the energy available for fracturing the specimen. However, in contrast to notched-bar testing, the energy required to fracture the specimen has to be determined from a large number of tests. In principle, the weight of the dart is increased on successive drops until fracture occurs. The variability of the onset of fracture, particularly in brittle materials, renders difficult the assessment of the limiting fracture energy. One of two alternative statistical methods is employed [5]. The statistical techniques are the Probit transformation or the staircase analysis. In the Probit transformation the percentage of failures of a relatively large number of specimen tests at constant energy levels within the range bounded by the levels at which about 10 and 90% failure probability occurs [4]. Subsequently a graph is drawn (the probit curve) of the percentage failure against the energy of striking. The probit curve is constructed to cover almost the whole range 0 to 100% failure. Finally the impact energy is quoted as that which causes a 50% failure level of the specimens (the F-50 value), if that is an appropriate value for the application considered [5]. The Probit transformation reveals several important aspects of impact behaviour, which are not given by the more common staircase analysis [4].

Where there is a rapid change in failure energy from 0 to 100% failure on the probit curve, the alternative step or staircase method can be adopted. In this technique, the dart is always dropped from one height but the dart weight is increased in uniform steps until failure occurs. Testing then continue, the dart weight being decreased by a specified increment if failure occurs or being increased by the same amount if it does not. All the results are tabulated; a typical presentation is shown in *Table 1* that the failure rates at 244, 258, 271 and 285J are 0, 12.5, 60.8 and 100% respectively.

Table 1. Typical results of a dart-drop test which adopts the 'staircase' method of analysis

DROP HEIGHT	JOULES IMPACT	F50 = 268 Joules																																	TOTAL	
																																			F	N
2.74 m	366																																			
2.64	352																																			
2.54	339																																			
2.44	325																																			
2.34	312																																			
2.24	298																																			
2.13	285		0				0	0						0	0							0	0							0	0		9	0		
2.03	271	X	0	0	X	X	0			0	0	X	X	0	0	0	0	X	X	0	0	0			0	0	X	X	0			14	9			
1.93	258			X	X				0	X	X	X				X	X	X				X	X	0	X	X	X				X	2	14			
1.83	244									X																							0	2		
1.73	230																																			
1.63	217																																			

The table shows the number of failures and non-failures at each energy level, so that the F-50 energy value can again be determined. Linear interpolation between the 285 and 271 values provides a 50% failure value of 286J.

Falling-weight impact test methods are also adopted to test plastic components. In many cases these are used as a quality assurance test during production of the particular component. One advantage of falling-weight testing is that the impact energy distribution can be made available, so providing information of the probability of failure over a range of impact energy values. Falling-weight tests may also approximate more closely to actual impacts received in service in some instances, but the large number of tests required for one F-50 value is a disadvantage of such methods [5].

2.1.3 High-speed tensile impact tests

Tensile impact tests may be performed on machines used for Izod and Charpy tests with suitable modifications to the pendulum. In these tests the specimen conforms to 'dumb-bell' or 'dog-bone' shape; one end is clamped to the pendulum hammer, while the other is held in clamps attached to a striker plate. When the pendulum is released from its raised position, it swings down between stop brackets, trailing the specimen behind. The striker plate is then arrested by the stop brackets as the pendulum bob swings on, causing the specimen to be strained rapidly in tension to failure. The energy required for fracture is determined in the same manner as for the Izod and Charpy tests. The impact strength of the material under test is defined as

(impact energy)/(minimum cross-section of specimen).

In tensile impact tests, the strain rate averaged over the entire specimen length is approximately constant during deformation. Local strain rates due to stress waves within the solid following impact can account for large deviations from the mean value. In flexural impact and falling weight tests the specimen is deformed at a rate which decreases progressively and rapidly [5].

2.1.4 Instrumented impact machines

All three categories of test method result in values of impact strength which are basically only suitable for ranking materials. However, the most popular machine used for impact tests is impact pendulum. It is designed to determine the impact resistance of plastic, ceramic and other materials. 'Resilience' is a critical testing parameter in the evaluation of characteristic properties of materials. Impact pendulums measure first the energy required to break a specimen and then resilience is calculated based on specimen cross-section.

In an effort to obtain more scientifically based information, which might lead to a material parameter being deduced the test methods described above have been instrumented by many investigators. A number of instrumentation techniques have been employed including the use of strain gauges, piezoelectric crystal transducers, semiconductor photo cells, accelerometers and dynamic load cells, and several different types of instrumented impact test machine are now commercially available. [4]

In such case, testing machine need to be connected with computer which records data during test and controls different types of sensors. The system based upon a modular structure allows the acquisition of simultaneous events and is able to note 8000 to 16000 data points during breaking the sample (20ms). The pendulum motion is checked with an optical encoder mounted on the shaft of the machine, accelerometer, or electronic positions detection.

The force calibration of instrumented hammers is a matter of primary importance since all test data and material properties are calculated on the basis of force: deformation, velocity, energy and all fracture parameters. Dynamic calibration procedure allows accurate force measurements due to the fact that calibration is performed at the same dynamic conditions as the test itself.

3 INSTRUMENTED TESTS

Instrumentation of the standard impact tests to provide load-deformation data rather than the all-embracing impact energy would seem to be a natural progression. It would be most unusual to merely quote the energy-to-rupture of a specimen after a tensile test for example. However, instrumentation of impact testing equipment is not simply a matter of casual attaching such strain gauges as happen to be available to the pendulum, tip or supports of an impact machine and recording the output.

Instrumented Charpy tests, in which sensors are attached to the pendulum, specimen and anvil show that the form of the load-deformation curve is different in three locations. The system considered was essentially linear-elastic. Clearly the load measured at any time, and especially at rupture, will depend on the location of the sensor. The observed load-time profiles for pendulum, anvil and specimen were satisfactory reproduced by selection of appropriate values for equivalent masses and spring constants.

The use of instrumented impact tests is particularly appropriate when testing composites and ductile materials. In these cases the load-deformation curve and/or the fracture pattern can be complex. If the full loading history is available, it is possible to consider the different sections of the load-deformation curves. [5] Moreover, instrumented impact tests are being increasingly used to assess the fracture behaviour of polymers at high rates of strain and the additional information such tests typically reveal about this poorly understood area will undoubtedly ensure that this trend continues [4].

3.1 Fracture mechanics

The basic tenet of fracture mechanics is that the strength of most real solids is governed by the presence of flaws and the application of fracture mechanics to crack growth in polymers has received considerable attention. Two main conditions for fracture are proposed. Firstly, the energy criterion arising from Griffith's [7] and later Orowan's [8] work which supposes that fracture occurs when sufficient energy is released by growth of the crack to supply the requirements of the new fracture surfaces. The energy released comes from stored elastic or potential energy of the loading system and can be calculated for any type of test piece. This approach provides a measure of the energy required to extend a crack over unit area and this is termed the fracture energy or critical strain-energy

release rate G_c . Secondly, the stress field around a sharp crack in a linear elastic material could be uniquely defined by a parameter named the stress-intensity factor and fracture occurs when the value of intensity factor exceeds some critical value.

A basic aim of fracture mechanics is to identify fracture criteria, which are independent of the geometry of the cracked body and, ideally, even of the test conditions, e.g. test temperature. Thus fracture mechanics parameters should greatly assist in developing a more fundamental understanding of the fracture process and should be of considerable use in the practical areas of data specification and engineering design. [4]

3.2 Fracture parameter

The most commonly quoted fracture parameter is that of impact strength. It is quoted as the energy absorbed from the pendulum bob during impact divided by the minimum cross-section of the specimen where fracture occurs. Defined in this way the ‘impact strength’ begins to resemble other material properties, such tensile strength.

$$U = U_I + U_{SD} + U_B + U_{MV} + U_{ME}$$

where U_I – energy to accelerate the specimen from rest;

U_{SD} – energy of bending the specimen;

U_B – energy consumed by Brinnell deformation under the nose of the hammer;

U_{MV} – energy absorbed by the machine through vibrations after initial contact;

U_{ME} – elastic energy stored by the machine

The definition of impact strength, suggesting that the energy measured can be assigned solely to the zone under the notch, is misleading. Any attempt to perform an energy balance and determine separately all the terms listed above, would be difficult. The only term separated easily is the tossing loss U_I , which can be from 29 to 83% of the total value. This can be partially estimated by lightly rejoining the broken pieces of the specimen

and repeating the impact test. In some instances, tossing losses so estimated are deducted from the total energy before calculating the impact strength. Attempts to reduce energy losses due to friction and windage on the pendulum are also made by the construction of the special high-precision machines, which lead to greater consistency in the energy values determined from any sample.

Criteria for failure in other mechanical tests are based on limiting stress, limiting shear-strain energy and, in fracture mechanics, limiting energy release rate. *Fig.7* shows a series of linear elastic load-deformation curves. The areas under the curve are identical; hence the energy absorbed in each deformation is the same. However, the loads- and strains-to-fracture differ greatly.

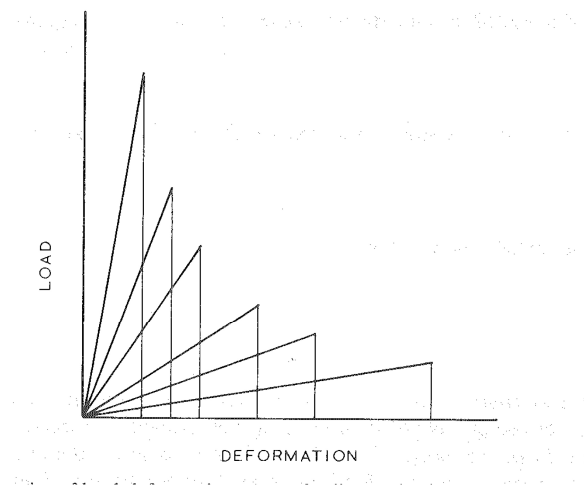


Fig.7. A series of load-deformation curves for linear elastic materials, for which the energy to rupture is constant.

An alternative method of analysing the data obtained from notched-bar tests, based on linear-elastic fracture mechanics consideration, has been proposed by Williams [9],[10]. He considered the linear-elastic deformation of a notched specimen [5]. The concepts of linear-elastic fracture mechanics may strictly only be applied to those materials, which obey Hooke's law so that stress is proportional to infinitesimal strains. However, the basic linear analyses may also be applied to materials, which exhibit inelastic deformations around the crack tip, provided that such deformations are confined to the immediate vicinity of the tip. Hence, the bulk of the body will still exhibit linear elastic property [4]. When this is

subjected to an applied load P , resulting in a deflection x under the load, the energy stored is given by

$$U = 1/2 Px \quad (1)$$

Introducing $C = x/P$, the compliance of the beam specimen for a given geometry,

$$U = 1/2 P^2 C \quad (2)$$

When fracture occurs at load P , the critical energy release rate G_c is then

$$G_c = \frac{P^2}{2B} * \frac{dC}{da} \quad (3)$$

where B – thickness

a – notch length

In terms of energy absorbed,

$$U = \frac{G_c B C}{\frac{dC}{da}} \quad (4)$$

By the introduction of the dimensionless factor

$$\Phi = \frac{C}{\frac{dC}{d(a/D)}} \quad (5)$$

$$U = G_c B D \Phi$$

where D – specimen width

This analysis predicts that a linear relationship should exist between the total energy absorbed in bending the specimen to fracture and the factor BDF , the slope of which provides a value for the critical strain energy release rate (G_c) for impact loading conditions.

Williams [9] prefers to express the fracture parameter in terms of G_c rather than fracture toughness K_c , since the former can be determined without reference to the strain-rate-dependent Young's modulus E , since

$$K_c^2 = E G_c$$

Plots of G_c against BDF are found to be linear for many thermoplastics after certain factors are considered.

Strain-energy release rates determined by Plati and Williams^{9,11} for a selection of plastics are given in *Table 2*.

Table 2: Strain-energy release rates for various plastics

Material	G_c [kJ.m ⁻²]
PMMA	1.3 – 1.6
PS	0.3 – 0.8
PVC	1.3 – 1.4
PC	2 – 5
Nylon 66	0.25 – 4
PE (medium density)	5 – 10
PE (low density)	5 – 40
HIPS	2 – 16

This analysis is based on certain basic assumptions:

- 1) linear-elastic fracture mechanics is applicable;
- 2) the energy U used in (5), suitably modified for tossing losses, is the energy stored in the specimen which can be released for fracture (i.e. $U = U_{SD}$);
- 3) values of the compliance C , and hence F , determined in quasistatic tests are equally applicable to the dynamic situation;
- 4) the quantities U , a and C are explicit functions of each other.

Whether these assumptions are valid in the impact test has not been justified.

Data on stress intensity factors determined under dynamic conditions are also available as a further means of characterising the behaviour of plastics under rapid loading conditions. [5]

3.3 Factors affecting the fracture parameter

Both the impact strength and strain-energy release rate are affected by number of factors, which include specimen geometry, test temperature and fabrication conditions.

3.3.1 Effect of specimen geometry

The impact strength determined in a conventional notched-bar test is a function of specimen width, specimen length, notch depth and notch tip radius. Vincent [11] quotes figures for rigid PVC samples of 3mm and 6mm width over a range of temperature. Impact strengths of the narrower specimens are always found to be greater than those for the wider specimens by a factor varying between 1.3 and 3.7. Specimens of larger span, and consequent lower strain rate, give rise to increased values for the impact strength. Increasing the notch depth, while maintaining the same notch tip geometry, also serves to increase the impact strength.

Varying the notch tip radius has a marked effect on the measured impact strength. Data presented by Vincent [11] are shown in *Fig.8*.

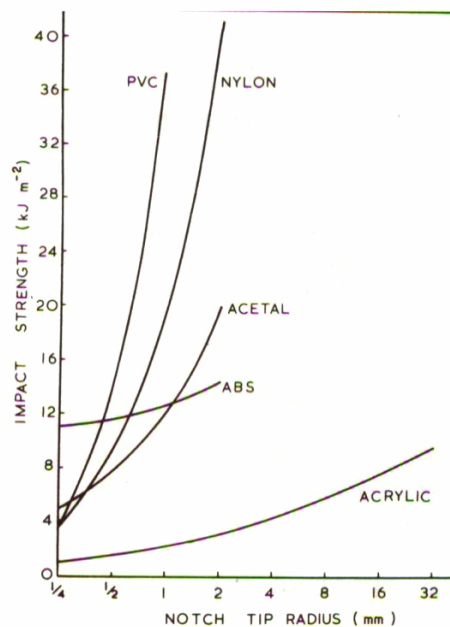


Fig.8. Impact strength as a function of notch tip radius for samples of five different polymers.

Attempts to rationalise these data by the introduction of a stress concentration factor $k = 1 + 2(a/r)^{1/2}$, where r is the notch tip radius, were only partially successful. Introduction of the stress concentration factor implies that it is the stress at the notch tip, which controls fracture. Since the stress concentration factors were computed based on linear-elastic considerations, it was suggested that results from those materials, which complied with

linear-elastic behaviour, would be more readily rationalised by the introduction of the stress concentration factor.

An alternative explanation of the decreasing impact strength with notch tip radius is that the strain rate at the notch tip increases with decrease in tip radius, all other factors remaining constant. This explanation offers more opportunity for unifying the effects of notch tip radius and temperature, particularly with regard to ductile/brittle transitions. [5]

3.3.2 Effect of temperature

The test temperature has a marked effect on the impact strength and strain-energy release rates determined. These quantities increase with temperature and often show a vehement change in value over a short temperature interval, which is associated with change from a brittle to a ductile mode of failure. The location of this transition is an important aspect of material selection for impact duty. Its position has been found to be a function of rate and notch severity, as well as fabrication conditions (*Fig.9*).

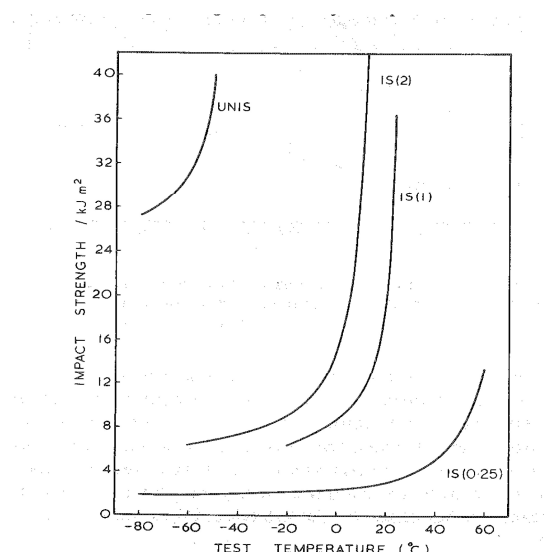


Fig.9. Effect of test temperature on impact strength of rigid PVC samples containing notches of different severity.

The transition in impact strength as a function of notch tip radius is shown in *Fig.9*; curves corresponding respectively to specimens without notches and with notches of three different radii, expressed in mm. Vincent found that there was no general relation between

the glass transition temperature T_g of the polymer and the brittle/ductile transition temperature.

Plati and Williams [9] have reported similar transitions in the strain energy release rate with temperature. Once again the transition point is found to move to higher temperatures as the severity of notch is increased (tip radius decreased). The respective transitions in impact strength and G_c for equivalent notch tip radii occur at very similar temperatures. Considering the range of substances covered by the term PVC this agreement is remarkable, although both tested materials were unplasticised PVC. The majority of Plati and Williams' work [9] is concerned with 'sharp' notches, i.e. notches machined with a very sharp cutter. It is interesting to note that, for these sharp-notched specimens, the transition in G_c is often in the region of -10°C for several polymers, which offer widely different general mechanical properties. Their results are interpreted in terms of constraints imposed by the specimen geometry in the vicinity of notch.

An alternative view has been expressed by Ryan [12]. Working with polycarbonate, he found that the position of the transition in impact strength was a function of the notch tip radius and the melt flow rate. It was also found that annealing the specimens prior to test caused a shift of the transition temperature to lower temperatures. Ryan's tests indicate that the position of the transition cannot be explained in terms of geometrical factors alone. It was argued that factors leading to higher rates of strain at the notch tip increase the possibility of more brittle type of behaviour. Annealing the sample causes a change in the relaxation-time spectrum, which was considered to be equivalent to shifting to a higher strain rate. [5]

3.3.3 Effect of processing variables

It has been demonstrated that the impact strength measured in conventional impact tests is a function of

- injection-moulder cylinder temperature
- molecular orientation in injected components
- polymer residence time in the injection-moulder cylinder
- annealing and quenching subsequent to moulding
- melt flow in the mould

Specimens in which the flow is along the length of the specimen and thus normal to the plane of the notch show enhanced strength. In contrast, those specimens cut with the plane of the notch parallel to the flow direction exhibit lower impact strengths. These differences may be directly attributed to molecular orientation in the specimens, the molecules tending to line themselves up in the direction of flow. At the lower cylinder temperatures, shear stresses in the melt flow will be greater. Increasing melt temperature leads to a less anisotropic specimen and greater equality of the two impact values. The markedly reduced impact strengths at the highest cylinder temperature may be attributed to degradation of the polymer and consequent reduction in molecular weight. Molecular weight is a further factor affecting the impact strength.

Annealing and quenching of specimens also modified the impact behaviour. The effects produced by thermal treatment were found to be complex, depending on the degree of initial working, material thickness and cooling rate. A transition in impact strength from a high to a low value, occurred for example in polycarbonate as the sheet from which the specimens were taken, increased in thickness. Annealing and quenching of samples taken from one sheet thickness produced impact strength values on either side of the transition point, depending on the rate of cooling applied. It was argued that the 'thickness effect' observed initially was not due to geometrical factors but could be again attributed to modifications in the residual stresses at the sheet surface caused by the thermal treatments.

Many factors have been shown to affect the impact behaviour of different materials. These factors considerably complicate the interpretation of data from any form of impact test. They also help to confuse attempts to compare data from different sources, since the test conditions and condition of material under test are rarely identical. [5]

3.4 Experimental examples

Some of the experiments examples are attached in the appendices. While the influence of various moulds' temperatures on impact strength behaviour within curing of polyester resin could be qualified comparing figure 10 and 11, the influence of moulds' temperatures during sPS injection moulding is shown in figure 12 – 15. It is clear from the figures that very significant effect of the mould temperature on ultimate material properties could be easily revealed using impact tests measurements.

4 CONCLUSION

Several methods like tensile and impact test, rheology, creep and relaxation tests are used for describing mechanical features of various materials as for example metals, glass, ceramics, polymers, etc.

Impact tests are employed to measure the ability of a specimen or a finished component to withstand a sudden blow. In other words they give us information about the amount of energy exerted to break the specimen, which help us better know the material and in this way to find suitability of tested material for specific application.

There have been classified three basic categories for measuring impact strength:

- Flexed-beam impact
- Falling-weight impact
- High-speed tensile impact

The most commonly used flexed-beam methods are Charpy and Izod. These tests are both swinging pendulum techniques in which a pendulum is released from a fixed height, swings down to strike and break the specimen at the bottom of the swing and then continues to a measured maximum height at the end of the first half-oscillation. Charpy and Izod tests differ mainly in the manner in which the notched-bar specimens are held.

Falling-weight tests are used for testing for example sheet or film. The specimen is struck by metal dart of variable weight which is falling freely to the centre of the film or sheet.

Tensile impacts tests are similar to Charpy and Izod, however the fixing and consequently the strain loading of the specimen is different. The specimen is not bent but is strained in tension.

To obtain more information from impact tests at high rates of strain it is necessary to employ variable types of instrumented impact pendulums. The use of modern technique then enables obtaining of several thousand measured data points, which give us a possibility of closer fracture behaviour description. Even the instrumented impact tests are being increasingly used to assess the fracture behavior of polymers, the methods are also widely used for other materials. Because the additional information of these tests helps to reveal poorly understood area of material behavior under sudden load conditions, the increase of instrumented impact tests use will undoubtedly continues.

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LIST OF SYMBOLS

F	Force
S_0	Cross-section
E	Young' modulus
U	Energy
B	Width
D	Depth
a	Length
I	Moment of inertia
v	Velocities
K	Machine constant
P	Load
x	Deflection
C	Compliance of the beam specimen
G_c	Energy release rate
F	Dimensionless factor
K_c	Fracture toughness

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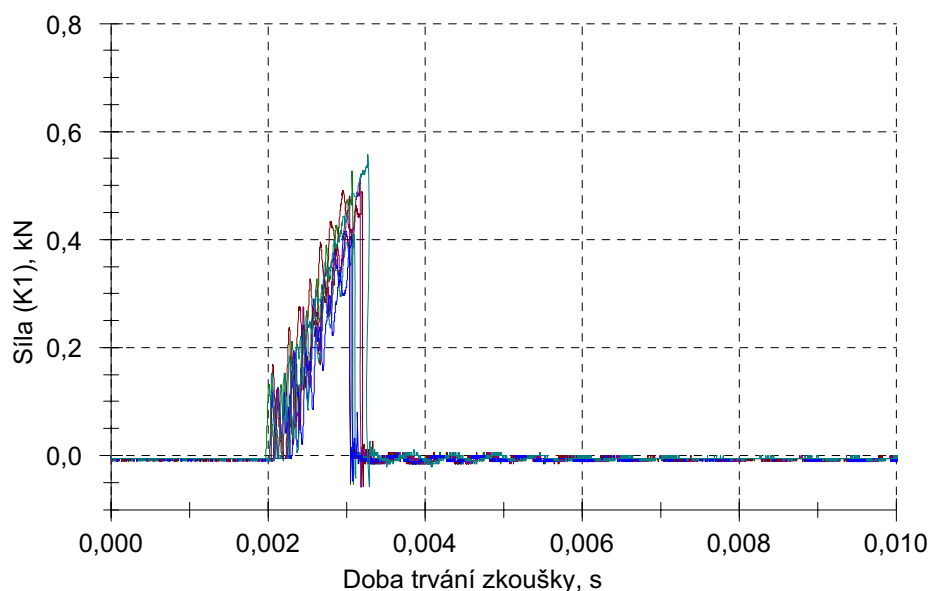
P VI sPS – 240

Stroj:

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Materiál	: Epoxidová pryskyřice	Výška vzorku	: 10,00 mm
Typ zkušebního tělesa	: ISO	Výška vzorku v místě vrubu	: 10,00 mm
Poloměr zaoblení vrubu	: 0,00 mm	Průřez zkuš. tělesa	: 31,60 mm ²
Úhel vrubu	: 0,0 °	Zkušební teplota	: 20,00 °C
Poloha vzorku	:		

Grafický záznam série zkoušek:



Statistika:

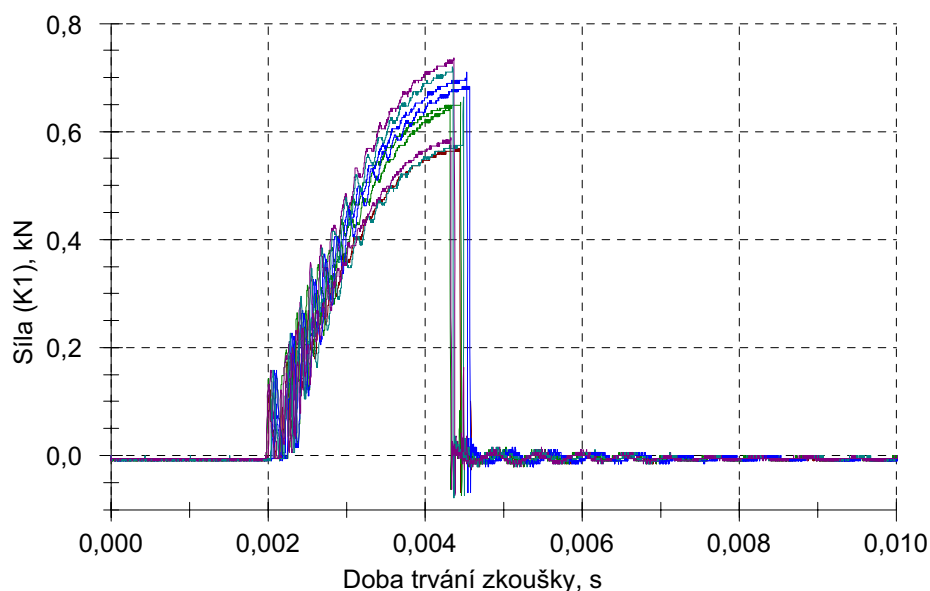
Podsérie #1 n = 8	F(m) kN	S(m) mm	V(m) m/s	W(TTL) J	(ak) KJ / m ²
$\bar{x}$	0,473	2,393	2,731	0,690	20,70
s	0,062	0,384	0,055	0,147	3,81
v	13,08	16,03	2,01	21,27	18,38

Stroj:

Typ stroje : ZWICK 5113

Zkoušel	: Simková	Vzdálenost opor	: 62,00 mm
Datum	: 20.04.2005	Šířka vzorku	: 3,05 mm
Čas	: 16:33:29	Délka vzorku	: 80,00 mm
Materiál	:	Výška vzorku	: 10,26 mm
Typ zkušebního tělesa	: ISO	Výška vzorku v místě vrubu	: 10,26 mm
Poloměr zaoblení vrubu	: 0,00 mm	Průřez zkuš. tělesa	: 31,29 mm ²
Úhel vrubu	: 0,0 °	Zkušební teplota	: 20,00 °C
Poloha vzorku	:		

Grafický záznam série zkoušek:



Statistika:

Podsérie #6 n = 9	F(m) kN	S(m) mm	V(m) m/s	W(TTL) J	(ak) KJ / m ²
$\bar{x}$	0,664	5,586	2,082	2,502	71,72
s	0,057	0,296	0,090	0,232	4,33
v	8,63	5,30	4,30	9,29	6,04

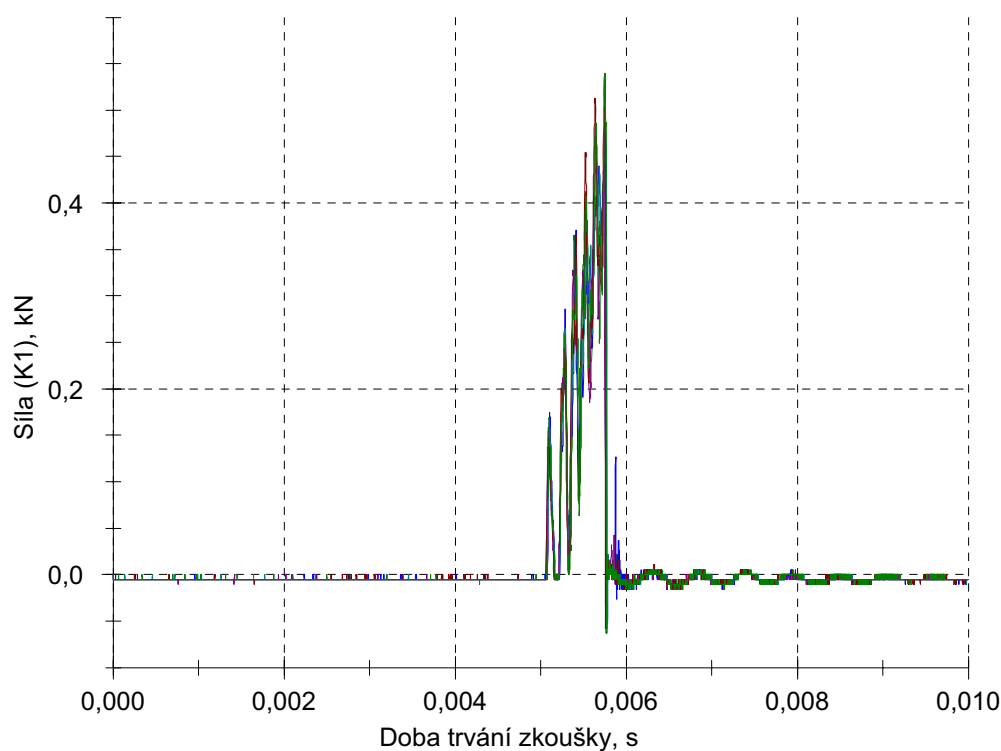
Stroj:

Typ stroje : ZWICK 5113

Zkušební tilesa:

Zadavatel	: Obadal	Poloha vzorku	:
Zkoušel	: Ěabla	Vzdálenost opor	: 62,00 mm
Datum	: 09.05.2005	Šířka vzorku	: 3,96 mm
Ěas	: 09:45:56	Délka vzorku	: 80,00 mm
Materiál	:	Výška vzorku	: 10,10 mm
Typ zkušební tilesa	: ISO	Výška vzorku v místi vrubu	: 10,10 mm
Polomir zaoblení vrubu	: 0,00 mm	Průřez zkuš. tilesa	: 40,00 mm ²
Úhel vrubu	: 0,0 °	Zkušební teplota	: 20,00 °C

Grafický záznam série zkoušek:



Výsledky:

Statistika:

Podsérie #2 n = 6	F(m) kN	S(m) mm	V(m) m/s	W(TTL) J	(ak) KJ / m ²
$\bar{x}$	0,493	1,372	2,813	0,444	9,81
s	0,039	0,186	0,007	0,005	0,56
v	7,98	13,59	0,25	1,23	5,71

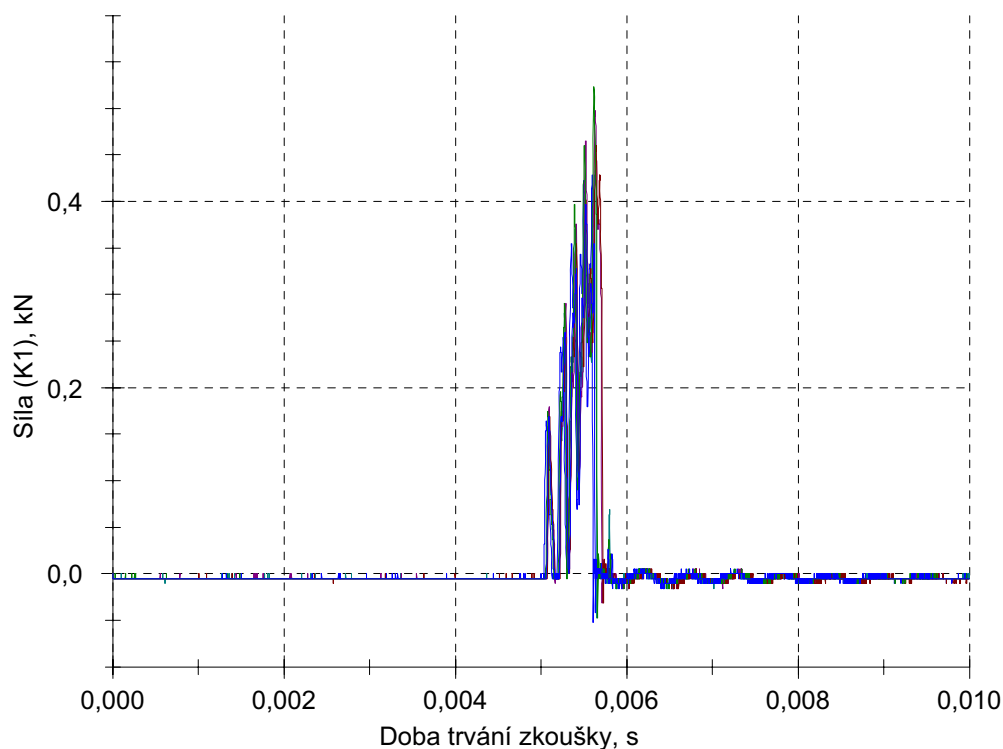
Stroj:

Typ stroje : ZWICK 5113

Zkušební tělesa:

Zadavatel	: Obadal	Poloha vzorku	:
Zkoušel	: Ěabla	Vzdálenost opor	: 62,00 mm
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Čas	: 09:51:33	Délka vzorku	: 80,00 mm
Materiál	:	Výška vzorku	: 10,13 mm
Typ zkušební tělesa	: ISO	Výška vzorku v místě vrubu	: 10,13 mm
Poloměr zaoblení vrubu	: 0,00 mm	Průřez zkuš. tělesa	: 40,11 mm ²
Úhel vrubu	: 0,0 °	Zkušební teplota	: 20,00 °C

Grafický záznam série zkoušek:



Výsledky:

Statistika:

Podsérie #3 n = 6	F(m) kN	S(m) mm	V(m) m/s	W(TTL) J	(ak) KJ / m ²
$\bar{x}$	0,456	0,816	2,863	0,341	6,59
s	0,047	0,127	0,012	0,042	1,01
v	10,30	15,56	0,42	12,34	15,25

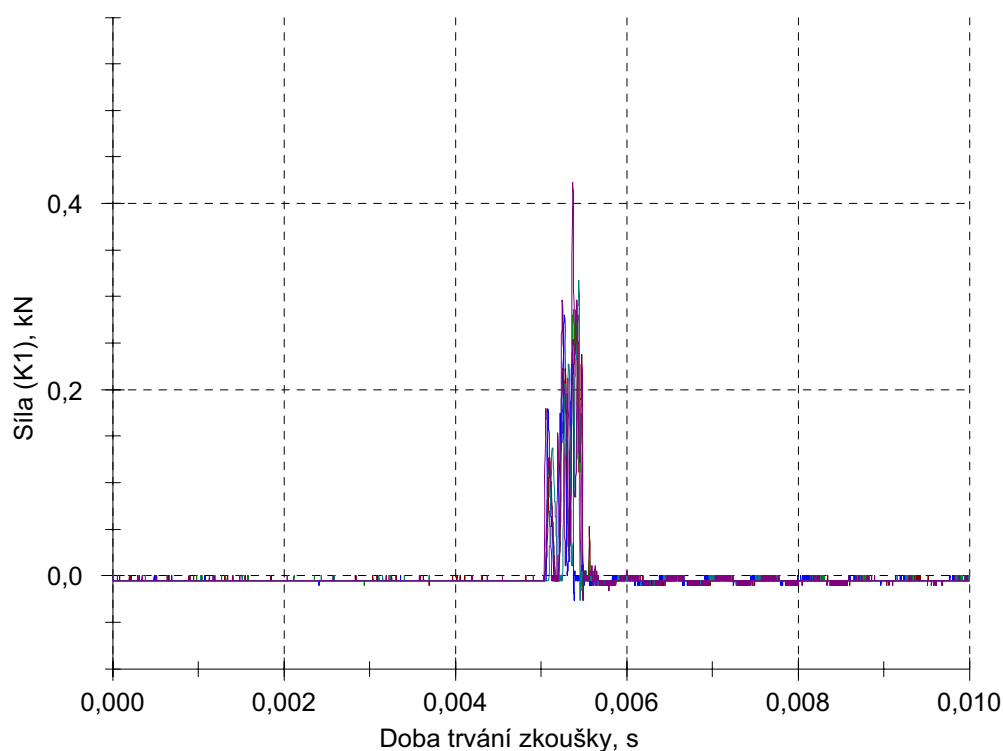
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Zkušební tělesa:

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Materiál	:	Výška vzorku	: 10,12 mm
Typ zkušební tělesa	: ISO	Výška vzorku v místě vrubu	: 10,12 mm
Poloměr zaoblení vrubu	: 0,00 mm	Průřez zkuš. tělesa	: 39,67 mm ²
Úhel vrubu	: 0,0 °	Zkušební teplota	: 20,00 °C

Grafický záznam série zkoušek:



Výsledky:

Statistika:

Podsérie #5 n = 6	F(m) kN	S(m) mm	V(m) m/s	W(TTL) J	(ak) KJ / m ²
$\bar{x}$	0,315	0,495	2,904	0,142	2,74
s	0,055	0,152	0,007	0,023	0,82
v	17,39	30,83	0,24	16,55	30,04

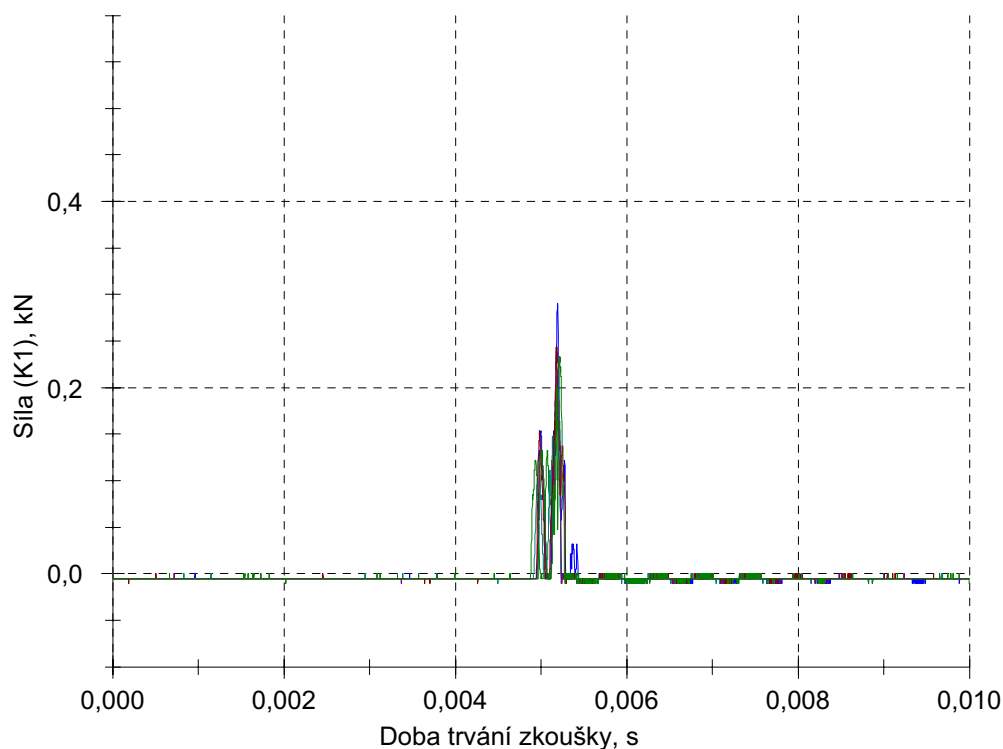
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Typ stroje : ZWICK 5113

Zkušební tělesa:

Zadavatel	: Obadal	Poloha vzorku	:
Zkoušel	: Ěabla	Vzdálenost opor	: 62,00 mm
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Materiál	: sPS	Výška vzorku	: 10,62 mm
Typ zkušební tělesa	: ISO	Výška vzorku v místě vrubu	: 10,62 mm
Poloměr zaoblení vrubu	: 0,00 mm	Průřez zkuš. tělesa	: 44,39 mm ²
Úhel vrubu	: 0,0 °	Zkušební teplota	: 20,00 °C

Grafický záznam série zkoušek:



Výsledky:

Statistika:

Podsérie #7 n = 6	F(m) kN	S(m) mm	V(m) m/s	W(TTL) J	(ak) KJ / m ²
$\bar{x}$	0,232	0,299	2,916	0,082	1,36
s	0,040	0,106	0,003	0,007	0,17
v	17,34	35,38	0,09	9,15	12,42