PARAMETER IDENTIFICATION OF STRESS-STRAIN CURVES AT CONSTANT RATE OBTAINED FROM AXIAL IMPACT TESTS OF PVC AND PP SAMPLES

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Abstract. *The competitive world market today encourages the application of polymeric materials in substitution of the traditional ones in several applications, like electric motor parts. As a result, a cost reduction in the final product is achieved, specially by the elimination of finishing processes. The part injected with polymer does not require machining, such that it can be sent directly to the assembly line. With this new demand for polymeric materials, comes also the challenge to obtain the correct characterization of its mechanical properties, according to their service applications. The response characterization to impact is one of the most challenging, not only because of the difficulty of capturing the signals, but also due to the polymer's highly non-linear response, and the manner in which its properties depend on the rate of deformation. Most of the constitutive models adequate to viscoplastic behavior in polymeric materials require experimental stress-strain data for constant strain rates or constant plastic strain rates. However, when an impact test is performed, the strain rate changes during the event, making algorithms necessary when post-processing the experimental data. This paper presents a procedure to test and identify stress-strain curves at constant rates of deformation, for PVC and PP samples in tensile impact tests at low energy levels and strain rates. The experimental data is obtained at a test apparatus specially developed and built, based on free-fall of calibrated masses. The force and deformation signals are obtained in real time respectively from a load cell and a strain gage adhered to the sample. The apparatus is adequate to standardized tests of plastic parts, such that the impact energy is limited to 100 joules, and mass velocity is limited to 6.5 m/s, which characterizes it as a low-velocity test. The raw force-time and deformation-time curves at several mass velocities are processed in different forms to generate estimates of stress-strain curves at constant rates, at constant plastic strain rates, and also curves of initial elastic modulus versus strain rates. The experiment apparatus limits the estimates to deformations prior to development of necking in the sample. Finally, a simulation of an impact on an electric motor fan cover is presented, in order to exemplify the use of the experimental curves.*

Keywords*: Impact, rate of deformation, polymer, finite elements.*

1. INTRODUCTION

Recent studies suggest the use of polymers as a substitute to older materials commonly utilized in several applications, like electric motor parts. With this new demand for polymeric materials, comes also the need to have adequate characterization of its mechanical properties and new models capable to describe its behavior, according to the applications to which they will be submitted. In general, the theories for mechanical behavior of polymers were developed from those initially developed for metal, (e.g. Perzyna model, 1966). Usually, the yield surface used for these materials is the von Mises failure criteria. In spite of its limitations, many researchers have used this criterion in polymers, (e.g. Pierce, 1984 and D'Ambra *et al*, 2003). This approach is more efficient in the analysis parts in traction before the necking and also on fiber reinforced polymers. In tests with necking, appropriate models have to be utilized, like Drucker-Prager, (Du Bois, 2004), or cavitation models, which take into account the cohesion on the internal voids in the material (Dean and Crocker, 2006).

Under impact loads, the polymer hardens with the increase in the rate of deformation. This is accompanied by a rise in the elastic modulus (Dean and Crocker, 2006 and Aretxabaleta *et al*, 2005). This fact limits the applicability of some of the constitutive models implemented in some commercial finite element codes.

In structural mechanics, a dynamic phenomenon is broadly classified as one with a rate of deformation above 1 s^{-1}. Rates from one to 10 s^{-1} are said slowly dynamic, values of 10 a 1000 s^{-1} are intermediate dynamic and values above 1000 s^{-1} are fast dynamic events. In the automotive industry, for instance, typical deformation rates are of the order of

100 s^{-1} in a vehicle impact at 60 km/h. It is, therefore, an average dynamic event. In explosions or ballistic events the rates can be above 1000 s^{-1}. To describe correctly the fast dynamic phenomenon, it is important to utilize constitutive laws which take into account, not only the rate of equivalent plastic deformation, but also the temperature, in order to be able to represent the softening resulting from the heating in the material (thermal softening). There are two main families of constitutive laws: the empirical models, for example the Johnson-Cook, Cowper-Symonds or Zhao models and the physically based models, like the Zerilli-Armstrong, Bodner and Partom or Rusenek and Klepaczko models, which consider microscopic phenomenon like the grain size and crystalline structure (Jeunechamps, 2008).

The classical procedure to analyze a structure under impact loads is by the theory of impulse, in which the short duration load is considered instantaneously applied (Goicoleia, 2000). The theoretical impulses are associated to the Dirac's delta generalized function.

Du Bois *et al*. (2004), make important considerations with regard to the behavior of plastics submitted to impact. It is recommended that, in some cases, their behavior can be modeled as pseudo-metals. However, in polymers, an increase in the rate of deformation causes an increase in the plastic limit, as in metals, but also causes an increase in the elastic modulus. Besides, a non-linear elastic response is observed. Therefore, since the yield stress in tension, compression and in shear, frequently do not obey the yield surface of von Mises, and since the hardening of the material is anisotropic due to the realignment of the polymeric chains, many polymers should not be simulated by laws strongly based on von Mises plasticity. A better option consists in alternative yield surfaces, like the Drucker-Prager one, in which the hydrostatic stresses are included.

Duan *et al*. (2001) proposed a phenomenological constitutive model for glassy and semi-crystalline polymers, which is capable to consistently describe an entire range of deformation under compressive monotonic loading, for different rates of deformation and temperatures. The model, called DSGZ, is derived from four other constitutive models, each one with its own applicability and limitations. The model requires experimental identification of eight parameters of material, which can be obtained from three tests in different rates and temperatures. More recently, Duan *et al*. (2003) incorporated the effect of hydrostatic pressure in the model. One notice that this effect is necessary in models for materials whose behavior in tension is different from compression, as is the case of many rigid polymers.

Aretxabaleta *et al*. (2005) proposed a new method for identification of stress-strain curves at constant rates of deformation for polymers, from tests performed at varying rates. It must be noticed that, most types of tests available, are performed in such a way that the rate of deformation changes during the loading process. Therefore, a procedure aimed at extracting constant rate information from this type of test is very attractive. The procedure is based on impact tests in tension, with instrumented specimens of polypropylene. Acceleration-time curves at different rates of deformation are obtained simply dividing the signal of force-time by the impact mass and performing numerical integration in time. Two subsequent integrations produce velocity-time and distance-time curves. From the initial length and transverse area of the sample, and the distance-time and force-time curves, the deformation-time curves are computed. Next, a value of rate of deformation-time is arbitrated, and it is possible to obtain, from the set of deformation-time and stress-time curves, a pair of values of stress and strain, at that rate, which are used to generate a stress-strain curve at constant rate of deformation. Besides this procedure, several positive aspects of the impact test in tension with regard to bending are pointed. First, in tension tests the stress state can be considered fairly homogeneous, different from the bending test, where complex stress states are generated, with part of the specimen becoming tensioned and part compressed. In the bending test, the rate of deformation ranges from a maximum value at the external faces of the specimen, to zero, at the neutral surface at the center; the impact mass makes direct contact with the specimen, generating a region of concentrated stresses and strains. These effects are avoided in the tension test, where the mass does not touch the sample. In the bending test, the force is measured at the impact mass, although this force is not the same as the one transmitted to the sample. These forces can only be supposed equals when the dynamic effects associated with the test method can be neglected. However, some of the most important dynamic effects are due to the high stiffness of the contact mass-sample. In the tension test the force is measured in the fixed grip, such that this problem is minimized.

The present paper develops a procedure to test and identify stress-strain curves at constant rates of deformation, for Polyvinyl Chloride (PVC) and Polypropylene (PP) samples in tensile impact tests at low energy levels and strain rates. The experimental data is obtained at a test apparatus specially developed and built, based on free-fall of calibrated masses. The force and deformation signals are obtained in real time respectively from a load cell and a strain gage adhered to the sample. The apparatus is adequate to standardized tests of plastic parts, such that the impact energy is limited to 100 joules, and mass velocity is limited to 6.5 m/s, which characterizes it as a low-velocity test. The raw force-time and deformation-time curves at several mass velocities are processed in different forms to generate estimates of stress-strain curves at constant rates, at constant plastic strain rates, and also curves of initial elastic modulus versus strain rates. The experiment apparatus limits the estimates to deformations prior to development of necking in the

sample. Finally, a simulation of an impact on an electric-motor fan cover is presented, in order to exemplify the use of the experimental curves.

2. EXPERIMENTAL PROCEDURE

The impact tests were performed in a bench test developed and built in the Mechanical Department of UFSC, by Quintero (2007). The bench is composed of a tension impact machine, the circuit board for conditioning of signals, digital oscilloscope and a common microcomputer. The entire test bench can be seen in Fig. 1.

The force and deformation signals are collected from the load cell and a strain gage at the sample, respectively. The Excel® PA-06-062TG-350L strain gage was used on the load cell and the PA-13-125BA-350L on the sample. The first is able to capture signal in two normal directions and the other in one direction. These signals are sent to the conditioning circuit board to filter and amplify the signals, which are fed to the Tektronix TDS2014 oscilloscope, whose maximum sample rate is one giga samples per second. Finally, the data are sent to the microcomputer for processing in the TDS2CMAX module. This module has its own user interface and can be connected to Microsoft Excel® software for post-processing.

The strain gages at the sample and at the load cell are in complete Wheatstone bridges. In the sample, only one strain gage is applied, and the other three strain gages are applied in a dummy, to complete the bridge. The deformation measurement with the strain gage is limited to the very beginning of the test, because after some level of deformation it becomes damaged, and more, confidence values of deformation are obtained only before the development of necking. However, it is useful in measurements which lead, after processing, to the initial elastic module of the sample, and its variation with the rate of deformation.

In order to obtain a stable power source, the conditioning board uses a separate source. Since the impact signal is a pulse of few milliseconds, it involves high frequencies. These frequencies, together with the elevated gain in the board, necessary for signal acquisition, makes the board susceptible to external interferences, with noises of electromagnetic and radio frequency origins. Although the board has filters to prevent these interferences, a good ground connection showed essential for the stability of the system. Once the bench is prepared and with noise reduced by ground cables, the tests can be performed normally.

The impact machine, shown in Fig. 2, applies axial load in traction by the free fall of a mass of 4.8 kg, in the shape of a short cylinder. The fall velocity and the rate of deformation are varied according to the height of fall chosen for the mass, and can reach approximately 6.5 m/s. The machine is composed of eleven components, listed in Fig.2b. Some of its characteristics are:

- The sample is standardized, with 215 mm in length;
- The useful length of the fall tube is 2200 mm;
- Communication with microcomputer though serial Chanel RS232;
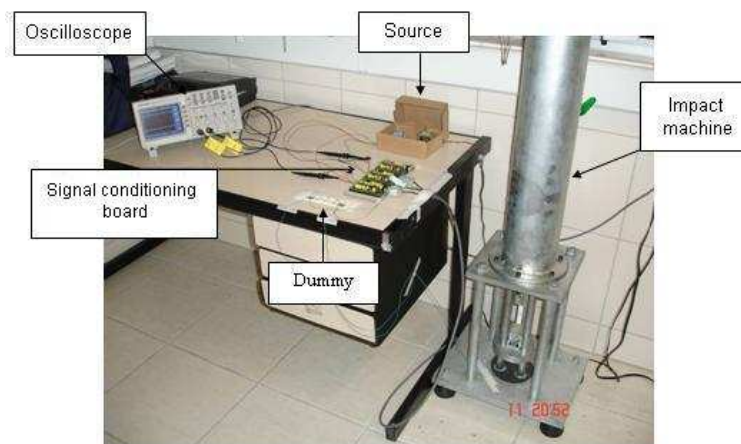- Load cell, specially developed.

Figure 1. Impact test bench.

(a)   (b)
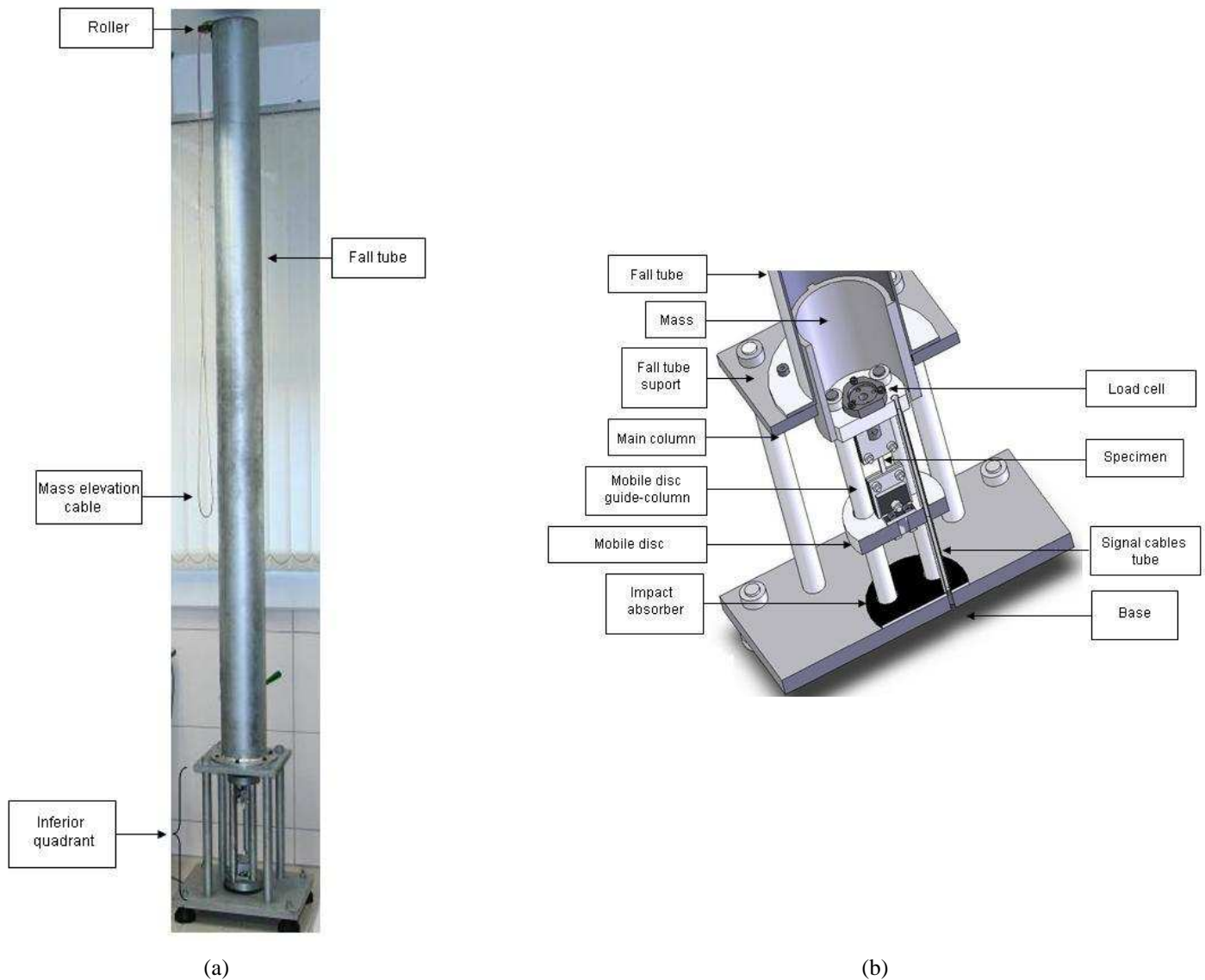
Figure 2. (a) Impact test machine; (b) Machine inferior quadrant. Quintero (2007).

Five different impact energies were chosen for the tests, according to the standards applicable to motors and electrical equipment. The chosen impact energy values were: 5, 7, 10, 15 and 20 J. Note that these are potential energy for the impact mass, and from equation (1), one obtains the height of the drop mass. Considering a system without energy dissipation, the drop mass potential energy can be equalized to its kinetic energy at the moment of impact, therefore estimating the velocity through equation (2). Table 1 presents the heights of the drop mass amongst the corresponding velocities at the moment of impact.

$$E_p = mgh \qquad (1)$$

$$v = \sqrt{2gh} \qquad (2)$$

Table 1. Heights and velocities of the drop mass for each impact energy.

Impact energy [J]	Drop height [mm]	Mass velocity [m/s]
5	105	1.4
7	150	1.7
10	210	2
15	320	2.5
20	425	2.9

According to Nemoto (2004), notches were done at the center of the specimens obeying the following relations: depth P equal to 0.4% of the specimen width and notch fillet R equal to 12 times the specimen thickness. The notches done following these relations do not cause excessive stress concentration; only promote the stress and deformation accumulation in this region, which has a reduced area. This region was chosen to glue the strain gage. The specimen's geometry and dimensions are shown in Fig. 3 and Tab. 2. Note that in Fig. 3, the representation of the notch is exaggerated only for illustration. As shown in Tab. 2, the dimensions of PVC and PP specimens are different. This is only because they came from different suppliers.
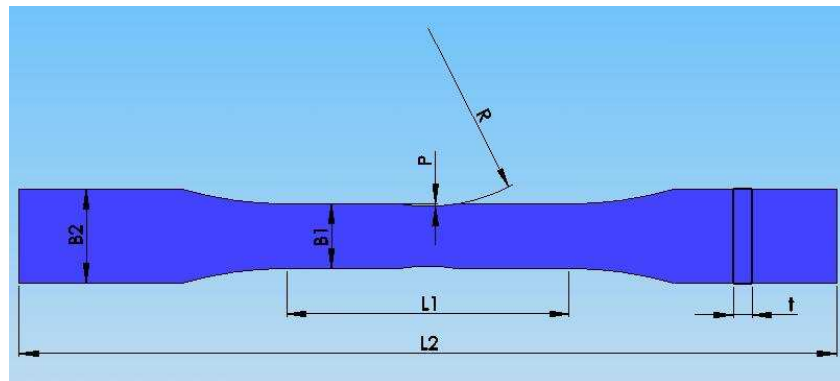
Figure 3. Notch machined at the specimen center.

Table 2. PVC and PP specimens dimensions. Dimensions in mm.

	PVC	PP
R	37.8	42
P	0.052	0.04
B1	13	10
B2	20	20
L1	50	50
L2	165	148
t	3.15	3.5

Typical force and deformation signals as function of time captured by the oscilloscope are illustrated in Fig. 4, in which the force signal is represented in blue and the deformation signal in yellow. Only the data between the two vertical red bars (Fig. 4) were utilized to compute the material properties. The data at the left of the first vertical bar were neglected because this is a region where no relevant data were measured, constituted only by signals before the mass impacts the machine disc. The data at the right of the second bar represents the final of the load history and were neglected because it is associated to a range of deformations which cannot be measured by the strain gage reliably. The deformation becomes large, damaging the bonding of the strain gage. Also, the cross section of the sample start to become distorted, and the strains becomes non uniform along the sample, due to the beginning of necking development.
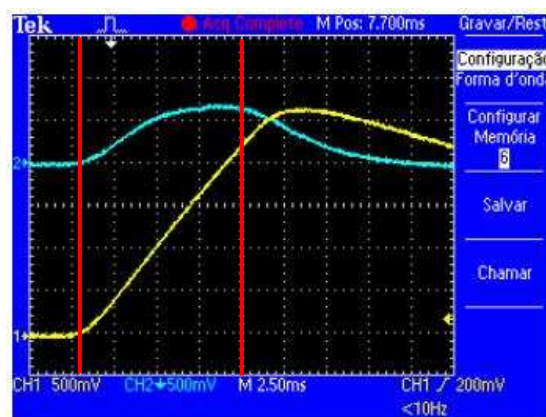

Figure 4. Region utilized to determine the stress-strain curves (between vertical red bars). Force and deformation are the blue and yellow curves, respectively.

A difficulty sometimes found during the tests with PP, was due to the phenomenon of the mass hitting the machine mobile disc twice. This happened when doing tests with impact energies of 20 J, meaning that for energies of 20 J and above, PP starts having an elastomeric behavior. Fig. 5 shows the characteristic signal. One can see the oscillation in the deformation signal (yellow curve) due the phenomenon. The force signal (blue curve) does not present relevant changes because the load cell has a stiffness much higher than the PP specimen.
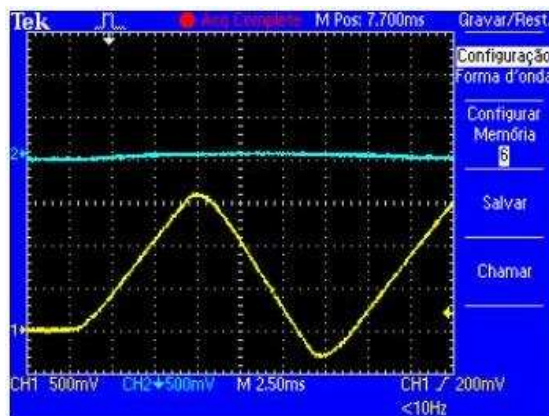
Figure 5. Example of characteristic signal found when the mass hits the machine mobile disc twice in tests with PP using impact energies of 20 J and above.

2.1. Constant rate stress-strain curves

The measured data are processed to obtain the necessary stress-strain curves. The stress-time curves are obtained simply by dividing the values of force in the force-time curves by the specimen's initial cross section area. Deriving the deformation-time curves, one obtains the strain rate-time curves. Note that the rate of deformation changes during the impact event, so, all of the above curves, which came directly from the impact test, are curves at variable rates.

From the strain rate-time, stress-time and the deformation-time curves, at the five impact energies chosen for the tests, it is possible to start the process to obtain the stress-strain curves at constant rate. These curves are result of a curve fitting process for three experimental points, plus the origin (0,0). The procedure follows the steps described below; which is illustrated in Fig. 6 for PP for rate of 4 s^{-1} and impact energy of 5 J.

Step 1 – In the strain rate-time curve for an arbitrary impact energy, choose a rate for which one intends to generate the stress-strain curve at constant rate and take the value of time corresponding to this strain rate;

Step 2 – In the stress-time curve for the same impact energy, take the value of stress corresponding to that value of time found in step 1;

Step 3 – In the deformation-time curve for the same impact energy, take the value of deformation corresponding to that value of time found in step 1;

Step 4 – Repeat steps 1, 2 and 3 for other impact energies until a sufficient number of stress-strain points are available to make the curve fitting of the stress-strain curve at constant rate.

Note that, in spite of the small variation of the impact energies, and also the rates of deformation involved, it was possible to distinguish between curves of very close rates, as shown in Fig. 7 and Fig. 8, in that the rate difference is only 1 s^{-1} from one curve to another. As can be observed, the major rate of deformation achieved in the tests was 5 s^{-1}, so if rates larger than 5 s^{-1} were desired, impact test using energies larger than 20 J must be made. Alternatively, one could find the equations of the experimental curves and then, estimate other curves for larger rates. A similarly approach was followed by Dean and Crocker (2006), which presented equations derived from experimental curves and could extrapolate their results to rates much superior than those utilized in the tests.
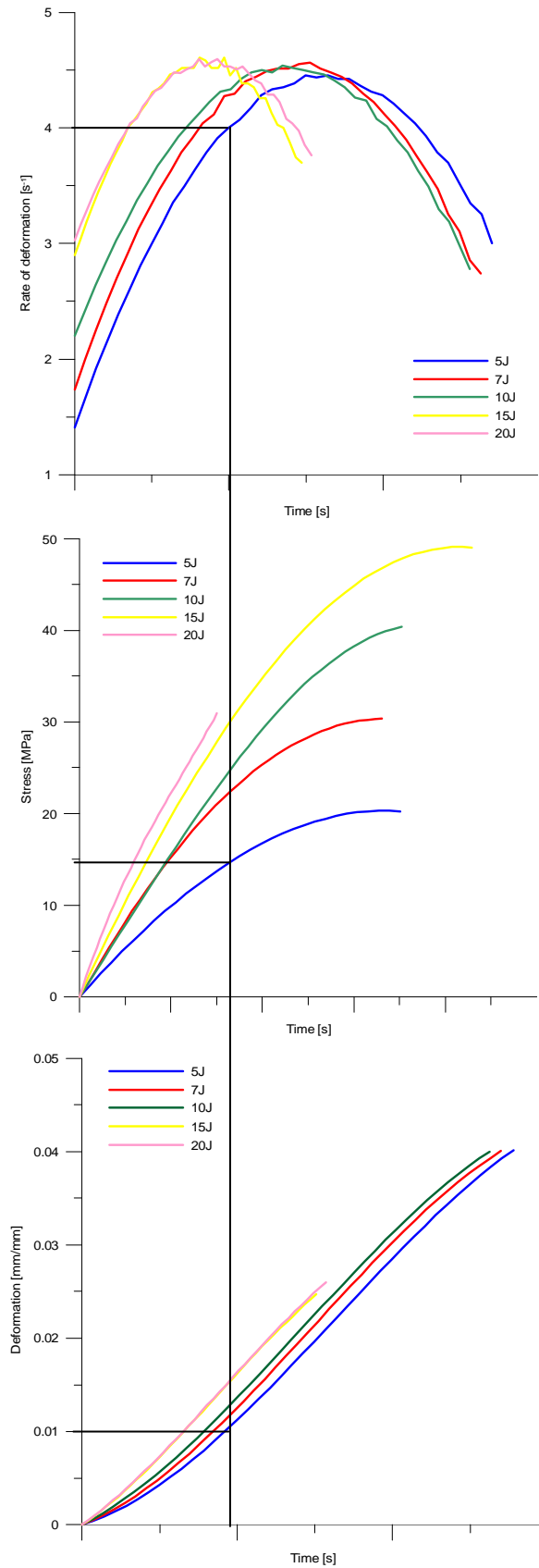
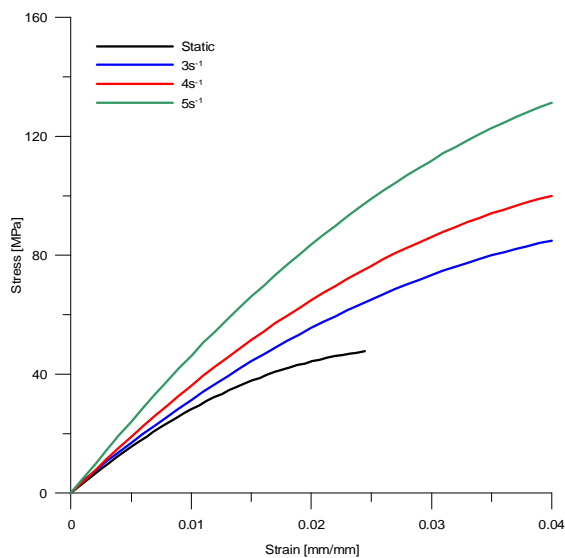Figure 6. Process for determination of stress-strain curves at constant rate.

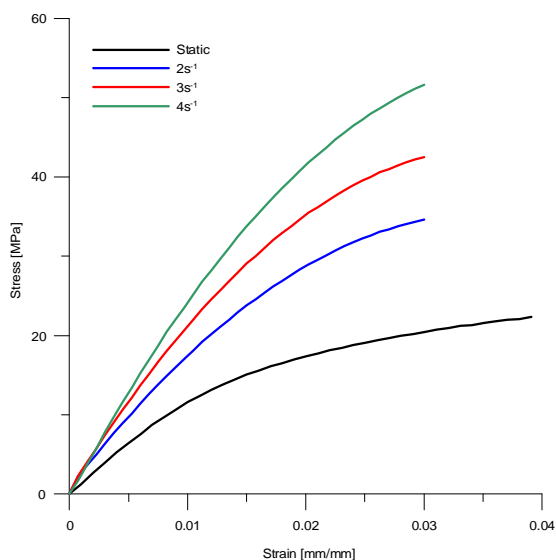Figure 7. Stress-strain curves at constant rate for PVC.

Figure 8. Stress-strain curves at constant rate for PP.

For stress-strain curves at constant rate, the processed elastic modulus are presented in Tab. 3 and Tab. 4 for PVC and PP respectively.

Table 3. Dynamics elastic modulus for PVC from stress-strain curves at constant rate.

Rates of deformation [s^{-1}]	Elastic modulus [MPa]
Static	3280
3	3300
4	3775
5	4815

Table 4. Dynamics elastic modulus for PP from stress-strain curves at constant rate.

Rates of deformation [s^{-1}]	Elastic modulus [MPa]
Static	1325
2	1870
3	2330
4	2700

From the curves shown in Fig. 7 and Fig. 8 and elastic modulus values in Tab. 3 and Tab. 4, it was possible to obtain the stress-plastic strain curves at constant rate, shown in Fig. 9 and Fig. 10. Processing the curves in these figures, using the 0.2 % secant method, it is possible to compute the yield stress for both the materials, which are listed in Tab. 5.

Table 5. PVC and PP yield stress from stress-plastic strain curves at constant rate.

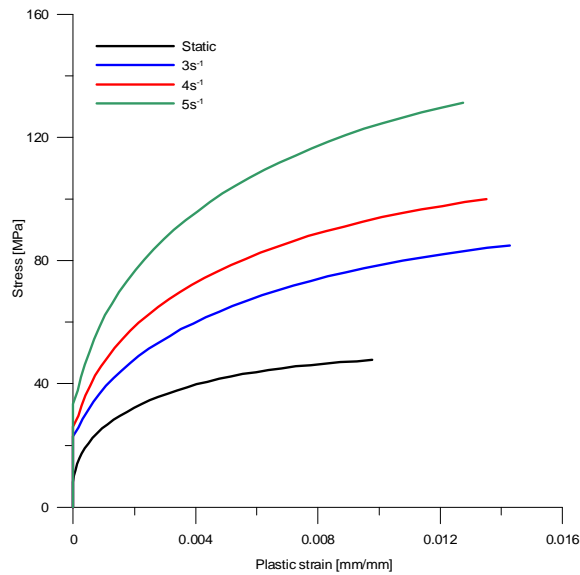| PVC yield stress [MPa]		PP yield stress [MPa]	
Static	12	Static	5.2
3 s^{-1}	23	2 s^{-1}	12.6
4 s^{-1}	26.2	3 s^{-1}	13.7
5 s^{-1}	33.4	4 s^{-1}	15.2

Figure 9. PVC stress-plastic strain curves at constant rate.
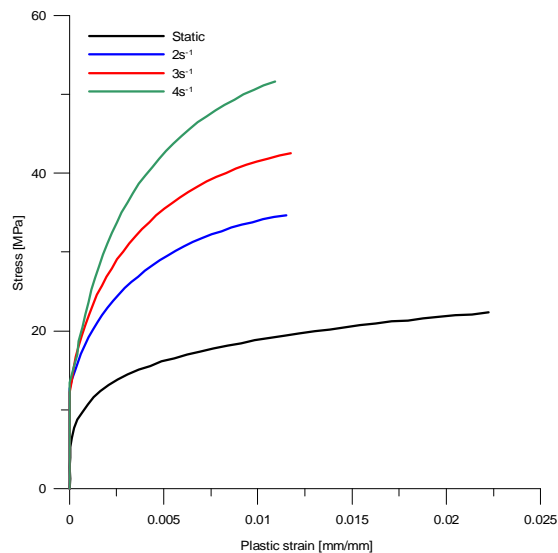
Figure 10. PP stress-plastic strain curves at constant rate.

3. IMPACT SIMULATION OF AN ELECTRIC MOTOR FAN COVER

The electric motor fan cover is one of the most critical components of the electric motor to be subjected to impact loads. This component protects the motor fan against possible falling tools and other materials, some of the associated to its own working environment. For example, motors in crushing machines work under constant risk of rock impacts.

An eventual fan cover failure can cause the breaking of the fan and consequently, the failure of the motor, causing losses to the plant.

Figure 11 shows a real fan cover prototype made in polymer assembled on an electric motor for impact tests. It must be noted that the material of this real fan cover is not PVC, but for the purposes of this study, the experiment data for PVC were used. There is no knowledge of impact curves for the real material. Usually the supplier does not offer such data or even has them. Therefore, in practical cases, it is necessary to build a prototype and test it following some applicable standards. If the component meets the standard requirements it is approved for use.
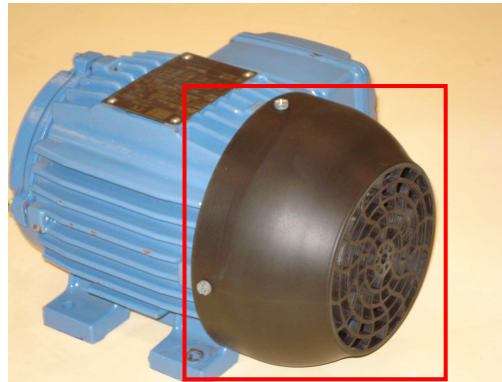

Figure 11. Real polymer fan cover. Courtesy WEG.

The objective of the fan cover impact analysis was to exemplify the use of the stress-strain curves at constant rate. These curves normally are utilized in algorithms which can interpolate between a group of given curves, for the determination of the stress-strain curve associated to the strain rate at a determined integration point. When a component is subjected to several dynamic loads, each point deforms at a determined rate through the deformation process. Thus, to have a group of curves and a formulation that allows interpolate between those curves, makes it possible to do a simulation in which each component point, in each time instant, is modeled using the adequate curve to the rate of deformation at this point. However, the software utilized in this analysis, ANSYS, does not allow interpolate between a group of different hardening curves, such that a single stress-strains curve was chosen for the analysis. Additionally, in non-linear problems, as in impact, involving large deformation and displacements, plasticity and viscoplasticity, it is recommended to use a fine mesh with simple and robust elements. The finite element commercial package used in the present simulations applies the radial return mapping algorithm along with implicit time integration method to update the plastic parameters of the model. The hardening option is the multilinear isotropic hardening with von Mises yield condition.

The analysis consists in the simulation of an impact test defined in IEC 62262 and IEC 60068 standards. The IEC 62262 standard defines the degree of protection against mechanical impacts, IK code. The IK code is followed by two numbers related to the impact energy in which the component must support. The IEC 60068 conducts the process of testing the component, defining the value of the impact mass to be used, its geometry and drop height. For the simulation, it was chosen to subject the fan cover to impact energy of 20 J, classifying it with IK 10 code as in IEC 62262. From IEC 60068, one obtains that for an impact energy of 20 J; a 5 kg mass must be used, and dropped from a 400 mm height. For this height value, the velocity of the impact mass at the moment of impact is 2.8 m/s.

In the simulation, the finite element mesh shown in Fig. 12 was utilized, in which only a 90° sector was used because of the geometric symmetry. For facility, the impact dropping mass effect in the center of the fan cover was simulated imposing an initial velocity of 2.8 m/s to the fan cover while restraining the fan cover center. A correction to the fan cover density was made to make sure the kinetic energy at the moment of impact was 20 J.
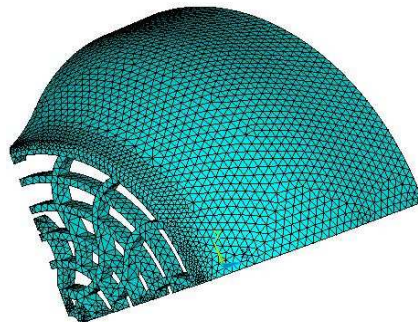

Figure 12. Fan cover finite element model.

As a dynamic material property, the PVC stress-strain curve obtained directly from the impact test with this energy was supplied to ANSYS. The experimental values of 3280 MPa and 0.38 were supplied as elastic modulus and Poisson coefficient respectively.

The stress field due to the impact of 20 J is shown in Fig. 13. Analyzing the critical point, denominated P, inside the red circle, one obtains the equivalent von Mises stress equal to 92 MPa. The total deformation in this point versus time is shown in Fig. 14.
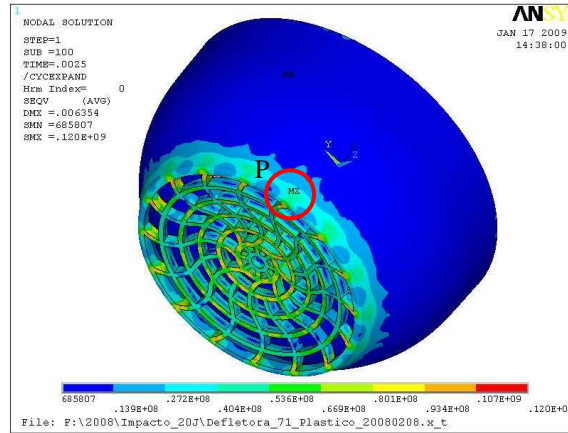

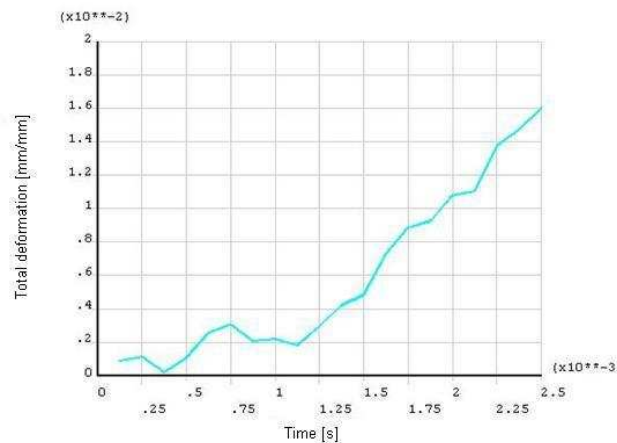Figure 13. Stress field resulting from the 20 J impact.

Figure 14. Total deformation *versus* time in point P.

The rate of deformation in this node is obtained deriving the total deformations by time, which results in the graphic of Fig. 15. Note that this graphic is oscillatory due to the nature of the problem. Despite the oscillation, one can note that the rate values oscillate around 5 s^{-1} (red line). This is the average rate of deformation in point P of the model.
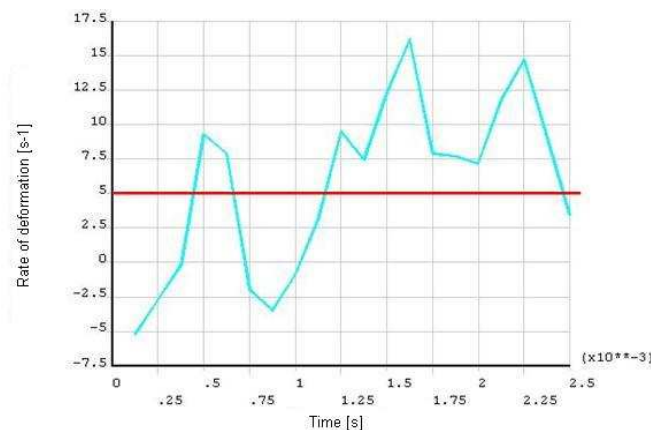

Figure 15. Rate of deformation *versus* time in point P.

Knowing the average strain rate in this node, it is possible to supply the software with a new curve adequate to this rate and compute the new stress field. In this manner, supplying the software with the stress-strain curve at constant rate of 5 s^{-1}, shown in Fig. 7 and repeating the analysis, one achieves a correction for the von Mises stress in point P, which changes to 65 MPa. It must be noted that in the available algorithms, this process is done in each integration point of the model, that is, in each node. Thus, the stress in each node would be corrected according to the curve adequate to its rate of deformation.

4. CONCLUSIONS

This present paper develops a procedure to identify stress-strain curves at constant rates of deformation, processing data obtained from tests at varying strain rates. The procedure is tested in PVC and PP samples in tensile impact tests based on free-fall of calibrated masses, such that it is adequate to low levels of energy and strain rates. The experimental data is obtained at a test apparatus specially developed and built. The force and deformation signals are obtained in real time respectively from a load cell and a strain gage adhered to the sample. The apparatus is adequate to standardized sample tests of polymeric materials. The raw curves of force *versus* time and deformation *versus* time at several mass velocities are processed in different forms to generate estimates of stress-strain curves at constant rates, at constant plastic strain rates, and also curves of initial elastic modulus *versus* strain rates. The experiment apparatus limits the estimates to deformations prior to development of necking in the sample.

In spite of the little difference between impact energies used in the tests, it was possible to obtain very distinct material curves, at several different constant rates. Still, tests performed at a larger number of energy levels, more widely spaced, makes it easier to perform the curve fitting process, due to the larger number of data available. The accuracy of the constant rate curves obtained are directly linked to the amount of measured points stress-deformation utilized in the final curve fitted. At the present study, only four points were utilized.

The application of strain gages for measurement of deformation at the sample is adequate. However, the values are adequate only before the development of necking. Its application in the industrial environment is possible, provided the test apparatus is available, specially the impact test machine, which is not a commercial model, but a specially developed design.

The manufacturing of the sample tests is such that it concentrates stresses and deformation at its central region, making the positioning of the strain gage easier. However, the process of fabricating the grove requires the use of precise machining equipment, available only at quality tooling houses.

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