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PHYSICAL INTERPRETATION OF IMPACT BEND TEST BY MEANS OF MATHEMATICAL METHODS

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The paper deals with the possibility to apply mathematical methods to process dynamic impact bend test diagrams in force–time $(F-t)$ lay–out. The paper presents both a methodology of taking off $F-t$ characteristics and a computer–aided testing stand, as well as processing algorithms of diagrams in the field of mathematical filtration based on averaging random variable and oscilation in the field of time and frequency. A procedure for defining characteristic points of the sample impact cracking process has also been defined. As a complement to theoretical consideration, the paper presents an example of specific processing of $F-t$ diagrams for $C-Mn$ steel sample, which may be the basis for evaluation of failure process parameters in crack mechanics bearing.

1. Introduction

The necessity to make provisions for material behavior in case of impact loads makes it indispensable to seek suitable research methods. The conventional impact bend test (PN–79/H–04370) is the simplest crack resistance research method. At present this test is given a more universal character by using it not only for evaluation of impact value (KCV), but also for evaluation of crack resistance parameters: K_{IC}, G_{IC}, δ_C (COD) and J_d. The investigations carned on specially equipped impact testing machines to register precise data on load variations $(F-t)$ and displacement $(l-t)$ curve analysis, within very short time of the impact bend process.

With all its simplicity, cracking of a material is a very complicated process in this test. Interference resulting from wave state of stresses in the ram–sample–support system, causes distortions in the real diagram taken in that test and that makes proper interpretation difficult. Therefore, it is difficult to determine characteristic points and parameters of failure of a material being tested. A great number of various additional factors disturbing the crack process, such as: system free vibrations, stress waves, plastic and elastic strains, system inertial action, friction on supports etc. (Parchański, 1984; Pogodin, 1970) and no satisfactory, explicit quantitative premises available about the nature of testing process also make sample failure process characterized by great influence of stochastic occurences. The

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application of suitable mathematical methods of dynamic run processing is needed to illustrate this process in a proper, orderly and intelligible form.

At present there is a great chaos in the field of physical interpretation of dynamic runs received in impact bend test. Only a few authors (Ireland, 1974; Kobayashi, 1984; Ranatowski, 1980) pay attention to this important problem. There is no univocal determination and evaluation of process characteristic point methodology. This results in the fact that crack resistance parameters received are burdened with serious errors and they are not very useful in further considerations or structural calculations.

The paper undertakes an attempt of physical interpretation of impact bend process with application of mathematical processing methods of recorded dynamic runs.

2. Testing Stand

The testing stand required accessories of impact ram for testing impact value type PWS–30. The instrumentation diagram of the ram with strain gauges and low linear displacement sensor is shown in Figure 1. Wiring diagram of these sensors and equipment for gaining, registration and storage of fast dynamic runs during impact testing is shown in Figure 2. The following main registration and data processing problems are connected with this part of the stand:

i) application of suitable sensitivity, transmitted frequency band, as well as temperature and nonlinear distortion compensation of transducer blocks and measurement amplifiers;

ii) scaling of sensors and selection of proper digital registration A/C transducer accuracy as well as suitable sampling frequency;

iii) choosing adequate registered dynamic run filtration algorithm and processing of filtered runs.

The procedures mentioned above in points i) and ii) are in fact strictly technical matters and are not taken into further consideration in this paper. Problem iii) above – choice of suitable dynamic run filtration algorithm and processing of dynamic runs is considered to be the main problem among the above mentioned. It is difficult to make proper physical interpretation of impact test fast runs.

3. Dynamic Impact Test Measurement Data Processing

This problem is treated as all–important in dynamic research of material failure resistance, though it is partly conditioned by instrumentation of the ram. It results from:

i) importance of methods employed for impulse processing (Max, 1981; Shabatin, 1982; Siebert, 1986) for correct physical interpretation of impact bend test and,

ii) insufficient *a priori* information about recorded runs.

Thus, it is required to take the least simplified model of dynamic impact test into consideration.

3.1 Models of Impact Bend Tests

With measurement of forces by means of tensometric gauges, the items where sensors are placed, are subject to elastic strain. Thus, for measurements of force FP from each side and force F from ram by means of tensometric gauges $R1$ and $R1'$ as well as $R2$, $R2'$ (Figure 1) the ram and supports must be fully elastic. The sample itself which undergoes the impact test is an elastic item. The sample is simulated by infinitesimal elements of sample and elementary springs which link them. Therefore, an adequate mathematical description of the model impact test, which is shown in Figure 3 (where springs $S1$ and $S2$ simulate strained parts of the supports and ram with strain gauges placed on these parts), requires partial differential equations. However, such a quite multiplex model is not necessary, when you want to obtain certain premises about selection of algorithm for processing and filtration of measured data of impact test. In this case, the most convenient solution is to use two mathematical models shown in Figure 4. The figure has the following descriptions: SP – springs simulating strained sample with their mass $4m_p$; k_1, k_2, k_p – elastic coefficients of springs $S1$, $S2$, SP; a_1, a_2, a_p – attenuation constants of springs $S1$, $S2$, SP; m_p – 1/4 of sample mass; $2FX$ – sample straining (fracturing) force. The models differ in this way that in the first model (Figure 4a) the sample elasticity has been omitted (no springs SP), whereas, in the other (Figure 4b) elasticity is centred in two points.

The simplified dynamic models of impact tests are characterized according to force measurement location of the following transmittances:

$$W_P(s) = \frac{2FP(s)}{2FX(s)}; \quad W_B(s) = \frac{F(s)}{2FX(s)}; \quad W_\Sigma(s) = \frac{F_\Sigma(s)}{2FX(s)} \tag{1}$$

where: $F_\Sigma(s) = [2FP(s) + F(s)]/2$ – resultant force, which is a mean from two supports and ram forces; s – complex frequency (Shabatin, 1982).

Assumming that the supports and ram (or their relevant parts, on which sensors $R1$, $R1'$ and $R2$, $R2'$ are located) have the same properties (i.e. $a_1 = a_2$, $k_1 = k_2$), transmittances (1) are as follows:

- for a model with rigid sample (Figure 4a):

$$W_P^a(s) = \frac{k_1}{m_p s^2 + a_1 s + k_1}$$

$$W_B^a(s) = \frac{2m_p s^2 + a_1 s + k_1}{m_p s^2 + 2a_1 s + k_1} \tag{2}$$

$$W_\Sigma^a(s) = \frac{2m_p s^2 + a_1 s + 2k_1}{2m_p s^2 + 2a_1 s + 2k_1}$$

- for a model with elastic sample (Figure 4b):

$$W_P^b(s) = \frac{k_1}{m_p s^2 + a_1 s + k_1}$$

$$W_B^b(s) = 1 + \frac{a_p}{k_p}s + \frac{m_p}{k_p}s^2 + \frac{m_p s^2}{m_p s^2 + a_1 s + 2k_1} \tag{3}$$

$$W_\Sigma^b(s) = \frac{m_p^2 s^4 + m_p(a_1 + a_p)s^3 + (k_1 m_p + 2k_p m_p + a_1 a_p)s^2}{2(m_p s^2 + a_1 s + k_1)k_p} + $$

$$+ \frac{(a_p k_1 + a_1 k_p)s + 2k_1 k_p}{2(m_p s^2 + a_1 s + k_1)k_p}$$

The following three primary inferences which concern filtration arise from the above formulas:

i) time runs of forces F and FP measured on the supports and ram, respectively, oscilate around the run of real $2FX$ force straining (fracturing) the tested sample;

ii) time run of force $2FX$ is delayed in relation to force run F, however, it gets ahead of the FP run;

iii) force F_Σ mean measurement allows partly to compensate phase displacements and oscilations of the measured forces F and FP in relation to force $2FX$.

Among the inferences mentioned above, the third conclusion is especially useful for filtration and processing of measured data. It should be stressed, however, that the advantage resulting from determining the mean force F_Σ (estimated by compensation rate of phase displacements and oscilations) will considerably depend on the testing machine (supports and ram) parameters and the tested sample. Thus, as it follows from formula (2) and required transmittance $W_\Sigma^a(s) = 1$, the vibration damping in hammer parts with strain gauges fixed on them, should be nearly zero (i.e. $a_1 \cong 0$). Their elastic constant k_1 should also be much greater than the tested sample elastic constant k_p ($k_1 \gg k_p$). These requirements are generally guaranteed by standard impact testing machine constructions. Thus, despite tested sample properties, on the basis of dependence (3), it can be assumed that mean value of transmittance $W_\Sigma^b(s)$ is as follows:

$$W_\Sigma^b(s) \cong 1 + \frac{a_p}{k_p}s + \frac{m_p}{k_p}s^2. \tag{4}$$

Thus, the mean force F_Σ specified on the measurement stand (Figure 2) should be additionally filtered by a low–pass filter of the following transmittance, e.g.:

$$W_F(s) = \frac{F'_\Sigma(s)}{F_\Sigma(s)} \approx \frac{k_p/m_p}{s^2 + (a_p/m_p)s + k_p/m_p} \tag{5}$$

where $F'_\Sigma(s)$ is filtered mean force in the field of complex frequency.

In this case, taking the expressions (1), (4) and (5) into account the following is obtained:

$$W^b_\Sigma(s)W_F(s) \approx 1 \quad \text{and} \quad F'_\Sigma \approx 2FX$$

Filtration on the basis of expression (5) is not a technical problem and it is the easier, the greater the own oscilation frequency of the tested sample is. However, this kind of filtration is not useful in research of impact tests of fast dynamic runs, since it is difficult to define each time parameters m_p, a_p, k_p of a new sample and apart from that parasitical outer interference would have to be filtered. Therefore the low–pass filtration (pre–processing) of registrated runs on the stand illustrated in Figure 2 will be conducted.

3.2 Filtration Algorithms

Algorithms have the form of complete program modules provided for computer processing of measured data. Filtration – pre–processing of data — executed in this way includes:

- cleaning off registered runs of incidental fast variable interference, so–called smoothing,
- determination of F_Σ mean force,
- decreasing influence of vibration at the bases of supports onto force F^*_Σ,
- final filtration–correction (post–equalization) of mean force F_Σ.

Smoothing – carried out by actual value change of each filtered run $f(t)$: $FP(t)$ – from sensors located on supports; $F(t)$ – from sensors located on ram; $w(t)$ – from gauges of supports free vibrations, into values of the so–called zero–rank moments (mean values), generally determined by Strzelecki *et al.*, (1984)

$$m_0(t) = (1/T)\int_{t-T/2}^{t+T/2} f(t)dt, \tag{6}$$

where: T – length of averaging interval.

In the performed programme module the values $m_0(t)$ are calculated for every discrete time $k = t/\Delta_t$ ($\Delta_t \cong 2\mu s$ sampling time of recorded runs) on the basis of the following dependence:

$$m_0(k) = \frac{1}{I+1} \sum_{i=k-I/2}^{k+I/2} f(i) = m_0(k-1) - \frac{1}{I+1}[f(k-1-I/2) - f(k+I/2)] \quad (6a)$$

where $k = 0, 1, ..., M$; $M + 1$ is general number of each registered run data; $I + 1 = T/\Delta_t + 1$ – number of averaging data estimated aproximately from inequality $I \leq M/50$.

At the same time: if $i < 0$, then $f(i) = -f(-i)$, and if $i > M$, then $f(i) = -f(2M - i)$. Thus runs $FP(k)$, $F(k)$ and $w(k)$, cleaned off fast variation interference are marked further as $FP'(k)$, $F'(k)$ and $w'(k)$.

Determination of mean force $F_\Sigma(k)$ – follows in a selected programme module, generally from the following dependence:

$$F_\Sigma(k) = \frac{1}{2}[a_w 2FP'(k) + (2 - a_w)F'(k)] \quad (7)$$

where a_w denotes weight factor taking into account non–uniform fraction of respective components of expression (7).

In the applied module the parameter a_w will be calculated from the following formula:

$$a_w = 2\sum_{k=0}^{M} F'(k) \bigg/ \sum_{k=0}^{M}(2FP'(k) + F'(k)) . \quad (8)$$

However, in the final version of the module, it is projected to take additionally into account other alternative values of the parameter a_w, determined on the grounds of

- dependence

$$a_w = 2/(K_K^F + 1) \quad (8a)$$

where: K_K^F – correlation coefficient between run $2FP'(k)$ and $F'(k)$, defined according to (Shabatin, 1982), as

$$K_K^F = \sum_{k=0}^{M}(2FP'(k)F'(k)) \bigg/ \sum_{k=0}^{M}(F'(k))^2 ,$$

- expression

$$a_w = \frac{2\sum_{k=0}^{M} |\nabla F'(k)|}{\sum_{k=0}^{M} F'(k)} \bigg/ \left(\frac{\sum_{k=0}^{M} |\nabla F'(k)|}{\sum_{k=0}^{M} F'(k)} + \frac{\sum_{k=0}^{M} |2\nabla FP'(k)|}{\sum_{k=0}^{M} 2FP'(k)} \right) \quad (8b)$$

where $\nabla F'(k) = F'(k+1) - F'(k)$, $\nabla FP'(k) = FP'(k+1) - FP'(k)$, $F'(M+1) = -F'(M-1)$, $FP'(M+1) = -FP'(M-1)$;

- optimization algorithm (taking into account that the value of $a_w \in (0,\ 2)$ parameter is only slightly different from 1), which minimizes the following index in relation to a_w parameter:

$$J_a = \sum_{k=0}^{M} |\nabla^2 F_\Sigma(k)| \Bigg/ \sum_{k=0}^{M} |\nabla F_\Sigma(k)| \tag{9}$$

where: $\nabla^2 F_\Sigma(k) = F_\Sigma(k+1) - 2F_\Sigma(k) + F_\Sigma(k-1)$, $\nabla F_\Sigma(k) = F_\Sigma(k+1) - F_\Sigma(k)$, $F_\Sigma(-1) = -F_\Sigma(1)$, $F_\Sigma(M+1) = -F_\Sigma(M-1)$.

Reduction of vibration effect from support bases on force $F_\Sigma(k)$ – will be carried out when the operator decides about it on the basis of visual estimation of run $F_\Sigma(k)$ and $w'(k)$. To objectify this estimation the operator may use standardized correlation coefficient, determined according (Shabatin, 1982), as:

$$K_N = K_K^W K_K^{\overline{W}}, \tag{10}$$

where:

$$K_K^W = \frac{\sum_{k=0}^{M}(\nabla^2 F_\Sigma(k) \nabla^2 w'(k))}{\sum_{k=0}^{M}(\nabla^2 F_\Sigma(k))^2}; \quad K_K^{\overline{W}} = \frac{\sum_{k=0}^{M}(\nabla^2 F_\Sigma(k) \nabla^2 w'(k))}{\sum_{k=0}^{M}(\nabla^2 w'(k))^2}$$

whereas $\nabla^2 w'(k) = w'(k+1) - 2w'(k) + w'(k-1)$, and $w'(-1) = -w'(1)$, $w'(M+1) = -w'(M-1)$.

If factor $K_N \leq 1/2$, then it should be assumed that vibration run $w'(k)$ at support bases has no over–effect on function $F_\Sigma(k)$ run. Thus, in this case it is advisable to omit a given filtration stage of force $F_\Sigma(k)$ run. Otherwise, if the operator has decided to perform a given stage, the run $F_\Sigma(k)$ compensation by run $w'(k)$ will be carried out. Adapted for this, the programmme module executes the following dependence:

$$F'_\Sigma(k) = F_\Sigma(k) - b_w(w'(k) - S_w) \tag{11}$$

where S_w is mean value of $w'(k)$ run defined by the following dependence

$$S_w = (1/M) \sum_{k=0}^{M} w'(k),$$

$F'_\Sigma(k)$ – mean force run compensated by vibration registered at support base, b_w – weight factor taking into account several components of expression (11).

Two different parameters b_w are calculated in the existing module:

$$b_{w1} = 1/K_K^W \quad \text{or} \quad b_{w2} = \sum_{k=0}^{M} |\nabla^2 F_\Sigma(k)| \Bigg/ \sum_{k=0}^{M} |\nabla^2 w'(k)| \,.$$

On the basis of formula (11) two runs, $F'_{\Sigma 1}(k)$ or $F'_{\Sigma 2}(k)$, are determined respectively for the above parameters and their adequate index

$$J_b = \sum_{k=0}^{M} |\nabla^2 F'_{\Sigma}(k)| \Big/ \sum_{k=0}^{M} |\nabla F'_{\Sigma}(k)| \,. \tag{12}$$

The calculated index values (the smaller the better) help the operator to undertake decisions about the correct run of mean force, i.e. $F'_{\Sigma}(k) = F'_{\Sigma 1}(k)$ or $F'_{\Sigma}(k) = F'_{\Sigma 2}(k)$. Another option is also projected to determine parameter b_w – through minimization of index J_b.

Final filtration–correction of mean force – is made when it is impossible to make explicit results interpretation of dynamic tests on the basis of $F'_{\Sigma}(k)$ (or $F_{\Sigma}(k)$). This may be carried out both in the field of discrete time as well as discrete frequency.

Final filtration of run $F'_{\Sigma}(k)$ in the field of discrete time is executed in the same way as "smoothing", on the basis of formula (6a), however, unlike this stage, values $F'_{\Sigma}(k)$ are usually averaged repeatedly and in longer interval (for greater number of averaged data $I+1$). This interval is determined by the operator and he decides about the repetition of averaging. Therefore, the result of this filtration – run $F''_{\Sigma 1}(k)$ – is largely subjective, conditioned by the operator's knowledge of several impact process runs.

In the case of final filtration by averaging it may be difficult to separate characteristic run ranges or to evaluate sharp variations of final force run $F''_{\Sigma 1}(k)$. Differentiation of that run (Parchanski, 1984) seems to be helpful. The difficulties mentioned above may be partially avoided by final filtration in the field of frequency.

Filtration in the field of frequency by separation will be carried out on the basis of frequency discrete spectrum (determined by use of Fast Fourier Transformation algorithm – FFT), defined for run $F'_{\Sigma}(k)$ by the following formula (Max, 1981)

$$F'_{\Sigma}(jm\,\Delta\omega) = \sum_{k=0}^{M} F'_{\Sigma}(k)\exp(-jm\Delta\omega\; k\Delta_t) \tag{13}$$

where $\Delta\omega = 2\pi/(M+1)$ – sampling interval in the field of frequency, m – number of following sampling in the field of frequency.

However, since $F'_{\Sigma}(jm\Delta\omega)$ is a product of spectrum $2FX(jm\Delta\omega)$ of the searched run $2FX(k)$ and unknown transmittance $W'_{\Sigma}(jm\Delta\omega)$ – (see dependence (1)), then a logarithm is found from the transform $F'_{\Sigma}(jm\Delta\omega)$ before making filtration. As a result we obtain a new spectrum described by the following formula

$$F^{L}_{\Sigma}(jm\Delta\omega) = \log F'_{\Sigma}(jm\Delta\omega) = \log 2FX(jm\Delta\omega) + \log W'_{\Sigma}(jm\Delta\omega) \tag{13a}$$

In the above formula undesirable changes involved in transmittance $\log 2W_\Sigma(jm\Delta\omega)$ are additive in relation to $\log 2FX(jm\Delta\omega)$. These changes usually take place in high frequencies and the operator may evaluate them visually and relatively easily. On this basis he decides about omitting suitable parts of the spectrum $F_\Sigma^L(jm\Delta\omega)$ in frequency intervals $[(m_d+1)\Delta\omega,\ (m_g-1)\Delta\omega]$, where: $m_d+1,\ m_g-1$ – the lower and upper number of sample from the cut frequency interval. In the cut intervals spectrum $F_\Sigma^L(jm\Delta\omega)$is interpolated by a polynomial, independently of the operator. Omission of this usually leads to essential differences between real force $2FX(k)$ straining the tested sample and force $F''_{\Sigma 2}(k)$ obtained by filtration of spectrum $F'_\Sigma(jm\Delta\omega)$. This may be essential for physical interpretation of test results.

In the programme module for final filtration of run $F'_\Sigma(k)$ in frequency range, the spectrum $F_\Sigma^L(jm\Delta\omega)$ in cut frequency intervals will be interpolated by the following complex polynomial:

$$G_w(jm\Delta\omega) = R(m\Delta\omega) + jQ(jm\Delta\omega), \tag{14}$$

where

$$R(jm\Delta\omega) = -[g_6(m\Delta\omega)^6 - g_4(m\Delta\omega)^4 + g_2(m\Delta\omega)^2 - g_0]$$
$$Q(jm\Delta\omega) = -[g_7(m\Delta\omega)^7 - g_5(m\Delta\omega)^5 + g_3(m\Delta\omega)^3 - g_1(m\Delta\omega)]$$

and where $m = m_d+1, m_d+2, ..., m_g-1$; $g_0, g_2, ..., g_6, g_7$ – real coefficients, calculated on the basis of complex variables of spectrum $F_\Sigma^L(jm\Delta\omega)$ for $m = m_d-1, m_d, m_g, m_g+1$.

To calculate the coefficients of complex interpolating polynomial (14), it is possible to use the function moments of $F'_\Sigma(k)$ with weight $k^n\exp(-\omega_r k)$, which are determined for $\omega_r = m_d\Delta\omega$ and $\omega_r = m_g\Delta\omega$ and $n = 0,1,2,3$ according to (Solodnikov, 1968). A new spectrum $F''_\Sigma(jm\Delta\omega)$ received in this way finds the antilogarithm and finally reversal Fourier transform.

The run $F''_{\Sigma 2}(k)$ received as a result of filtration in frequency domain will be thus compared with the similar result of final filtration in time range – the run $F''_{\Sigma 1}(k)$. This will allow us to choose one of them as a final result of operation. The run chosen in this way is defined as $2FX''(k)$.

3.3. Final process

The final processing of the filtrated run $2FX''(k)$ will comprise the following steps

- determination of force $2FX''(k)$ by ram transformation,
- normalizing–scaling the force run $2FX''(k)$ in absolute values,
- approximation of $FX''(k)$ run by linear spliced function with free knots,
- calculation of parameters characterizing crack resistance of material of the sample being tested.

Determination of dependence $2FX''(k)$ on ram tramsformation:

i) the purpose of testing is to determine areas of elastic and plastic strains as well as the begining of stable and unstable sample crack depending on its bend,

ii) normal scaling of force $2FX''(k)$ in absolute values is performed on the basis of gauge pointer swings, where the gauge is scaled in operating units of sample failure.

The programme module used in this way utilizes a simple assigning procedure of run $2FX''(k)$ value and linear ram transformation $l = Pl(k)$, where $Pl(k)$ – ram displacement at discrete time measured by a suitable sensor (Figure 1) and registered from the moment of ram stroke in the sample. The exchange of "k" argument into argument "l", carried out in this way for $2FX''(k)$ run, is reduced to determine the following dependence:

$$2FX''(l) = 2FX''(PL^{-1}(l)), \tag{15}$$

where $PL^{-1}(l) = k$ – an inverse function to $PL(k) = l$.

Normalization consists in calculating proper proportionality factor K_N and multiplying it by the runs $FX''(l)$ as well as $FX''(k)$. The programme module separated for this purpose defines K_N factor from the following formula

$$K_N = A_N \Big/ \sum_{k=1}^{M} (1/2)[2FX''(l_k) + 2FX''(l_{k-1})](l_k - l_{k-1}) \tag{16}$$

where A_N is the whole work of tested sample failure taken of a proper scale (the scale is a standard equipment of the ram), the work may also be dynamometrically defined and entered to computer by the operator; l_k – ram displacement (sample bend) for discrete k–time.

As a result we obtain absolute values of filtered force runs, and the whole failure work calculated on their basis is equal to readings from the ram scale. Therefore, from these runs we may determine failure parameters which characterize tested samples at the time of their impact bend. It is advisable to do this after approximation of obtained runs.

Approximation of runs $2FX''(l)$ and/or $2FX''(k)$ may be carried out both before and after normalization and even omitting final filtration step (due to its good filtration characteristics). Analysed runs are approximated here by spliced functions FS with free knots (Suchomski, 1990), in particular cases – by linear intervals in the following form

- for $2FX''(k)$

$$FS(k) = a_{n-1} + (k - k_{n-1})\frac{(a_n - a_{n-1})}{(k_n - k_{n-1})} \tag{17a}$$

- for $2FX''(l)$

$$FS(l) = a_{n-1} + (l - l_{n-1})\frac{(a_n - a_{n-1})}{(l_n - l_{n-1})} \tag{17b}$$

where k_n, l_n denote discrete time and ram displacement corresponding to the end of "n" and start of "$n+1$" approximation interval (points of splicing), a_n – value of FS function at splicing points, $k_0 = 0$, $k_N = M$, $a_0 = a_N = 0$, N – number of approximation intervals.

In the approximation module the parameters $a_1, a_2, ..., a_{N-1}$ and $k_1, k_2, ..., k_{N-1}$ and/or $l_1, l_2, ..., l_{N-1}$ from function (17) are determined as a result of minimization of the following indices

* for run $2FX''(k)$

$$Q = \sum_{n-1}^{N} \sum_{k=k_{n-1}}^{k_n} \left| \frac{(k_n - k_{n-1})2FX''(k) - a_n(k - k_{n-1}) - a_{n-1}(k_n - k)}{(k_n - k_{n-1})^2} \right| \tag{18a}$$

* for run $2FX''(l)$

$$Q = \sum_{n-1}^{N} \sum_{l=l_{n-1}}^{l_n} \left| \frac{(l_n - l_{n-1})2FX''(l) - a_n(l - l_{n-1}) - a_{n-1}(l_n - l)}{(l_n - l_{n-1})^2} \right| \tag{18b}$$

The optimization algorithm for random research (with modification) will be used to reach this aim (Novosielcev *et al.*, 1990).

Calculation of parameters characterizing crack resistance is the simplest among the steps described in paragraph 3.2 – 3.3. The programme module used for this purpose will calculate values K_{IC}, G_{IC}, J_d and others based on formulae known from common literature, on the basis of strictly determined characteristic points of approximated or filtrated runs. This module also contains all options of test documentation print–outs, including runs of recorded forces before and after filtration (selected by the operator).

4. The Practical Example

Precise knowledge of force changes in time, or force and displacement provides comprehensive information about the behaviour of material in fracture process during impact bend and it is the primary condition for estimation of tested material crack resistance.

Several programme modules and algorithms described above (paragraph 3) form one comprehensive data process programme of tested samples according to the block diagram shown in Figure 5. This programme, as it has already been mentioned, employs different algorithms of correction-filtration with the possibility of the operator interference. Below, find practical results of selected filtration–correction stages and measured data processing in time field, obtained for tested sample of Charpy's type, impact bend and made of C–Mn steel. Resulting force runs are shown in Figures 6–9

- recorded directly from strain gauges placed on the ram — Figure 6,
- cleaned off fast–varying random interference ("smoothing" for $I = 11$) — Figure 7,
- after final filtration of $F'(k)$ run in time field (excluding force from supports) carried out by tripple "smoothing" for $I = 21$, and also after differentiation of this run — Figure 8,
- after aproximation of run $F''(k)$ by linear splicing function with free knots for $N = 7$ — Figure 9.

The appropriate values are recorded in $M = 710$ time points with sampling frequency of $500\ kHz$.

It is clearly seen from the received force–time diagram of impact bending of C–Mn steel sample (Figure 6) that it is extremely distorted and noised, and thus a correct physical interpretation appears to be difficult. In this case it becomes difficult to determine accurately both the dynamic elastic limit and the beginning of fracture initiation, both stable and unstable, and their corresponding forces. Determination of maximal fracture force and division of fracture complete work area (A_N) into individual components, i.e. the component of beginning of fracture work in the plastic area (A_z), the component of failure expansion work in the unstable cracking area (A_r), and the component of brake cracking work (A_h), seems to form a problem. As a result of the above, that diagram makes it very difficult to evaluate the characteristic points as well as to calculate precisely the parameters of tested material sample fracture based on these points.

Correction–filtration stages of real force diagram during impact sample bend test, described in this paper, carried out by mathematical methods, provide more precise interpretation of received final diagrams (Figures 8 and 9) than the output diagram (Figure 6). On the basis of these final diagrams it is therefore possible to determine precisely the characteristic points of failure sample runs during impact bend sample test. The accurate valules of force and time (Figures 8 and 9) have been determined on the basis of these points. The values concern

- plastic limit — F_e and T_e,
- start of stable fracture — F_s and T_s,
- start of unstable fracture — F_n and T_n,
- maximal value — F_m and T_m.

The above values also make it possible to divide the whole failure work of tested sample (A_N) into individual failure work areas A_z, A_r and A_h. Knowing these parameters it is also possible to evaluate correctly the failure parameters of tested sample as: K_{IC}, G_{IC}, J_d and others, and also to collect additional information about mechanism of the complete process of C–Mn steel tested material failure in the given conditions.

5. Conclusions

Finally the following may be stated:

- it is possible to improve fast dynamic signals registration and processing in impact bend test by means of special instrumentation of an impact testing machine;
- mathematical processing — correction–filtration of fast dynamic runs by means of proper algorithms may be the basis for correct physical interpretation and precise evaluation of failure parameters of tested samples during impact bend;
- mathematical processing of fast–variable signals extends technical possibilities of the impact test itself, and may also be helpful for the analysis of material behaviour during failure process, especially for complicated heterogeneous systems like e.g. bond joint.

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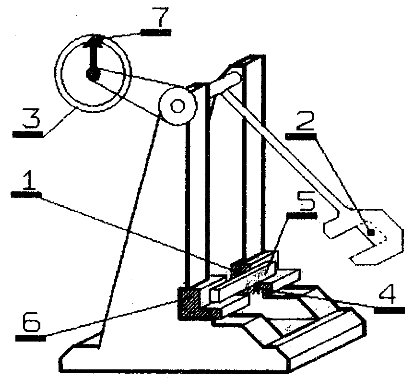


Fig. 1. Simplified diagram of instrumented impact testing machine for dynamic impact tests:

1 – basic strain gauges $R1$ and $R1'$ on each support,
2 – basic strain gauges $R2$ and $R2'$ on each side of linear ram,
3 – multi–rotary potentiometric sensor for determination of linear ram displacement,
4 – auxiliary strain gauges $R4$ and $R4'$ for compensation of support free vibration,
5 – sample, 6 – supports, 7 – microswitch.

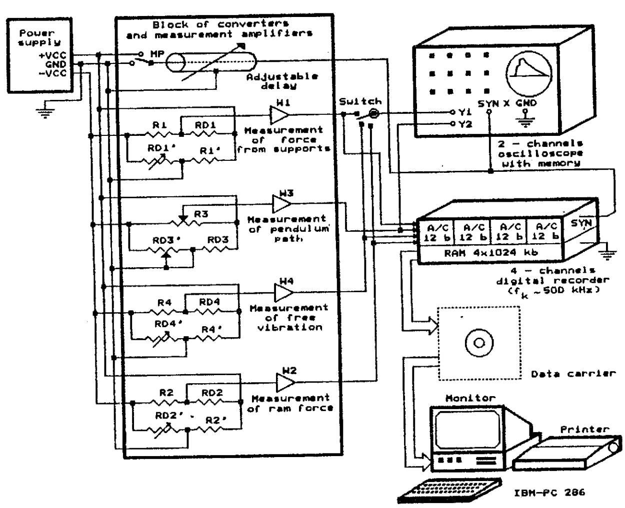
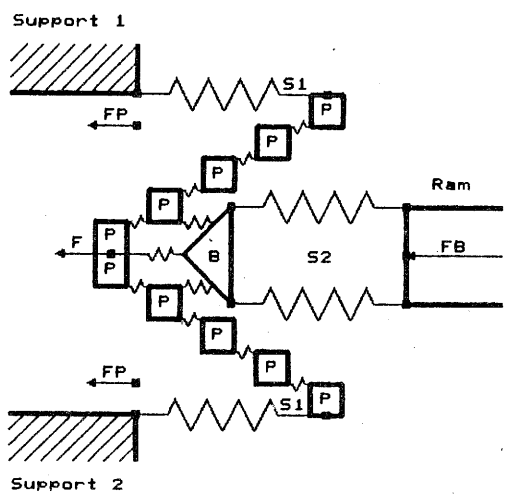
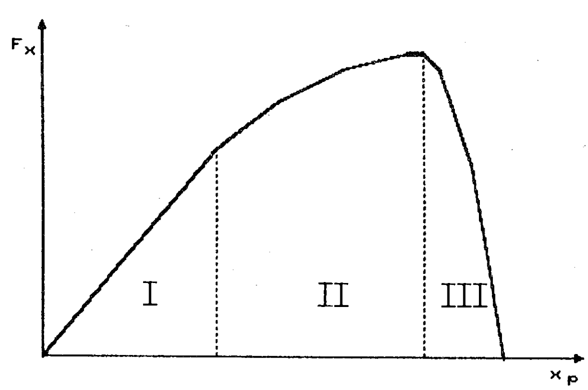


Fig. 2. Measuring position block diagram for dynamic impact tests.



a)

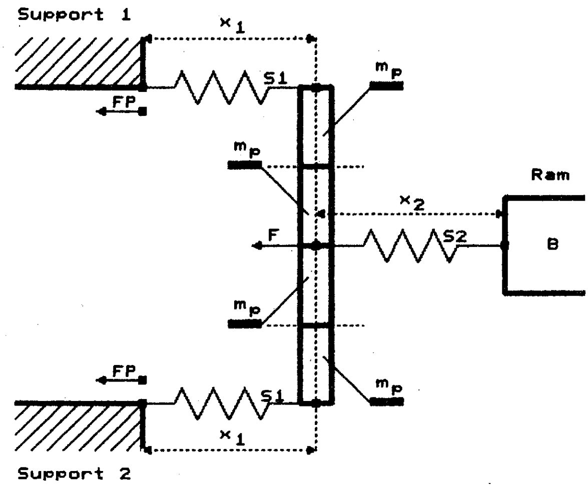


b)

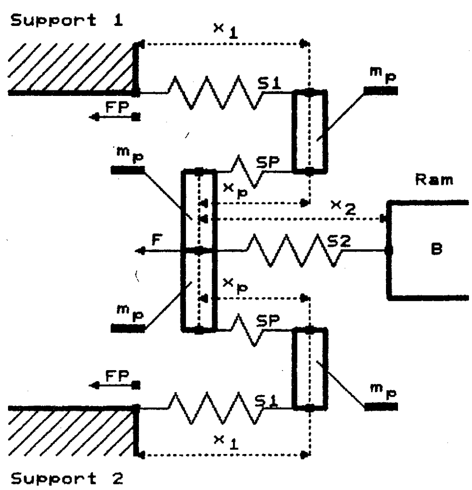
Fig. 3. General diagram of impact bend process:

a) dynamic model of impact test (B—ram, P—sample element).

b) dependence of force Fx straining the spring between the two nearest elements of the sample (I – elastic strain; II – plastic strain; III – spring rapture).



a)



b)

MATHEMATICAL MODEL DESCRIPTION	
$F = -k_2 x_2$	
Model a) — rigid sample	Model b) — elastic sample
$F = -2(2m_p\ddot{x}_1 + a_1\dot{x}_1 + k_1 x_1)$	$F = 2m_p(\ddot{x}_p - \ddot{x}_1) + 2a_p\dot{x}_p - 2k_p x_p$
$FX = (-a_1\dot{x}_1 - k_1 x_1 + F/2)/2$	$FX = -(m_p\ddot{x}_1 + a_1\dot{x}_1 + k_1 x_1)$
$FP = -k_1 x_1$	$FX = k_p x_p, \quad FP = -k_1 x_1$

Fig. 4. Simplified dynamic models of impact test.

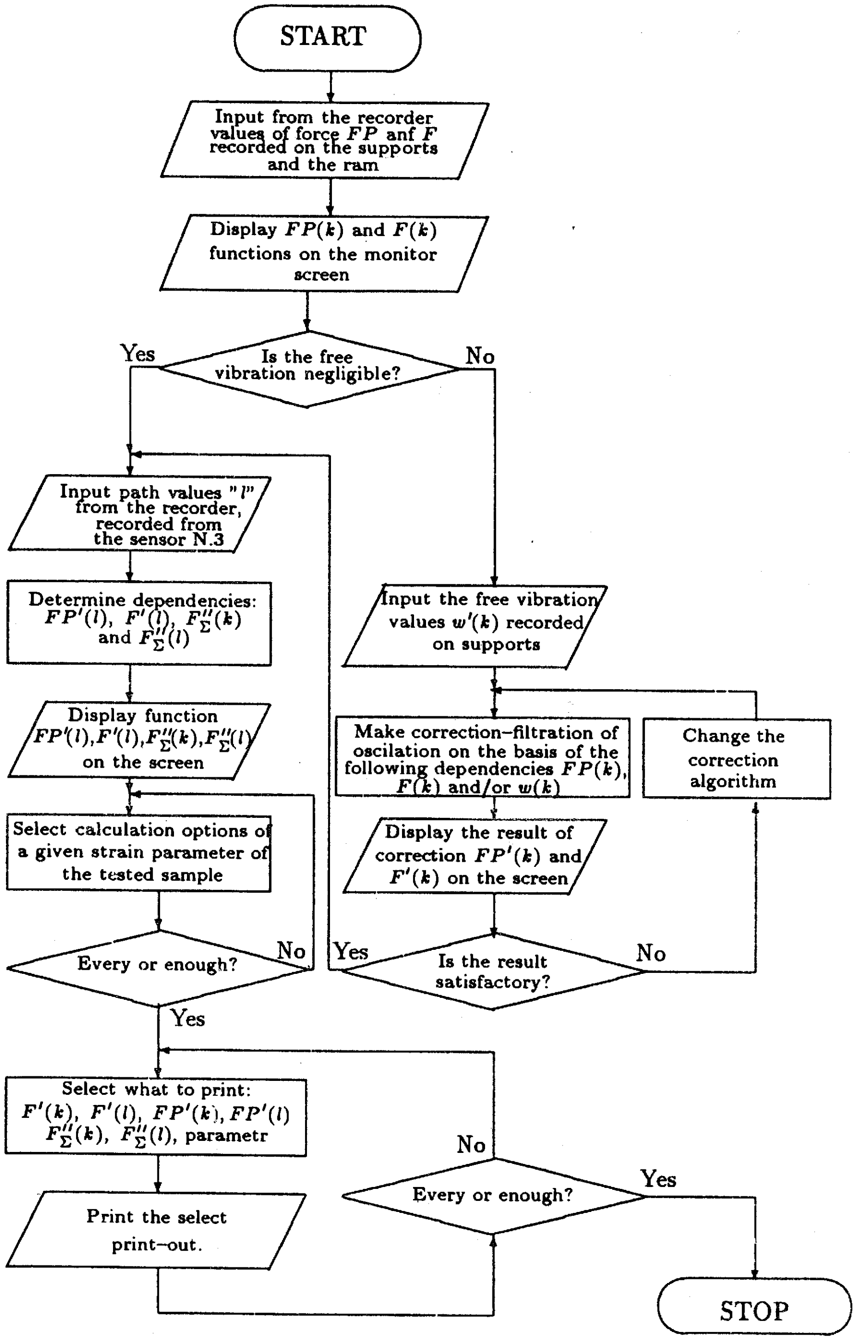


Fig. 5. Block diagram of measurement data processing stored in a digital recorder using IBM-PC 286 computer.

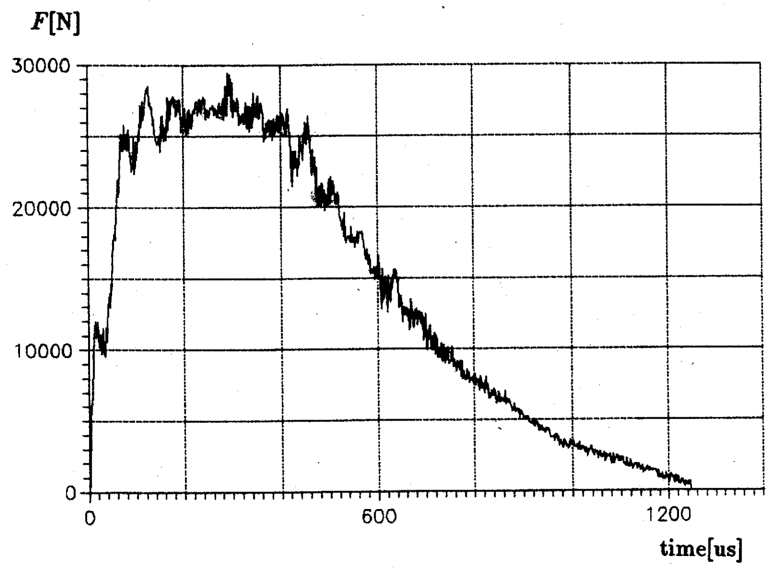


Fig. 6. Real diagram $F = f(t)$ recorded directly from the sensors on the ram.

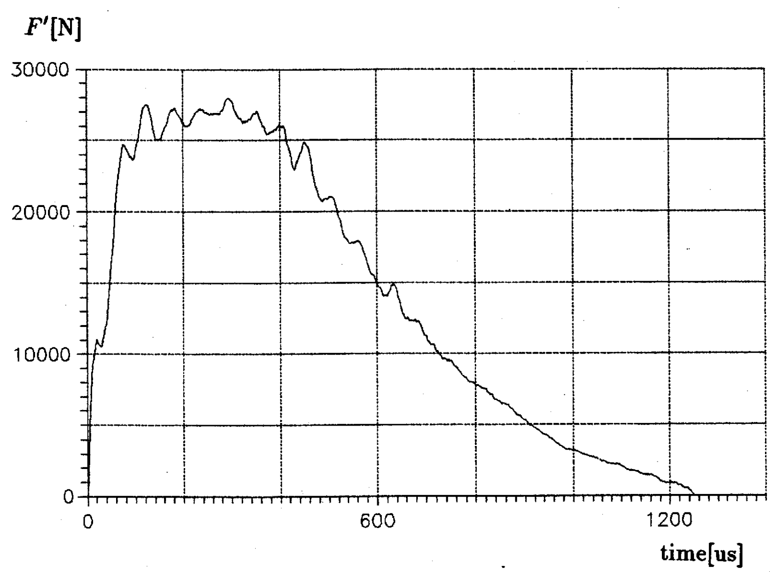


Fig. 7. Pre–cleaned dependence from Fig. 6 by means of zero-moments method (smoothing for $I = 11$).

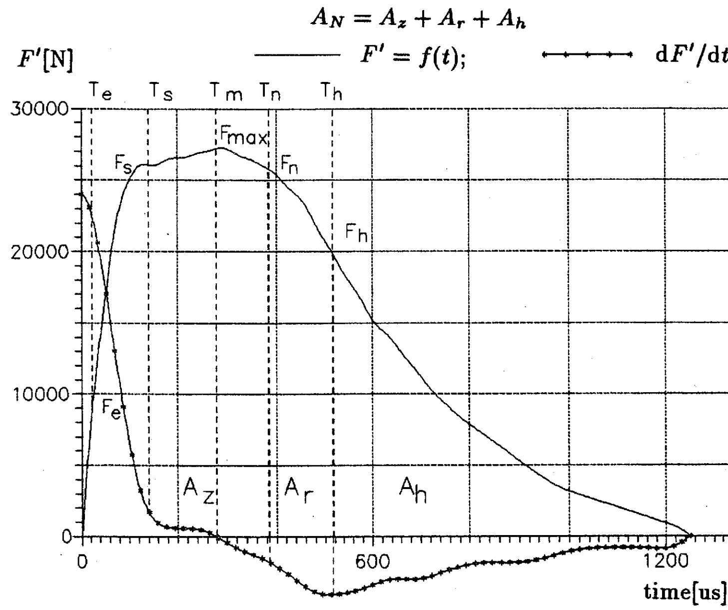


Fig. 8. Filtration final result of the run from Fig. 7 for $I = 21$, $K = 3$ by means of zero-moments method and after differentiation in order to determine characteristic points.

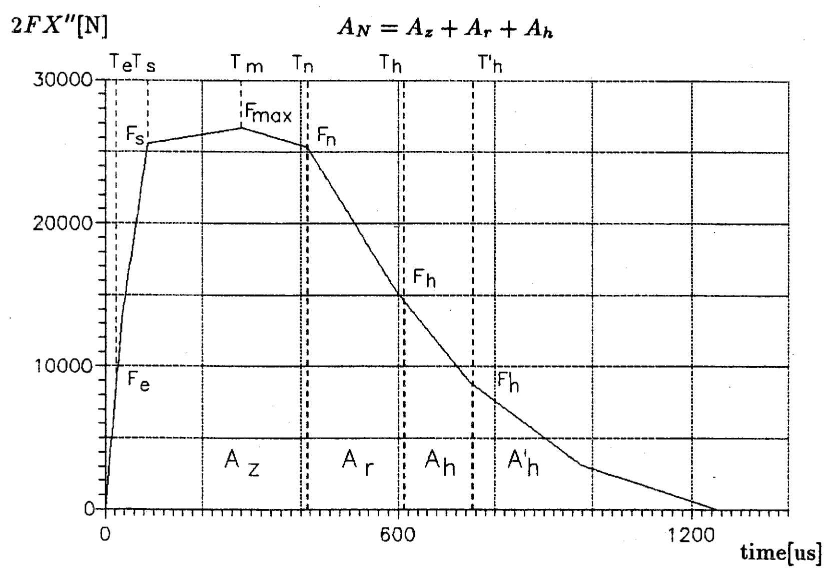


Fig. 9. Approximation of the diagram from Fig. 8 by means of spliced function method (method of linear function) for $N = 7$.