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POSSIBILITIES OF MATHEMATICAL PROCESSING OF THE IMPACT BEND TEST OF CHARPY V SAMPLES DIAGRAM

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The problem of proper interpretation of impact bend test diagrams for an accurate evaluation of cracking parameters of tested materials seems to be very important. The paper presents possibilities of the use of mathematical methods for processing fast dynamic phenomena in an impact bend test. Established are exemplary algorithms of diagram processing within mathematical filtration based on averaging the random variable an oscillation within the scope of time and frequency. A procedure for determination of charakteristic points of the sample impact cracking process has also been provided using an example of specific processing F-t diagram for Charpy V sample of 18G2A steel.

1. Introduction

The necessity of making provisions for material behaviour in case of impact loads makes it indispensable to seek research methods suitable for this purpose.

To describe the run of the impact bend test from the physical view point it should be stated that interaction between the tup, anvil and the sample has a wave character. Just as the tup strikes the sample, the reaction of the

Charpy sample will be determined by coupled interaction of the stress waves of compressive or tensile, as well as shear character, which are spreading within the sample at velocitis C_1 and C_2, respectively. The energy supplied by the stress waves produces:

- mechanical bending of the sample
- oscillations of the hammer-sample system due to a pulse caused by the impact
- acceleration of the sample.

Part of energy related to acceleration of the sample is connected with an intertial effect which plays an important role, particulary at the initial stage, immediately after the impact.

Simultaneous superposition of the above phenomena causes the proper interpretation of the impact bend test to be essentially difficult both from the theoretical and practical point of view. If we take into consideration the Charpy V sample with the initial crack as a notch end, subject to a dynamic action of the load $F(t)$, then we will be able to reduce the problem of a material effort to determination of the state of stress σ_{ij} near the crack tip which, within dynamic linear mechanics of fracture, can be determined as follows

$$\sigma_{ij} = K_n(t)\frac{g_{ij}(Q,u)}{\sqrt{2\pi r}} \tag{1.1}$$

where

$K_n(t)$	–	dynamic stress intensity factor, $n = I, II, III$
t	–	time of ther force $F(t)$ action
$g_{ij}(\Theta, v)$	–	angular function of stress pattern and velocity v of crack tip connected with the movable coordinate system Θ, r and $i,j = x,y$, $r \to 0$.

Because the state of stress is explicitly characterized by the dynamic stress intensity factor $K_I(t)$, evaluation of material effort can be reduced and conditions of the crack development determined as follows

$$K_I(t) = K_{Id}(v) \tag{1.2}$$

where $K_{Id}(v)$ – resistance against the crack development in dynamic conditions.

The problem resolves then itself into theoretical calculation of $K_I(t)$ and experimental determination of $K_{Id}(v)$. The evaluation of $K_I(t)$ is made after the solution linear elastodynamics equations, whereas the evaluation of K_{Id} conected with plotting the $F(t)$ curves during the dynamic bend process of the Charpy V sample. Owing to that it is possible to assign on the diagram points which characterize individual stages of the sample failure, allowing, among other things, the K_{Id} values to be determined.

Complexity of the dynamic bend process, previoulsy mentioned, causes the actual run of the F-t diagram to be, in most cases, disturbed due to influence of stochastic phenomena. In the main, first oscillations within an interval of $0 \div 20\mu s$ on the F-t diagram are attributed to an inertial effect, and next oscillations result from an accumulated elastic strain energy and reflected stress waves. The force as a result of mechanical bending of the sample will not be predominant on the diagram before the long time run of $t > 50\mu s$. Due to a sudden impact of the tup on the sample a sudden change in elastic strain energy, accumulated in the hammer, occurs. This energy is transferred in the form of a damped sine curve leading to oscillation of the force of interaction between the tup, anvil and the sample. The frequency of reflected waves is 100 kHz between the load points, and 60 kHz on the tup. The effect of suddenly released elastic strain energy are stress waves of approximately 30 kHz of frequency. Moreover, from theoretical considerations one can come to a conclusion that:

- time runs of forces F and FP measured on the anvil and tup, respectively, oscillate around the run of actual force $2FX$ deforming (fracturing) the sample being tested
- time run of the force $2FX$ is delayed in relation to the run of force F, but it gets ahead of the FP run
- measurement of the resultant force F_σ allows partial compensation of phase displacements and oscillations of measured forces F and FP in relation to the force $2FX$.

In connection with the above situation, evaluation of the dynamic bend process will be explicity dependent on location of the sensore which record the signals, relative the stress waves created. The phenomenon evaluation process it self, connected with the mathematical processing of the diagrams received, needs a competent simulation of the impact bend process in order to include essential physical phenomena previously mentioned.

A necessary and sufficient condition of analogy between the model (sample model) and real object (sample real) is the description of the processes, occuring by means of identical differential equations, and compatibility of similarity numbers. The above conditions have been included assuming an appropriate discrete model described by Ranatowski et al. (1993).

At present, there is a great chaos in the field of physical interpretation of dynamic runs obtained in the impact bend test. Only a few authors (cf Ranatowski, 1980; Kobayashi, 1984) pay attention to this important problem. As yet, there are no explicit methods of determination and evaluation of the process characteristic points. This results in the fact that the crack resistance parameters obtained in such a way, by proper calculations, are burdened with serious errors and they are not very useful for further considerations.

2. Mathematical run processing

Mathematical processing of measurement data of impact bend tests can be treated as crucial in dynamic research into the bend resistance. It is difficult to make a proper physical interpretation of the recorded runs without their appropriate processing (filtration). Therefore, the use of proper methods of impulse processing (cf Rabiner and Gold, 1975; Max, 1984) becomes a question of great importance. The mathematical processing of these runs will be based on their filtration by means of specific algorithms and will include:

- Filtration of interference within recorded runs, the so-called smoothing
- Determination of the resultant force F_σ
- Final filtration-correction of the resultant force
- Normalization and calculation of the parameters which characterize the cracking.

The paper, because of its limited volume, deals only with the most important questions of the measuring data filtration.

Smoothing – carried out by instantaneous value change of each filtered run $f(t)$: $FP(t)$ – from sensors located on the anvil; $F(t)$ – from sensors located on the tup, into values of the so called zero-rank moments $m_0(t)$ (mean values) (cf Ranatowski et al., 1993). The values $m_0(t)$ are calculated for discrete time $k = t/\Delta_t$ ($\Delta_t \cong 2\ \mu$s) on the basis of the following dependence

$$m_0(k) = \frac{1}{I+1} \sum_{i=k-\frac{I}{2}}^{k+\frac{I}{2}} f(i) = m_0(k-1) - \frac{1}{I+1}\Big[f\Big(k-1-\frac{I}{2}\Big) - f\Big(k+\frac{I}{2}\Big)\Big] \tag{2.1}$$

where

$I+1=\frac{T}{\Delta_t+1}$	–	number of averaging data estimated from inequality $I \leq M/50$
$M+1$	–	general number of data for every recorded run
T	–	length of averaging interval.

The runs $FP(k)$, $F(k)$ cleaned of high-frequency interference are marked farther on as $FP'(k)$, $F'(k)$.

Determination of the resultant force $F_\sigma(k)$ – is performed in a selected program module, generally after the following dependence

$$F'_\sigma(k) = \frac{1}{2}[a_w 2FP'(k) + (2-a_w)F'(k)] \tag{2.2}$$

where

a_w – weight factor including uneven fraction of individual components of expresion (2.2)

In the module applied the parameter a_w will be calculated from the follcwing formula

$$a_w(k) = 2\frac{\sum\limits_{k=0}^{M} F'(k)}{\sum\limits_{k=0}^{M}(2FP'(k)+F'(k))} \tag{2.3}$$

Final filtration of resultant force – is carried out when it is impossible to make explicit interpretation of the results on the basis of $F'_\sigma(k)$. Such a filtration may be carried out both in the field of discrete time as well as discrete frequency.

The final filtration of run $F'_\sigma(k)$ in the field of discrete time is carried out just as "smoothing" (formula 3), the values $F'_\sigma(k)$ being, unlike this stage, averaged repeatedly for greater number of data.

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 subjective, what may make it difficult to separate characteristic run ranges of force $F''_{\sigma 1}(k)$. Differentation of that run (cf Parchański, 1984) seems to be helpful.

The filtration in the field of frequency by separation will be carried out on the basis of discrete frequency spectrum determined by use of the Fast Fourier Transformation algorithm (DFT), defined for run $F'_\sigma(k)$ by the following formula

$$F'_\sigma(jm\Delta\omega) = \sum_{k=0}^{M} F'_\sigma(k)\exp(-jm\Delta\omega k\Delta_t) \qquad (2.4)$$

where

$\Delta\omega = \frac{2P}{M+1}$ – sampling interval in the field of frequency

m – number of succeeding sampling in the field of frequency.

However, since $F'_\sigma(jm\Delta\omega)$ is a product of spectrum $2FX(jm\Delta\omega)$ of the run $2FX(k)$ searched for and the unknown transmittance $W_\sigma(jm\Delta\omega)$ (cf Rabiner and Gold, 1975), then a logarithm is found from the transform $F'_\sigma(jm\Delta\omega)$ before making the filtration. As a result we obtain a new spectrum described by the following formula

$$|F^L_\sigma(jm\Delta\omega)| = \log|F'_\sigma(jm\Delta\omega)| = \log|2FX(jm\Delta\omega)| + \log|W_\sigma(jm\Delta\omega)|$$
$$\arg[F^L_\sigma(jm\Delta\omega)] = \arg[F'_\sigma(jm\Delta\omega)] = \arg[2FX(jm\Delta\omega)] + \arg[W_\sigma(jm\Delta\omega)]$$

In the above formula undesirable changes caused by the transmittance $W_\sigma(jm\Delta\omega)$ are additive in relation to the component $\log 2FX(jm\Delta\omega)$. These changes usually take place at high frequences and will be evaluated visually. On this basis, the operator will make a decision about cutting off suitable parts of the spectrum then $F^L_\sigma(jm\Delta\omega)$ will be interpolated with a properly choosen function. An antilogarithm is found from the new spectrum $F''_\sigma(jm\Delta\omega)$ obtained and the latter undergoes a reverse Fourier transform.

Because, when cutting off the part of the spectrum $F^L_\sigma(jm\Delta\omega)$ and interpolating it, the influence of the operator is greater than in the case of "smoothing", the result of this filtration is usually more subjective than in the case of filtration in the field of discrete time. This may essentially influence the results (cf Rabiner and Gold, 1975). Therefore, the run $F''_{\sigma 2}(k)$ obtained as a result of filtration in the field of frequency should be rather compared with the similar result of the final filtration within time range – the run $F''_{\sigma 1}(k)$, usually a final result of the filtration. This allows a certain evaluation of the run $F''_{\sigma 1}(k)$ for which is also helpful the frequency of stress wave oscillation determined on the basis of spectrum $F^L_\sigma(jm\Delta\omega)$. In reasonable cases, as a final result of filtration, the operator may also accept the run $F''_{\sigma 2}(k)$.

It should be mentioned that practically, when the filtration algorithm of spectrum $F^L_\sigma(jm\Delta\omega)$ is performed, it is convenient to omit the interpolation in the field of complex variables. To this end, including the DFT features (cf Rabiner and Gold, 1975), the succeeding operations of filtration in the field of frequency will be made for symmetric run $F'_D(i)$ being created as follows

$$F'_D(i) = \begin{cases} F'_\sigma(i) & \text{for} \quad i = 0, 1, ..., M \\ F'_\sigma(2M - i) & \text{for} \quad i = M + 1, M + 2, ..., 2M - 1 \end{cases} \tag{2.5}$$

Approximation of runs may be carried out both before and after normalization, and even omitting the final filtration stage (because of its good filtration properties) which results in the run denoted farther on as $2FX''(k)$. Within this process the analysed runs are approximated by spliced functions FS of free nodes (cf Suchomski, 1990), at a given case – by linear intervals in the following form

$$FS(k) = a_{n-1} + (k - k_{n-1})\frac{a_n - a_{n-1}}{k_n - k_{n-1}} \tag{2.6}$$

where

- k_n – discrete time corresponding to the end of n and start of $(n+1)$ approximation intervals (splicing points), with $k_0 = 0$, $k_N = M$, respectively
- a_n – value of FS function at splicing points, with $a_0 = a_N = 0$
- N – number of approximation intervals.

The above results from the main aim of this processing stage, explicit determination of the fields of elastic and plastic strains and of stable and unstable cracking of the sample tested.

In the module performing the above approximation the parameters $a_1, a_2, ..., a_{N-1}$ and $k_1, k_2, ..., k_{N-1}$ of the function (2.6) are assigned as a result of minimization of the square error with weight $1/(k_n - k_{n-1})^2$ within the n interval of approximation (cf Ranatowski et al., 1993). To this end, a self-learning optimization algorithm for random searching (with modification) Novoselcov et al. (1990) will be used. Initial values of the parameters sought for will be determined by the operator on the basis of selected numbers of intervals N (usually $N = 7$ will be efficient) and approximated run of suitable force.

Normalization and calculation of parameters which characterize the resistance against cracking is the simplest stage among the steps described above. The program module used for this purpose will calculate the values of K_{IC}, G_{IC}, J_d etc. on the basis of formulas which are known from greater part of the bibliography. These calculations are carried out basing on the characteristic points determined.

3. Practical example

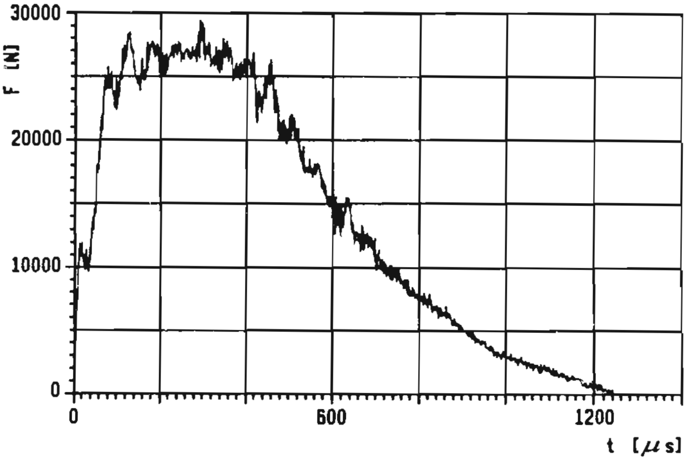

Fig. 1. Practical diagram $F = f(t)$ recorded on the ram

Below, in Fig.1 to Fig.3, are shown the practical results of the selected stages of filtration – correction and processing of measurement runs in the field of time obtained for the Charpy V sample of 18G2A steel, under impact bend. The filtration-correction stages used for the practical force diagram during the impact bend test (Fig.1) make it possible to interpret the obtained final diagrams (Fig.2, Fig.3) much more exactly than the initial diagram. On the basis of the final diagrams it is possible to determine more precisely the characteristic points of the sample failure run examined during the impact bend test, and to divide the whole failure work of the tested sample (A_N). Owing to the above interpretation it is also possible to more accurately evaluate the parameters of the sample tested as: K_{IC}, G_{IC}, J_d etc., and also to collect additional information about the mechanism of the process of tested material failure. The amplitude spectra shown in Fig.4 (curves 1,2,3) correspond to the time runs $F(t)$, $F'(t)$ and $2FX''(t)$ shown in Fig.1 to Fig.3.

These spectra have been obtained by initial symmetrization of the above runs in compliance with the relationship (2.5). The spectrum obtained after final filtration in the field of frequency is also shown in Fig.4 (curve 4). This spectrum has been obtained using the time run spectrum obtained after initial filtration of the run $F(t)$ by means of single "smoothing" for $I = 11$. This initial filtration which had eliminated the noise essentially simplified filtration in the field of frequency. As we can see in Fig.4, it is identical to

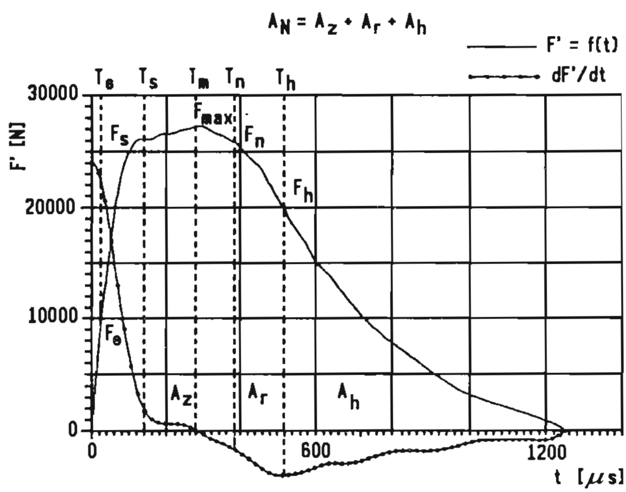

Fig. 2. Final filtration result of the run $F(t)$ from Fig.1 obtained by means of the triple smoothing method for $I = 21$, and diferential of the obtained run

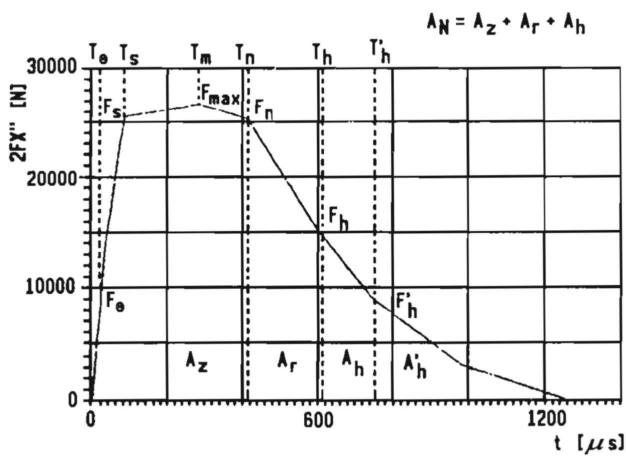

Fig. 3. Approximation of the run from Fig.2 by means of the spliced function method (linear function method) for $N = 7$

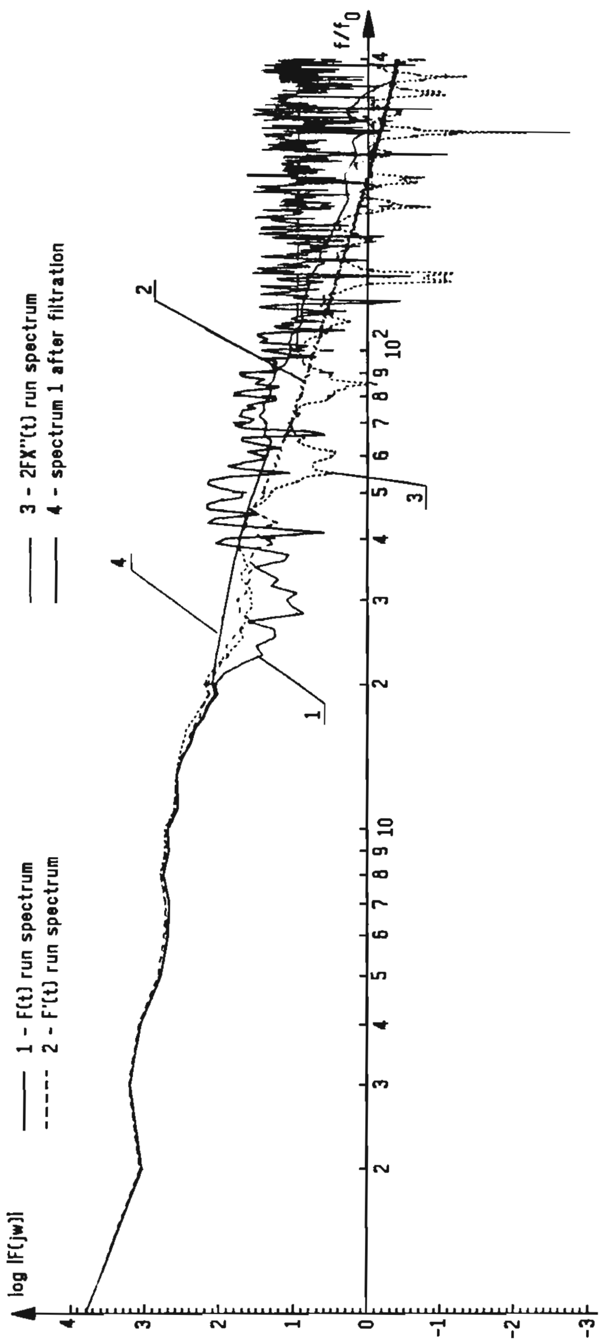

Fig. 4. Amplitude frequency spectrum of the runs from Fig.1 and 3, and in the field of frequency after filtration

the results of filtration in the field of time and approximation. Nevertheless, authors recommend, however, using the filtration in the field of time and/or the approximation. Examinations within the range of run filtration are being carried on.

4. Conclusions

Finally the following may be stated:

- 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 the failure process, especially for complicated heterogeneous systems like e.g. weld joint.

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Możliwości matematycznej obróbki wykresu udarowego zginania próbek Charpy V

Problem właściwej interpretacji wykresów próby udarowego zginania dla dokładnej oceny parametrów pękania badanych materiałów wydaje się być bardzo ważny. W artykule podano możliwości wykorzystania matematycznych metod dla obróbki szybkich zjawisk dynamicznych w próbie udarowego zginania. Podano przykładowe algorytmy obróbki wykresów w zakresie matematycznej filtracji opartej na uśrednianiu zmiennej losowej i oscylacji w dziedzinie czasu i częstotliwości. Określono procedurę wyznaczania punktów charakterystycznych procesu łamania udarowego na przykladzie konkretnej obróbki wykresu *F-t* dla próbki Charpy V ze stali 18G2A.

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