Destruction of brittle materials by microsecond pressure pulses at their formation by magnetic pulse method

S. I. Krivosheev, N. V. Korovkin, V. K. Slastenko, S. G. Magazinov

***Abstract*—** The possibility to use the magnetic pulse method of controlled pressure pulses formation in the microsecond interval with amplitude of up to 2 GPa has been presented. The comparison of test results of brittle materials has exhibited the possibility to analyze the destruction process both of samples having macro defects and defect-free ones. The controlled magnetic pressure makes possible to form by using the ultimate potential energy a set of key parameters (strength under static conditions, ultimate elongation, time of energy storage) featuring the process of destruction. Application of described criteria approach allowed to determine the relation between surface fracture energy and impact parameters using the measured initial crack propagation velocity. The application of magnetic pulse method for testing conducting materials has also been proven.

***Keywords*—** crack, magnetic pulse method, magnetic pressure, fracture, pulse strength, shock action

I. Introduction

THE ability of materials to withstand large transient loads has been proven by multiple papers, however, the research of fracture processes is still of the utmost interest both from theoretical and application-oriented stand points. The complexity of destruction process analysis is due to the influence of multiple factors and features that are function of material performance, parameters of influence, variety of types and structures of force fields during the tests.

The loss of strength properties and bearing capacity of samples is owing to the failure of material homogeneous structure and to the occurrence of structural integrity rupture zones. Multiple papers examine the issues of fracturing and fracture propagation under different loading conditions, however, an adequate analysis of brittle fracture under conditions of pulse loading is not definitely shaped yet.

The experiments carried out with various materials exhibit the threshold nature of fracture and increase of failure amplitude with load pulse shortening during destruction of both defect-free samples and those having macro-defects of mode of cracks [1- 3]. You will find below the results from the analysis of materials destruction under magnetic pulse action.

This work is done by the authors on their own initiative.

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II. Distinctive features of magnetic pulse action

Under magnetic pulse action the following loading schemes may be implemented, where

•the stress field is formed, its spatial localization is substantially smaller than sample sizes (magnetic pulse shock action);

•the loading takes place under known parameters controlled on load formation;

•the sample may be considered as energy-closed system because at the end of load pulse there is no energy interchange between sample and loading device.

Loading conditions having these distinctive features may be implemented in laboratories when studying material destruction upon spallation loading scheme [3-6]. Except for spallation loading schemes, the magnetic pulse technique allows us to implement pulse loading with aforementioned peculiarities while studying the destruction of samples having macro defects of mode of cracks [7, 8]. Such a situation takes place in some technologies dealing with manufacture of meals and ore beneficiation, as well as during natural and induced earthquakes [9].

III. Distinctive features of magnetic pulse action

It has been known that when the current flows on closely spaced conductive parts, the latter experiences the action of mechanical force determined by interaction of flowing current and magnetic field created by this current. In general case the direction and distribution of acting forces is specified by current distribution on cross-section of conductive parts and depends on their geometric sizes and relative position. In case of perfect conductivity a normal force (magnetic pressure) acts on conductor's surface unit:

$$\overline{P}_m = \frac{1}{2}\cdot\left[\overline{J},\overline{B}\right], \tag{1}$$

where $\overline{J},\overline{B}$ - surface current density and field density at a point on surface.

As it is described in [10] for flat parallel buses of *s* thickness and gap *h* that is substantially less than their width *b*, one can neglect the fringe effect and consider the current I and magnetic field distribution as edgewise uniform. Under this estimation the instantaneous value of magnetic pressure P_m(t) from the side of gap can be determined as

$$P_m = \frac{1}{2} \cdot \frac{I}{b} \cdot B = \frac{1}{2} \cdot H \cdot \mu H = \frac{B^2}{2 \cdot \mu}, \quad (2)$$

where *B(t),H (t)* - inductance and strengths of magnetic field, $\mu = \mu_0 = 4 \cdot \pi \cdot 10^{-7}$ H/m.

In order to reduce the error while specifying the value of pressure pulse transferred to the sample caused by the energy of buses pressing, the bus thickness is minimized in accordance with the current integral

$$I_c = \int_0^{t_c} (I(t)/(s \cdot b))^2 dt \ , \quad (3)$$

where *I(t),* t_c –current and duration of its action. It is known that copper remains in a solid state until the current integral I_c is less the critical value $0.89 \cdot 10^{17}$ $A^2 \cdot s \cdot м^{-4}$ [11]. In most cases the thickness of buses corresponding to this condition is less than the depth of magnetic field penetration and it should be considered that the current distribution in the bus is close to be uniform.

The most convenient and the simplest way to get heavy pulse currents necessary for forming the pressure sufficient to destroy materials is a direct discharge of the bank of capacitors on low-inductance load, for example, flat busbar.

The circuit of surge-current generator working on flat buses upon symmetric scheme of sample loading is given on Fig. 1.

The waveform of pressure pulse in this configuration is determined by that one of current flowing on flat buses. A transient phenomenon in equivalent circuit of pulse current generator (Fig. 1) at fixed inductance is described by the following equation:

$$L\frac{d^2 I}{dt^2} + \frac{d(R \cdot I)}{dt} + \frac{1}{C} \cdot I = 0, \quad (4)$$

which is solved according to initial conditions (t=0): I=0, $U=U_0$, $dI/dt=U_0/L$ [12].

The formation of single pressure pulses is urgent for the issues of fracture mechanics. To solve this type of problem one should install non-linear resistors into the circuit where the current flows. Non-linear vylite, thervite, zinc oxide resistors are widely used in strong pulse currents engineering [13, 14].

A generator PCG-125 containing two pulse low-inductance KMK-50-6 type capacitors of 6 uF for charge voltage up to 50 kV and acting as storage batteries, has been used to carry out the experiments. This generator allows getting a unidirectional pulse under pulse loading up to 20 nH, its amplitude is 600 kA of 4 microseconds that corresponds to the pressure pulse of up to 2000 MPa.

In the event of uniform distribution of current on buses as wide as b, the values of pressure pulse acting on them are uniquely related to the values of current pulse and expressed by equation (2). In such a case a complicated problem of pressure pulse measurement is reduced to a simple procedure of current pulse measurement [8].

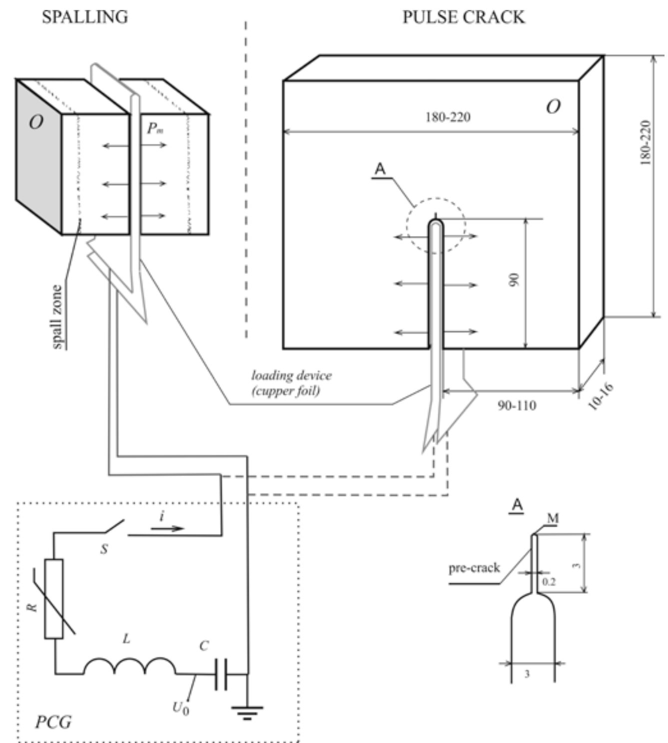

Fig. 1. Schematic circuit of pulse current generator (PCG) device and sample schemes of loading for pulse testing of spalling and crack resistance. C, L - capacity and self-inductance of PCG; S – high-voltage commutation switch; R - nonlinear resistor; O –sample under test. Sizes are in mm.

IV. Destruction of Samples Having Macro Defects of Mode of Cracks

Following the technique of magnetic pulse loading described in [8] there have been performed the studies of fracturing the samples made of various materials. The samples having typical sizes given on Fig.1 have been used for these experiments. At microsecond loading duration the formation of magnetic pulse shock conditions has been ensured in these samples as opposed to experimental conditions implemented in [15, 16]. Due to the symmetric nature of loading and sample symmetry the main crack (MC) is developing practically in one way [1].

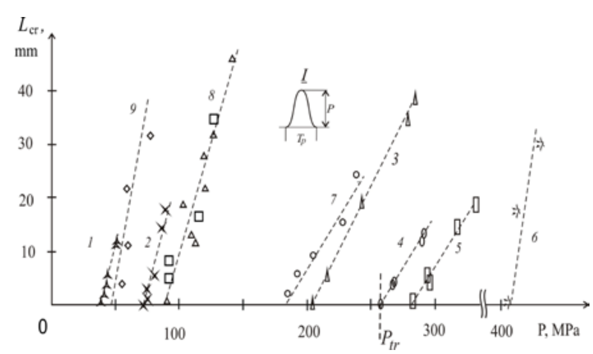

Fig. 2. Dependences of the length of penetrated crack on the amplitude of single pressure pulse at loading duration: 1 – limestone, 4.4 μs; 2 - marble, 3.6 μs; 3 – gabbro-diabase, 3.6 μs; 4 – sandstone, 3.6 μs; 5 - basil, 3.6 μs; 6 – polymer compound - 1.5 μs [17]; PMMA: 7-1 μs; 8 –2 μs; 9 – 4.3 μs [1, 18]. ***I*** - pulse waveform.

Typical dependences of the length of penetrated crack in samples containing macro defects of mode of cracks loaded according to mode I by pulse pressure uniformly distributed on crack faces on pulse amplitude and duration are shown on Fig. 2.

The example of PMMA destruction (curves 7, 8, 9 on Fig. 2) shows the increase of threshold fracture loads with action duration reducing. Threshold fracture loads P_{tr} are specified by extrapolation of the length of penetrated crack L_{cr} to an area $L_{cr} \to 0$, the example is given for curve 4.

The dynamics of crack increasing investigated on optically transparent samples, created from PMMA according to the method, presented in [18]. For image registration is used superspeed camera SFR-2, working in photochronograph mode. Fragment of movie with the start of crack progression is shown on Fig. 3. The synchronization of the destroy process and the pressure pulse carried out according the start of optical radiation (R zone) from plasma channel of electrical discharge in high-voltage commutation switch. As in the experiments mentioned above there is delay τ_d of the start of the developing MC by comparison with the start of the pressure pulse $P(t)$.

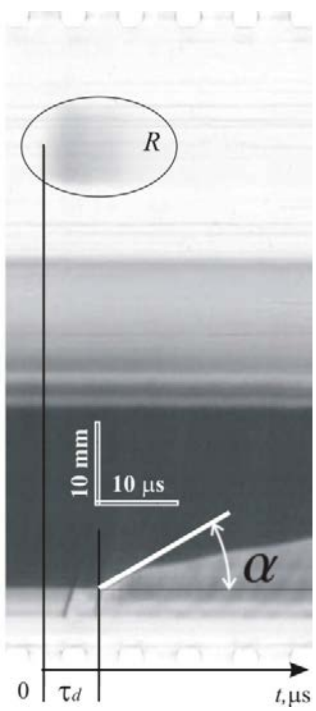

Fig. 3. Visualization of the initial phase of crack propagation.

The initial speed of crack spread is determined from angle of inclination of tangential curve to the crack path. The increasing of the pulse magnitude by the constancy of his duration result to the increasing of the crack spread velocity on the initial stage. The subsequent spread of crack there is under influence of reflected waves from the boundaries of sample.

V. Destruction criterion

The analysis of experimental data related to crippling tests under mechanical effect is reduced to determine the stress-strain state of a specimen and to select a relevant fracture criterion.

The transition of an object (system) from one state into another is due to the change in its characteristic parameters. We shall consider the destruction process as the transition of an object into the state when the implementation of its functionality becomes impossible. It is evident that this process is strictly non-equilibrium and non-reversible and results in increasing of system entropy. The transition of a system in fractured state requires a certain effect whose parameters exceed the values that are typical for normal state. Examples of these transitions are as follows: rupture of materials under conditions of exceeding allowable mechanical stresses; clearance electric breakdown when the limit electric field intensity is exceeded; electric burst of conductors when the limit current density is exceeded; breakdown of optical parts in case when the limit optical radiation density is exceeded, etc.

The pulse effect renders difficult the analysis of destruction process that is due to the occurrence of not only spatial but also time-related features of stress state of medium. The key difference of the destruction under static and pulse action is the lack of comparability of time scales (characteristic times) of loading process and destruction, the relationship of which is by an order of magnitude less in case of dynamic effect than in the event of static impact. As a result, we see the dependency of the amplitude of destructive effect on its duration (rate of rise) proving the generic case of thermodynamics – the increase of the capacity of destructive action along with time shortening for system transition from one state into another.

The analysis of destruction process depends largely on the choice and validity of destruction criterion. A phenomenological approach makes it possible to reveal general regularities of loading process, which antecedes the destruction, without going into details when analyzing the whole body of physical mechanisms of fracture.

Many experimental works and analytical and calculation researches have been dedicated to study the destruction, the generalization of their results is an independent task. The variety of stress patterns and load modes may be substantially restricted if we point out the modes of pulse loading having the stated features.

The analysis of criteria (of force, energy, thermodynamics) used to estimate and describe destruction processes under pulse loading was given in [19]. We have to expressly focus on experimental and analytical researches dealing with pulse destruction carried out in Russian Federal Nuclear Centre - All-Russian Scientific Research Institute of Experimental Physics. These researches gave the opportunity to establish a master dependency between the strength of different materials and thermodynamic invariant [20] $J_1 = P_{cr} / \left(G\rho \left(H + L_m \right) \right)$, where P - critical density of absorbed energy, G – Gruneisen factor, ρ - material density, H and L_m - enthalpy and melting heat and structural and on time-dependent approach proposed in [21].

It has been known that the enthalpy is specified as follows $H = U + pV - \sum X_i y_i$, where U -internal energy of a system, X_i and y_i - integrated force and coordinate of non-mechanical force action. In the absence of non-mechanical forces the enthalpy of a system is only specified by internal U and potential energy pV. On the assumption that in the event of pulse action the process of potential energy storage is of adiabatic nature, that is to say that it takes place at constant entropy $S \sim const$, the enthalpy change will take the form $dH = V \cdot dp$, and the change of internal energy will depend only on the action of external forces and will be expressed as follows $dU = p \cdot dV$. This explains the time dependence-strength (*TDS*) correlation described by Zhurkov model [22] with the use as internal energy parameter of materials and results of [20] obtained based on thermodynamic approach. To evaluate the state of a system let us introduce the ultimate value of potential energy $p_{fr} V_{fr}$, when once being exceeded the system passes into destroyed state.

Under dynamic (pulse) effect the potential energy is determined by time-dependent parameters $p(t)$ and $V(t)$. Taking into account that the process of transition from one state into another should take time we will suppose that the transition of a system into destroyed state is considered as completed once the potential energy achieves the ultimate value $p_m V_m$ within a certain time frame τ_L. This statement may take the following form

$$\frac{1}{\tau_L} \int_0^t p(t)V(t)\, ds \le p_m V_m , \qquad (5)$$

Its violation means the destruction of a system.

A graphic illustration of described situation is given on Fig. 4 for triangular form of the loading function. For simplicity and clarity, the dependence $V(p)$ presented for the case of a linear relationship between load and deformation. In general, however, it may be highly nonlinear.

It is evident that under such a scenario the destruction takes place when the volumes of a parallelepiped $V_0 \cdot p_0 \cdot \tau_L$ and of a hexahedron with vertices $0\,A_{V,t} A\, A_{p,t} t_{fr}$ are equal. In plane $p\ ,t$ the path described by point **F** passes through *TDS*-curve dividing non-destroyed *I* and destroyed *II* states of a system. It should be noted that the *TDS*-curve describes the behaviour of the system under the action of the minimum failure load given duration for which the condition (5) is violated.

To describe the behavior of a system under conditions of one-dimensional elongation implemented during materials testing according to spallation destruction pattern the expression (5) may take the following form:

$$\frac{1}{\tau_L} \max_x \int_0^t \varepsilon(s,x)\sigma(s,x)\, ds \le \varepsilon_m \sigma_0 , \qquad (6)$$

where $\varepsilon(s,x), \sigma(s,x)$ - actual values of deformation and stress in a point with coordinate *x*, ε_m -value of deformation corresponding to material breaking strength σ_0 under static conditions. Thus, assuming that the function $\varepsilon(s,x)$ is continuous from action start to the moment when the system passes into destroyed state, the expression (6) may take the form

$$\frac{1}{\tau_L} \varepsilon_\xi \int_0^t \sigma(s,x)\, ds \le \varepsilon_m \sigma_0 , \qquad (7)$$

here $\varepsilon_\xi \in \left[\min_{(0,t)} \varepsilon(t), \max_{(0,t)} \varepsilon(t) \right]$ and depends on function type $\varepsilon(t)$.

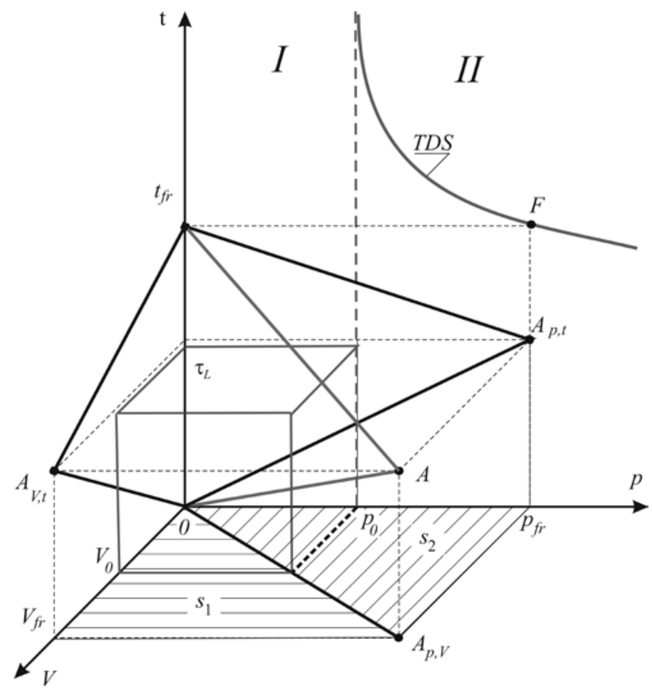

Fig.4. Destruction scenario at triangular type of loading.

In this scenario the line $0A_{p,V}$ on Fig. 4 represents the deformation dependence $\sigma(\varepsilon)$ in case of uniaxial extension of material and is non-linear in general case. For brittle materials this dependence is close to a linear one up to the destruction [23, 24] and the areas determining the change of internal energy S_1 and enthalpy S_2 are equal.

With an accuracy up to the lower limit of integration ($0 \Leftrightarrow t - \tau$ while at action start there is no physical ground for such a substitution at time zero) and in general case differing of a unit of expression $\varepsilon_m / \varepsilon_\xi$ equation (7) is relevant to the statement of structure-time criterion [21] for unidimensional elongation under spallation conditions

$$\frac{1}{\tau}\int_{t-\tau}^{t} \sigma\ (s,x)\ ds \le \sigma_0\ , \qquad (8)$$

where τ – structural time of destruction. In this case the principle of equal areas is implemented; it is used to describe the voltage-time characteristics of electric strength of a gap [25, 26].

From expressions (7) and (8) it is seen that the structural time of destruction depends not only on the material properties, but also on the type of loading:

$$\tau = \tau_L \cdot \varepsilon_m / \varepsilon_\xi \qquad (9)$$

This fact is an obstacle to use of this parameter τ as part of the parameters defining the properties of material.

VI. Analysis of Experimental Data

In case of testing the samples, having macro defects of mode of cracks whose results are given on Fig. 2 the stress state at defect point is mainly determined by its design. The experiments described above were performed on standard samples whose general view is shown on Fig. 1.

A. Fracture analysis

A numerical analysis of wave loading of samples carried out in ANSYS environment with due account made for actual sizes of pre-crack and time parameters of load pulse exhibits a substantial impact of actual sizes of defect point not only on the stress state in a point neighborhood but on the change of potential energy fixed at a point of maximum stress. In such an event one could observe a significant difference between calculation data for defects with actual sizes and those to be calculated while taking into account an approach described in [27] for crack tip. On Fig. 5 are given the values of parameter

$$PE(t) = \int_0^t \varepsilon(s,x)\sigma(s,x)\ ds \qquad (10)$$

at a point M (see Fig. 1), corresponding to maximum stresses.

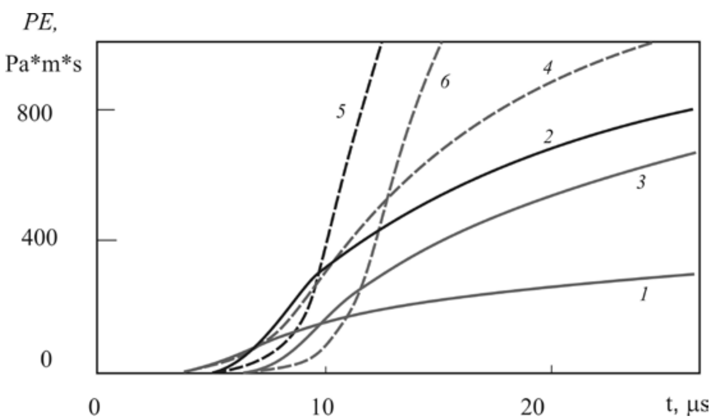

Fig. 5. Dependence $PE(t)$ in PMMA sample at pre-crack length of: 1 and 4 – 0 mm; 2 and 5 – 1.5 mm, 3 and 6 – 3 mm, loaded by pulse of 320 MPa of 5.6 microsecond duration –curves 1-3 and of 11.6 microsecond duration.

It is evident that the condition (6) may be met at different moments of time upon macro defect occurrence and duration of loading. Accounting for an actual structure of defect point makes possible to describe the delay of PMMA samples destruction observed in [18].

A generalized dependence of threshold load uniformly applied to crack faces for various materials plotted with relation to ultimate potential energy – condition (6) is given on Fig. 6.

Under spallation, loading a pulse of compression is created on one end of a sample as a result of interaction of the latter with a striker accelerated by some means or other. The pulse of compression once passed on a sample is reflected from a free end and returns into the sample in the form of tension wave under the influence of which the destruction occurs.

Parameters of acting pressure pulse are restored in terms of running speed of free surface of a sample and depend on the properties of striker materials, its speed and sizes. The magnetic pulse technique makes possible to extend the potential of this pattern by means of formation of transient pressures under control within a wide range of parametric variation directly at the edge of a sample [8].

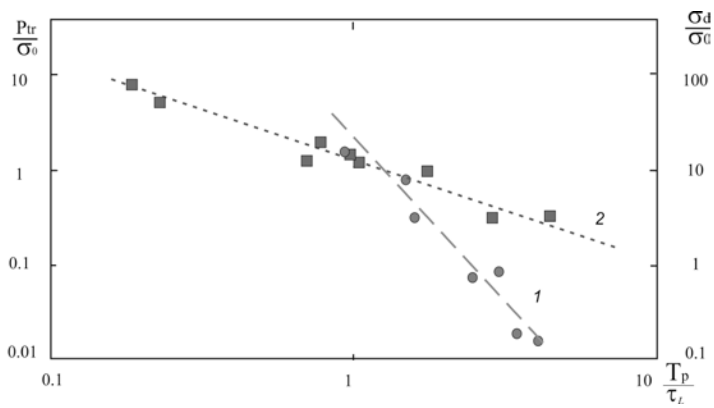

Fig.6. Generalized dependence of threshold destruction load for various materials for testing the samples having macro defects – 1 and according to spallation destruction pattern – 2.

In [28, 29, 30] are given the data of tests of some rocks performed under spallation loading conditions with the use of magnetic pulse loading technique. An integrated dependence of the strength of various materials against the relative pulse duration obtained as a result of analysis of these data with the use of condition (6) is given on Fig. 6 curve 2.

In Table I are given major mechanical characteristics of materials used for testing by magnetic pulse technique.

The dependences given on Fig. 6 prove that it is possible to determine the parameter upon data obtained during the tests with the use of various loading patterns. Together with static behavior of material makes it possible to forecast the behavior of materials under pulse loading. When comparing the obtained relationships one may note that to specify the parameter by using the scheme of symmetric loading of samples having macro defects substantially much smaller amplitudes of pressures will be required against those for spallation destruction schemes.

Table I. Parameters of materials used for testing

Parameter *material*		σ_0, MPa	c_1, m/s	ρ, kg/m^3	τ_L, μs
1	*Gabbro diabase*	17.5	5600	3286	11
2	*Limestone*	12.4	3780	2570	1.75
3	*Marble*	6.2	3790	2550	2.75
4	*Sandstoun*	4.12	5100	2520	14.7
5	*Granite*	5.2	4250	2670	12.4
6	*PMMA*	72	2450	1140	4.2

B. *Initial crack velocity and surface energy of fracture*

The typical behavior of initial trajectory of cracks under the different magnitudes of load are shown on Fig.7.

Initial velocity v_0 of crack spread for the polymethylmethacrylate (PMMA) samples has linear connection with exceeding of threshold magnitude P_{tr} of pressure pulse P_{cr}:

$$v_0 \approx K_s \cdot (P_{cr} - P_{tr}), \quad (11)$$

where $K_s \approx 2,67 \cdot 10^{-6}$, dimension in SI units. The threshold magnitude of the damaging pressure P_{tr} for pulse with duration ~5,2 mcs is determined with accuracy not less then 10% and is equal 95 MPa.

In according to Griffith A. A. [31] for crack development is

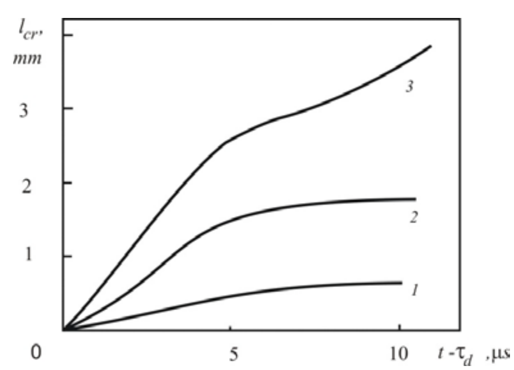

Fig. 7. Trajectory of crack on the initial stage of destruction. $P_{\max_i} < P_{\max_{i+1}}$.

necessary that stored system energy was enough for the creating of the new surfaces.

The surface energy γ is released during the damaging of elastic medium with the creation of new surfaces relate with the storage energy in medium by the relation:

$$\gamma = \pi\sigma^2 l / E, \quad (12)$$

where E - Young's modulus, l - length of crack.

During the increasing the tension at the moment t^*, corresponding to the violation of condition (6), start the crack formation. Note, that time moment t^* (with take into account size of precracking zone) is correlated with the observed in experiment delay τ_d of damage [18]. Differentiating (12) with respect to t, we get:

$$\frac{d\gamma}{dt} = \pi l \frac{d}{dt}\left(\frac{\sigma^2}{E}\right) + \pi\left(\frac{\sigma^2}{E}\right)\frac{dl}{dt}, \quad (13)$$

At the time moment t^*, length of crack $l = 0$ and relation (13) acquire a form:

$$\frac{d\gamma}{dt} = \pi\left(\frac{\sigma^2}{E}\right)\frac{dl}{dt} = \pi\left(\frac{\sigma^2}{E}\right)v_0 \equiv \pi(\sigma\cdot\varepsilon)v_0, \quad (14)$$

where v_0 - initial velocity of crack.

It is possible by the integrating (12) to obtain the relation between surface energy of damage and initial velocity of crack.

$$\gamma\big|_{t^*} = v_0\int_0^{t^*} \varepsilon\cdot\sigma\, ds = = v_0 \cdot PE(t^*) = v_0 \cdot (\varepsilon_0 \cdot \sigma_0 \cdot \tau_L) \quad (15)$$

With taking into account (11), surface energy of damage of PMMA is increased with increasing of magnitude of pressure pulse on crack boundaries.

For the initial velocity $v_0 \approx 570$ m/s of crack, corresponding to the increase of threshold value pulse $(P_{cr} - P_{tr}) \approx 210$ MPa, the surface energy of damage has risen more then 30 times (in comparison with static value, γ/γ_0 =33). The same behavior this parameter is noted in spalling damage experiments [32].

VII. Next Step - Metal Testing

The application of magnetic pulse technique together with described loading system in the form of flat buses to test conducting materials will require the modification of loading device. The possibility to form various magnetic systems has been analysed in [33].

A simple example of magnetic system whose magnetic flux will not interact with conducting sample and will not affect its

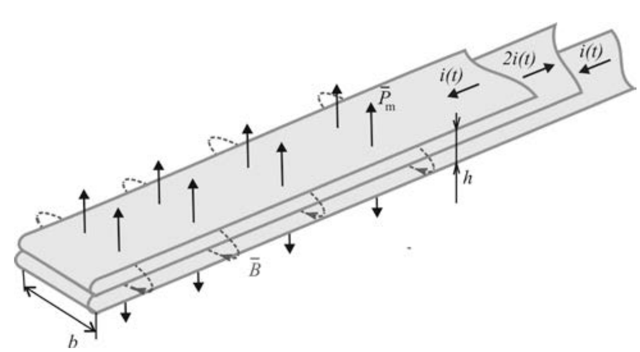

Fig. 8. Loading device for testing metal samples having macro defects.

characteristics is a quasi-coaxial system of flat buses (see Fig. 8). The choice of foil parameters is determined by condition (3). If the width b of system exceeds greatly the distance between direct and return current lead h/2 the magnetic pressure will be defined following equation (2).

VIII. Conclusion

The magnetic pulse technique makes possible to form controlled pressure pulses of microsecond duration with amplitude of up to 2 GPa and to implement various test patterns of materials under magnetic pulse shock loading. The introduction into the system of key time parameters of energy storage and conversion τ_L enables to analyse the destruction process under various loading patterns. Substantially smaller amplitudes of pressure required for testing the samples with macro defects of mode of cracks give grounds for such studied to be performed on metals with account made for modifications of loading device.

The investigation of the damages of the samples with cracks-shape microdefects, that had been loaded on mode 1 by the homogeneous distribution of pulsed pressure along the crack boundary allow us to determine the correlation between the surface energy of damage and the parameters of actuating pulse.

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