Response of Inherently Brittle Materials on Higher Loading Rates

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Abstract. Generally, there are components loaded in a wide spectrum of loading rates, however most of design work is based on the data obtained using quasi-statical and uniaxial loading conditions. In case of inherently brittle materials the situation is all the more complicated because of their brittleness. There is a lack of experimental data and knowledge base of material response at loading in the range between quasi-static and ballistic loading rates.

Cast basalt and soda-lime glass were the main experimental materials used in this investigation as a representative of natural based and structural brittle materials. These materials are widely used in civil industry as a building and decorative material, in chemical industry for transport of chemicals and in mining industry for transportation of powders (e.g. coal).

Application in extreme conditions and safety requirements, in particular, raise an issue of fracture behaviour at higher loading rates. The main aim of the contribution is to investigate influence of strain rate on fracture resistance and to analyze response of the microstructure to high strain rate loading including the change of mechanical properties. The fractographic analysis of fracture surfaces was employed in the investigation with the aim to identify changes in fracture behaviour.

Introduction

Many structural components are working at stable conditions of external load where the mechanical properties obtained at static and/or quasi-static loading conditions are supposed to be sufficient for their design. However, there are components loaded during their service or accidentally by the dynamic (impact) manner where statically determined properties are inappropriate and could be hazardous for the components. There is generally a lack of knowledge about the material response to the dynamic loading however there are approaches how to model or estimate the behaviour on the empiric, semi-empiric and/or physical base [1-3].

For ceramic based material a range of quasi-static loading (i.e. order of CSH of 1 mm/min ≈ deformation rate of 10^{-2}) and further high velocity (ballistic) loading (i.e. order of loading rates from 10 m/s ≈ deformation rate higher than 10^{4}) appears to be well described. For conditions of quasi-static loading there is a number of standardized procedures for evaluation of mechanical properties including the fracture resistance represented mainly by the fracture toughness [4]. The loading is performed on common mechanical or servo-hydraulic testing systems. The high speed tests are efficiently covered by a number of ballistic tests [5] and different adaptations of split Hopkinson bar test [6-8] including necessary supporting modelling. Comparably smaller effort has been paid to the loading rates of 1 up to 10 m/s (deformation rates from 10^{-2} to 10^{4}).

This work is concerned on loading rates lying between quasi-static and ballistic range. In this region an instrumented Charpy impact tester and/or drop weight tower can be used as a testing instrument. Many works are done in this area based on metallic materials especially on structural steels. In fact the Charpy test is more than one hundred years old and up to now is playing considerable role in testing mechanical properties of steel [9] as well as plastic [10].

In case of ceramic based materials there is no unambiguous methodology how to evaluate fracture properties at higher deformation rates. The present knowledge is rather not providing an easy insight into the fracture behaviour and material response during dynamic loading. The interpretation of the flexural strength appears to be slightly more clear because there is known that up to point of fragmentation onset there is an increase of flexural strength caused by forcing material to fracture from the place of maximum stress and not from an ideal (weakest, energetically more convenient) initiation point due to a lack of time for the material response together with overhang of available energy [11]. But still there is a problem of exact determination of fracture force for flexural strength determination due to oscillations (superposed dynamic effects) on loading trace. Quite different situation is when fracture resistance characteristics are coming in to the focus of interests. The most widely used characteristics for material fracture resistance characterisation is the fracture toughness. Determination of this characteristic is not straight forward (what is opposite to the case of metals) even at quasi-static loading rates where approximate approaches are very often used [4]. Only a few authors report results of dynamic fracture toughness obtained on ceramic based materials under. There is general presumption that no change in the fracture behaviour over pronounced range of loading rates is present. This view is based on fundamental knowledge about ionic and/or covalent coupling bringing together with presumed unchanging dislocation activity at room temperature, typical in ceramic based materials. However, some works have shown on experimental data an increase of fracture resistance with the increasing loading rates [12-15].

All results mentioned above suffer from the lack of reliable data which is caused by complicated and/or not standardized testing approach. The experimental techniques involved are facing to a number of obstacles comparing to the situation when rather plastic material as metal or plastic are observing. For example the time to the fracture is smaller in order of magnitude comparing to metals and therefore equipment sufficient for metals is becoming to be insufficient when ceramic materials are investigated. The aim of the paper is to describe the effect of loading rate and fracture behaviour of selected inherently brittle materials.

Experimental

A flat soda-lime glass was selected as a model experimental material because no grain boundaries are present and therefore the fracture mechanism is relatively simple to interpret. Moreover glass is commonly use in civil engineering as well as in automotive industry where dynamic loading is obvious. Also an influence of specimen behaviour on the response of measurement system is well predictable.

Other selected material, cast basalt was selected as representatives of rather natural structural ceramic based materials. The natural based basalt was produced by casting and was supplied by company Eutit, Czech Republic.

Samples were cut under intensive cooling from the plates using a precise saw Isomet 5000 equipped with a micrometric holder allowing to cut beams typically of cross-sections 3 x 4, 4 x 6 and 6 x 8 mm^2, respectively. Rectangular bars were further grinded and polished by standards ceramographics methods using a diamond as an abrasive. To prepare initial chevron notches for fracture toughness determination using a chevron notch beam specimen (CNB) a thin diamond blade was used as a cutting tool. The same technique was applied to prepare straight edge V notch bend specimen (SEVNB). To sharpen last mentioned notch, a razor blade with diamond paste was used.

The influence of high speed loading rate on mechanical properties of selected materials was studied using versatile impact testing machine Zwick 5113. The pendulum impact tester is equipped with a set of instrumented pendulums of nominal impact energy (from 7.5 J up to 50 J). The machine is equipped with positioning system allowing stepwise change of release angle with the five degrees step which results in speed variation from 150 mm/s up to 3850 mm/s. For all tests presented in this contribution instrumented pendulum of nominal energy 15 J was used.

The force/strain -time traces were recorded together with impact energy in Zwick ImpactWin and TestExpert software. The sampling frequency used for data logging was 1 MHz. To find out if there is any additional information loosed by using the lower sampling rate, some of experiments were recorded also with frequency of 20 MHz. Due to possibility of the data recording from different channels with the same time base the combination of force response on tup with one of strain response of pendulum anvil or strain response of the tested specimen was recorded. The exact position of strain gage placed on the specimen surface was carefully chosen upon results of finite element simulation. All obtained data were further evaluated quantifying the response of specimen on dynamic loading.

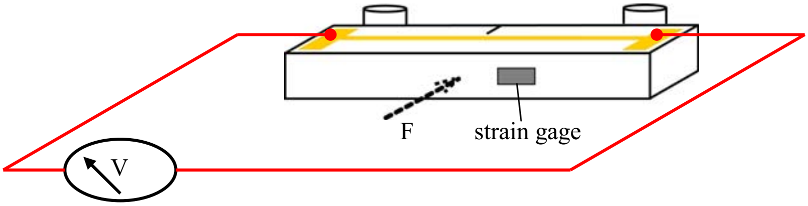

Fig. 1 Scheme of the specimen with deposited golden layer.

For the time to the fracture measurement a new method was used. On each specimen an ultra-thin strip of gold positioned close to the notch tip as displayed on Fig. 1 was deposited. Ends of the strips were connected to the measurement device having the same time base and same or higher sampling frequency as one for force measurement. After final fracture of the specimen a sharp change of conductivity appeared. Using this method it was possible preciously measured the time to fracture of very brittle materials necessary for application of the dynamic key curve methodology.

Quasi-static tests were conducted using an Instron 8862 testing system equipped with three point bend fixtures. Two testing methods for the fracture toughness determination were used. Straight V notch and chevron notch technique. The force vs. time and/or force vs. deflection traces were used for fracture toughness evaluation. The evaluation procedure using the geometrical compliance function based on Bluhm's slice model was applied in case of chevron notch technique [16]. Resulting fracture toughness value is calculated using following formula

$$K_{IC}=\frac{P_f}{B.\sqrt{W}}.f\left(\frac{a}{W}\right), \qquad (1)$$

where B and W are thickness and width of specimen, respectively, P_f is the maximum force and $f(a/W)$ is given compliance function dependent on testing methods and geometry.

Dynamic fracture toughness was experimentally determined using an instrumented impact pendulum. Two approaches were used to overcome measuring difficulties resulting from inertia effects.

(i) A method is based on dumping of dynamic component of measured instrumented tup-force using application of substance with appropriate viscosity to the contact areas of specimen with both pendulum striker and anvil. The goal of this methodology is to minimize sudden change in specimen momentum (from zero to pendulum initial loading speed) during the first loading phase. Thickness of placed layer varied from 0.5 up to 1 mm.

(ii) For fracture toughness measurements conducted under loading rates, where dumping technique failed, direct instrumentation of sample (very costly and technically difficult way) and/or dynamic key curve (DKC) methodology presented by Böhme and Kalthoff [17] was used. It is an analytical – experimental approach predicting dynamic stress intensity factor on the crack tip of specimen $K_I^{dyn}(t)$ according to following formula:

$$K_I^{dyn}(t) = K_I^{q.s.}(t)\, x\, k^{dyn}(c.t/W);\ t = t_f \tag{2}$$

where $K_I^{q.s.}(t)$ is roughly estimated stress intensity factor using analytical approach (Eq. 3) and $k^{dyn}(c.t/W)$ correction function (Eq. 4). Critical value of stress intensity factor i.e. fracture toughness, is set from the Eq. 2 placing t equal time to fracture t_f.

$$K_I^{q.s}(t) = v_0 . Y\left(\frac{a}{W}\right) . \sqrt{\frac{E.M}{W.B.C_S^*}} . \sin\left(\sqrt{\frac{E.B}{M.C_S^*}} . t\right), \tag{3}$$

where v_0 is the initial loading speed, M is mass of the pendulum, $Y(a/W)$ is geometrical function, C_s^* is dimensionless compliance of the specimen, B and W are thickness and width of the specimen, respectively, E is elastic modulus and t is time.

$$k^{dyn} = \frac{K_I^{dyn}}{K_I^{q.s.}}, \tag{4}$$

where $K_I^{q.s.}$ is stress intensity factor according to Eq. 3 and K_I^{dyn} is real stress intensity factor in the crack tip which was measured by direct instrumentation of the specimen in pre-experiment.

Both the optical and scanning electron microscopy was employed for fractographic analyses of fracture surfaces. The fracture origins were determined for all tested specimens. An image analyses was used for initial notch depth and specimen dimension measurement as well as for verification of notch and specimen geometry.

A numerical simulation of dynamically loaded specimens was undertaken using finite element method implemented in program package Ansys. The numerical simulations were used to interpret the measured data.

Results and Discussion

Soda-lime glass was used in all experiments with the aim to map possible approaches for dynamic fracture toughness determination. Main reason to use material with amorphous microstructure was elimination of grain boundary effects during loading (stress wave propagation) and due to presumption of flat fracture resistance curve where no change of fracture toughness values was expected.

Fracture toughness values determined under quasi static loading (crosshead speed of 0.1 mm/min) using the three point bending by the standardized approach using the SEVNB specimen had an average of 0.94 MPa.m$^{0.5}$ and standard deviation of 0.06 MPa.m$^{0.5}$.

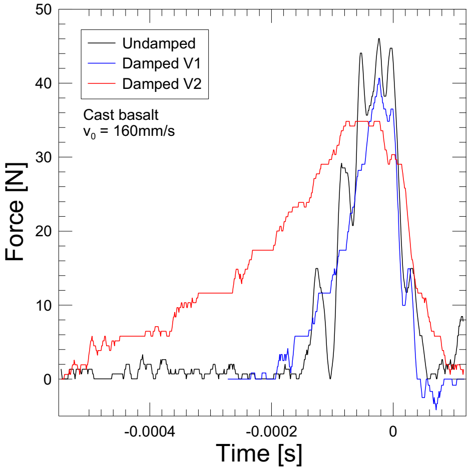

Fig. 2 Example of loading traces of acquired data during test at initial impact speed of 160 mm/s with application of dumping substance having various viscosity.

Dumping technique is an effective and simple way applicable in loading rates approximately up to 1 m/s. Above this speed is not possible to eliminate dynamic effects completely and/or by the sufficient level. A number of vaseline types was tested and no uniform recommendation can be given, nevertheless, the highest is loading rate the higher viscosity should be. The appropriate viscosity is governed by pendulum compliance, material and dimensions of specimen and applied loading rate.

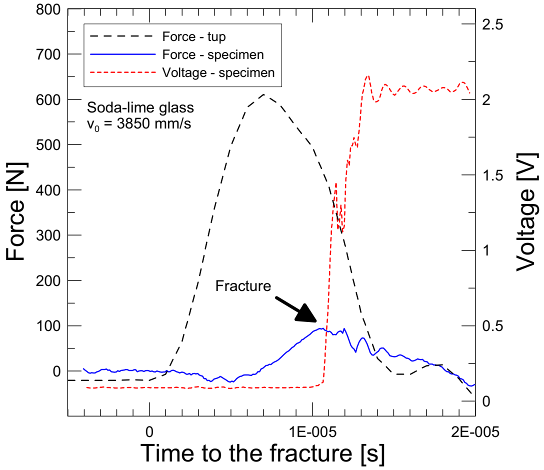

Fig. 3 Example of traces of acquired data during test at initial impact speed of 3850 mm/s using an instrumented specimen by both strain gage and golden strip.

Fig. 2 demonstrates appropriately chosen viscosity (blue line) and too high viscosity lead to the significant decrease of loading speed (red line). The damping effect is apparent from the comparison of loading traces from test with (blue line) and without (black line) application of dumping substance. Note, both mentioned traces have the same rising slope (the same loading rate) what approve correct selection of viscosity. The fracture toughness value is finally calculated from the maximum fracture force measured by the instrumented pendulum tup using the same formula (Eq. 1) as for quasi-static loading.

Loading rates exceeding the level of 1m/s are characteristics by strong influence of the inertia in force time dependence measured by the pendulum tup. The inertia peak can be in some cases the only peak measured before specimen is fractured and maximum force measured by this way is not appropriate for valid fracture toughness determination. An example of such behaviour is displayed in Fig. 3 where force measured by the pendulum tup represents black dashed line. Resulting force – time dependence obtained from instrumented specimen is in Fig. 3 plotted by blue line. Difference between both measured forces (i.e. on the pendulum tup and directly by specimen instrumentation) is obvious and it is clear that use of maximum force from the pendulum tup would lead to the considerable overestimation of fracture toughness value. As a result of this experience application of DKC method for fracture toughness testing under above mentioned loading conditions was chosen.

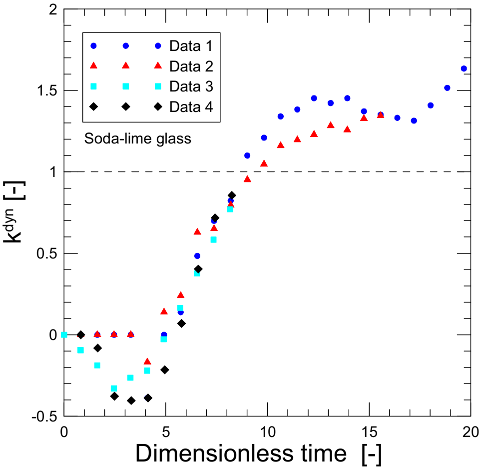

Fig. 4 Dynamic Key Curve constructed from data obtained on the specimens having geometrical parameters a/W = 0.14, L/W = 8.4, S/W = 3.7 tested at various initial impact speed (1000, 1170, 2990 and 3850 mm/s).

Plot of correction function k^{dyn} on dimensionless time is displayed in Fig. 4. For its determination soda-lime glass SEVNB specimens tested at various loading speeds, having the same geometrical parameters a/W = 0.14, L/W = 8.4 and S/W = 3.7 (where a is initial notch depth, W is specimen width, L indicate specimen total length and S is distance between supporting points), were used.

When DKC is known than time to the fracture t_f is the only parameter necessary for fracture toughness determination. With reference to Fig. 4 there was applied newly developed method for time to fracture measurement based on sudden voltage change on thin deposited golden strip when fracture appears. Proposed method (see Fig. 1) is relatively simple and can be applied without application of any additional equipment or sensors.

Summarization of the achieved dynamic fracture toughness data using both described methods (i.e. the dumping and DKC method) compared to those determined quasi-statically is for soda-lime glass and cast basalt in Fig. 5.

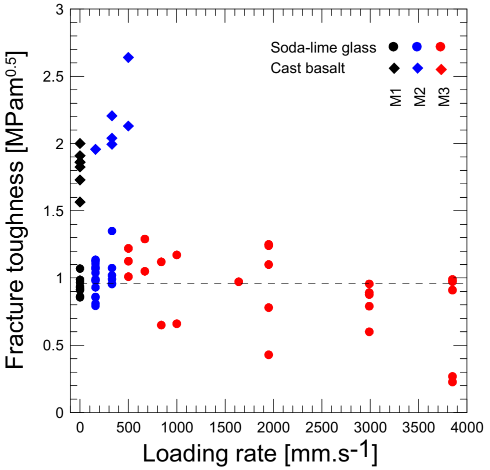

Fig. 5 Results of fracture toughness data obtained using different method (M1 – quasi-static, M2 – dynamic with damping, M3 – Dynamic Key Curve).

A slight decrease of dynamic fracture toughness values with increasing loading rate was obtained contrary to the prognosis. This behaviour can be explained by deviations of sample geometry from those used for DKC construction. Especially a/W ratio can slightly vary because of notch processing. Cast basalt exhibits observable increase of measured fracture toughness with increasing loading rate. The observed trend was supported by fractographical findings obtained on prepared sections perpendicular to the fracture surface. An example of micrograph taken close to straight notch root region is displayed for quasi-statically loaded specimen in Fig. 6a, and for dynamically loaded specimen in Fig. 6b. The extensive micro-cracking associated with the fracture surface in case of higher loading rate was identified. This micro-cracking under main fracture surface is a source for dissipation of energy and can be responsible for the increase of fracture toughness values.

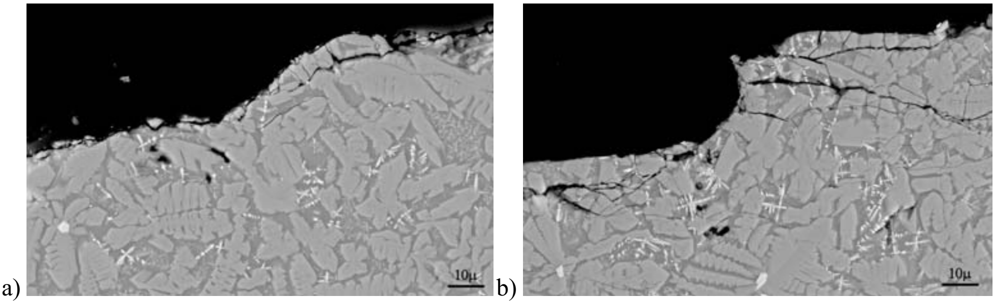

Fig. 6 An example of section perpendicular to sharp notch root after fracture for a) quasi-statically loaded b) dynamically loaded SEVNB specimen (BSE image)

Summary

As an experimental material soda-lime glass was selected for dynamic fracture toughness determination using various approaches. A method using dumping of inertia effects by application of suitable substance having appropriate viscosity to the contact area (specimen – testing machine) was developed. Conditions for usages of this method were described and upper limit of reliability was found for the initial impact speed of 1 m/s for soda-lime glass and cast basalt. Dynamic fracture toughness at higher loading rates was determined by application of DKC concept. A new simple technique for time to the fracture was proposed. Obtained data by both mentioned methods were verified by combination of direct instrumentation of the specimen and results from numerical simulations. Cast basalt exhibit in contrast to soda-lime glass a slight increase of dynamic fracture toughness with increasing loading rate. This behaviour observed in cast basalt was explained on the basis of fractographical observations.

Acknowledgement

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