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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 the case of inherently brittle materials the situation is all the more complicated because of their brittleness. Cast basalt and soda-lime glass were the main experimental materials used in this investigation as representatives of natural based and structural brittle materials. The main aim of the paper 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.

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1. Introduction

Many structural components are working at stable conditions of external load where the mechanical properties obtained at static and/or quasi-static loading 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 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 materials a range of quasi-static loading (i.e. order of CSH of 1 mm/min ≈ strain rate of 10^{-2}) and further high velocity (ballistic) loading (i.e. order of loading rates from 10 m/s ≈ strain 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 various adaptations of the split Hopkinson bar test [6–8] including necessary support of numerical modelling. Comparably smaller effort has been paid to the loading rates of 1 up to 10 m/s (strain 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 a 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 of mechanical properties of steel [9] as well as plastics [10].

In case of ceramics based materials there is no unambiguous methodology how to evaluate fracture properties at higher strain 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 clearer. It 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. This behaviour is caused by a

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lack of time for the material response together with an overhang of available energy [11]. However, there is still a problem of exact determination of fracture force for the flexural strength determination due to oscillations (superposed dynamic effects) on the 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 for ceramics (what is opposite to the case of metals) even at quasi-static loading rates where approximate approaches are very often used [4]. Only few authors report results of dynamic fracture toughness obtained on ceramics based materials. 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 ceramics 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 materials as metal or plastics are observed. 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.

2. 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 used 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.

Second material involved in investigation was cast basalt a representative of rather natural structural ceramic based materials having complicated microstructure. 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 3×4, 4×6 and 6×8 mm^2, respectively. Rectangular bars were further grinded and polished by standard ceramographic methods using a diamond as an abrasive. To prepare initial chevron notches for fracture toughness determination (CNB technique) 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. It is a pendulum impact tester equipped with a set of instrumented pendulums of nominal impact energy (from 7.5 J up to 50 J). Additionally, the pendulum was equipped with positioning system allowing stepwise change of the release angle with five degrees step which results in speed variation from 150 mm/s up to 3850 mm/s. For all tests presented in this contribution the instrumented pendulum of nominal energy 15 J was used.

The force/strain/time traces were recorded together with impact energy in Zwick ImpactWin and TestXpert software. The sampling frequency used for data logging was 1 MHz. In order to find out whether any additional information is loosed using the lower sampling rate, some of experiments were recorded also with frequency of 20 MHz. Due to possibility of the multichannel data acquisition a combination of force response on the tup, strain response of pendulum anvil and/or strain response of the tested specimen having the same time base was available for the evaluation. Two different specimen/loading setups were introduced during the experiment: symmetric (Fig. 1a) and eccentric (Fig. 1b) bending configuration, respectively.

A set of numerical simulations of dynamically loaded specimen was carried out for both loading configuration in order to pinpoint main differences between both arrangements and to clarify measured data. Finite element method implemented in program package Ansys was used. Typical results from numerical simulations are displayed for both arrangements in Fig. 2. Based on this results two main advantages of eccentric arrangement are to be highlighted. First of all, strain measured via

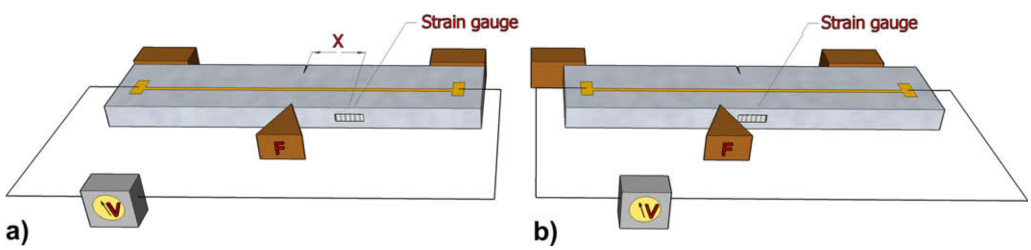

Fig. 1. Scheme of the specimen with deposited golden layer in two loading arrangements: (a) symmetrical and (b) eccentrical.

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