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Ballistic impact behaviour of some ceramics in different environments

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Résumé

On a étudié non seulement la dépendance de l’épaisseur de la céramique, mais aussi l’influence de confinements différents sur la résistance de pénétration contre des barreaux longs à haute vitesse. Pour des céramiques différentes des mesures de la profondeur de pénétration montrent que l’influence de l’environnement sur l’ordre hiérarchique de la performance balistique est relativement faible et indiquent que les confinements les plus lourds causent un changement vers un comportement d’impact des matériaux ductiles. On présente des mesures de pénétration au moyen d’une sonde spéciale, qui fournissent une vitesse de cratérisation moyenne correspondant à la théorie de Tate. Des radiographies après expérience et des photographies de la face arrière du bloc de céramique donnent des informations supplémentaires concernant la cratérisation et la morphologie de rupture.

Abstract

Ceramic thickness dependence as well as the influence of various confinements on the penetration resistance against high-velocity long rods are investigated. Measurements of penetration depth for different ceramics indicate that there is a relatively little environmental influence on the ballistic performance screening and they show a resemblance to impact behaviour of ductile materials in the heaviest confinement scenario. Penetration measurements made with a special gauge are presented, yielding an average cratering velocity in accordance with the Tate theory. Post-test radiographs and rear face photographs of the ceramic block give further information about cratering and fracture morphology.

1. INTRODUCTION

The penetration resistance of ceramic targets against long rods impacting at high velocities and its dependence on the ceramic thickness are both influenced by constructive environments \([1,2,3]\). Thus the first aim of this investigation was to find out whether the environmental influence on the ballistic performance is so strong that it might prevail over the material dependence. Secondly, research was made on the relationship between ceramic thickness and penetration resistance. The object was to see if by varying the confinement of a target configuration - from an unconfined to a completely confined block - the results more closely resemble the behaviour of ductile materials.
Appropriate experiments were run with different ceramic materials; results for Al₂O₃, B₄C, and TiB₂ versus glass are presented here.

2. EXPERIMENTAL SET-UP

The experiments were designed using a kinetic energy projectile developed at ISL [4]. The effective penetrator consists of a heavy alloy rod (tungsten, diameter: 7.25 mm, length: 145 mm, mass: 105 g) attacking at a constant velocity of approximately 1800 m/s. So the experiments were executed under high-velocity impact conditions, meaning in the impact region, pressure exceeded material strength; materials tended to behave like fluids; and density became a dominant material parameter [5,6].

A schematic description of the target mountings is given in the lower picture of figure 1. The ceramic component (C) is investigated in three different environments represented by the following configurations: firstly, it is merely placed in front of a steel backing of semi-infinite thickness (B), a configuration which is called “unconfined” later on in the text. Secondly, the ceramic block is in addition encased by lateral steel plates (L). This configuration is referred to as “laterally confined”. Thirdly, a frontal steel plate (F) with a circular hole in the impact region is added. This configuration is called “completely confined”. The hole is necessary in order to have comparable impact conditions for all configurations. The ceramic block (C) consists of several tiles (thickness: 20 mm, lateral dimensions: 100 x 100 mm², density: \( \rho \)). The block thickness \( t_z \) is changed in each scenario by varying the number of tiles used (1 to 6).

The main ballistic result is the depth of penetration (DOP) in the steel backing \( P_{ref} \), which is compared to the depth of penetration \( P_{ref} \) attained in a reference steel block of semi-infinite thickness. The backing and the reference target consist of RHA (lateral dimensions: 100 x 100 mm², density: \( \rho_{ref} \)).

The impact velocity is measured by several laser light barriers. Three X-ray pictures of the arriving projectile are taken during the first penetration phase. In the first exposure the angle of attack can be determined. The second one shows the position of the rod after the shock wave has travelled through it; and in the third frame, the position of the rod can be seen shortly before its tail disappears in the target. Therefore, the second and the third exposures yield a mean tail velocity.

The movement of the interaction zone between projectile and target material is measured during the penetration process by a special gauge which has been developed at ISL recently [7]. Figure 2 shows the function of this probe schematically. A metallic tube with an electric resistance wire inside is placed into a bore along the expected penetration axis (diameter of the hole: approx. 1 mm). The contact between the tube and the wire is closed dynamically in, or just in front of, the interaction zone. So the ongoing penetration process shortens the probe, thereby causing an electrical resistance decrease measured as a continuous tension increase.

Fig.1: Target configurations

Fig.2: Penetration gauge
3. BALLISTIC PERFORMANCE CHARACTERISTICS

Based on the DOP measurements described above, different quantities exist which characterize the ballistic performance of the investigated ceramic targets. An average target resistance can be derived by applying a modified Bernoulli equation of a steady-state penetration process, known as the Tate theory [8]. Other well known ballistic factors directly compare the projectile's penetration of the considered target with penetration of the reference target. The factors describing the space gain (subscript s) or the mass gain (subscript m) that relate to the ceramic block thickness itself compare t_z with a reference layer that yields the same residual penetration.

The factors are designated by different names in the literature [9,10,11,12]. Here they are called equivalence factors to clearly distinguish them from the efficiency factors describing the gains of the whole target (ceramics plus backing) [13]:

\[ F_s = \frac{P_{\text{ref}} - P_{\text{res}}}{t_z}, \quad P_m = F_s \frac{P_{\text{ref}}}{\rho}. \]

Supposing that the ceramic penetration process did not change during the ongoing cratering, or that the resistance did not depend on the thickness, then the residual penetration depth should depend linearly on ceramic thickness. This linear relation is a good approximation for the quasi-steady state penetration of long rods into ductile materials but it is found to be invalid for thick unconfined ceramics under observation [3]. It seemed that an exponential law would describe the fracture-induced decrease in resistance more accurately. This was validated by the experimental results attained for block thicknesses considerably different from the ballistic limit of the unconfined ceramic target. The failure of this first empirical attempt to have no ballistic limit (P_{\text{res}} remains greater than 0) is corrected by a simple linear adjustment.

To facilitate the application of those formulas to the approximation of the DOP experiments with slightly different impact velocities, they can advantageously be defined in a normalized manner. Figure 3 represents schematically the three attempts mentioned above relating the normalized residual penetration P_{\text{res,n}} = P_{\text{res}}/P_{\text{ref}} to a normalized ceramic block thickness t_{z,n} = t_z/P_{\text{ref}}. The linear relation is designated by (a) and the exponential relation by (b). The recent attempt (c) depends on two parameters c and d, which at the moment are determined solely from the experimental results applying an optimization process:

\[ P_{\text{res,n}} = \exp(-c t_{z,n}) - d t_{z,n}. \]

When parameter c reaches 0, we get the linear relation of metallic materials. The ballistic limit T_{z,n} is defined as the root of the transcendental equation P_{\text{res,n}} = 0. This relation also yields the ballistic factors to be analytically related to the target thickness. It follows, for example, that the equivalence factors decrease monotonically. Some special values are:

\[ F_s(0) = c + d, \quad F_s(T_{z,n}) = \frac{1}{T_{z,n}}. \]
4. RESULTS

The screening of the protective power of the ceramics depends on the chosen ballistic factor, as in the definitions given above. In figure 4, the results are presented in terms of the two mass factors for the three ceramics Al$_2$O$_3$, B$_4$C, and TiB$_2$ and glass in each of the three investigated environments, using a constant block thickness of 120 mm. In the totally confined scenario TiB$_2$ turns out to have the highest $E_m$ factor, whereas B$_4$C is on top in the $F_m$ screening. Until now the results have shown that the three different target configurations do not considerably affect the protective power ranking, though different gains caused by confinement are obtained. The only exception is the $E_m$ increase of the laterally confined B$_4$C target, which must be proven in further experimentation. Consequently, the environmental influence does not prevail over the dependence of the protective power on the material behaviour, i.e., if material parameters exist correlating to the ballistic resistance in the unconfined case, then they should correlate in the totally confined case as well.

Some experiments with unconfined Al$_2$O$_3$ ceramics of increased lateral dimensions indicate a dependence of the ballistic factors on lateral size which may be valid for other ceramics too. For the investigated Al$_2$O$_3$, the performance of the laterally confined target was approximately equal.

Concerning the influence of the target thickness on the penetration resistance of ceramic materials, figure 5 shows the mass equivalence factors of TiB$_2$ for the three configurations. In all cases, the improved exponential model of the $P(t)$ function fits the experimental results best. For the unconfined and the laterally confined targets, the $F$ curves heavily rely on the exponential term. Whereas in the case of the total confinement, the nearly horizontal slope shows an approximately linear $P(t)$ fit, thus indicating a similarity to the penetration behaviour of ductile targets.

The other ceramics yield practically similar curves. For B$_4$C, even the lateral confinement caused metal-like behaviour. Consequently, a relatively small $F_m$ increase for the totally confined configuration was observed.

Figure 6 shows an example of a penetration gauge measurement for Al$_2$O$_3$. Except for some oscillations which at present cannot be completely explained, the experimental values fit to second and third degree polynomials. Assuming that the measured gauge shortening corresponds to the instantaneous penetration depth, and an average cratering velocity of 1130 m/s occurred, which is in close agreement with the value estimated by the Tate theory. For measurements in a glass target, a slightly lower velocity of 1080 m/s was recorded.
In the case of total confinement, the condition of the ceramic block after the impact load and the cratering process is visualized by X-ray pictures (fig.7) and by photographs of the fractured rear face (fig.8). It has to be noted that the ceramic, remaining under a certain compressive load after the test, is unloaded during the dismantling of the steel confinement. To prevent the fractured ceramic block from falling to pieces, it is stabilized by a fluid adhesive. In so doing, the crater and the fracture morphology remain well preserved.

The post-test X-ray pictures of glass and Al$_2$O$_3$ in figure 7 provide some insight into the different cratering behaviours of glass and ceramics in general. Both target blocks had lateral dimensions of 100 x 100 mm$^2$ and consisted of six 20 mm-thick tiles each. The vertical shotline is from top to bottom.

At the beginning of the penetration, the semi-spherical entrance crater has nearly the same size for both materials. Later on, the crater contours differ considerably. X-rays of the glass target do not allow one major difference to be distinguished: namely, in glass the crater collapses, whereas in the Al$_2$O$_3$ target sharp contours indicate a non-collapsed crater. This can be observed when looking at the spatial distribution of the projectile remnants. In the case of glass, they are pressed together near the axis by the crater collapse; in the case of ceramics, they are scattered on the crater surface. Obviously a partial unloading of pressure occurs in the glass target via the crater surface, a phenomenon well known from shaped charge jet penetration into glass. In the ceramic target such an unloading is less facilitated because its bigger fragments quoin each other.

The extensive dark/light transition in the radiograph of the glass crater zone also indicates varying porosity and very small particles of the fractured glass.

Figure 8 shows three photographs with rear face fracturings of the ceramics Al$_2$O$_3$ (upper left picture), B$_4$C (lower left), and TiB$_2$ (lower right). Each of the totally confined 120 mm-thick ceramic blocks consisted of six tiles. The crater holes are well visible in the center of all three targets and do not differ significantly in diameter (approx. 20 mm). The rear surfaces are not planar because a lot of fragments near the crater could not be separated from the backing to which the ceramic tile was glued before the test. Furthermore, some of the particles could not be prevented from breaking off, but the macroscopic fracture morphology remains visible. The presence of two clearly separate fracture zones is striking. The inner zone around
the crater contains smaller fragments and cracks, with a more easily distinguished orientation, with the exception of Al₂O₃ where the orientation is missing at first glance. Fracturing in that region occurs by the direct pressure load of the penetrating rod, whereas the sporadic cracks in the outer region are initiated by the tension wave rebounding from the block interfaces. In the case of B₄C, it is possible to distinguish two inner zones with different fragment size classes; at least, the fragment size increases with increasing distance from the crater, which is not true for TiB₂. The fracture surfaces of these two ceramics are oriented in two directions; besides radial cracks, there are also concentric ones which might indicate that a pressure release has taken place to a certain degree in the ceramics as well. The transgranular fracture in the Al₂O₃ target disorders such structures and additionally disturbs the weak correlation between fragment size and fracture toughness.

5. CONCLUSIONS

The modified exponential model describing the thickness dependence on residual penetration of ceramic targets has proven to be valid in different environments. Changing parameters in this thickness relation according to environmental conditions indicate that the more the ceramic block is confined the more ceramic materials seem to behave like ductile ones. Nevertheless, the ballistic performance screening of the examined thick ceramics is not significantly influenced by the different target configurations investigated here. Quantitatively, the confinement-induced increase in the protective power differs for the ceramic materials. In this context, it has to be kept in mind that the ballistic factors have been calculated neglecting all additional confinement volumes and masses; this fact may qualify the gains observed.

Until now, the penetration gauge measurements yielded average cratering velocities which correspond well to theoretical estimates. More detailed information will probably be available due to further developments of the procedure. In any case, this method allows diagnostics where the X-ray technique fails. Attempts to visually record the fracture morphology need methodical improvements too in order to correlate the microstructural characteristics to the macroscopic impact behaviour.

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