TRANSIENT RESPONSE OF HARD AND BRITTLE ARMOUR MATERIALS: NEW INSIGHTS FROM SCALED EXPERIMENTS

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Summary Hard and brittle armour materials, such as glass or ceramics, experience a non-steady penetration response; the rate of penetration increases abruptly as time progresses. We circumvented technological limitations related to ballistic experiments at high impact velocities by using scaled experiments at low impact velocities. Our results suggest that the impact pressure and, consequently, the rate of penetration increase when the flow of eroded projectile material first reverses.

INTRODUCTION

The transient response of hard and brittle armour materials – ceramics for instance – to an incoming projectile is characterised by a transition from projectile defeat to penetration (Fig. 1). This transition can only be observed within a narrow range of impact velocities. The main difficulties in determining the underlying mechanisms arise from the short time-scale and the length-scale of potential failure mechanisms [1]. Using ballistic laboratory tests it is currently not feasible to capture the impact process at a sufficient temporal and spatial resolution. Consequently, the aim of our research is to use a simple, well-defined scaled experiment to investigate this phenomenon.

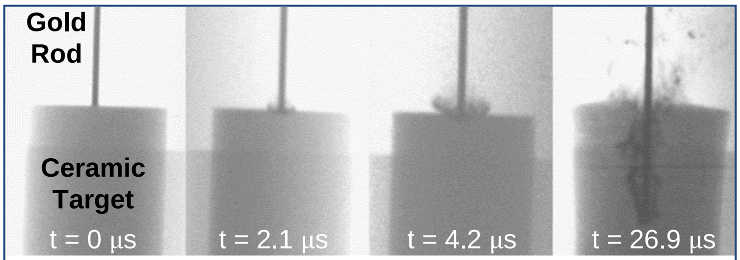

Fig. 1. X-ray images of gold projectile impacting ceramic target at $v_0 = 1500$ m/s (adapted from [4])

The described phenomenon, which is known as *dwell*, was first observed by Wilkins and co-workers in 1967 [2]. The majority of experiments to investigate dwell were conducted with long-rod projectiles impacting thick, confined ceramic targets [3,4]. These experimental set-ups utilise flash X-ray technology with 4 to 6 X-ray tubes to record the motion of the penetrating projectile. Considering that impact velocities are of the order of 1 mm/µs and dwell can persist for more than 20 µs, it is not feasible to resolve the impact conditions sufficiently.
LaSalvia et al. proposed that the stresses due to impact loading will pulverise the target material in a zone beneath the projectile-target interface. According to the proposed mechanism, dwell is the time it takes to extend this pulverised zone to the projectile-target interface. However, not all published experimental results support a damage-related onset of penetration [1]. Moreover, the target material beneath the projectile is strongly confined and it seems more likely that the material will, at least initially, deform plastically without cracking.
In the present study, we investigated the transient response of a target made of high-vacuum grease to a normally impinging water jet. Creep indentation experiments with a flat-ended, circular indenter at equivalent pressures serve as a reference because the contact conditions are well defined. Based on a comparison of these experimental results a new potential mechanism governing dwell is proposed.

EXPERIMENTS

Water jet impact

The water jet was generated by a metal syringe using a servo-hydraulic load frame (Instron 8872 with a 8800 controller unit). A jet of 2 mm diameter was ejected from a stainless steel tube. The tip of the tube was placed at a height equal to three times the diameter above the target. The impact force of the jet was measured using an ICP® dynamic force sensor (209C12, PCB). For the fluid jet normally impinging onto a flat surface the impact force for a given jet velocity v_0 can be calculated assuming no rebound of the water jet. In order to achieve a desired jet velocity, the load frame displacement rate was adjusted to match the corresponding theoretical value of the impact force. The calibration process was carried out till the measured impact force was within a ±3% tolerance of the theoretical value. The penetration of the water jet was recorded using a backlit specimen in combination with a high-speed camera (Vision Research, Phantom V12).

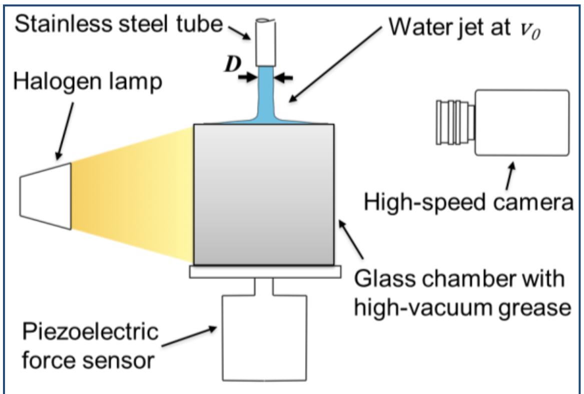

Fig. 2. Setup for water-jet impact experiments

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Creep indentation

For creep indentation experiments a custom-made apparatus with a flat-ended, cylindrical indenter of 2 mm diameter was employed. By using a spring-loaded mechanism the indenter was released and impressed into the sample surface under a constant load. The displacement of the indenter was recorded using a high-speed camera or a laser extensometer (LE-05, EIR) for penetration rates higher or lower than 0.1 mm/s, respectively. Indentations were carried out at loads ranging from 0.07 to 0.24 N, which equate to average pressures of 21 to 81 kPa.

RESULTS AND DISCUSSION

Penetration experiments using a water jet show that, for a jet velocity of v_0 = 7 m/s, the instantaneous elastic deformation of the target material is followed by a constant rate of penetration, as shown by the dashed line in Fig. 3. After about 300 ms the initially constant rate of penetration increases gradually. The nominal pressure, which is defined as the measured normal force divided by the cross-sectional area of the jet, increases rapidly at a penetration depth close to half the jet diameter. It is noted from Fig. 3b and c that the increase in impact pressure is associated with the reversal of the flow direction (backflow).

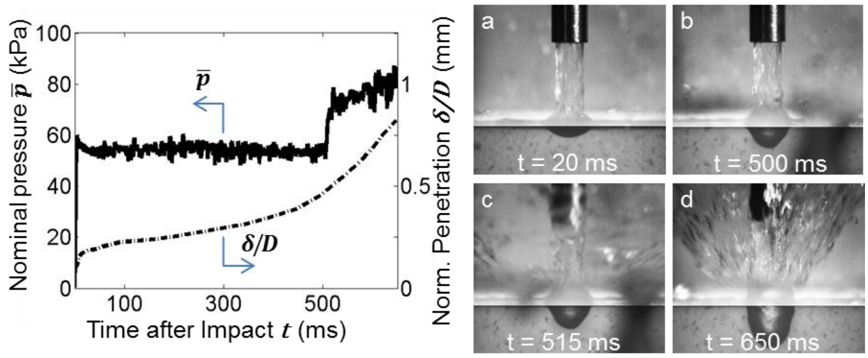

Fig. 3. Impact pressure and penetration depth as a function of time for a Ø 2mm water jet at v_0 = 7 m/s. High-speed camera images at: (a) 20 ms; (b) 500 ms; (c) 515 ms; (d) 650 ms after initial impact.

Creep indentation experiments at equivalent loads yielded penetration-time curves with two distinct stages as shown exemplarily by the solid line in Fig. 4. On application of the load, the penetration almost instantaneously reaches a certain value, which is attributable to the elastic response of the material. Oscillations occurred as a result of the rapid load increase but died away within the first 50 ms. The second stage is characterized by an approximately linear relationship between the elapsed time and the indentation depth similarly to conventional uniaxial creep tests.

A comparison of penetration curves from creep indentation and water-jet impact experiments reveals that elastic deformation and initial penetration rate are almost identical. However, in contrast to the constant penetration rate of the indenter, the water jet impact leads to a significant increase of penetration rate as the penetration event progresses.

CONCLUDING REMARKS

A penetration response similar to ceramic armour systems has been observed in a material with low hardness impacted by a low-velocity water jet. Once the penetration depth reaches a critical value, which is about half the jet diameter, deformation of the target surface induces backflow. The formation of backflow has been shown to cause a rapid increase in impact pressure and an increase in rate of penetration. Creep indentation experiments demonstrate that dwell does not occur under constant pressure conditions and that dwell is not damage related (at least in our experiments).

With certain restrictions, our observations are consistent with the penetration response reported for ceramic armour materials. The occurrence of dwell is shown to be due to the backflow of the projectile and not related to damage in the target; this is contrary to explanations of dwell proposed in the literature.

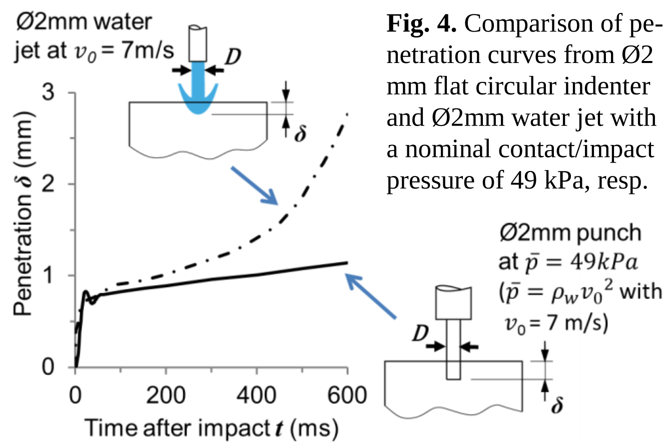

Fig. 4. Comparison of penetration curves from Ø2 mm flat circular indenter and Ø2mm water jet with a nominal contact/impact pressure of 49 kPa, resp.

References

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