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SIMULATION OF DWELL-TO-PENETRATION TRANSITION FOR SiC CERAMICS SUBJECTED TO IMPACT OF TUNGSTEN LONG RODS

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ABSTRACT

For a ceramic armour impacted by a long rod projectile, increasing the dwell-to-penetration transition velocity significantly improves its ballistic performance, whereas it can be achieved by prestressing of the ceramic or placing a buffer over the impact surface. In this paper, numerical simulation using the AUTODYN hydrocode is conducted to investigate how dwell-to-penetration transition is affected by the radial prestress and the presence of a buffer. Taking account of the pressure-dependent strength of SiC ceramics, it is found that distribution of hydrostatic pressure and equivalent stress in the ceramics controls damage initiation and dwell-to-penetration transition. Ceramic damage initiates from the edge of the projectile and then forms a damaged zone in front of the projectile. Compared to the radial prestress, the buffer more effectively suppresses damage initiation to fulfil interface dwell at a higher transition velocity.

INTRODUCTION

The phenomena of interface dwell for ceramics against long rods has been widely investigated to establish the potential of improved ballistic performance of ceramic armour systems. A good literature review of experimental research work can be found in reference [1]. For analytical modelling and numerical simulation of interface dwell, Lundberg et al. [2] derived the upper and lower bound predictions for the transition velocity and the corresponding critical surface pressure as a function of yield strength of ceramics, whereas the critical surface pressure initiates plastic yielding below the surface of the ceramics. LaSalvia et al. [3] established a physically-based model which was based on coupling the wing-crack micromechanical model for compressive failure with Hertz's contact theory. Holmquist et al. [4,5] developed constitutive models of JH1 and JHB for SiC ceramics and demonstrated capability of hydrocode simulation of dwell and interface defeat.

Lundberg et al [2] applied compressive pre-stress to confined ceramics and observed the increased dwell-to-transition velocity. Holmquist et al [6] placed a copper cylinder buffer over the surface of a unconfined ceramic to defeat long rod impact at a velocity up to 1600 m/s with little or no penetration. However, numerical simulation work on the pre-stressing of the ceramics, such as the works of Holmquist and Johnson [7], are scarce in the literature [8]. In addition, there continues to be uncertainties regarding the transition from dwell to penetration and the effects of prestress and buffer [1]. Therefore, detailed simulation works are needed to explore mechanism controlling dwell-to-penetration for improved ballistic performance of ceramics using prestress and buffers.

In this paper, numerical simulation of dynamic response of SiC ceramics, taking account of prestress and applying a buffer over the ceramics surface, against impact of tungsten long rods is conducted using the AUTODYN hydrocode to investigate damage development in ceramics and dwell-to-penetration transition.

NUMERICAL SIMULATIONS

Interface Dwell and Transient Surface Pressure

When a long-rod projectile impacts a ceramic, the projectile material is forced to flow laterally from the impact direction with little or no penetration, which is termed interface dwell. Distribution of the surface pressure (the normal stress on the surface of the ceramic) varies during the impact process, which can be divided into two stages, stage-I initial transient and stage-II subsequent steady responses. In stage-II subsequent steady response of the impact process, the projectile material flows steadily on the surface of the ceramics and consequently quasi-static surface pressure is applied on the surface of the ceramics with the quasi-static surface pressure at the central point of impact is ^[2,9]

$$p_0 = q_p \left(1 + \frac{q_p}{2K_p} + \frac{3.27\sigma_p}{q_p} \right) \quad (1)$$

where $q_p = \frac{1}{2}\rho_p v_0^2$ is the stagnant pressure, K_p is the bulk modulus, σ_p is the yield strength, and ρ_p is the density for the projectile.

In stage-I initial transient response of the impact process, the normal stress at the central point of impact is not affected by the disturbances reflected from the lateral boundaries of the projectile; therefore, a one-dimensional strain plane wave problem, whereas a moving projectile impacts a still target, can be applied to estimate the surface pressure at the central point of impact. Assuming elastic response in projectile-target interaction and strain plane wave conditions, the transient normal stress at the central point of impact is ^[10]

$$p_t = v_0 / \left(\frac{1}{\rho_p c_p} + \frac{1}{\rho_t c_t} \right) \quad (2)$$

where c_t and ρ_t are respectively the sound velocity of P (or irrotational) wave and the density for the target, and c_p is the sound velocity of P wave for the projectile.

For a tungsten long rod ($K_p=254\text{GPa}$, $\sigma_p=0.77\text{GPa}$, $\rho_p=17.6\text{g/cm}^3$, $c_p=4,883\text{m/s}$) impacts a SiC tile ($\rho_t=3.22\text{g/cm}^3$, $c_t=12,168\text{m/s}$) at $v_0=1250\text{ m/s}$, we have $p_0=16.6\text{GPa}$ from Eqn.1 and $p_t=33.6\text{GPa}$ from Eqn.2; hence, $p_t/p_0=2$ is obtained. The transient surface pressure p_t (Eqn.2) is two times of the quasi-static response p_0 (Eqn.1); therefore, damage and failure of the ceramics will occur in the stage-I initial transient response of the impact process. In addition, comparison of Eqns. 1 and 2 with hydrocode simulation will be provided in the below section.

Ceramics Failure Analysis

An ANSYS AUTODYN ^[11] axisymmetric model was established to explore damage and failure of the ceramics in the stage-I initial transient response of the impact process. The 30mm long SiC cylinder in a diameter of 30mm was subjected to a long tungsten rod in a radius $r_0=1\text{mm}$. The material property data of tungsten alloy and SiC were taken from AUTODYN material library. The tungsten rod was modelled with a polynomial equation of state, JC strength models, and a plastic strain failure criterion. A polynomial equation of state, in combination with the JH1 strength and damage models, was used for SiC. SPH particles were used to build the long rod, meanwhile the SiC cylinder was represented in Lagrange with an erosion feature. The size of grid and SPH particles was 0.05 mm and thus there were 20 SPH particles along the radius of the projectile. Material model constants were

validated against available experimental data in the literature, which were consistent [8].

Figure 1 shows interface dwell in which the damage parameter of the ceramic JH1 model has been artificially suppressed to allow the elastic response to be computed. Figure 2a depicts distribution of the surface pressure at different time of the impact process. Figure 2b displays variation of the surface pressure, that is averaged over the region from $r=0$ to $r=r_0$ (the diameter of the projectile), with the time. In Fig.2a, the surface pressure σ_n drops from high stress in the stage-I initial transient response (e.g. at times $t=0.1\mu s$ and $0.3\mu s$) to low stress in the stage-II subsequently steady response (e.g. at times $t=10\mu s$). In Fig.2b, the average surface pressure σ_0 rises up to a maximum value of 58GPa in the initial transient response of the impact process before it drops and approaches the quasi-static response of 16.5G as the time increases. It also can be seen that the duration of the stage-I initial transient response is around $0.7\mu s$ (Fig.2b). In addition, the surface pressure at the central point of impact p_0 (Eqn.1) and p_t (Eqn.2) are well consistent with the simulation prediction as shown in Fig.2a.

Figure 1: Interface defeat at $v=1250$ m/s without SiC failure.

(a) Stress distribution along the r-axis

(b) variation of average stress with time

Figure 2: Surface pressure applying on the surface of the ceramic.

The strength of SiC ceramic is pressure-dependent [Error! Bookmark not defined.]. Figure 3 plots the curve of the strength of SiC material in JH1 model, σ_{yield} , in terms of von Mises equivalent stress versus the hydrostatic pressure P . The initial linear part of curve $\sigma_{yield} - P$ is

$$\sigma_{yield} = c(P + T) \quad (3)$$

where $c=2.185$ is the slope meanwhile $T=0.75\text{GPa}$ is the tensile pressure at which the ceramic fails.

Figure 4 shows distribution for Von Mises equivalent stress σ_e and strength σ_{yield} in ceramics along the r-axis and z-axis directions, when the projectile impacts the ceramic at $v=1250\text{m/s}$. In Fig.4a, it can be seen that in the projectile-ceramic contact region (from $r=0$ to $r=r_0$), $P>0$ is maintained so that the ceramic is strengthened (high σ_{yield}) and thus $\sigma_e < \sigma_{yield}$; however, outside the projectile-ceramic contact region ($r > r_0$), $P=0$ results in weakening of the ceramic (low σ_{yield}) and thus $\sigma_e > \sigma_{yield}$ exists in the vicinity of the edge of the projectile (from $r=r_0$ to $r=2.5r_0$) to generate ceramic failure. Similarly, the ceramic locating at a distance from the surface (from $z=0.5r_0$ to $z=2.2r_0$) will also fail due to $\sigma_e > \sigma_{yield}$.

Figure 3: Pressure-dependent strength for SiC ceramics in JH1 model ^[4].

Figure 4: Distribution of σ_e , P , and σ_{yield} in ceramics at $t=0.3\mu\text{s}$ after impact.

Simulation of development of ceramic damage is shown in Fig.5. It can be seen that the zone of complete damage ($D=1$) initiates in the vicinity of the projectile edge at $t=0.2\mu\text{s}$ and extends until it forms a cap in front of the projectile tip at $t=0.4\mu\text{s}$. As the penetration increases, cracks are generated together with ejecting of failed ceramics at $t=3.0\mu\text{s}$. The damage development displayed in Fig.5 is resulted from the distribution of σ_e , P , and σ_{yield} as shown in Fig. 4, whereas $\sigma_e > \sigma_{yield}$ results in ceramic failure.

Figure 5: Development of damage in the ceramic.

Effect of Radial Prestress

In the experiments of Lundberg et al ^[2], both radial and longitudinal prestress were applied to confined ceramics. Here only the radial prestress is investigated. When a radial prestress σ_r is applied to the ceramic, simulation of damage in the ceramic under 4 different radial prestress, i.e. non-prestress, -900MPa, -1600MPa, and -2400MPa, are displayed in Figs. 6 and 7. The hydrostatic pressure generated by the radial prestress is

$$P_{pre} = -2\sigma_r/3 \quad (4)$$

A numerical procedure for pre-stressing of a ceramic before applying impact was developed in AUTODYN. Firstly, a constant radial stress was applied on the lateral boundary of the ceramic in the simulation model; secondly, the simulation model was run until uniform stress distribution was achieved throughout the ceramic by applying the static damping in AUTODYN to eliminate stress oscillations due to dynamic simulation; lastly, the impact of the long rod was applied using dynamic simulation in AUTODYN without the static damping.

According to Eqns. 3 and 4, the hydrostatic pressure P_{pre} generated by the radial prestress enhances the strength of the ceramic. With the increase of the radial prestress, the zone of damaged ceramic decreases as shown in Fig.6. But the zone of complete damage ($D=1$) exists around the tip of the projectile even in the case of $\sigma_r = -2400\text{MPa}$ in Fig.6. Moreover, the interface dwell can be achieved after some penetration in the case of $\sigma_r = -900\text{MPa}$ in Fig.7 or after little penetration in the case of $\sigma_r = -1600\text{MPa}$ in Fig.7. The radial prestress increases the strength of the ceramic but does not alter the features of the distribution of σ_e and P in Fig.4; therefore, the zone of complete damage ($D=1$) in the ceramic still appears in front of the projectile tip.

Figure 6: Damage in the ceramics at $t=3.0\mu\text{s}$ under different lateral prestress.

Figure 7: Damage in the ceramics at $t=6.0\mu s$ under different lateral prestress.

Effect of Placing a Buffer over the Ceramics

Using reverse ballistic tests, Holmquist et al [6] placed a copper cylinder buffer over a unconfined SiC ceramic and observed interface defeat against high density long rods launched at velocity up to 1600 m/s with little or no penetration. Leavy et al [12] placed a cover plate made of Titanium alloy over the confined SiC to study interface dwell. In this study, interface dwell against a tungsten long rod at $v=1250\text{m/s}$ by using a Ti-alloy buffer is simulated. In simulation, a $D=5\text{mm}$ and $L=60\text{mm}$ tungsten long rod impacts a SiC ceramic at $v=1250\text{m/s}$, meanwhile a $D=20\text{mm}$ and $L=10\text{mm}$ Ti-alloy buffer is placed over the ceramic surface, as shown in Figs. 8 and 9. The buffer is simulated by using a SPH solver.

In Fig.8, the long rod reaches the surface of the ceramic at time $t=0\mu s$, after perforating the Ti-alloy buffer. $P>0$ exists over the ceramic-projectile/buffer contact region so that $\sigma_{\text{yield}} > \sigma_e$ along the r -axis; therefore, no failure in the surface of the ceramic occurs. Consequently, interface dwell has been achieved.

It is noted that the compressed buffer applies a compressive surface pressure over the ceramic-buffer contact region. As the buffer moves apart as shown at time $t=7\mu s$ in Fig.9, the laterally-flowing projectile material is able to exert a surface pressure on the projectile-ceramic contact region. Partial damage ($D<1$) is observed in Fig. 9, which forms cone cracks and microcracks. The cone cracks and microcrack region were observed from the post-testing ceramics [13].

Figure 8: Stress distribution and damage in the buffered ceramic at $t=0\mu s$.

Figure 9: Stress distribution and damage in the buffered ceramic at $t=7\mu\text{s}$.

Figure 10: Typical distribution of P , σ_e , and σ_{yield} in ceramics.

DISCUSSION AND SUMMARY

In this paper, interface dwell in the SiC ceramics subjected to impact of the tungsten long rods is numerically investigated using the AUTODYN hydrocode. The results of this study are summarized as follows:

- (1) In the stage-I initial transient response of the impact process, the transient surface pressure applying on the ceramic-projectile contact surface is high, which results in localized damage and failure in the ceramic. The duration of stage-I is less than $1\mu\text{s}$ as shown in Fig.2. After that, the surface pressure reduces significantly in the stage-II subsequent steady response of the impact process.
- (2) Distribution of the hydrostatic pressure P and the equivalent stress σ_e in the ceramic controls initiation of ceramic damage. Figure 10 shows the typical distribution of P and σ_e along the r -axis (surface) and z -axis (depth) directions of the ceramic, which exhibits the same features as that in Hertz contact theory^[14]. In the vicinity of the edge of the projectile, $\sigma_e > \sigma_{\text{yield}}$ initiates damage (Fig.10a). The surface damage extends to form a damage zone ($D=1$) in front of the tip of the projectile, as shown

in Fig.5, and thus penetrating the ceramic.

- (3) The radial prestress increases the strength of the ceramic but does not alter the features of stress distribution in Fig.10; therefore, the complete damage zone ($D=1$) in the ceramic still occurs in the region close to the tip of the projectile as shown in Fig.6. Interface dwell can be achieved after little penetration as shown Fig.7. The radial prestress is unable to eliminate damage initiation in the vicinity of the edge of the projectile.
- (4) When a buffer is placed over the ceramic, the compressed buffer exerts a surface pressure in the ceramic-buffer contact region that surrounds the edge of the projectile. This surface pressure significantly increases the local hydrostatic pressure and strengthen the ceramic, so that the complete damage zone ($D=1$) in the surface of ceramics does not occur, as shown in Figs. 8 and 9. Consequently, interface dwell is achieved. The buffer effectively suppresses damage initiation in the vicinity of the edge of the projectile.
- (5) It is noted that the strain rate effect on the strength of ceramic is not considered in Eqn.3. For estimation, a strain rate of 5000 s^{-1} increases the strength of Eqn.3 by 7.7% in JH1 model. Moreover, the above simulation is conducted using $v=1250\text{m/s}$, which is for the purpose of verification of the simulated results with the experimental work to be carried out in future.

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