Simulation study on influence of component thickness on dwell-penetration transition time of long rod projectile impacting ceramic armour module

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Abstract. The influence of component thickness of ceramic armour performance against long rod projectile is a critical information for the process of armour design optimization. In this study, the correlation between dwell time and cover plate thickness and mechanism shift with different ceramic to backing plate thickness ratio were studied using hydrocode simulation software LS-Dyna. The projectile is a long rod projectile with a length to diameter ratio of 14 at a nominal velocity of 1.25 km/s. In this study the cover plate performance is studied based on a surrogate module configuration, where the backing thickness is 10 mm instead of the usual semi-infinite thickness backing which has minimal bending deformation. The parameters used in the simulation were calibrated against experimental data in previous studies. From the study, the cover plate needs a minimal thickness to establish dwell. For thicker cover plate, the dwell time starts to decrease due to the confinement provided by thickness of the cover, which limited the lateral flow of the cover plate. This restriction of lateral flow, resulted in pressure build-up at the ceramic surface, thus, reducing the dwell time.

1. Introduction

Dwell phenomenon is an essential defeat mechanism of ceramic armour against long rod projectile [1–5]. Many studies had tried to improve the dwell performance of ceramic armour through confinement [6–9], adding of interlayer [10]. However not many studies focused on how the thickness of module influence except for the work by [11] where copper cover plates of different thicknesses were used and it was observed the best performance was by 3 mm copper and not thicker 6 mm copper. However, the mechanism that led to the result was not discussed. Therefore, in this study, the focus is to understand the influence of the thickness of cover plate, ceramic and backing on the dwell time. In this work the focus will be on the mechanism shift which led to the change of dwell time, hoping to bring more insight in to the design process of the ceramic armour. In this study, it will be study based on a length to diameter (L/D) ratio 14 tungsten alloy long rod projectile impacting at 1.25 km/s. As for the armour module, it is a surrogate armour module which consist the 3 basic components of an armour module namely cover plate, ceramic and backing plate and the backing plate is thin backing plate for considerations of application purpose.
2. Methodology
The simulation model used in this paper had been validated against experiment in the work by Goh et al [13]. The simulations were carried out in LS-dyna explicit solver. For the model, FEM with element size of 1 mm was used for the modelling of the module while the element size of the projectile which was modelled using SPH was kept at 0.4 mm. JC-model was used for tungsten and steel while JH-1 model was used for the SiC. The material parameters used in the simulations are listed in table 1 and 2 below.

Table 1. JC parameters for different hardness steel and tungsten alloy [14].

| JC Model Strength Parameters | HRC 30 | HRC 40 | HRC 50 | Tungsten Alloy |
|-----------------------------|--------|--------|--------|----------------|
| Yield Strength, A (MPa)     | 719    | 1026   | 1463   | 697            |
| Hardening Coefficient, B (MPa) | 456         | 650    | 927    | 1160           |
| Strain Hardening Exponent, n | 0.093       | 0.265  | 0.426  | 0.626          |
| Strain Rate Constant, c     | 0.008  | 0.007  | 0.006  | 0.056          |
| Softening Exponent, m       | 1.03   | 1.03   | 1.03   | 1.00           |

Material Properties
- Density (g/cm³) = 7.85
- Young’s Modulus (GPa) = 201
- Shear Modulus (GPa) = 78
- Poisson’s Ratio = 0.29
- Melting Temperature (K) = 1723
- Specific Heat (J/kg.K) = 477

Table 2. Material parameters of JH-1 model for different grade of SiC [14].

| SiC Grade | Grade T | Grade T+ | Grade F | Grade F+ |
|-----------|---------|----------|---------|----------|
| Strength Parameters: JH-1 Model |
| Intact Strength Constant, $S_1$ (MPa) | 6000 | 6082 | 6692 | 7100 |
| Intact Strength Constant, $P_1$ (MPa) | 2500 | 2500 | 2500 | 2500 |
| Intact Strength Constant, $S_2$ (MPa) | 10300 | 10450 | 11500 | 12200 |
| Intact Strength Constant, $P_2$ (MPa) | 10000 | 10000 | 10000 | 10000 |
| Strain Rate Coefficient, C | 0.01 | 0.01 | 0.01 | 0.01 |
| Tensile Strength, $T$ (MPa) | 750 | 750 | 750 | 750 |
| Failure Parameters: JH-1 Model |
| Max Fracture Strength, $S'_{max}$ (MPa) | 1300 | 1300 | 1300 | 1300 |
| Failed Strength Constant, $\alpha$ | 0.4 | 0.4 | 0.4 | 0.4 |
| Damage Constant, $\varepsilon'_{max}$ | 0.8 | 0.8 | 0.8 | 0.8 |
| Damage Constant, $\phi$ | 0.8 | 0.8 | 0.8 | 0.8 |
| Damage Constant, $P_1$ (MPa) | 99750 | 99750 | 99750 | 99750 |

3. Results and Discussion
3.1 Cover Plate Influence on Dwell Time
A series of simulations were carried out with only the thickness of the cover plate was changed. The cover plate thickness simulated were 1.6 mm, 2.5 mm, 3.2 mm, 4.1 mm, 5mm and 8.3 mm respectively. The dwell time for each cover plate is listed in the table 3 below. From table 3, dwell phenomenon no longer occurred when the cover plate thickness is less than 1.6 mm. This phenomenon can be explained by figure 2, where the impact pressure history showed that the impact pressure reaching Hugoniot elastic limit of SiC (HEL = 11.7 GPa) at time $t = 7 \mu s$. The impact pressure of 14 GPa exceeded the dynamic strength of the ceramic, thus generating cracks and prevented dwell phenomenon from occurring.
Table 3. Results of dwell time for different thickness cover plate.

| CP Thickness (mm) | Areal Density (kg/m²) | Dwell Start Time (μs) | Dwell End Time (μs) | Total Dwell Time (μs) | Dwell Time /AD ratio |
|------------------|-----------------------|-----------------------|---------------------|----------------------|---------------------|
| 8.3              | 65.2                  | 17                    | 41                  | 24                   | 0.368               |
| 5                | 39.3                  | 10                    | 41                  | 31                   | 0.789               |
| 4.1              | 32.2                  | 10                    | 44                  | 34                   | 1.055               |
| 3.2              | 25.1                  | 9                     | 45                  | 36                   | 1.434               |
| 2.5              | 19.6                  | 8                     | 44                  | 36                   | 1.836               |
| 1.6              | 12.6                  | -                     | -                   | 0                    | 0                   |

Figure 1. Impact pressure on ceramic surface for 1.6 mm cover plate.

The dwell time is plotted against cover plate thickness in figure 4. From the graph, it was observed that thicker cover plate did not equate to longer dwell time. The dwell time remained rather consistent varying between 31 μs to 36 μs for cover plate thickness ranging between 2.5 mm to 5 mm. However, for cover plate thickness of 8.3 mm, it was observed that the dwell time decreased rapidly to 24 μs.

To understand the cause of this rapid decrease, the simulation results were analysed. The damage profile of the ceramic 1 μs before dwell termination for cover plate thicknesses of 2.5 mm and 8.3 mm are shown in figure 5. According to the damage profile, the damage for 2.5 mm cover plate was about to connect from the ceramic rear face to the comminution zone near the surface of the ceramic. This was identical with the mechanism shown in the work by Goh et al [13]. However, for 8.3 mm cover plate, it was observed that the damage zone was far from connecting from the rear to the ceramic surface. This was an indication of premature dwell termination.

Through analysis of the deformation profile for the cover plate as seen in figure 6, it was observed that the thickness of 8.3 mm cover plate had worked against its dwell performance. The thickness limited the deformation allowed on the cover plate, thus preventing the characteristic flow of eroded material in the lateral direction which is observed in figure 6(a) for thinner cover plate. The eroded material was confined within the cavity of the of the cover plate, which forces the material downwards towards the ceramic, leading to premature dwell termination for thicker cover plate. The result was consistent with work conducted by Hauver et al [15] and Espinosa et al [7], [8], where in their studies to achieve interface defeat in ceramic armour, a thin layer of soft material was inserted between the
cover plate and the ceramic. This was to allow lateral flow of material, thus preventing premature dwell termination in the experiment.

Figure 2. A plot of dwell time against cover plate thickness.

Figure 3. Damage profile of ceramic before dwell termination for (a) 2.5 mm thick cover plate and (b) 8.3 mm thick cover plate.
Therefore, from the simulation work above, it was concluded that (1) minimal cover plate thickness is required for the establishment of dwell phenomenon through shock attenuation and maintaining the impact pressure below the HEL of SiC and (2) increase cover plate thickness beyond a limit will result in lateral flow which will terminate the dwell time prematurely.

3.2 Ceramic and Backing Thickness on dwell time

As ceramic performance was highly influenced by the backing conditions, i.e. thickness and strength [9], [13], [17], [18] and weight is critical consideration for armour designer, this study will study ceramic and backing thickness as a single entity where the areal density (AD) was kept constant for all the cases.

The simulation matrix was shown in table 4. The cover plates used in all cases were 2.5 mm thick AISI 4340 steel concluded in previous section. The correlation between ceramic / backing thickness and dwell time will be analysed.

| Set No | Ceramic Thickness (mm) | Backing Thickness (mm) | Ceramic / Backing Ratio | Ceramic %wt | Total Thickness (mm) |
|--------|------------------------|------------------------|-------------------------|-------------|---------------------|
| 1      | 10                     | 14                     | 0.71                    | 19.8        | 26.5                |
| 2      | 15                     | 12                     | 1.25                    | 29.7        | 29.5                |
| 2      | 20                     | 10                     | 2                       | 39.5        | 32.5                |
| 3      | 25                     | 8                      | 3.13                    | 49.3        | 35.5                |
| 4      | 30                     | 6                      | 5                       | 59.0        | 38.5                |
| 5      | 35                     | 4                      | 8.75                    | 68.7        | 41.5                |
| 6      | 40                     | 2                      | 20                      | 78.3        | 44.5                |

The results in table 5 showed that the dwell time was heavily influenced by the ceramic to backing thickness ratio. It was observed that the dwell time was longest time occurred when the ceramic-backing ratio was ~3. The results were then plotted in figure 7. From the plot, it was observed that were two distinct slopes. The first slope was when ceramic to backing thickness was between 0.5 to 3 and the second slope was from 5 to 25. It was observed that the first slope had a steep increase in dwell time while the second slope had a very gradual decrease of dwell time.
Table 5. Dwell time for different ceramic armour configurations.

| Set No | Ceramic Thickness (mm) | Backing Thickness (mm) | Ceramic / Backing Ratio | Dwell Time (μs) |
|--------|------------------------|------------------------|-------------------------|-----------------|
| 1      | 10                     | 14                     | 0.71                    | 10              |
| 2      | 15                     | 12                     | 1.25                    | 26              |
| 3      | 20                     | 10                     | 2                       | 48              |
| 4      | 25                     | 8                      | 3.13                    | 48              |
| 5      | 30                     | 6                      | 5                       | 42              |
| 6      | 35                     | 4                      | 8.75                    | 41              |
| 7      | 40                     | 2                      | 20                      | 39              |

Figure 5. A plot of ceramic/backing thickness ratio against dwell time.

To understand the trend observed, the damage profile of ceramic was studied. The profile of 10 mm, 25 mm and 35 mm thick ceramic is shown in figure 8. The diagram showed the damage profile of ceramic just before dwell termination. It was observed that for thinner ceramics, dwell termination occurs when the damage region connected from the rear face to the front face of ceramic as seen in 10 mm SiC. By increasing the thickness of ceramic, two phenomena were observed; (1) the damage propagation was slower as the 15mm tile had experienced some failure (D=1) at 25 μs while 25 mm tile had barely any damage accumulated at the same time (figure 9) and (2) damage propagation took a longer path to connect to the front face of ceramic i.e. the path distance was the thickness of the ceramic (figure 8). Slower damage propagation was due to the higher stiffness of the ceramic armour module due to larger total thickness of module which resulted in slower deformation of armour structure. The longer path was due to the thickness of ceramic hence longer time needed to travel the distance. As the dwell termination occurred due to damage connecting from the rear to the front surface, increased ceramic thickness translated to significant increase in dwell time as the process of damage connecting was delayed.

However, this was not the case when the ceramic was 30 mm thick or more. From figure 8, it was observed that although damage accumulation occurred at the back face of ceramic, the damage did not propagate through the tiles. The high stiffness of the ceramic provided sufficient support, preventing the damage from loss of backing support. Instead, failure occurred on the surface of the ceramic. The outcome was similar to the prediction by LaSalvia et al [17], where it was predicted that a transition of
dwell termination mechanism according to the normalized thickness of ceramic, however in his work it was working on the transition to ideal “thick tiles” i.e. semi-infinite thick ceramic.

With increased thickness, the damage at the rear was observed to decrease as seen in figure 10. The damage for 40 mm thick tiles was significantly lesser than the 30 mm tiles. The slight reduction of dwell time for ceramic was due to better support of thick ceramic thus allowing the peak stress to be reached earlier for thicker ceramic as seen in figure 11. The peak stress of 40 mm tile occurred at 45 μs while 35 mm tile occurred at 47 μs, which corresponded to the 2 μs difference in dwell time measured, supporting the hypothesis of better support resulted in peak stress achieved at an earlier time.

Therefore, according to the observed trend, it was predicted that dwell time reduction due to ceramic thickness would stop when the ceramic reached the ideal “thick ceramic”, i.e. when there was minimal deformation at the ceramic rear surface.

Figure 6. Damage profiles of 10mm, 25mm and 35mm tiles one frame before dwell termination.

Figure 7. Damage profile of 15mm and 25mm ceramic at 25μs.
Therefore, from the above simulation, it was concluded that the ceramic thickness is critical for the dwell process. With increased thickness, the increase stiffness and distance of travel for the damage in the tile will improve the dwell time. However, when the tile thickness increases beyond a specific thickness, the dwell time will no longer increase due to the pressure built up on the impact face, in fact the dwell time may decrease.

4. Conclusion
A series of simulation work were carried out to study the influence of the thickness of cover plate,
ceramic and backing on dwell time of long rod projectile impacting ceramic armour. It was observed that the cover plate has a minimal thickness for dwell to occur but with increased thickness, the dwell time will not increase significantly and when exceed a certain thickness, the cover thickness will decrease the dwell time due to restriction to lateral flow of projectile material. As for ceramic and backing thickness, increasing thickness of the ceramic will improve the dwell time through improve stiffness of module and distance of travel for damage, but exceeding certain thickness the dwell time will no longer increase due to a shift of damage mechanism.

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