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EFFECTS OF HARDNESS AND TOUGHNESS OF CERAMIC IN A CERAMIC ARMOUR MODULE AGAINST LONG ROD IMPACTS

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ABSTRACT

A series of experiments and simulations were conducted to investigate the effects of hardness and toughness of ceramic on the ballistic performance of ceramic armour modules. The experiment was conducted using ceramics from 3M technical ceramic, using the tiles Grade T, T+, F and F+ with dimensions of 100 mm X 100 mm X 20 mm. These ceramic tiles were assessed using a simplified ceramic armour module consisting of the ceramic tile sandwiched between a cover plate and a backing plate. The test samples were made of either single tile module or multiple tile modules. They were tested against tungsten alloy long rod projectiles at a nominal velocity of 1250m/s. Experimental results showed that ballistic performance of the ceramic correlated with hardness but not fracture toughness, based on mass efficiency. Fracture toughness correlated instead with the damage radius in the ceramic. Simulation using LS-DYNA revealed that improved ballistic performance of the ceramic tiles was due to long dwell time. High fracture toughness of ceramics could suppress damage by tensile stress wave generated.

INTRODUCTION

Ceramic armour has been deployed by the U.S. Military since the 1960s and has undergone continuous evolution since then [1, 2]. Two of the important material properties that may be used to guide the selection of ceramics for lightweight armour were hardness and fracture toughness [3, 4]. Improving both the hardness and toughness of SiC simultaneously was a difficult task, as a trade-off between hardness and toughness always occurred [5]. Balancing between ceramic hardness and toughness has always been a challenge to ceramic armour designers.

Ballistic testing with a WC–Co core at 907 m/s showed that higher hardness resulted in lower depth of penetration [6], indicating performance of ceramic armour module increased with the increase of hardness of ceramics. However, the experiments showed that higher fracture toughness did not result in improved ballistic performance [5]. In the work carried out by Ray et al. [7], depth of penetration (DOP) testing using 7.62 x 51 mm projectile was shot at a velocity of 907m/s at 6.35 mm thick ceramic targets backed with 130 mm thick 5083 Al, where it was concluded that hardness made improved armour but not toughness.

The reported studies made use of small calibre projectiles. Moreover, they did not provide the mechanism how hardness and fracture toughness affect ballistic performance of ceramic armour. The current study aimed to understand if the relation between ceramic hardness carried on to higher level threat and to shed light on the role which fracture toughness play in ceramic armour. On top of that, this study sought to understand ceramic as an integral part of a ceramic armour rather than a single tile. The tests were designed to understand the role of ceramic hardness and toughness in a ceramic armour module against long rod projectile impact.

MATERIALS AND TEST METHODS

Experiments were conducted at the Ma Jan High Speed Dynamics Laboratory, Temasek Laboratories, Nanyang Technological University, Singapore. The experiments were carried out on a two-stage light gas launcher. Figure 1 showed the schematic of the test setup. The penetration process was recorded using a high-speed camera meanwhile the pitch/yaw of the striking projectile was

measured using a flash X-ray system. Projectiles were made of 93W-4Ni-3Fe tungsten alloy with a mass of 96g, an L/D ratio of 13.8, and a diameter of 8.3mm. The nominal velocity was 1.25km/s.

Figure 1. Schematic of experimental setup for ballistic test.

The ballistic performance of the ceramic armour was assessed using mass efficiency E_m ,

$$E_m = \frac{\rho_b p}{\rho_{st} t_{st} + \rho_c t_c + \rho_b p_r} \quad (1)$$

where ρ_b was the density of the witness block, p was the reference depth of penetration (DOP), p_r was the residual penetration in the witness block, and $\rho_{st} t_{st} + \rho_c t_c$ was the areal density of the armour module where subscripts st and c denote steel and ceramic, respectively. The reference DOP, p , in Equation (1) was determined from the below equation which was obtained from a series of penetration tests [8],

$$DOP = 0.1091v - 71.52 \quad (2)$$

where the units of DOP and v are mm and m/s, respectively.

Two types of ceramic modules were applied in this study, i.e. single tile module and multiple tile module, to assess the ceramic armour capability in terms of ballistic performance, integrity after shot, and damage radius.

Single Tile Module

The configuration of single tile module is shown in

Figure 2. It consisted of a 5mm thick steel cover plate, 20mm thick ceramic tile and 10mm thick steel backing plate. The ceramic was bound to the steel backing using an epoxy adhesive, Loctite NA3909.3, with a controlled thickness of 0.1mm. The cover plate was secured to the module with 8xM8 screws. The single tile module was used to assess the ballistic performance of the ceramic tile.

Figure 2. Single tile module (a) front view and (b) side view and (c) sectioned view of module

The cover plate and backing were made from AISI 4340 steel of hardness HRC 30 and the ceramic used was Silicon Carbide (SiC). Tension and hardness tests of the steel and tungsten alloy were carried out to measure their mechanical properties, as listed in Table 1. Four grades of SiC were

used for the study, i.e. Grade F, Grade F+, Grade T and Grade T+ from 3M Technical Ceramic. The hardness and toughness of the ceramics were measured from indentation method, using the indentation testing machine FV-800 from FutureTech and test standard JIS R 1607. Two ceramic tiles of each grade were tested, and each tile was measured at 6 different locations. The measured hardness and fracture toughness were listed in Table 2. As seen from the Table 2, the F-series ceramic tiles had higher hardness but lower fracture toughness than the T-series tiles. The selected SiC ceramics covered the hardness range of HV20 - HV24 and the toughness range of 3 - 7MPa.m^{1/2}.

Table 1. Measured mechanical properties of AISI 4340 steel and Tungsten Alloy

Materials	$\rho_0(\text{kg/m}^3)$	E (GPa)	Yield Strength (MPa)	Ultimate Tensile Strength (MPa)	Vickers Hardness (kg/mm^2)
4340 (HRC 30)	7850	210	850±59	1020±37	298±7
Tungsten Alloy	17600	320	636±11	902±9	260±10

Table 2. Measured mechanical properties of four grades of SiC tiles

Ceramic	Grade F	Grade F+	Grade T	Grade T+
Hardness (HV)	23.1±0.9	24.4±0.9	20.6±0.3	20.9±0.8
Toughness (MPa.m ^{1/2})	2.84±0.20	2.89±0.23	5.79±0.49	6.99±0.78

Multiple Tile Module

The configuration of multiple tiles module was shown in Figure 3. It consisted of a 5mm thick steel cover plate, 20mm thick ceramic tiles and 13mm thick steel backing. The configuration had 6 tiles placed side by side in one row, with a layer of 0.1mm thick of epoxy adhesive filling the gap between the tiles. The ceramic chosen for the test was Grade T+ and Grade F+ which had fracture toughness of 2.84MPa.m^{1/2} and 6.99MPa.m^{1/2} respectively.

The multiple tile configuration was designed to assess the effect of fracture toughness on the damage region of the neighbouring tiles surround the impacted tile. In this study, the multiple hit performance of the ceramic armour module was represented by the damage radius, where the damage radius was measured from the center of the impact point to the edge of the fractured tiles.

Figure 3. Multiple tile module (a) 6 tiles inside the module (b) the module test setup inside the target chamber and (c) sectioned view of the module.

EXPERIMENTAL RESULTS

Single Tile Module

The experimental results of the single tile module are listed in Table 3. Each grade of ceramic had 3 shots conducted except for Grade F+, where 6 shots were tested instead due to a relatively larger spread of data. Grade F+ (HV=24.4GPa) showed the highest mass efficiency ($E_m = 1.73$), while Grade T (HV=20.6GPa) and Grade T+ (HV=20.9GPa) had similar low mass efficiency $E_m=1.52$.

Table 3. Test results of the armour modules made of ceramics in four different grades

Ceramic	S/N	Velocity (m/s)	DOP (mm)	E_m	Average E_m
Grade T	T ₁	1220	16.5	1.55	1.53
	T ₂	1261	24.0	1.40	
	T ₃	1228	14.7	1.65	
Grade T+	T ₊₁	1258	19.7	1.53	1.52
	T ₊₂	1259	20.2	1.52	
	T ₊₃	1204	16.8	1.50	
Grade F	F ₁	1265	17.6	1.63	1.62
	F ₂	1253	18.9	1.55	
	F ₃	1224	14.0	1.67	
Grade F+	F ₊₁	1269	16.3	1.70	1.73
	F ₊₂	1239	19.7	1.49	
	F ₊₃	1231	6.6	2.11	
	F ₊₄	1195	14.0	1.59	
	F ₊₅	1256	10.9	1.93	
	F ₊₆	1236	16.7	1.59	

A linear relation between the mass efficiency and the hardness was observed, as shown in Figure 4. The mass efficiency (E_m) increased by 0.2 (13.3%) as the hardness increased by 3.8 (15.6%). The higher the hardness of the ceramic tile, the better the ballistic performance of the armour module. However, ballistic performance was not influenced by the fracture toughness as seen from Figure 5. These test results were in agreement with the work of Darin et al.[7], where 7.62mm projectiles at $v=907$ m/s were used.

Figure 4. Ceramic hardness plotted against mass efficiency of ceramics

Figure 5. Ceramic fracture toughness against mass efficiency of ceramics

Multiple Tile Module

Figure 6 shows the damage in the multiple tile modules tested. The damage was confined to 2 tiles, including the impact tile, in the Grade T+ SiC sample; meanwhile, damage in the Grade F+ sample spread to 5 tiles. The damage radius was measured to be $r_d=138\text{mm}$ in Grade T+ and $r_d=420\text{mm}$ in Grade F+ samples, respectively. Therefore, it can be concluded that fracture toughness had significant influence on the damage in tiles adjacent to the impact tile.

In the T+ module, the crack was observed to originate from the point of impact. In comparison, in the F+ module, two different crack patterns were observed. The tile directly next to the impact tile had a similar crack pattern as observed in the T+ module, however in the adjacent tiles, wave-like crack patterns were observed.

Figure 6. Damage and fracture in neighbouring tiles of Grade T+ and Grade F+ ceramics after impact.

The fracture surfaces of the fragmented tiles were observed using SEM, as shown in Figure 7. From Figure 7(a), it was observed that Grade T+ tiles with high fracture toughness had predominantly intergranular fractures, where multiple crack deflections along the crack path were observed. In Grade F+ tiles with low fracture toughness, the cracks presented little deflection, indicating it was dominated by transgranular fracture. Similar results of the relationship between fracture toughness and microstructural fracture in ceramic grains had been reported in the literature

[9], where static flexure tests were conducted. Therefore, it was concluded that the fracture toughness of SiC correlated with the mode of microstructural fracture under ballistic loading.

Figure 7. SEM images of fracture surface of ceramic fragments of (a) Grade T+ and (b) Grade F+

SIMULATION

The simulation was carried out using LS-Dyna explicit analysis, using two material models; Johnson-Cook (JC) model for the AISI 4340 steel and tungsten alloy, and Johnson-Holmquist-1 (JH-1) model for SiC.

The parameters of tungsten alloy and AISI 4340 parameter was obtained from literature[10], [8], as shown in Table 4.

Table 4. Material parameters for JC strength model of tungsten alloy and AISI 4340 steel.

Parameters	WHA [8]	HRC 30[10]
A (MPa)	697	719
B (MPa)	1160	456
n	0.626	0.093
c	0.056	0.008
m	1.00	1.03

JH-1 model was applied for the SiC ceramic. The grade F+ parameters were obtained from literature[8], where the strength parameters S_1 and S_2 of the remaining grades of SiC were scaled proportionately against the measured hardness of the ceramics. The parameters were listed in Table 5. As shown in the literature[12, 13], S_1 represented the limit of linear response of the strength of the intact ceramic at hydrostatic pressure P_1 , meanwhile S_2 represent of the maximum strength of the intact ceramic at hydrostatic pressure P_2 . The strength of ceramic was known to closely relate to the hardness of the ceramics. As hardness is a measure of the strength of ceramic against a permanent indentation when a compressive force is applied. For simplification, it was presumed that S_1 and S_2 were proportional to hardness, whose validity would be evaluated in the following simulation.

Table 5. JH-1 parameters of different grade of SiC

SiC Grade	Grade T	Grade T+	Grade F	Grade F+[8]
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	100001

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, $S_{\max}^f$ (MPa)	1300	1300	1300	1300
Failed Strength Constant, α	0.4	0.4	0.4	0.4
Damage Constant, $\epsilon_{\max}^f$	0.8	0.8	0.8	0.8
Damage Constant, ϕ	0.008	0.008	0.008	0.008
Damage Constant, P_3 (MPa)	99750	99750	99750	99750

Single Tile Module and Hardness of SiC

The simulation of single tile module using half model was applied to investigate the effect of hardness on ballistic performance of ceramic module, as seen in Figure 8. Consistent with the literature [8], SPH was used for the projectile, FEM-to-SPH for ceramic, and FEM for the remaining components. The typical size of SPH and FEM was 0.4mm and 0.8 mm respectively, which had been selected after a series of simulations with different element size to address the size effect. The nominal impact velocity 1.25km/s was applied in simulation.

Figure 8. Simulation model for single tile module

Figure 9 shows the comparison between the obtained test data and the simulation, demonstrating that the simulation was able to predict the mass efficiency with accuracy, thus confirming that the method of scaling the strength parameters to the ceramic hardness in the JH1 model was a feasible method for simulation of ballistic impact of ceramics with different hardness.

Figure 9. Comparison of experimental results and simulation results of various ceramics

In the preceding study [8], it was identified that the increased ballistic performance was predominantly contributed by a longer dwell time. Dwell being the most efficient phase in defeating long rod projectile; extending dwell time brought about a more efficient armour, thereby improving the ballistic performance of the ceramic armour module. Figure 10 shows the variation of the dwell

time versus the hardness of SiC ceramic, obtained from simulation. It was observed that the dwell time increased from $23\mu\text{s}$ to $31\mu\text{s}$ when the hardness of ceramics increased from 20.6GPa to 24.4GPa . The relative projectile tip position with respect to time is shown in Figure 11. It was observed that the penetration rate into ceramic armour, i.e. gradient of line, for each phase was identical, with only the length of dwell time varied.

Figure 10. Variation of dwell time vs ceramic hardness

Figure 11. Variation of projectile tip position versus time for 4 types of ceramics, where 3 distinct phases were observed (1) penetration of cover plate, (2) dwell and (3) penetration of ceramic.

Multiple Tile Module and fracture toughness

Simulation of the multiple tile module was modelled using full model to investigate the effect of fracture toughness on the damage in the neighbouring tiles close to the point of impact, as seen in Figure 12. The 6 ceramic tiles were modelled separately as individual part with an air gap of 0.1mm to represent the adhesive layer between the tiles. To study how stress wave caused damage in the ceramic tiles, erosion criteria of the ceramic tiles was removed in the simulation.

Figure 12. Top view of model used for multiple tile module

Figure 13 shows stress σ_x propagation along the direction of tile alignment (x-axis) in the first $44\mu\text{s}$ after impact. The impact at tile 1 created an initial compressive wave (blue box) in tile 2, propagating through the tiles from left to right. The compressive stress wave reflected at the adhesive interface between ceramic tile 2 and 3, creating tensile stress wave (red box) as seen in tile 2 at $t=17\mu\text{s}$, tile 3 at $t=25\mu\text{s}$, tile 4 at $t=35\mu\text{s}$, and tile 5 at $t=44\mu\text{s}$ (Figure 13). Based on the heat map, it was

observed that the magnitude of reflected tensile stress, σ_x , was reduced significantly as it propagated through the tiles from tile 2 to tile 5.

Figure 13. Normal stress σ_x along x-axis at different time of $0\mu s$, $10\mu s$, $17\mu s$, $25\mu s$, $35\mu s$ and $44\mu s$. Blue boxes and red boxes represented compressive stress wave and reflected tensile wave respectively.

Comparison was made between the stress wave profile and the fracture pattern at tile 3 of the Grade F+ multiple ceramic module, as shown in Figure 14, displaying similar features between. The stress wave profile (left) and fracture pattern (right). The fracture pattern formed an arc in the direction of the reflected tensile wave, indicating the fracture was caused by the reflected tensile wave. The low fracture toughness of Grade F+ tiles made them highly susceptible to tensile failure. Damage was observed in tile 5, where the peak tensile stress was only 49MPa.

Figure 15 shows normal stress σ_y in the ceramic tiles, along the y-axis. In both Grade F+ and Grade T+ ceramic modules, cracking along the y-axis was observed in tile 2. The cracking patterns in tile 2 of Grade F+ and Grade T+ ceramic tiles are shown in Figure 16(a) and (b). The fracture pattern was then compared against σ_y wave in Figure 16(c). It was observed that the fracture pattern corresponded to the σ_y wave. This indicated that the crack propagation across the tiles was due to tensile stress σ_y .

The peak tensile stress obtained from simulation for each tile is shown in

Table 6. According to the stress values, σ_x was consistently larger than σ_y up to tile 4. Based on that, one would expect wave-like damage pattern from tiles 2 to 4. However, it was not the case. Consequently, the time at which stress peaked, along with the location of the stresses, was analysed. Two stress profiles were read from elements A and B indicated in Figure 17(c). Looking at the two stress profiles in Figure 17, it was observed that in element A, the σ_y peaked before σ_x , while in element B, the reverse was observed. The result meant that the damage could be caused by either σ_x or σ_y , depending on the location of the crack. After taking 16 readings from each tile, the results are shown in Figure 18. It was observed that in tile 2, σ_y induced crack propagation was dominant while in tiles 3, 4 and 5, σ_x induced crack propagation dominated. The observation corresponded with the experimental results as seen in Figure 19, where two distinct damage patterns were observed: crack propagation from the origins in tile 2 and wave like fracture pattern from tile 3 onwards.

Figure 14. Comparison of ceramic damage pattern and stress wave profile of Tile 3.

Figure 15. Normal stress along y-axis in the ceramic tiles at 10 μ s, 13 μ s and 23 μ s respectively.

Figure 16. Fracture pattern of tile 2 of (a) Grade F+, (b) Grade T+ ceramic with the white lines indicating the crack paths, and (c) profile of stress wave σ_y based on simulation.

Table 6. Peak tensile stress measured in various tiles after impact.

Tile No	2	3	4	5
Peak σ_x (MPa)	378	190	145	49
Peak σ_y (MPa)	272	169	80	59

Combining the abovementioned findings, it was concluded that the damage of neighbouring tiles was a result of tensile waves generated during the impact process. The fracture pattern was induced by the stress which peaked first at the specific location of a tile, while the damage radius was determined by the fracture toughness of the tiles. Based on the results, the key to reducing damage radius was to either (1) reduce the incoming stress, or (2) increase fracture toughness of the ceramic used. As the stress generated was controlled by the incoming projectile, it would be highly unlikely to confine the damage to the impact tile at higher level threats. It was observed that the initial drop of stress from Tile 2 to Tile 3 was the largest, it was suggested that the fracture toughness of the ceramic tiles to be designed to survive the stress experienced in Tile 3. In this example, the fracture toughness required was approximately $7\text{MPa}\cdot\text{m}^{1/2}$.

Figure 17. Plot of σ_x and σ_y against time in (a) element A and (b) element B, (c) a diagram indicating locations of elements A and B.

Tile 1	Tile 2	Tile 3	Tile 4	Tile 5	Tile 6
	Y Y Y Y	X X X X	Y X X X	X Y X X	
	X Y Y X	Y X Y X	X X X X	Y X X X	
	X Y Y X	X X X X	X X X X	Y X Y X	
	Y Y Y Y	X X X X	Y X X X	Y Y X X	

Figure 18. Schematic map of the peak stress at various location of ceramic tiles, the X and Y on the diagram represented σ_x and σ_y peak respectively.

Figure 19. Illustration of the dominant mechanisms of fracture across ceramic tiles.

CONCLUSION

Ballistic testing of ceramic armour modules using ceramic tiles with difference hardness and fracture toughness were conducted. Hydrocode simulation of the experiments were conducted to understand target-projectile interaction during impact process.

Higher hardness ceramic had better ballistic performance due to dwell time increase. When the ceramic hardness increased from HV 20.6GPa to HV 24.4GPa, the dwell time increased from 23 μ s to 31 μ s, resulting in mass efficiency increase from 1.52 to 1.73. Meanwhile, no obvious influence of fracture toughness on ballistic performance was found.

However, fracture toughness had a strong effect on the damage in neighbouring tiles. When the fracture toughness increased from 2.8 MPa.m^{1/2} to 7 MPa.m^{1/2}, the damage radius was reduced from 420mm to 138mm. In addition, the damage of neighbouring tiles was determined by tensile waves generated during the impact process. When the fracture toughness was as low as 2.89 MPa.m^{1/2}, the tensile stress was able to generate cracks in tile 5, which significantly reduced the multiple hit capability of the ceramic module.

Therefore, it is recommended for ceramic armour designs to optimize the ceramic material parameters by determining the minimum fracture toughness required to withstand reflected tensile wave while maximizing the hardness of the ceramic used.

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