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# Prestressed ceramics and improvement of impact resistance

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## Abstract

The shrink-fit technique has been used to study the effect of prestress and confinement on ceramic materials. Calculation of prestress in ceramics tile wrapped by metal and optimized design for the composite are presented. Alumina tile confined with aluminum alloy, which was in a state of triaxial compression, was chosen as the target in impact tests to investigate the impact resistance of prestressed ceramics. The results from two types of impact tests indicate that both impact resistance and armor-piercing resistance are greatly enhanced due to the presence of prestress and compact confinements, and that triaxial prestress is much better than biaxial prestress for enhancing the impact resistance of ceramics.

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## 1. Introduction

Because of its high hardness, high moduli and light weight, ceramics have important applications in modern armor [1–3]. However, a fatal weakness of ceramics is their relatively low toughness and impact resistance. Prestress techniques could effectively improve the impact properties. A lot of research in this aspect has been carried out and some encouraging results have been reported [4,5]. Ceramic tile bonded on metal or polymer plate is widely used as armor material, and a modeling of layered ceramics under impact load has been given by Rajendran [6] and Rajendran and Chou [7]. Vural et al. [8] investigated the effects of projectile velocity and tile thickness on the ballistic efficiency of alumina ceramics, with thick

baking method. They found that the ballistic efficiency parameter of ceramics is not constant, contrary to common assumption, and ceramic tile of 4–6 mm thick will show the greatest ballistic efficiency.

It is well known that the compressive prestress is helpful in improving the fracture energy and impact resistance of brittle materials. There are many ways to form prestresses in ceramics, and most of them result in both compressive and tensile stresses in ceramic sample due to the self-equilibrium of inner forces. Generally, it is best to create compressive stress in whole ceramic body and tensile stress in ductile material in the composite. This is because tensile failure in ceramics can occur at very low stress level. Two common approaches to produce compressive prestress and to increase the impact resistance are: (a) laminating composite in which thermal residual stresses are developed upon cooling due to the difference of thermal expansion coefficient in adjacent layers [9,10] and (b) shrink-

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fitting by using biaxial confinement of metals to ceramic tile [11,12]. In case (a), compressive stress is produced in the layer having relatively lower expansion coefficient and tensile stress is induced in the layer with relatively higher coefficient, and those stresses originate from interfacial shear stresses. In case (b), biaxial compressive stress would be produced in ceramic sample and it is adjustable through changing the thickness of outer confinement materials; but the tensile strain normal to the compressive plane (due to Poisson's ration), has negative effect on the strength and impact resistance.

Although biaxial prestress in ceramics has showed nice effect in improving fracture resistance, compared to the ceramics without prestress, there are some problems such as delamination or flaking off along the direction normal to the stress plane when the sample was impacted. Therefore, seeking more effective prestress method is meaningful and necessary. Three-axial prestress is a possible way to further improve the impact resistance and penetration resistance of ceramics. Brar et al. [13] experimentally studied the impact resistance of ceramics confined in steel fixture and demonstrated the enhancement of ballistic efficiency of the confined ceramics. However, stress concentration and uneven stress in ceramics is a problem when the brittle ceramics is fixed in hard steel fixture at room temperature. In this work, a method of strengthening ceramics using multiaxial compact confinement was investigated and some satisfactory results are presented. The main contents of this study include (i) creating three-axial prestress in ceramics by slowly shrink fit of melted metal, (ii) residual stress calculation and optimal design of prestressed ceramics and (iii) effects of the prestress on impact resistance and armor-piercing resistance.

## 2. Prestress design

Generally, ceramics have low fracture energy and fast rate of crack growth [14]. It seems difficult to greatly improve the impact properties of ceramics through controlling the sintering process. Therefore, it is practical and useful to strengthen sintered ceramics by prestress techniques for engineering applications. Alumina tile confined in aluminum alloy

was used in this study to investigate the effect of confinement and prestress. Aluminum alloy was chosen as the wrap material due to its low weight and low melting point. For preparing the specimens, molten aluminum alloy was cast around a hot ceramics tile (about 600 °C) which was fixed in the center of a special mould, and then cooled down by fan. The shrinkage of aluminium alloy during the cooling process produced compact confinement on the ceramic tile, leading to multiaxial compressive stress in the tile and tensile stress in the metal. The value of the prestress depended on the temperature difference, the elastic moduli and the ratio of the section of the alloy to the section of the ceramics. The ceramics/alloy composite specimen is schematically shown in Fig. 1. Based on elastic mechanics, compressive prestress  $\sigma_1$  in the ceramic tile and the tensile prestress  $\sigma_2$  in metal can be approximately determined by Eqs. (1) and (2).

$$\sigma_1 = -\frac{\Delta\alpha\Delta TE_1E_2S_2}{E_1S_1 + E_2S_2} \quad (1)$$

$$\sigma_2 = \frac{\Delta\alpha\Delta TE_1E_2S_1}{E_1S_1 + E_2S_2} \quad (2)$$

where  $\Delta T$  is the temperature difference between the solidifying temperature of the metal and room temperature,  $\Delta\alpha=\alpha_2-\alpha_1$  is the difference of the thermal expansion coefficients between the alloy and the ceramic tile,  $E$  is the average value of the elastic modulus in the range of temperature variation,  $S$  is the side sectional area and subscripts 1 and 2 repre-

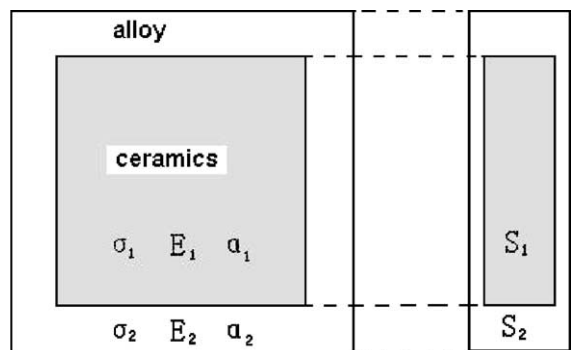


Fig. 1. Schematic illustration of the front and side sections of the ceramic/alloy composite specimen.

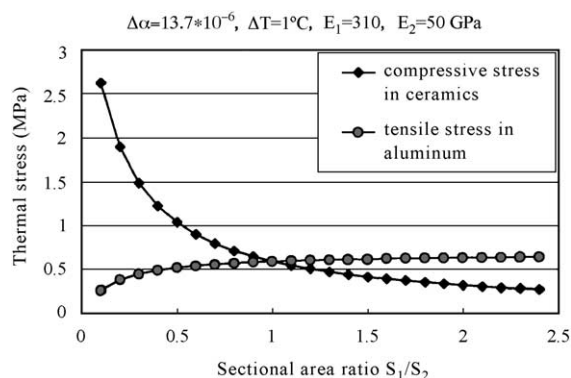


Fig. 2. Calculated residual stresses in confined ceramic and aluminum alloy as wrap material, and their variation with the sectional area ratio  $S_1/S_2$  for unit temperature drop. Because the thermal stress is in linear proportion to the temperature difference,  $\Delta T$ , the thermal stress caused by any temperature drop can be known if the stress resulting from unit temperature drop is obtained.

sent the ceramics and the alloy, respectively. In fact, the elastic modulus and expansion coefficient change with increasing temperature, so the average value of those parameters in the temperature range was used for the calculation. Given the ceramics and metal materials, the residual stress depends on the ratio of sectional area,  $S_1/S_2$ , and the functional relationship is calculated as in Fig. 2. For improving impact resistance, the compressive stress in the ceramics needs to be as high as possible, while the tensile stress in the metal needs to be low, at least lower than the yield strength of the metal. Since the inner forces in a cross-section should be in equilibrium, the stresses in ceramics and in the metal obey the following relations

$$\sigma_1 S_1 + \sigma_2 S_2 = 0 \quad (3)$$

Thus, given a stress ratio, the ratio of sectional area can be determined by Eq. (3). Let  $\sigma_y$  be the yield strength of the metal,  $\sigma_2 < \sigma_y$  should be satisfied and the corresponding ratio of sectional area for this requirement can be derived on the basis of Eq. (2).

$$\frac{S_2}{S_1} > \frac{(\Delta\alpha\Delta TE_2 - \sigma_y)E_1}{E_2\sigma_y} \quad (4)$$

It is well known that a hard and brittle body under hydrostatic pressure and compact confinement has very high fracture resistance and impact resistance.

A hard ceramic tile in the center of melted metal shrinking gradually with cooling process will show similar effects as in hydrostatic pressure. Modern armor materials are usually required having properties as: (1) high specific strength (strength/density), high hardness, (2) high softening temperature, (3) high impact resistance and (4) high toughness. Advanced ceramics can meet the first and second requirements, but energy concentration is unavoidable for brittle ceramics under impact load. On the other hand, metal can bear a relatively large deformation and absorb a large amount of energy when it is impacted. The composite of ceramics/alloy will combine their individual merits, so that the impact resistance might be greatly enhanced.

### 3. Experiment and analysis

The mechanical properties of the ceramics and metal in the composite samples are shown in Table 1.

#### 3.1. Experiment 1. Critical load to contact crack

The technique of impact contact and sphere indentation is useful for evaluating the degree of brittleness and impact strength of ceramics [15,16]. In spherical contact, the critical load to the initiation of ring crack on brittle materials can reflect the level of local strength and toughness of the specimens. In this experiment, an alumina bar of  $4 \times 4 \times 30$  mm was confined in aluminium alloy ( $S_1/S_2=0.1$  in the impact surface) and the upper surface of the bar keeps free as the impact surface. Biaxial compressive stress in plane was produced in the ceramic bar during the cooling process. In the impact contact test, freely dropping hammer was used to impact a steel ball on the surface of the sample. The speed of the dropping hammer depends on the initial height of the hammer.

Two types of tests, sphere indentation and impact contact, on the  $\text{Al}_2\text{O}_3$  tiles with and without prestress

Table 1  
The mechanical properties of the materials at room temperature

Materials	Strength (MPa)	$E$ (GPa)	$\alpha$ ( $10^{-6}/\text{K}$ )	Hv (GPa)
$\text{Al}_2\text{O}_3$ (99%)	250	310	8.3	19
Aluminium alloy	300	70	25	2.3

were performed respectively, using a steel sphere of 5 mm radius as the contact head. The results of the tests are shown in Table 2. The data indicate that for the prestressed specimens, both the critical load and critical kinetic energy to impact damage were enhanced by approximately 15 times, compared to the  $\text{Al}_2\text{O}_3$  tiles without prestress and stuck on a metal plate. The kinetic energy  $J$  was calculated in term of the mass  $m$  and the height of freely dropping  $h$ , i.e.,  $J=mgh$ .

### 3.2. Experiment 2. Impact resistance

Square alumina tiles with the size of  $60 \times 60 \times 8$  mm wrapped in aluminium alloy were used in this experiment. The size of each composite sample was  $90 \times 90 \times 22$  mm. The specimens were impacted using a nail-shooting gun by which the steel-nail projectile can easily penetrate a 6-mm thick steel plate or a 30-mm thick aluminum alloy plate. It was surprising that a prestressed ceramic composite sample was not penetrated after it has been shot six times sequentially at a fixed point. As a comparison, a ceramic tile glued on aluminum alloy plate was also tested in the same way, but it was broken and penetrated by only one shooting. Observation and analysis on the broken ceramics showed an impact process with three steps: (a) the ceramic tile was cracked at impact load, (b) the nail penetrated through the cracked ceramic tile into the substrate and (c) the fractured pieces splashed out. This broken mode would not occur in the prestressed ceramics because the ceramics is confined tightly. Since the prestressed ceramic sample absorb little deforming energy, most of the kinetic energy of steel nail was transformed into the fracture energy and deforming energy of the nail itself. The appearance of the specimen and the nail after impact are shown in Fig. 3.

Table 2

Critical load and kinetic energy of  $\text{Al}_2\text{O}_3$  with and without prestress in slow-loading contact test and freely dropping body impact test using the steel ball of 10-mm diameter as the contact head

	Critical load kg (1 mm/min)	Critical kinetic energy, $J$ (drop hammer)
$\text{Al}_2\text{O}_3$ without prestress	60	0.118
$\text{Al}_2\text{O}_3$ with prestress	940	1.78
Ratio	15.6	15

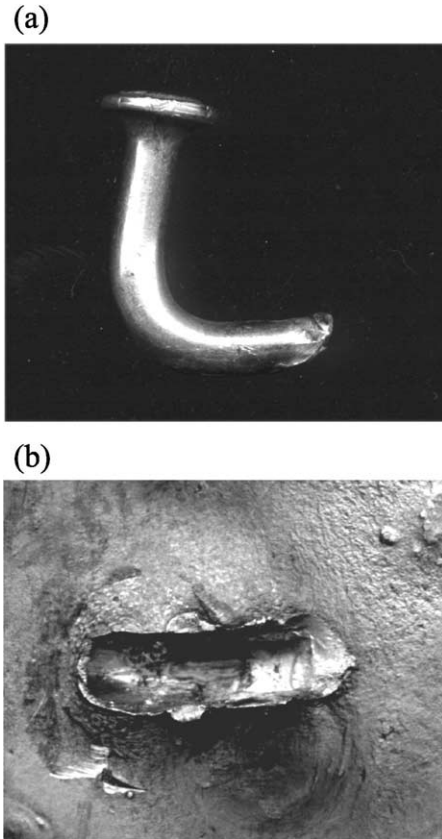


Fig. 3. Photos of the steel nail and the target specimen after impact by the steel nail shooting gun. Alumina ceramic core behind the aluminium layer was not damaged and its armor function was reserved after the shooting. The sample was subsequently shot in succession at the impact point for six times, and it was not penetrated but bended six nails.

### 3.3. Experiment 3. Armor-piercing resistance

The armor-piercing resistance of the prestressed ceramics was investigated with armor-piercing projectile. The hard projectile with a velocity of 820 m/s and a very high rotary speed (50,000 rpm) made the ceramics locally powdery in a circle area, with a diameter of about 30 mm around the shot point. It was noticed that over 2/3 of the projectile body became scraps and the shot target sample was not penetrated. The front and rear surfaces of the shot samples are shown in Fig. 4 that displayed a circle cavity in the sample. When the hard projectile penetrated the alloy layer and impacted the ceramics, parts

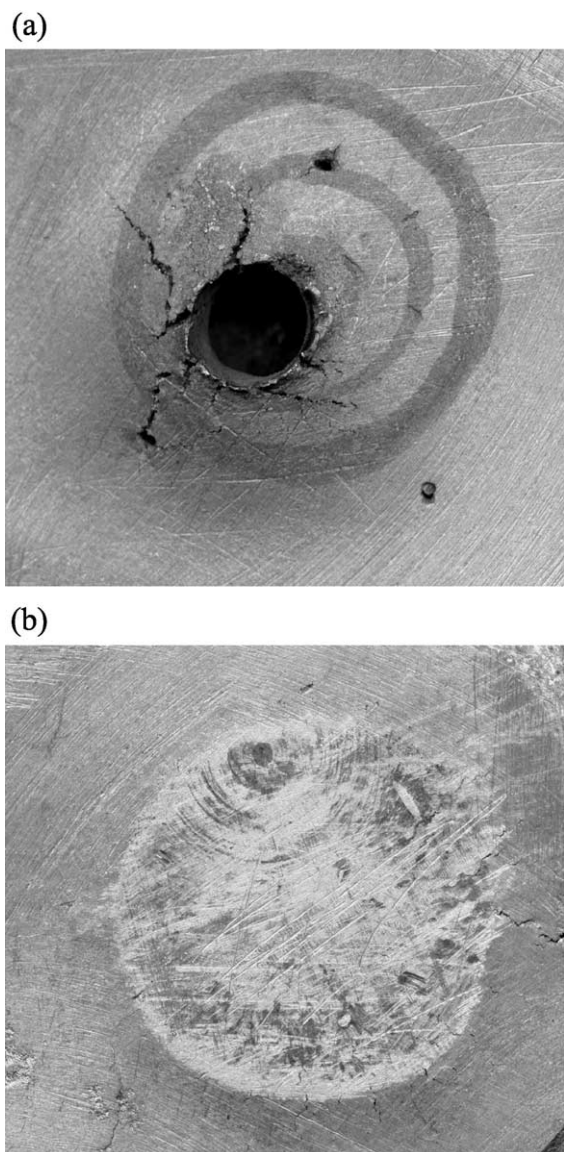


Fig. 4. The front and rear appearances of the ceramic/aluminum composite sample shot by armor-piercing projectile. The size and shape of the shot-formed cavity is approximately as the rear appearance in (b), which is much larger than the size of the entrance hole of the projectile as in (a). The cracks caused by the expansion of ceramics and projectile scraps in the cavity also consumed parts of energy.

of ceramics and projectile body became scraps and powders, but they did not splash out due to the confinement of the surrounding metal. Great inner pressure was then formed in the cavity during the

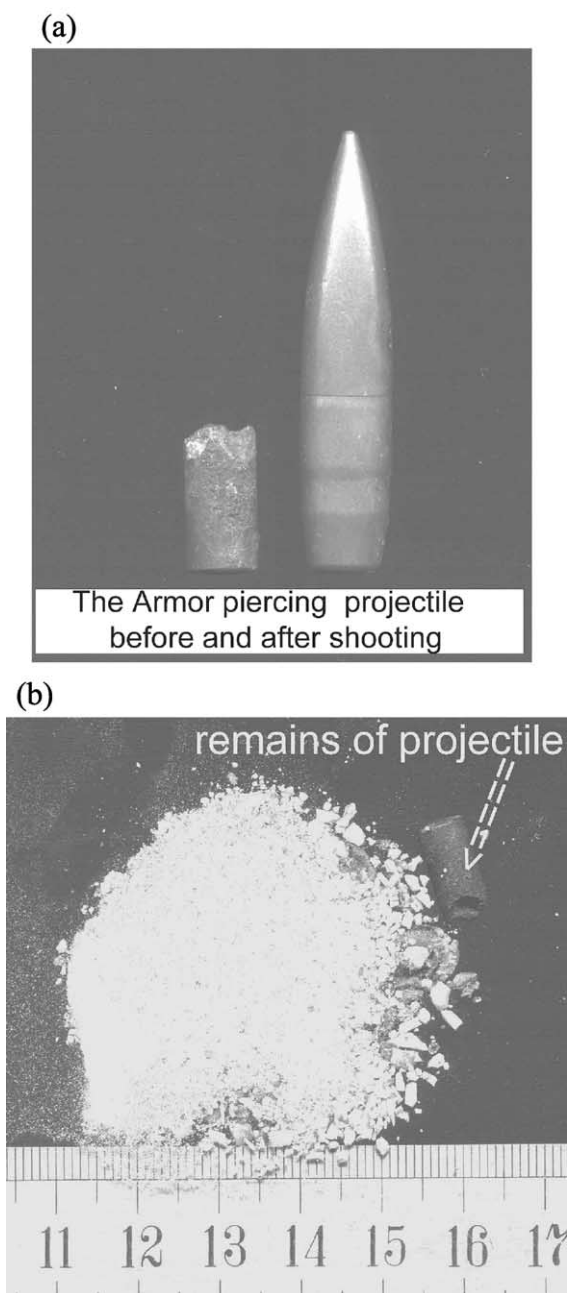


Fig. 5. (a) The Photo of armor-piercing projectile before and after shooting. (b) Scraps, powder and the remains of the ceramics and projectile, from the shot-formed cavity in the prestressed ceramic/aluminum alloy target.

short process of impact, so that many cracks were produced in the surrounding metal material. Part of powder and the remains of the projectile were taken out from the cavity and shown in Fig. 5. It indicates that the kinetic energy of the projectile was mostly transformed into surface energy of the scraps and heat energy of the powder, and strain energy of surrounding alloy. Thus, energy concentration produced by the projectile impact was greatly weakened.

The experimental results indicated that the ceramics compactly confined by metals possessed a very high impact resistance and penetration resistance. Part of the instantaneous tensile stresses in the impacted area of the prestressed ceramics could be balanced by the preexisting compressive stress. Furthermore, when a prestressed composite sample is shot, the instantaneous impact kinetic energy is completely transformed into surface energy of scraps and the deformation energy of the surrounding alloy material. That is why the impact resistance of the prestressed ceramics was substantially enhanced.

The compact confinement made the ceramic tile unmovable even if it had been broken up. That is another important reason for enhancement of the armor piecing resistance. In the state of triaxial compression and confinement, broken ceramics were confined and could not splash out when the projectile impacted into them, the penetration resistance becomes much higher than that of the ceramics in biaxial confinement.

#### 4. Conclusions

(1) A strengthening technique for sintered ceramics is proposed to improve the impact resistance. The ceramics with high hardness, compactly confined in metal, will have a very high penetration resistance due to the presence of triaxial prestress in ceramics. Prestressed ceramics composite was produced by casting molten alloy around a hot ceramic tile and then cooling down with air blowing.

(2) The residual stresses in ceramics and in the metal were calculated for the metal-wrapped ceramics composite. Given temperature difference, the stress depends on the ratio of sectional area  $S_1/S_2$ . The residual stress in the metal should be lower than the yield strength of the metal, and this require-

ment can be realized by using a reasonable value of  $S_1/S_2$ .

(3) The critical load to contact damage or impact damage could be enhanced up to 15 times when alumina ceramics was prestressed by confinement of aluminum alloy, with  $S_1/S_2=0.1$ . The enhancement of the impact resistance depends on the confinement states of a ceramic tile. A series of confinement states of ceramics, having different impact resistances and armor-piercing resistances, are ranked as follows: a free ceramic tile has low impact resistance; a ceramic tile glued on a tough material has high resistance; a ceramic tile under biaxial confinement has higher impact resistance; triaxial prestressed ceramic composite has the highest impact resistance.

(4) When a ceramic tile under triaxial compression is impacted by a hard projectile, its penetration resistance mainly depends on the hardness of the ceramics and the resistance can be kept even if the ceramics is cracked because the volume and location of the ceramics is tightly confined.

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#### References

- [1] Z. Rosenberg, Y. Yeshurun, *Int. J. Impact Eng.* 7 (3) (1988) 357.
- [2] R.L. Woodward, B.J. Baxter, *Int. J. Impact Eng.* 15 (2) (1994) 119.
- [3] Z. Rosenberg, J. Tsaliah, *Int. J. Impact Eng.* 9 (2) (1990) 247.
- [4] D.A. Shockey, A.H. Marchand, S.R. Skaggs, C.E. Cort, M.W. Burkett, R. Parker, *Int. J. Impact Eng.* 9 (3) (1990) 263.
- [5] C.T. Sun, D.S. Adams, C. Han, in: V. Shim, S. Tanimura, C.T. Lim (Eds.), *Impact Response of Materials and Structures*, Oxford Univ. Press, 1999, p. 75.
- [6] M. Rajendran, *Int. J. Impact Eng.* 15 (1994) 749.
- [7] M. Rajendran, S.C. Chou, in: V. Shim, S. Tanimura, C.T. Lim (Eds.), *Impact Response of Materials and Structures*, Oxford Univ. Press, 1999, p. 432.
- [8] M. Vural, M.Z. Erim, A.H. Ucisk, in: V. Shim, S. Tanimura, C.T. Lim (Eds.), *Impact Response of Materials and Structures*, Oxford Univ. Press, 1999, p. 369.

- [9] K.J. Chen, C.T. Sun, *Compos. Struct.* 4 (5) (1985) 9.
- [10] T. Sun, S.H. Yang, NASA CR-159884, NASA, Washington, DC.
- [11] D.A. Shockey, A.H. Marchand, S.R. Skaggs, C.E. Cort, M.W. Burkett, R. Parker, *Int. J. Impact Eng.* 9 (3) (1990) 263.
- [12] W. Chen, G. Ravichandran, *J. Am. Ceram. Soc.* 79 (3) (1996) 579.
- [13] N.S. Brar, H.D. Espinosa, G. Yuan, *Rev. High Press. Sci. Technol.* 7 (1998) 855.
- [14] Z. Jin, Y. Bao, *Characterization of Mechanical Properties for Brittle Materials*, Chinese Railway Press, Beijing, 1996.
- [15] B. Lawn, *J. Am. Ceram. Soc.* 81 (8) (1998) 1977–1994.
- [16] A.G. Evans, E.A. Charles, *J. Am. Ceram. Soc.* 59 (7–8) (1976) 371.