(19) Europäisches Patentamt
European Patent Office
Office européen des brevets

(11) Publication number: 0 334 263 A1

(12) # EUROPEAN PATENT APPLICATION

(21) Application number: 89104961.1

(22) Date of filing: 20.03.89

(51) Int. Cl.4: F41H 5/04

(30) Priority: 23.03.88 US 171971

(43) Date of publication of application: 27.09.89 Bulletin 89/39

(84) Designated Contracting States: AT BE CH DE ES FR GB GR IT LI LU NL SE

(71) Applicant: FMC CORPORATION
200 East Randolph Drive
Chicago Illinois 60601(US)

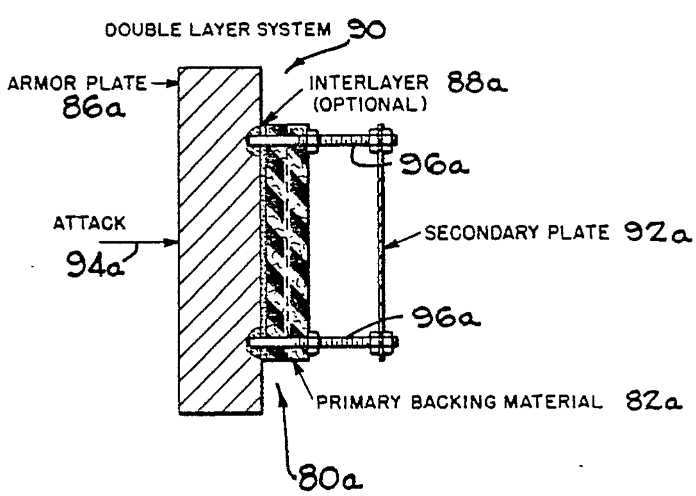
(72) Inventor: Morrow, John D.
5268 Kentfield Drive
San Jose, California 95124(US)

(74) Representative: Bardehle, Heinz, Dipl.-Ing. et al
Patent- und Rechtsanwälte
Bardehle-Pagenberg-Dost-Altenburg-Frohwitter und Partner Galileiplatz 1 Postfach 86 06 20
D-8000 München 86(DE)

(54) **Improved active spall suppression armor.**

(57) An improved active spall suppression armor is disclosed which includes at least a primary spall backing plate (82a) which contacts the inner wall of the armor (86a). The backing plate material is formed as a polymeric matrix having metal or ceramic powders therein which form particles of low mass, low kinetic energy and low penetration capability when the outer surface of the armor is contacted by the type of weapon which the spall backing material is designed to protect. A secondary spall backing plate (92a) may be spaced from the primary plate for reducing the angle of dispersement from fragments released from the armor and the weapon.

FIG_9



EP 0 334 263 A1

IMPROVED ACTIVE SPALL SUPPRESSION ARMOR

CROSS REFERENCE TO RELATED APPLICATION

The present invention is an improvement over that disclosed in Musante et al Application Serial No. 098,633 filed September 18, 1987 entitled ACTIVE SPALL SUPPRESSION ARMOR. (European Application 88 113 787.1)

BACKGROUND OF THE INVENTION

Field of the Invention

The present invention relates to the reduction of injury and damage from the spall typically generated off the inside surface of armor plate or the like, by contiguously attaching light weight spall backing material having a sonic impedance such that the stress reflected into the armor is below that which causes significant spallation in the armor. The lightweight backing is frangible or of low strength such that when it fractures, the particles are of low mass and/or kinetic energy and of minimal concentration capability.

Description of the Prior Art

It is well recognized that spall is a primary cause of armor vehicle kills during combat. Spall may be characterized as a cloud of high velocity fragments of metal which is released from the inside surface of the vehicle's armored hull and is lethal to soft targets inside the vehicle. The soft targets include electrical cables, electrical components, fuel lines, fuel cells, and personnel within the vehicle.

Spall liners consisting of aramid fiber reinforced polymer panels are currently being used for minimizing the spall effect, but are quite expensive and heavy. Application of these liners is hindered by limited space in vehicles and the low space efficiency of the liners. The effectiveness of these liners require that the liners be spaced from typically about 4 to 17 inches from the inner wall of the vehicle and are therefore undesirable since the useable space within most vehicles is quite limited. Also, the hardware within the vehicles makes it difficult or impossible to secure the liner within all portions of the vehicle without interfering with the operation and location of vehicle components. Significant areas in vehicles, such as turret and driver areas, have spall protection which is either limited or non-existent due to lack of space for any standoff.

SUMMARY OF THE INVENTION

In general, active spall suppression armor includes an armor material or plate backed by a spall backing material which is contiguously attached to the inside surface of the armor, typically by adhesives. The spall backing material may be of the consistency of pliable putty, or may be in the form of hard, soft, or elastic tiles or sheets. In the event that the spall backing consists of a uniform dispersion of particles in a binder matrix, the matrix binder may serve to contiguously adhere the backing material to the armor. The spall material when fractured, due to stresses transmitted through the armor material, forms nonlethal fragments of low mass and kinetic energy. The sonic impedance of the spall material is such that the stress reflected by the spall backing material into the armor is below that which causes failure in the armor, which failure would result in lethal spall particles being propelled from the inner surface of the metal armor. Spall may be created in the backing material but the effect is minimized by assuring that the spall created in the backing material has low energy and is therefore of limited penetration capability. The armor material may be steel armor, aluminum armor, and other types of armor including composite materials.

The improved active spall suppression armor is directed to the use of different types of either monolithic or composite materials in contact with the armor plate, used alone or with a secondary layer or plate spaced therefrom.

In particular, the improved active spall suppression system performs better than present spall liners where minimal space is available, typically under four inches.

BRIEF DESCRIPTION OF THE DRAWINGS

Figure 1 is a perspective in section illustrating an armor plate without spall backing material attached thereto being impacted by a shaped charge, or projectile, and showing armor spall being discharged therefrom.

Figure 2 is a diagrammatic elevation of a military vehicle illustrating a projectile passing through the two armor walls and two spall liners of a prior art vehicle illustrating spall cone angles.

Figure 3 is a diagrammatic elevation in vertical section illustrating an armor plate with spall backing material attached to a test stand, and a witness sheet attached to a frame.

Figure 4 is a diagrammatic elevation illustrating a saw-toothed stress wave created in the armor by the impact of a shaped charge explosive at four separate time intervals relative to the free inner surface of the metal armor.

Figure 5A is a diagram illustrating the saw toothed stress waves at an interface between an armor plate and a backing material having a lower sonic impedance than that of the armor plate.

Figure 5B is a diagram illustrating the saw-toothed stress waves at an interface between an armor plate and a backing material having a greater sonic impedance than the armor plate.

Figure 6 is a vertical section taken through an armor plate having a spall backing material contiguously attached thereto by an optional interlayer.

Figure 7A is a copy of a photograph illustrating the back of an armor test plate without spall backing illustrating the area from which armor spall has been released and further illustrating a hole therein formed by the shaped charge jet.

Figure 7B is a copy of a photograph illustrating the front of a witness plate illustrating the usual pattern of holes formed therein from spall from the armor plate of Figure 7A and the slug from the shaped charge slug, respectively.

Figure 8 is a vertical section through an improved single layer spall suppression system, the dotted lines indicating that the backing material may be used in the form of a single plate or a plurality of plates.

Figure 9 is a vertical section through an improved double layer spall suppression system similar to Figure 8 but having a secondary plate or sheet spaced from the backing material.

Figure 10 is a copy of a back lighted photograph of the front of a witness plate, at reduced scale, illustrating the results of a TOW 11 shot through an unbacked armor plate of 1.75" 5083 aluminum and showing the usual circular pattern of holes formed from lethal spall and a central hole formed by the jet and slug of the weapon when shot at 0°.

Figure 11 is a copy of a back lighted photograph with test conditions the same as Fig. 10 but of a witness plate illustrating the results of a test shot through an armor plate backed by a single layer of 4.5 PSF aramid fiber backing material at 4" spacing and showing a hole formed by the slug but very few holes formed by spall.

Figure 12 is a copy of a back lighted photograph of the front of a witness plate with test conditions the same as Figure 10 but illustrating the results of a test shot through the armor plate having a 4.3 PSF single layer of backing material attached thereto, and a hole formed by the slug with a slightly larger amount of holes formed by spall.

Figure 13 is a copy of a back lighted photograph of the front of a witness plate with test conditions the same as Figure 10 but illustrating the results of a shot through the armor plate having a 2.8 PSF single layer of primary backing material attached thereto and a 1.5 PSF aramid fiber plate spaced 2 inches from the primary backing material showing the hole formed by the slug plus two holes of lethal spall believed to be formed by fragments from the slug.

DESCRIPTION OF THE PREFERRED EMBODIMENT

In order to better understand the improved active spall suppression armor of the present invention, Applicant, who is a co-inventor of cross-referenced Application Serial No. 098,633, has included herein the general theory of operation along with definitions of terms, formulas, tables and sample calculations which appear in the cross-referenced application. The improved armor of the present invention begins at the title IMPROVED ACTIVE SPALL SUPPRESSION ARMOR.

Prior to describing the active spall suppression armor 18 of the present invention, it is believed that a brief description of spallation would be helpful.

Figure 1 diagrammatically illustrates a section of metal armor 20, without a spall backing material attached thereto, being contacted by a weapon 22 which may be a shaped charge or a high velocity projectile. The weapon 22 contacts an outer surface 23 of the armor with sufficient force to dislodge spall fragments 24 from the free or inner surface 26 of the armor 20. The spall fragments are propelled from the inner surface 26 of the armor along a conical path of about 100° at high velocity with many of the fragments being of sufficient mass to be highly penetrating to soft targets that are contacted by the fragments. More particularly, spalling is a failure mode wherein fracture occurs near the free surface 26 (Fig. 1) remote from the outer surface 23 where an impulse load is applied. The impulse load is typically generated by an explosive detonation from a shaped charge, or by the impact of a high velocity projectile. The impulse induces a compressive shock wave which propagates to the opposite free surface 26 where it reflects as a tensile wave. The intensity of the tensile wave will increase as it propagates back through the material. At some distance from the surface 26, the stress intensity exceeds the threshold required for initiation and fracture at which time spallation occurs discharging the spall 24 inwardly at high velocity.

Figure 2 diagrammatically illustrates a vertical section through two armor plate walls 28,29 of a vehicle having two prior art spall liners 32,34 spaced inwardly of the vehicle. The path 36 of the projectile is illustrated by arrows as passing through both walls 28,29 and liners 32,34. However, a primary spall cone angle in the first contacted wall 28 indicates that the first spall liner 32 stops some spall but allows larger high velocity pieces to pass through and be stopped by a second spall liner 34 as illustrated by a narrow secondary spall cone 38.

Figure 4 represents stresses caused by shaped charge weapons and illustrates the formation of compressive and tensile waves when passing through the first contacted armor at four separate time intervals to the free surface 26 without spall backing material attached thereto. At time T-1 a saw-tooth wave or pulse 39 illustrates the stress intensity relative to the back or inner surface 26 of the armor caused by the detonation of an explosive. As illustrated at time T-2, when the compressive wave 39 reaches the free surface 26 it reflects as a tensile wave 42, which is partially cancelled by the incident compressive pulse 39. The tensile stress will increase until the maximum stress occurs at a distance from the surface 26 of the plate 20 equal to one-half of the pulse length as indicated at time T-3. At time T-4 the intensity of the tensile wave exceeds the compressive wave thus indicating that spall will not be created.

When a projectile, as opposed to an explosive detonation or a shaped charge, applies the impact load, a square wave (not shown) is produced which will provide no tensile stress until the maximum occurs at the half pulse distance at T-3 of Figure 4.

The creation of spall fracture is dependent upon both the magnitude and duration of stress. Sufficient time at the sufficient stress are required to first nucleate cracks, and then to grow the cracks. Fracture is therefore dependent upon amplitude and the shape of the stress pulse. When the condition of stress intensity and time are such that the criterion for fracture are met, then the spall will be formed. When fracture occurs, the strain energy remaining in the material between the fracture and the rear face is released as kinetic energy and the spall particles fly from the rear face, usually with significant velocity. The velocity is limited theoretically by the equation: $V = 2M/DC$ where M is the magnitude of the stress wave, D is the density of the material, and C is the material sound speed.

Interaction of Stress Waves at Interfaces

When a stress wave encounters an interface or free surface between two dissimilar materials such as the armor plate material 20 (Figs. 5A,5B and 6) and the spall backing material 40, the stress waves behavior becomes more complex. The simplest situation is a normal impact by a projectile with a diameter of the same order of magnitude as the armor plate thickness. The stress wave can then be considered to have a planar front and to travel perpendicular to the face of the plate. In general, when this wave reaches an interface, one wave is reflected and another is transmitted. The intensities of the waves are dependent upon the relative sonic impedances of the two materials.

The sonic impedance (Z) of a material is the product of the sound speed (c) in the material, and its density (D). The values of density and sound speed are not constant, but vary to some degree with pressure. Consequently, impedance can vary with the pressure and will definitely change when the yield strength of a material is exceeded. Generally, for most fully dense, elastic materials, the impedance below the yield point is relatively constant. The density, sound speed, and impedance are listed in Table 1 for a number of common materials. The intensities of the transmitted and reflected waves from a stress wave impinging an internal interface are given by the following equations:

$R = I(D_2 C_2 - D_1 C_1) / (D_2 C_2 + D_1 C_1)$
and;
$T = I(2D_1 C_1) / (D_2 C_2 - D_1 C_1)$
or;
$R = I(Z_2 - Z_1) / (Z_2 + Z_1)$
and;
$T = I(2Z_1) / (Z_2 - Z_1)$
where;
R = REFLECTED WAVES
T = TRANSMITTED WAVES
I = INCIDENT WAVES
Z = IMPEDANCE OF THE MATERIAL
D = DENSITY
and where subscript;
1 = the armor material
2 = the spall backing material

By convention, compressive stress has a positive value and tensile stress has a negative value.

From the above equations, a compressive wave will reflect as a tensile wave in the armor material if the second layer or backing material has a lower impedance, as illustrated in Figure 5A; and as a compressive wave if the backing material has a higher impedance as illustrated in Figure 5B. The amplitude of the reflected tensile wave will always be less than or equal to that of the incident compressive wave.

The relative intensity of the reflected wave in the armor material is related to the relative impedance of the spall backing material as follows:

For an impedance ratio (n) of the armor material the following equations apply: $n = Z_2/Z_1$.
$R/I = (Z_2 - Z_1) / (Z_2 + Z_1) = nZ_1 - Z_1 / (nZ_1 + Z_1)$
or;
$R/I\ (n-1) / (n+I)$

This ratio is tabulated in Table 2 to illustrate how a second layer, or backing material 40 (Fig. 6), can be used to reduce the magnitude of the reflected stress. It can be seen that a material with only one-fifth of the impedance of the first layer (armor material) can reduce the reflected tensile stress by as much as 33 percent.

TABLE 1

Density D, sound speed (C) and Impedance values (Z) for selected materials.

MAT'L	D (lb/ft^3)	C (k ft/s)	Z (k lb/ft^{2}sec x 10^5)
Aluminum	88.6	17.8	1.58
6061-T6 Aluminum	88.7	17.1	1.52
2024 Aluminum	91.4	17.2	1.57
Berylliun	60.7	26.5	1.61
Brass	276.6	12.2	3.36
Boron Carbide(75% Dense)	63.0	9.7	0.61
Silicon Carbide(72% Dense)	76.1	9.4	0.71
Tungsten Carbide	492.8	17.0	8.38
Carbon Phenolic	48.9	13.8	0.67
Chromium	233.6	17.4	4.06
Cobalt	289.4	15.7	4.56
Copper	293.0	12.9	3.77
Epoxy	39.4	8.8	0.34
Graphite (Commercial)	53.4	4.8	0.26
Pyrolitic Graphite	72.2	13.6	0.98
Armco Iron	257.6	14.8	3.80
Lucite	38.7	7.2	0.28
Magnesium	57.3	14.9	0.85
Manganin	277.6	12.5	3.46
Mylar	45.6	7.2	0.33
Nickel	290.7	15.3	4.44
Nylon	37.4	7.1	0.26
Paraffin	30.1	9.7	0.29
Phenolic Fiberglass(AVCO)	62.3	5.6	0.35
Phenolic Fiberglass (GE)	63.7	10.7	0.68
X-Cut Crystalline Quartz	86.9	18.8	1.63
Plexiglass	38.9	9.0	0.35
Polyethylene	30.2	9.6	0.29

MAT'L	D (lb/ft^3)	C (k ft/s)	Z (k lb/ft^{2}sec x 10^5)
Polystyrene	34.5	9.8	0.34
Polyurethane	41.5	6.8	0.28
304 SS	259.1	15.0	3.87
Mild Steel (EN3)	257.2	11.8	3.03
Teflon	70.9	4.7	0.33
Tin	238.9	8.4	2.02
Titanium	148.0	15.4	2.28
Tungsten	629.0	13.0	8.19
Uranium/3% Moly.	605.3	8.4	5.07
Zinc	234.3	10.0	2.35
Zirconium	213.4	12.3	2.63

TABLE 2

Reduction in the reflected tensile stress for a given relative impedance of a layer of backing material.	
Impedance Ratio n	% Reduction in Reflected Tensile Stress
.10	18
.20	33
.30	46
.40	57
.50	67
.60	75
.70	82
.80	89
.90	95
1.00	100

When the spall suppression armor 18 (Fig. 6) of the present invention is to be used on light weight armored vehicles, as well as heavy armored vehicles, it is of course desirable to minimize any added weight to the vehicle. Accordingly, the spall backing material is not designed to completely suppress fractures in the spall backing material 40 by all known weapons but is designed to provide backing material which, if fractured, will fracture into low energy, particles of low penetration capability when the armored plate and backing material are contacted by a weapon, either a shaped charge weapon or a projectile. It is, of course, understood that the backing material may be thickened or be in layers of the same or different backing materials if added weight is not a problem.

The concept of the subject invention involves the backing of armor plate 20 with a backing material 40, or a series of backing materials, which must satisfy two conditions. First, the impedance of the backing material must be such that the stress reflected into the armor plate 20 is below that which would cause spall-type failure in the armor plate. Second, the fragments from the fracture of the backing material, caused by transmitted stress, must be nonlethal, that is, of low mass and/or velocity. Varying impedance in the backing material may be used to condition the stress wave in the backing material to control fragmentation. The impedance may be varied by either layering or by controlling the material properties continuously through their thicknesses.

A preliminary design analysis was made for identifying the relationship between design variables and system weights. First, the amount of the stress wave which must be transmitted into the spall backing material was estimated by comparing spall strength to the stresses involved in jet penetration. With this data, the properties of the spall backing material was determined.

The weapons used were shaped charge TOW-II with a jet impacting aluminum armor. A 2009 GPa (giga pascals) shock stress was generated with a pulse time length of 1.175 microseconds, which shock stress was calculated from the jet diameter divided by the sound speed in 5083 for MIL-A-46027G(MR) aluminum having a thickness of one inch. It was assumed that the aluminum had about the same spall "strength" as steel, the stress is so much higher in the aluminum than its strength, that essentially the full amplitude of the stress wave must be transmitted into the backing material.

The relationship between the impedance of the backing material 40 and the areal density AD required to suppress spall in the aluminum armor was derived as follows:

Let:

l_{ns} = stress pulse wavelength in the backing material

l_{al} = stress pulse wavelength in the aluminum

c_{ns} = wave velocity in the backing material

c_{al} = wave velocity in the aluminum

th = minimum thickness of any backing material for passage of the full stress wave

d = diameter of the shaped charge jet

D_{ns} = density of the backing material

t_{al} = time length of the stress wave in the aluminum

Z_{ns} = sonic impedance of the backing material

AD_x = minimum areal density of backing material "x" for passage of the full stress wave

The wavelength of the stress pulse in the aluminum armor can be estimated by:

$t_{al} = d/c_{al}$

$l_{al} = t_{al}c_{al} = d$

The wavelength in the backing material is:

$l_{ns} = l_{al}(c_{ns}/c_{al})$

Assuming that the backing material will separate from the aluminum when the stress wave reaches the interface after reflecting in tension from the backface of the backing material (because the interface cannot support significant tensile stress), and that conservatively, the whole wave should pass into the backing material:

$l_{ns} = 2th$ or $th = (1/2)l_{ns}$

Combining the above three equations gives the minimum backing material thickness for any given material:

$th = (d/2)c_{ns}/c_{al}$

The minimum areal density (AD) of the backing system can be calculated as follows:

$AD = D_{ns}th = D_{ns}[(d/2)c_{ns}/c_{al}] = D_{ns}c_{ns}[(d/2)c_{al}]$ (Equation 1)

Since $Z_{ns} = D_{ns}c_{ns}$:

$AD = Z_{ns}[(D/2)c_{al}]$ (Equation 2)

Since the jet diameter, d, and the aluminum wave velocity, c_{al}, are constant for any given case, the minimum areal density of a backing system is linearly related to its impedance. If again it is conservatively assumed that there must be no reflected tensile wave in the aluminum, then the optimum backing material areal density will be when the Impedance of the backing material matches that of the aluminum.

Sample calculations

Assuming a 3/8 inch jet diameter vs. aluminum armor with aluminum as a backing material (matched Impedance), optimum areal density can be calculated as follows:

Using equation (1):

$AD_{al} = D_{al}[(d/2)(c_{al}/c_{al})] = D_{al}(d/2)$

For aluminum, $D_{ns} = 14$ lb/ft^2, which yields:

$AD_{al} = 2.625$ lb/ft^2

The fired alumina, which worked well in the preliminary testing, would yield an optimum from equation (2) (considering that $Z_{alumina}/Z_{al} = 2.33$):

$AD_{alumina} = 2.625(2.33) = 6.116$ lb/ft^2

The above calculations indicate that aluminum would be a lighter backing material than the fully-fired alumina. However, the aluminum is not frangible. While the aluminum backing material would successfully extract the stress wave from the aluminum armor plate or hull structure of a vehicle, the aluminum backing material could itself produce highly penetrating spall.

This design methodology also suggests the merits of a metallic or ceramic particle loaded polymer. In this case, the individual particles may have a higher sonic impedance than that of the armor. However, when the particles are combined with a polymer, the particle content must be sufficient to insure that the particle/polymer blend has an impedance value sufficient to reduce the reflected tensile stress below that required to form spall. A particle/polymer blend may also afford the advantage of sticking directly to the armor without the need of an intermediate adhesive.

A low density strength solid which fractures in a brittle manner, and which has a suitable impedance, may also be used. For instance, solid, polycrystalline sodium chloride (NaCl) in a 1/2 inch thickness has suppressed spall formation in aluminum armor when bonded to the back of the armor plate.

Tests have been conducted to investigate the effect of spall backing material thickness, warhead size, obliquity, armor alloy, and armor thickness on the performance of the various backing materials. The general procedure consists of adhesively bonding the backing material 40 (Fig. 6) to the armor plate 20 which together comprise a piece of active spall suppressive armor 18 in the form of a target 50 (Fig. 3). The target is fixed to a test stand 52, and the target 50 and a witness sheet 54 are subjected to a warhead attack. Base line targets of unbacked and liner-backed armor plates were also tested for comparison purposes. The witness sheets 54 were placed behind the test stand to record the distribution of spall and jet particles.

THE IMPROVED ACTIVE SPALL SUPPRESSION ARMOR

The improved active spall suppression armor of the present invention discloses two systems for suppressing the formation of spall. A first system is a single layer system 80 (Fig. 8) which uses a single layer (or two or more thin plates to make up the single layer) of several preselected types of spall backing material 82 that is preferably bonded to the inner wall 84 of armor plate 86 (sometimes referred to as the target) by an interlayer 88 of adhesive. The material used to form the spall backing system differs from those previously described and provides improved spall suppression with spall backing materials of reduced weight.

The second system is a double layer system 90 (Fig. 9) which bonds the same type of spall backing material 82a to the armor plate 86a by an interlayer 88a of adhesive. In addition, the second system includes a second plate or liner 92a spaced from the spall backing material 80a for defeating secondary particles of the jet and armor which are disturbed from the penetration interface by the presence of the active spall suppression backing.

In the single layer system 80 (Fig. 8) the primary spall backing material 82 is placed in contact with the armor plate 86 and may be bonded thereto if desired by the interlayer 88 of adhesive. Alternately, the tacky nature of the polymer matrix of the backing material may be used as an adhesive if applied to the backing material before it is cured. Before curing, the backing material may be sprayed or troweled onto the armor plate. Alternately, the polymer matrix backing material may be cast into plates, allowed to cure, and thereafter be bolted to the armor plate 86. The spall backing material is formed of materials such that the composite backing was an impedance which is tailored so that the tensile stress is reduced below that required for spall formation. The spall backing material breaks up into fine, low energy, non-penetrating fragments after absorbing the shock wave.

The spall backing materials tested in the cross-referenced co-pending application were primarily alumina-type ceramics, whereas the spall backing material of the present invention are primarily metal and ceramic powder loaded polymer composites.

DISCUSSION OF THE SPECIFIC PROBLEMS

Spall generated from armor plate used on combat vehicles, as a result of being overmatched by shaped charge or projectile attacks, is perhaps the largest contributor to casualties and fire power kills. Spall consists of a cloud of high velocity fragments ejected from the back surface of an armor plate due to an impact on the front surface. The present state-of-the-art method for prevention of damage from spall is to place aramid fiber reinforced plastic liners (sometimes referred to as panels or plates) behind the armor in order to catch the spall particles. These liners, specified for application in armored personnel carriers and fighting vehicles, require significant space for crew member efficiency and for mounting hardware to the inner vehicle surfaces, and have limited ability to function after a single hit.

The space aspects are especially important in that internal volume is very limited in most light and all heavy armored combat vehicles. In the personnel carriers, the liners are sometimes mounted 16 inches off the inner surface of the armor plate on a sliding rail system (for access behind the liners) whose weight equals that of the liner panels. A four inch standoff is used for most applications in the fighting vehicle, which limits efficiency. it would be very desirable to regain some or all of this lost volume without a loss of protection. In both types of light vehicles, there are significant areas, such as turret and driver areas, where protection is either limited or nonexistent due to lack of space for any stand-off liners. All armored vehicle purchasers would be interested in space and weight efficient spall suppression systems at reasonable costs.

APPROACH TO THE PROBLEMS

The primary spall backing material 82 (Fig. 8) and 82a (Fig. 9) is placed in contact with the armor and has an impedance which is tailored such that the reflected tensile stress is reduced below that required for spall formation. This backing material breaks up into fine, low-energy, nonpenetrating fragments after absorbing the shock wave. This material preferably consists of metal powder filled polymers but the metal powders may be mixed with ceramic and glass powders, or fibers and whiskers. A relatively light secondary plate 92a (Fig. 9) of different material, spaced one or two inches from the armor 86a, may be used to fully suppress secondary particles of disrupted jet and armor. This system 90 has demonstrated improved performance at short stand-off spaces compared to prior art liners.

As indicated previously but stated in a different way, spall can be characterized as a cloud of high velocity fragments of fractured material ejected from the back surface of an armor plate 86 (Fig. 8) due to impulse loading on the front surface of the plate. The impulse typically results from the impact of a high velocity projectile or a shaped charge jet and its slug as indicated by the attack arrow 94 in Figure 8. The impulse induces a compressive shock wave which propagates through the armor plate 86, and reflects from the rear free surface as a tensile wave. The reflected tensile wave superimposes with the incident compressive wave until at some distance from the back surface the tensile stress rises to a level sufficient to cause nucleation and growth of fracture. At this point, the strain energy remaining in the material between the fracture plane and the back surface is released as kinetic energy and the spall particles are ejected with significant kinetic energy.

When a shock wave interacts with an interface, such as interlayer 88, between two materials the situation is considerably more complex. As an illustration, consider a planar wave traveling perpendicular to the interface. As the wave impinges upon the interface, both a transmitted and a reflected wave will form. The intensity and sign (tensile or compressive) of the transmitted and reflected waves are a function of the sonic impedance of the material (the impedance is the product of the density and sound speed of the material). For instance, the relative intensity of the reflective wave compared to the incident wave can be expressed as a function of the relative impedance of the backing material 82 compared to that of the armor plate 86.

The impedance ratio (n) is determined by the following formula where Z_1 is the sonic impedance of the armor plate 86, where Z_2 is the sonic impedance of the backing material, where the subscript $_r$ and $_i$ refer to the reflected and incident wave, and where the letter "a" refers to the stress amplitude.

As can be seen, when n is less than 1 (that is, where the backing material 82 has an impedance below that of the armor plate 84) the reflected wave is tensile at a fraction of the amplitude of the incident wave; for $n = 1$ there is no reflected wave; and for n that is greater than 1, the reflected wave is compressive.

Although complete elimination of spall or fractures in the armor plate 86 and in the backing material 82 appears to be desirable, the added weight to the vehicle is objectionable. In contrast, the backing material of the present invention is a frangible or low strength backing, which subsequent to suppression of spall in the armor, fractures into particles of low mass and/or velocity and low penetration capability. The requirements for backing material 82,82a are then: 1) the impedance of the backing material must be such that the stress reflected into the armor is below that which would cause armor spall; and 2) the fragments from the fracture of the backing material (caused by the transmitted stress) must have low penetration capacity.

It has been discovered that an interaction occurs between the jet and backing material causing fine flying target and jet particles to be dispersed behind the armor. It is unclear what mechanism causes this effect but two possibilities have been considered. One explanation is that the shock waves in the vicinity of the penetration are causing local disruption of the jet/armor penetration interface. The other is that relief of pressure as the jet penetrates the back surface of the backing material 82 (Fig. 8) and 82a (Fig. 9) imparts a lateral force on the jet and target material which carries portions thereof through by the penetration process. The number and dispersion of these particles has been significantly reduced, although not eliminated, through continued development of the primary backing material. The remaining particles can be defeated with the relatively thin secondary plate 92a (Fig. 9) spaced from for instance, one to four inches off the back of the armor plate 84a. The double layer system 90 when using aluminum armor, with a two inch space, has demonstrated nominally equivalent performance, at lower weight, compared to the aramid fiber system in contact or with a four inch space.

As mentioned previously, primary backing materials have progressed from commercial alumina ceramics, to ceramic and metal powder loaded polymer composites.

The powder loaded composites, especially the metal loaded composites are the materials of choice for two major reasons. First, they yield reduced dispersion of the hypervelocity particles discussed above. Secondly, the areal density of the backing materials was found to be proportional to its impedance; the composites allow tailoring of the backing materials impedance to optimal values.

While the performance of the present single layer system 80 (Fig. 8) and double layer system 90 (Fig. 9) are already satisfactory, there is a potential for eliminating the secondary layer 92a (Fig. 9), with consequential reduction in weight, space, mounting hardware and complexity. This would constitute a major breakthrough in small liner design, and make application feasible on any interior surface of an armored vehicle.

In testing to date, reduced dispersion of hypervelocity particles was observed with backing materials 82 (Fig. 8) loaded with metal powders (copper and steel alloys) compared with those loaded with alumina powders when both materials have similar impedance values. The volume percent loading with metal powders is almost half that with alumina powder due to the much higher density of the metals. The metal loaded composites also have lower elastic modulii. While it is presently unknown which mechanical properties control the jet/target interaction, it does appear that reduced particle loading will lead to reduced interaction.

With the current state of polymer science, the viscoelastic properties of the backing material matrix should be tailored such that the required impedance could be obtained with lower particle loading thereby potentially limiting the spall disruption and also eliminating the requirement for a secondary plate 92a as shown in Figure 9. The elimination or reduction of the metal or ceramic fillers will provide lighter, more compact designs with fewer human factors and safety concerns related to inhalation of small hypervelocity particles or powders after attack.

The passage of a shock wave through a polymeric matrix is a complex process dependent upon a number of factors. Polymers are viscoelastic in nature: that is, their mechanical properties, such as complex share modulii (G^*), complex elastic modulus (G'), and complex shear loss modulus (G''), are rated and temperature sensitive. These properties also influence the impedance of the material as shown below.

The mechanical impedance of a polymer element to a stress wave is the sum of two components given by the expression:

$$Zm = Rm + IXm$$

Where the value of ZM is the characteristic complex impedance, Rm is the mechanical resistance, and Xm is the mechanical reactance.

These components are given by:

$$Rm = (p/2)^{[1/2]} [G^2 + G''^2)^{[1/2]} + G'^{[1/2]}$$

$$Xm = (p/2)^{[1/2]} [(G'^2 + G''^2)^{[1/2]} - G'\ ]^{[1/2]}$$

Where G' and G'' are the viscoelastic properties described above. As can be seen, tailoring of the impedance can be accomplished through control of the viscoelastic properties. Fillers and plasticizers can significantly influence the viscoelastic properties and their rate-temperature dependency, as well as other mechanical responses such as fracture toughness. The performance of the polymeric phase within the backing material 82, and that of the loaded polymer, will therefore be reliant upon specific compositions, ambient temperature, and penetration velocity of the jet or projectile.

Improved performance is obtained with polymers which exhibit high energy loss and damping. Interaction of the shock waves in the vicinity of the jet (or projectile) penetration is then limited and the jet/backing material interaction suppressed. Materials with secondary fractured toughening mechanisms should also improve performance through greater energy absorption.

The initial work performed in the cross referenced application concentrated on ceramic materials exclusively. Fully fired, unfired, and bisque fired alumina all functioned in suppressing spall in aluminum armor plate. The angular distribution and energy of spall particles, and other behind-armor debris, is measured by examination of penetration holes in a thin steel sheet called a witness sheet such as sheet 54 (Fig. 3). The sheet (not shown in Figure 8) is placed some distance behind the armor plate 86 and backing material 82. While spall was eliminated in the backing material, and the angle of distribution of damage shown on the witness plates decrease compared to unbacked armor plate 86, there is still a significant number of penetrations in the witness plate when using ceramic materials.

The nature of the witness plate penetrations from spall backing material 82 and/or armor plate 86 is considerably different than from spall penetrations from an armor plate without spall backing material as illustrated in Figures 10-13. A penetration hole from a spall particle from armor plate alone shows only a shear lip in the direction of penetration. The diameter of the penetration from armor plate 86 and backing material 82 were smaller and show a raised edge on both the front and back of the sheet, typically of hypervelocity penetration. Small indentations formed by these particles in steel plates were analyzed. Both aluminum and copper were found, indicating that the interaction occurs between the copper jet slug and the spall backing material, causing dispersion of fine particles from the armor plate 86 and the shaped charge jet (not shown) behind the plate 86.

The original concept of the cross-referenced application was to have the impedance of the backing material equal to or above that of the armor plate 86 to insure that no tensile stress was reflected. However, an analysis made to determine the effect of the backing material properties on total system weight indicates that the required weight of primary backing material 82 increases proportionally to increasing impedance and increasing wavelength of the stress wave. Accordingly, the concept was changed to utilize materials whose impedance allowed some tensiled reflection, but not enough to cause spall fracture to occur.

Four ballistic test series were conducted consisting of 130 shaped charge shots. Warheads for these evaluations included 105 mm and TOW-2 simulants at 0, 37, and 53 degrees obliquities. Armor plate alloys including 5083 (MIL-A-4602G(MR)Z and 7039 (MIL-A-46063F) aluminum, and RHA steel (MIL-A-12560) at wall thicknesses ranging from 1 to 2". The performance variables measured were spall volume, penetration hole area, and the angle of dispersion of penetrations in the witness sheets. Prior art unbacked and aramid filter backed armor targets were tested for baseline comparison during system development. High speed photography was also conducted to examine the jet/target interaction.

For the first test series an alumina particle loaded polymer system was selected as having a tailorable impedance which can be easily varied by using different amounts of alumina particles in the polymer. An eight factor 1/8th fractional factorial experimental matrix was included to investigate the effect on performance of warhead obliquity, alloy type, alloy thickness, polymer type, aluminum particle size, aluminum loading content, and spall backing material thickness. Response variables measured for correlation to performance include the volume of spall in the armor and the angle of dispersion of particles (Fig. 2) penetrating the witness sheet. The only statistically significant factor in this matrix were alloy type and warhead obliquity. In further tests, decreasing the loading of the epoxy from 60 to 47 volume percent showed some decrease tendency to cause jet/target interaction, while maintaining spall suppression in the aluminum armor.

The minimum allowable impedance of these backing material composites 82 (Fig. 8) to suppress spall in aluminum armor 86 was found to be about 0.65 g/cm^2us (grams per centimeter squared per microsecond), which compared to 1.44 g/cm^2us for the impedance of the aluminum armor. Impedance was determined by multiplication of sample density by the measured velocity of ultrasonic wave transmission. In addition, a proof-of-principle test of fully fired alumina backed RHA steel was conducted which successfully suppressed spall in the steel.

The objective of the second test series was to identify methods of suppressing the hypervelocity particles from the jet/target interaction. Two methods were evaluated, powder substitution and addition of a secondary layer of backing material. Additional powders were evaluated as fillers in the polymeric matrix. Copper, bronze, stainless steel, magnesia (MgO), and spinel ($MgAl_2O_4$) powders were tested, along with alumina powders, in a matrix of a toughened epoxy. These powders were selected to give a broad range of powder, and consequently mechanical properties of the backing material. Prior to fabrication of the target materials, samples of each composite were produced and their impedance measured. This allowed production of backing materials with similar impedance values.

Due to the higher density of the metal powders, the volume loading of the metal loaded epoxies were 30 volume percent versus the 47 volume percent for the ceramic loaded epoxies. There was a significant reduction observed in the of the angle of dispersment of the hypervelocity particles with the metal loaded epoxies; the copper and stainless steel powder materials performed best. The metal loaded polymers have lower hardnesses and elastic modulii values compared to the ceramic loaded polymers, as well as the lower loading content. The properties responsible for the reduction in jet/target interaction are still undetermined.

While the number and distribution of the hypervelocity penetration holes in the witness sheet 54 (Fig. 3) decreased when using the single layer system 80 (Fig. 8), their elimination required a secondary plate 92a (Fig. 9) of material spaced one or two inches behind the armor plate 86a. When plate 92a was placed in contact with the primary backing material 82a, it was found to be ineffective in suppressing the particles. The plate 92a when spaced from the armor plate 86a, acts to defeat the hypervelocity particles. The space is required to allow some dispersion of the particles away from the axis of the jet. This prevents the particles from passing through a hole formed in the secondary plate 92a created by the passage of the weapons jet. Thin plates 92a of aramid fiber and fiberglass composite, ballistic nylon batting and elastomer sheets all show good performance at low weights to defeat the particles.

The objective of the third test series was to evaluate the potential for fiber reinforcing the backing material 82 (Fig. 8) to provide single layer protection. Polmers of toughened epoxy or silicon rubber were loaded with copper or alumina powders and used as the matrix for aramid fiber or fiberglass cloth reinforced composites. These armor plate targets 86 suppressed spall formation. However, similar to those in the previous series with the secondary layer in contact with the primary backing material 82, they were not found to be completely effective in suppressing the hypervelocity particles.

The backings in the series were placed on 1-3/4" of 5083 aluminum armor plate 86; all previous tests had been done on a maximum of 1-1/2" of 5083 armor plate. Unreinforced materials, similar in loading and thickness to those from the previous test series, were used as controls. These fiber reinforced materials, did not fully suppress spall in the 1-3/4" aluminum as they did in the 1-1/2" aluminum tests without fiber reinforced materials. In parallel with these ballistic tests, a simulation computer test was run using two dimensional hydrocode computer program, to estimate the difference in stress state in different thicknesses of armor. Impact was modelled in an axisymmetric configuration with a copper rod impacting semi-infinite aluminum with similar condition to those in the tests. Pressure was calculated at depths of 1" and 1-1/2" and at points from 1" to 2-1/2" increments off the axis of penetration. The axes of the attack arrows 94,94a illustrated in Figures 8 and 9, respectively, are the axes of penetration for the two targets, which axes are illustrated as being at 0° obliquity.

Examining the points 1" off axis, it was seen that the stress wave had both higher amplitude and duration at the 1-1/2" depth. The results of these tests indicate that the backing material 82 must therefore be specifically designed for a specific thickness of armor.

The objective of the fourth series of ballistic tests was two-fold. The first objective was to determine the minimum volume loading and thickness (or total areal density) of the primary backing material 82 required to suppress spall in 1" of 5083 and 7039 aluminum, and for 1-3/4" thick 5083 aluminum. Stainless steel powder in a toughened epoxy matrix was used at 15, 20, 25, 30, 35 and 40 volume percent thicknesses of 1/8, 3/16, 1/4, and 5/16 of an inch.

As mentioned previously, 130 test shots were made with 105 milliimeter, TOW-II and Rockeye warheads. The results of a portion of the shots are illustrated in Tables 1-6.

The data in the several tables indicate the armor thickness and type, the warheads, the degrees of obliquity, the spall cone angles as determined in .024" thick soft steel witness plates for unbacked, aramid fiber composite backed, and various types of active spall suppression armor of the present invention.

It will be apparent that the smaller the secondary spall cone angle (Fig. 2), the better the protection since less soft targets in the vehicle will be hit with spall. As is conventional when describing the weight of military armor, the amount of square feet of armor required in a vehicle is determined, and the pounds per square foot (PSF) is used rather than the pounds per cubic foot, to provide the desired weight comparison. In all tests, the spacing is measured from the back surface of the armor.

Figure 10 illustrates a witness plate 100 that was mounted behind an armor plate without spall backing material illustrating a plurality of lethal spall holes 102 having a spall cone angle of about 90 degrees. The witness plate also illustrate a large central hole 104 which is formed by the jet and the jet slug.

Figure 11 illustrates a witness plate 100a subjected to the same test conditions as Figure 10 except that the armor plate armor plate was backed by a single layer of 4.5 PSF aramid fiber spaced 4" behind the target. This test indicates by the pattern of spall holes 102a that the aramid fiber backing material reduced the spall cone angle to about 27 degrees with very little lethal spall being shown, and with a jet and slug hole 104a of reduced size.

Figure 12 illustrates a witness plate 100b subjected to the same test conditions as the test of Figure 10 but with the armor plate being backed by a single layer of 4.3 SPF attached to the back of the armor plate. This test shows a main pattern of spall holes 102b within about the same spall cone angle of about 27 degrees but shows several other spall holes 102b′ within about a 39 degree spall cone angle. The jet and slug hole 104b is slightly larger than that of Figure 11.

Figure 13 illustrates a witness plate 100c subjected to the same tests condition as the test of Figure 10 but with the armor plate being backed by a 2.8 PSF primary spall backing material in contact with the back of the armor and a 1.5 PSF aramid fiber secondary backing spaced 2" from the rear of the armor plate. This test illustrates spall angle of about 25 degrees with the most spall holes 102c within that range but several spall holes 102c′ being slightly out of that angle. The witness plate also illustrates a jet hole 104c and a slug hole 106 spaced from each other thereby indicating that the secondary backing material deflected the slug.

TABLE 1

1-3/4" 5083 ALUMINUM AGAINST 105 mm WARHEADS AT 0 DEGREES OBLIQUITY					
BACKING	SPACE	WEIGHT		CONE ANGLE	
UNBACKED ARMOR				93	DEG.
ARAMID FIBER COMPOSITE	4"	4.5	PSF	27	DEG.
2 LAYER ACTIVE SPALL SYSTEM				25	DEG.
30% COPPER /SILICONE RUBBER	CONTACT	2.8	PSF		
ARAMID FIBER COMPOSITE SHEET	2"	1.5	PSF		
TOTAL WEIGHT		4.3	PSF		
ARAMID FIBER COMPOSITE	CONTACT	4.5	PSF	60	DEG.
1 LAYER REINFORCED ACTIVE SPALL SYSTEM					
COPPER/FIBERGLASS/SILICONE RUBBER	CONTACT	4.3	PSF	39	DEG.

TABLE 2

1" 5083 ALUMINUM AGAINST 105 mm WARHEADS AT 0 DEGREES OBLIQUITY					
BACKING	SPACE	WEIGHT		CONE ANGLE	
UNBACKED ARMOR				67	DEG.
2 LAYER ACTIVE SPALL SYSTEM				18	DEG.
30% STAINLESS STEEL/EPOXY	CONTACT	2.8	PSF		
ARAMID FIBER COMPOSITE SHEET	2.25"	1.2	PSF		
TOTAL WEIGHT		4.0	PSF		
2 LAYER ACTIVE SPALL SYSTEM				20	DEG.
30% STAINLESS STEEL/EPOXY	CONTACT	2.0	PSF		
ARAMID FIBER COMPOSITE SHEET	1"	2.0	PSF		
TOTAL WEIGHT		4.0	PSF		
2 LAYER ACTIVE SPALL SYSTEM				28	DEG.
30% STAINLESS STEEL/EPOXY	CONTACT	2.8	PSF		
ELASTOMER SHEET	2"	0.8	PSF		
TOTAL WEIGHT		3.8	PSF		

TABLE 3

1" 5083 ALUMINUM AGAINST 105 mm WARHEADS AT 53 DEGREES OBLIQUITY					
BACKING	SPACE	WEIGHT		CONE ANGLE	
UNBACKED ARMOR				88	DEG.
ARAMID FIBER COMPOSITE	CONTACT	4.5	PSF	77	DEG.
1 LAYER ACTIVE SPALL SYSTEM				55	DEG.
56% ALUMINA/SILICONE RUBBER	CONTACT	4.7	PSF		

TABLE 4

2" RHA STEEL AGAINST TOW-2 WARHEADS AT 0 DEGREES OBLIQUITY					
BACKING	SPACE	WEIGHT		CONE ANGLE	
UNBACKED ARMOR				91	DEG.
ARAMID FIBER COMPOSITE	CONTACT	9.0	PSF	70	DEG.
2 LAYER ACTIVE SPALL SYSTEM				58	DEG.
35% TUNGSTEN/SILICONE RUBBER	CONTACT	9.5	PSF		
ARAMID FIBER COMPOSITE	1"	3.0	PSF		
TOTAL WEIGHT		12.5	PSF		

TABLE 5

1" RHA STEEL AGAINST ROCKEYE WARHEADS AT 0 DEGREES OBLIQUITY					
BACKING	SPACE	WEIGHT		CONE ANGLE	
UNBACKED ARMOR				87	DEG.
ARAMID FIBER COMPOSITE	CONTACT	9.0	PSF	32	DEG.
1 LAYER ACTIVE SPALL SYSTEM				20	DEG.
25% TUNGSTEN/SILICONE RUBBER	CONTACT	7.4	PSF		
2 LAYER ACTIVE SPALL SYSTEM				10	DEG.
30% TUNGSTEN/SILICONE RUBBER	CONTACT	8.2	PSF		
ARAMID FIBER COMPOSITE	1"	1.55	PSF		
TOTAL WEIGHT		9.75	PSF		

TABLE 6

1-3/4" 5083 ALUMINUM AGAINST TOW-2 WARHEADS AT 0 DEGREES OBLIQUITY					
BACKING	SPACE	WEIGHT		CONE ANGLE	
UNBACKED ARMOR				103	DEG.
ARAMID FIBER COMPOSITE	16"	4.5	PSF	22	DEG.
1 LAYER ACTIVE SPALL SYSTEM				82	DEG.
10% TUNGSTEN/SILICONE RUBBER	CONTACT	3.8	PSF		
2 LAYER ACTIVE SPALL SYSTEM				55	DEG.
25% STAINLESS STEEL/EPOXY	CONTACT	3.7	PSF		
ARAMID FIBER COMPOSITE	2"	1.0	PSF		
TOTAL WEIGHT		4.7	PSF		
2 LAYER ACTIVE SPALL SYSTEM				26	DEG.
13% TUNGSTEN/SILICONE RUBBER	CONTACT	4.5	PSF		
ARAMID FIBER COMPOSITE	16"	0.5	PSF		
TOTAL WEIGHT		5.0	PSF		

As indicated in Table 6, a test matrix was provided to examine the performance of tungsten powder loaded silicone elastomers. The silicone elastomer was selected for three reasons: a) It has relatively low strength to allow very fine particulation of the material from the transmitted shock wave; b) It has high elongation to failure which should limit the damage area from the jet penetration; and c) It is relatively highly attenuating for shock waves which may limit the interaction and consequential distribution of hypervelocity jet particles. The tests include volume loading of 25 to 35 percent of tungsten for application to RHA steel armor, and 10 to 13 percent for application to 5083 aluminum armor. Single (Fig. 8) and two layer (Fig. 9) systems 80 and 90, respectively, where investigated when using the RHA steel armor and when using the 5083 aluminum armor. In the single layers system 80, the distribution of hypervelocity particles was the lowest seen to date with this particular warhead. In addition, the two layer system using the RHA steel armor performed considerably better than a layer of aramid fiber composite in contact with the armor equivalent in thickness to the active spall suppression armor disclosed in the cross referenced Musante et al application.

TEST CONCLUSIONS

From the testing to date the following conclusions can be drawn relative to the cross referenced Musante et al system:

Concerning the Primary Layer In Contact With The Armor

The primary backing material may be either a monolithic or a composite material. The preferred material is a composite material which may be tailored to the specific optimal properties required.

Monolithic Material

Monolithic materials, such as sodium chloride, which have appropriate fracture and impedance properties may be used. Fracture properties include either low strength or frangibility; that is, the material must break-up into particles of low mass or kinetic energy after the shock wave is transmitted into the backing.

Composite Matrix Material

The matrix polymer may be of almost any type of relatively high strength epoxies to low strength elastomeric materials. The preferred materials appear to be relatively low strength, high elongation elastomers. In particular, materials which are highly dampening to shock and sound waves will function best in order to limit the disruption of the jet and dispersion of jet and target particles behind the armor.

Composite Particulates/Fillers

The materials which will be loaded into the matrix may be single or combinations of metals, ceramics, glass, or organic material in particulate, whiskers, or fiber form which allow tailoring of the composite to the appropriate impedance level. Fiber or whisker additions may be advantageous for the layer to give additional protection to the armor against penetration from projectiles. In particular, high density materials are preferred in order to limit the volume loading of the polymer and thereby limit the distribution of the jet and dispersion of jet and target particles behind the armor. The preferred material for loading is tungsten powder due to its high density and low toxicity. The optimal range of loading levels of tungsten is up to 25 volume percent for aluminum armor plate, and up to 50 volume percent for steel armor plate. In addition the porosity, introduced into the composite matrix material from a gas or from hollow particulates, would be advantageous to cause a attenuation of shock waves to limit the disruption of the jet and dispersion of jet and target particles behind the armor, and further to reduce the weight required.

Thickness

The thickness of the contact layer required will be dependent upon the impedance of the material and the length of the shock pulse in the armor. Thicknesses which have been successful range from 1/8" to about 1-1/2".

Impedance

The impedance level must be sufficient to reduce the amplitude of the reflected shock wave in the armor below that required for significant spall to form. While ideally no spall should form, the weight of the total system may be reduced if some amount of spall in the armor is allowed to form as long as this spall either remains attached to the armor, or is limited to a narrow angle of dispersion off the axis of the jet due to the nature of its fracture, influence from the primary layer, or influence from a secondary layer. The impedance required will then reduce the reflected shock wave such that the formation of spall is limited, and the kinetic energy of any spall that does not form will also be limited.

Configuration

The layer of material loaded into the matrix may be of uniform or nonuniform loading. For ease of manufacture the layer may be uniform, while for optimal performance, the layer may be of graded impedance. The grading of the impedance may both decrease the weight of the material required, and limit the distribution of the jet and dispersion of jet and target particles behind the armor.

Attachment

The backing material may be attached to the armor either with a separate adhesive or by direct bonding from the matrix material. Processes could include casting, troweling, or spraying of the composite when in the uncured state, with subsequent curing in place on the armor interior surface. The preferred adhesive is a tough, high elongation to failure polymer material.

Concerning The Secondary Plate

It should be noted that the secondary plate 92a (Fig. 9) is not absolutely necessary for the Figure 8 and/or Figure 9 system, but constitutes an advantage for particular designs and requirements.

Material

The secondary plate material 92a (Fig. 9) may consist of single or multiple component polymers or of reinforced polymers. Limitation of the dispersion of the disputed jet and target particles has been accomplished with thermoplastic polymers, with rigid, thermoset resin matrix fiber reinforced polymers, and with elastomeric matrix fiber reinforced polymers.

Weight

The required weight of the secondary plate 92a is dependent upon the amount of disruption of the jet and dispersion of the jet and target particles and to the distance the plate is spaced off the armor. Weights (expressed in pounds per square foot - PSF) found to function in limiting the dispersion range are from 0.5 to 3 PSF.

Spacing

The stand off spacing of the secondary plate 92a effects the dispersion of the disrupted jet and target particles behind the armor 86a and backing material 82a. Larger spacing are more efficient, but up to 4 inches have been found to be sufficient. In particular, spacing in the range of 1 to 2 inches off the interior surface of the interlayer 88a are sufficient while still offering a compact package.

Attachment of Secondary Plate

The attachment method should be such that the layer remains attached to the armor plate 86a after experiencing the loads resulting from the jet penetration and blast wave loading of the secondary layer. The preferred method is bolting the plate 92a to studs 96a welded to the armor.

Configuration

While all work has been done with a single secondary plate 92a there may be advantages to splitting this "secondary plate" into multiple plates. For instance, two thin plates, one at 1" stand off and one at 1-1 2" stand off, may be more efficient than equivalent weight of a single layer of 1-1/2" standoff. In addition, a contact layer alone or in combination with a spaced layer may be of benefit.

Concerning The Spall Formation Weapon Type

Type

Shaped charge warheads are the weapon for which spall suppression has been demonstrated. The single layer system 80 (Fig. 8) and the double layer system 90 (Fig. 9) should also be suitable for suppression of spall from other weapons, especially those with spall as a major lethality mechanism. The weapons include, but are not limited to: explosively formed projectiles (EFP'S), high explosive squash heads (HESH), fragmenting artilliary shells, and directed energy weapons. This includes all shock wave forming mechanisms including projectile and jet impacts, explosive detonations, and high speed ablation.

From the foregoing description it will be apparent that single and double layer spall suppression systems have been disclosed for preventing or suppressing warhead induced formations of highly penetrating spall. Both systems include an armor plate and at least a primary backing material which contacts the rear surface of the armor plate and is formed from a metal or ceramic loaded composite spall backing material which if fractured by stress transmitted through the metal armor form light, particles of low mass and kinetic energy. The primary backing material has a sonic impedance relative to that of the metal armor which suppresses formation of spall in the armor. A second plate may be attached to and spaced from the armor to reduce the angle of dispersement from secondary fragments of the armor and weapon.

Although the best mode contemplated for carrying out the present invention has been herein shown and described it will be apparent that modification and variation may be made without departing from what is regarded to be the subject matter of the invention.

Claims

1. An apparatus for suppressing spall from being created on the inside surface of metal armor when the outside surface is being subjected to an impulse load from a weapon causing a compressive stress and shock wave to be applied through the thickness of the armor, comprising:
means defining a primary powder loaded composite spall backing material which if fractured due to stress transmitted through the metal armor will form particles of low mass, low kinetic energy and low penetration capability, said spall backing material having a sonic impedance relative to the sonic impedance of the metal armor such that the stress reflected into the armor by the backing material at least suppresses the formation of significant spall in the armor; and
means for maintaining said spall backing material in contiguous contact with said inner surface of said metal armor.

2. An apparatus according to claim 1 wherein said composite spall backing material is formed with an elastomeric matrix.

3. An apparatus according to claim 1 wherein said spall backing material has a sonic impedance which reduced the reflected tensile stress below that required for spall formation which causes the spall backing material to break into fine, low energy, nonpenetrating hypervelocity particles after absorbing the shock wave.

4. An apparatus according to claim 1 wherein the impedance of the backing material is such that the stress reflected into the armor is below that which would cause spall failure from the metal armor and wherein fragments from stress transmitted fractures of the backing material are of low penetration capability and non-lethal.

5. An apparatus according to claim 2 wherein the metal in said metal loaded composite is copper powder.

6. An apparatus according to claim 2 wherein the metal in said metal loaded composite is a steel alloy powder.

7. An apparatus according to claim 2 wherein the metal loaded composite material allows tailoring of the backing material to optimum value for protecting a specific type and thickness of the armor.

8. An apparatus according to claim 2 wherein the metal loaded composite spall backing material has a low elastic modulus.

9. An apparatus according to claim 2 wherein the spall backing material has viscoelastic properties such that the required impedance is obtain with small amounts of metal powder thereby minimizing spall disruption, inhalation of hypervelocity particles in response to being hit by a weapon, and providing a spall backing material of reduced weight.

10. An apparatus according to claim 2 wherein said backing material has an impedance which provides tensile reflection into the armor which is less than that which will cause spall fracture to occur.

11. An apparatus according to claim 2 wherein said backing material has low hardness and elastic moduliii values for providing smaller hypervelocity particles.

12. An apparatus according to claim 2 and additionally comprising a secondary backing plate spaced from said primary backing material for precluding said hypervelocity particles from passing through a hole formed in the secondary backing plate by a component of the weapon.

13. An apparatus according to claim 2 wherein said armor is formed from alumimum, and wherein the minimum allowable impedance of said composite spall backing material to suppress spall from said aluminum armor is about 0.65 grams per square centimeter per microsecond.

14. An apparatus according to claim 2 wherein said powder may be any one of the following; bronze, stainless steel, magnesia (MgO), spinel ($MgAl_2O_4$), tungsten, and tungsten carbide, and any high density particle.

15. An apparatus according to claim 1 wherein the metal in said backing material is tungsten powder in a silicone elastomer having relatively low strength allowing fine particulation of the material from a weapon transmitted shock wave, and further has high elongation before failure.

16. A spall suppression composite elastomeric matrix backing material as an article of manufacture comprising:

an elastomer in said matrix; and

a metal powder loaded in said elastomer.

17. An article of manufacture according to claim 16 wherein said backing material has a minimum allowable impedance of about 0.65 g/cm^{2}us when abutting aluminum armor.

18. An article of manufacture according to claim 16 wherein said metal powder is uniformly dispersed within an epoxy resin of the composite elastomeric matrix.

19. An article of manufacture according to claim 16 wherein said metal powder is non-uniformly dispersed within said elastomeric matrix for providing graded impedance for decreasing the weight of the packing material.

20. An article of manufacture according to claim 16 wherein said composite polymeric matrix is a toughened epoxy matrix.

21. An article of manufacture according to claim 16 wherein the thickness of the composite polymeric matrix is between about 1/8" and 1-1/2".

22. An article of manufacture according to claim 18 wherein said metal powder is tungsten powder which forms between about 5-50 volume percent of the composite polymeric matrix backing material.

23. An article of manufacture according to claim 18 wherein said metal powder is mixed with a fiber for providing additional protection against penetration from a projectile.

24. An article of manufacture according to claim 16 wherein said metal powder is stainless steel.

25. An article of manufacture according to claim 17 wherein said metal powder is of high density.

26. An article of manufacture according to claim 16 wherein said metal powder is copper.

27. An article of manufacture according to claim 16 wherein said metal powder is bronze.

28. A method of suppressing lethal spall from being discharged from one surface of an armor plate when another surface of the plate is subjected to a stress sufficient to form lethal spall on said one surface when protected by spall backing material, comprising the steps of:

placing a powder loaded composite spall backing material which if fractured due to stress transmitted through the metal armor plate forms light non-lethal hypervelocity particles of low mass and kinetic energy, said spall backing material having a sonic impedance relative to the sonic impedance of the metal armor such that the stress reflected into the armor by the backing material at least suppresses the formation of spall in the armor; and

maintaining said spall backing material in contiguous contact with said inner surface of said metal armor.

29. A method according to claim 28 wherein said spall backing material has a sonic impedance which reduces the reflected tensile stress below that required for spall release in the armor plate which causes the spall backing material adjacent said one surface of the armor plate to break into fine, low-energy, non-penetrating particles after absorbing the shock.

30. A method according to claim 28 wherein the spall backing material has viscoelastic properties such that the required impedance is obtained with small amounts of metal powder thereby minimizing spall disruption, inhalation of hypervelocity particles in response to being contacted by a weapon, and provides a spall backing material of reduced weight.

31. A method according to claim 28 wherein said metal powder is uniformly dispersed within said composite material.

32. A method according to claim 28 wherein said metal powder is non-uniformly dispersed within said composite material for providing graded impedance for decreasing the weight of the backing material and for tailoring the backing material impedance to optimal values.

33. A method according to claim 27 wherein said backing material has an impedance which allows tensile reflection that is less than that which will cause spall fracture to occur.

34. A method according to claim 28 wherein said backing material includes tungsten powder in a silicone elastomer which forms said spall backing material and which allows very fine particulation of the material resulting from transmitted shock waves and has high elongation to failure.

35. A method according to claim 28 wherein said backing material is a monolithic material consisting of a mass exhibiting solid uniformity and one harmonious pattern throughout having low strength and frangibility.

36. A method according to claim 35 wherein the spall backing material has relatively low strength and high elongation characteristics providing high damping to shock and sound waves.

37. A method according to claim 28 wherein the composite backing materials include metal powders and fibers for tailoring the composite to the appropriate impedance level.

38. A method according to claim 28 wherein the powdered metal is tungsten powder having high density and low toxicity.

39. A method according to claim 28 wherein the thickness of the backing material is within the range of about 1/8" to about 1-1/2".

40. A method according to claim 28 and additionally comprising the step of controlling the weight of the backing material which is reduced by tailoring the spall backing material to allow a small amount of armor plate spall to form and remain attached to the armor as a bulge.

41. A method according to claim 28 and additionally comprising the step of attaching the uncured spall backing material to the armor plate by direct bonding from matrix materials which form the backing material.

42. A method according to claim 28 and additionally comprising the step of attaching the spall backing material by a separate adhesive.

43. A method according to claim 28 and additionally comprising the step of mounting a secondary plate formed from polymers at a predetermined distance from said spall backing material for limiting the angle of dispersion of jet slug and armor plate particles.

44. A method according to claim 43 wherein said predetermined distances is up to about 4" away from said one surface of the armor plate.

45. A method according to claim 27 wherein the spall backing material has relatively low strength and high elongation characteristics providing high damping to shock and sound waves.

46. A method according to claim 44 wherein the thickness of the backing material is within the range of about 1/8" to about 1-1/2" .

47. A method according to claim 44 and additionally comprising the step of mounting a secondary plate formed from polymers at a predetermined distance from said spall backing material for limiting the angle of dispersion of particles from the jet slug and armor plate.

48. An apparatus according to claim 1 wherein when contacted by a 105 mm warhead at 0 degree obliquity, the apparatus provides a secondary spall cone angle of about 39° when said primary spall backing material includes copper powder, fiberglass and silicone rubber weighing about 4.3 PSF and is placed in contact with the inside surface of the metal armor of 1-3/4" 5083 aluminum.

49. An apparatus according to claim 1 wherein when contacted by a 105 mm warhead at 0 degrees obliquity the apparatus provides a secondary spall cone angle of about 60° when said primary spall backing material is a composite of aramid fiber weighing about 4.5 PSF and is placed in contact with the inside surface of the metal armor of 1-3/4" 5083 aluminum.

50. An apparatus according to claim 12 wherein when contacted by a 105 mm warhead at 0 degrees obliquity, the apparatus provides a secondary spall cone angle of about 25° when said primary spall backing material includes 30% copper in silicone rubber and weights 2.8 PSF and is placed in contact with the inside surface of the metal armor of 1-3/4" 5083 aluminum; and wherein the secondary backing plate is formed from an aramid fiber composite weighing 1.5 PSF and is placed about 2" away from the inside surface of the metal armor.

51. An apparatus according to claim 12 wherein when contacted by a 105 mm warhead at 0 degrees obliquity, the apparatus provides a secondary spall cone angle of about 18° when said primary spall backing material includes 30% stainless steel/epoxy weighing 2.8 PSF and is placed in contact with the inside surface of the metal armor of 1" 5083 aluminum; and wherein the secondary backing plate is formed from an aramid fiber composite weighing 1.2 PSF and is placed about 2.25" away from the inside surface of the metal armor.

52. An apparatus according to claim 12 wherein when contacted by a TOW-2 warhead at 0 degrees obliquity, the apparatus provides a secondary cone angle of about 58° when said primary spall backing material includes 35% tungsten/silicone rubber which weighs 9.5 PSF and is placed in contact with the inside surface of the metal armor of 2" RHA steel; and wherein said secondary backing plate is formed from an aramid fiber composite weighing 1.5 PSF and is placed about 2" away from the inside surface of the metal armor.

53. An apparatus according to claim 1 wherein when contacted by a Rockeye warhead at 0 degrees obliquity, the apparatus provides a secondary spall cone angle of about 32° when the primary spall backing material includes 25% tungsten/silicone rubber and weighs about 7.4 PSF and is placed in contact with the inside surface of the metal armor of 1" RHA steel.

54. An apparatus according to claim 12 wherein when contacted by a Rockeye warhead at 0 degrees obliquity, the apparatus provides a secondary spall cone angle of about 10° when the primary spall backing material includes 30% tungsten/silicone rubber about 8.2 PSF and is placed in contact with the inside surface of metal armor of 1" RHA steel; and wherein said secondary backing material is formed from aramid fiber composite weighing 1.55 PSF and is placed about 1" away from the inside surface of the metal.

FIG_1

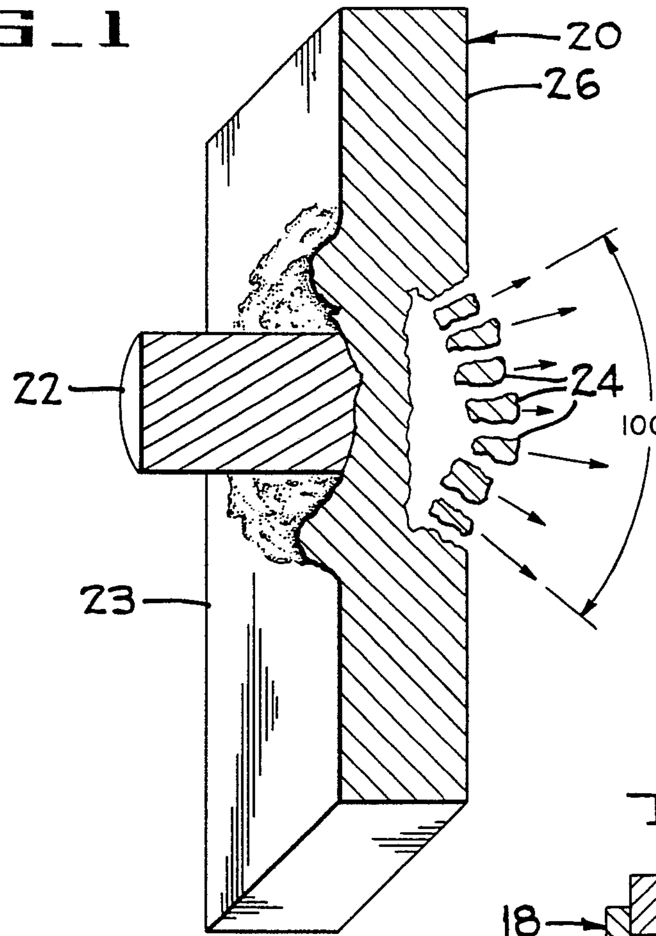


FIG_3

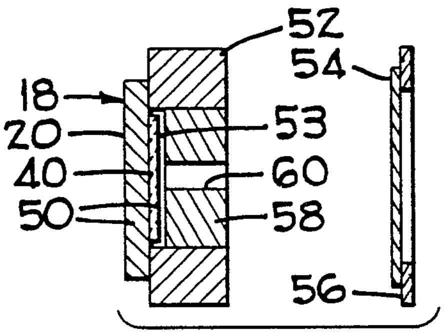


FIG_2

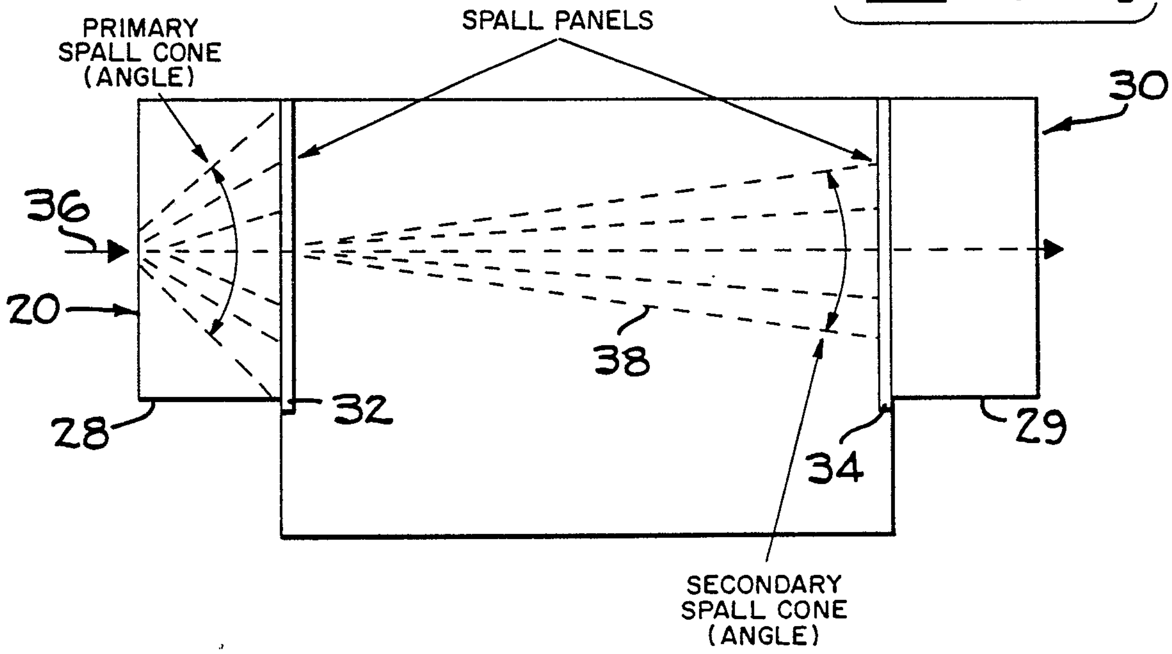


FIG_4

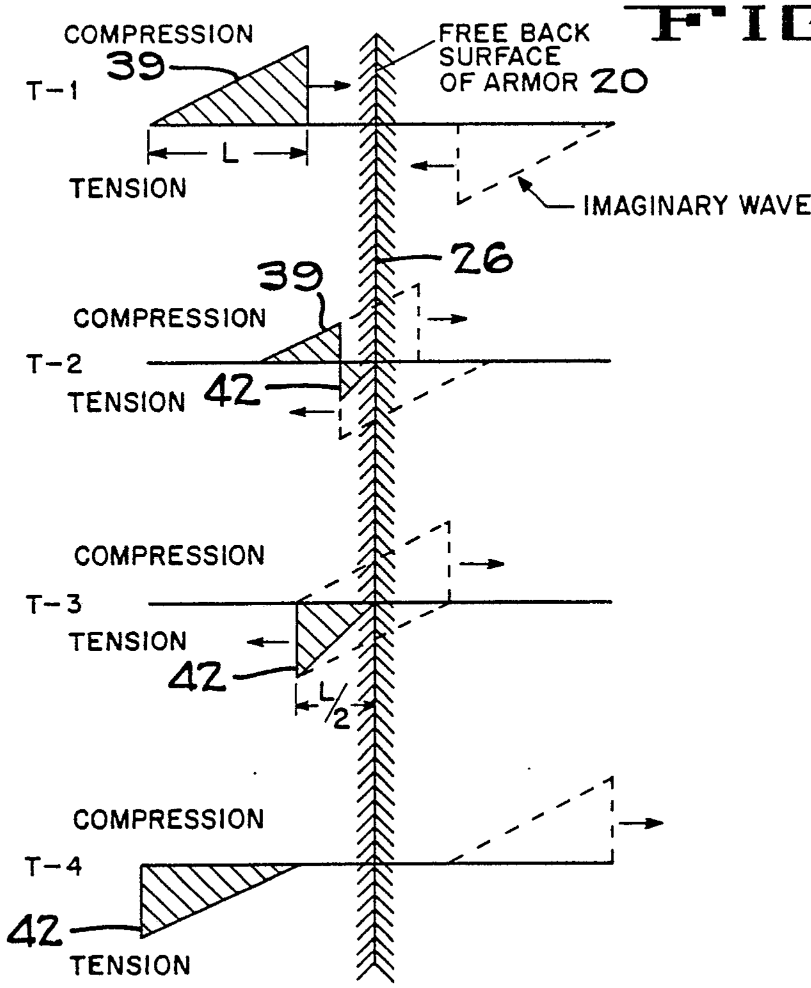


FIG_5A

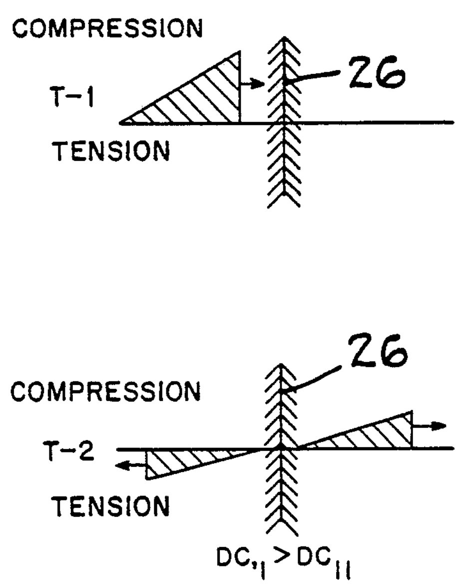
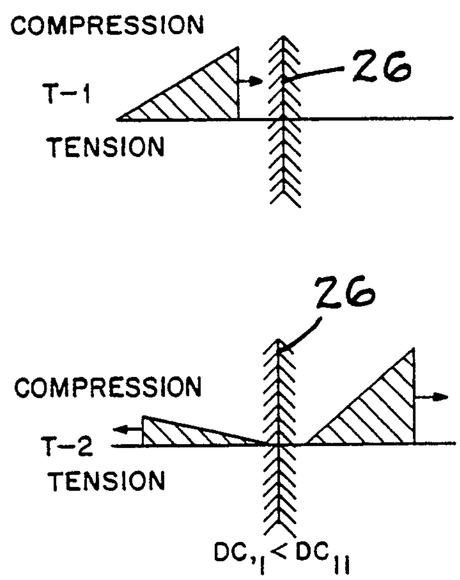


FIG_5B



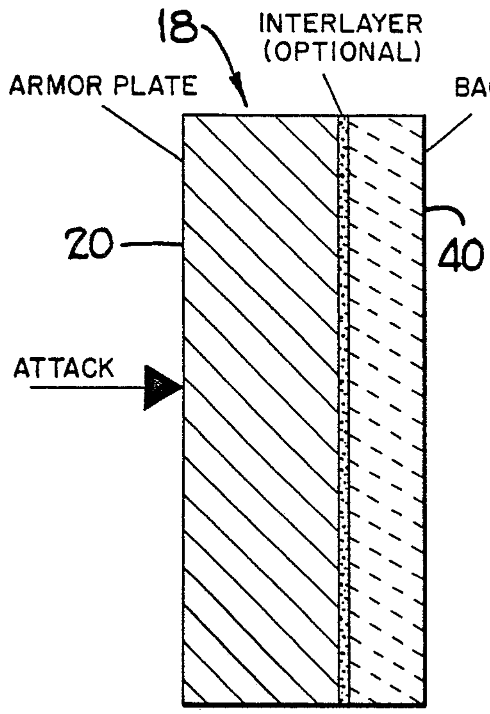
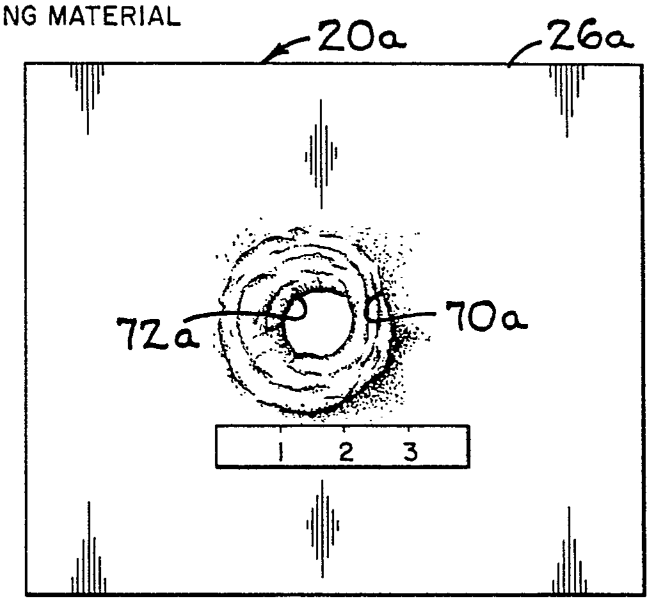


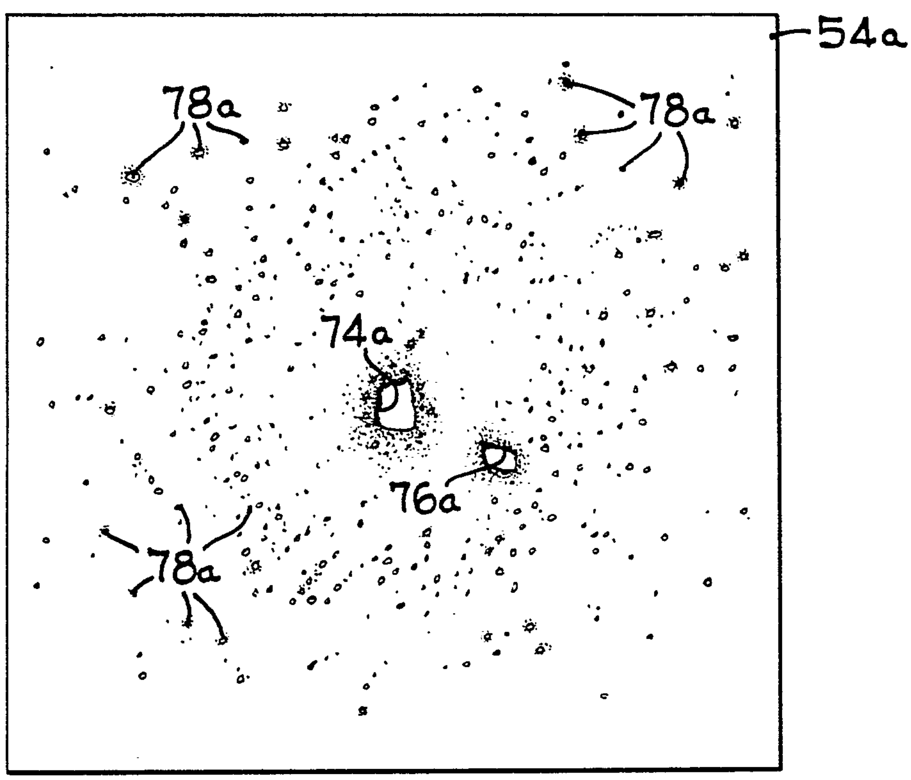
FIG_6



BACK OF TARGET

FIG_7A

FIG_7B



FRONT OF WITNESS
WITNESS OF FIGURE 7A WARHEAD: 105 mm AT 0°
TARGT: 1.5" 5083

FIG_8

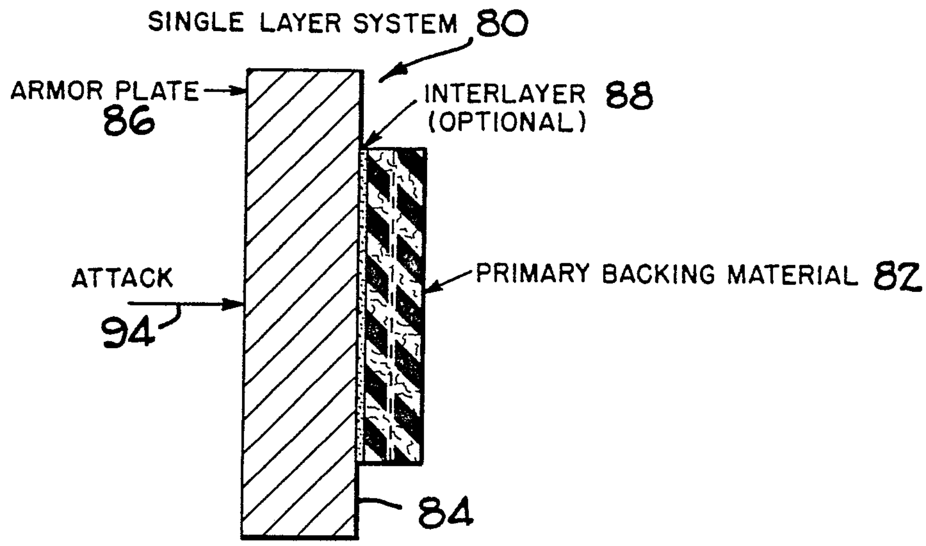

SINGLE LAYER SYSTEM 80
ARMOR PLATE 86
INTERLAYER 88 (OPTIONAL)
ATTACK 94
PRIMARY BACKING MATERIAL 82
84

FIG_9

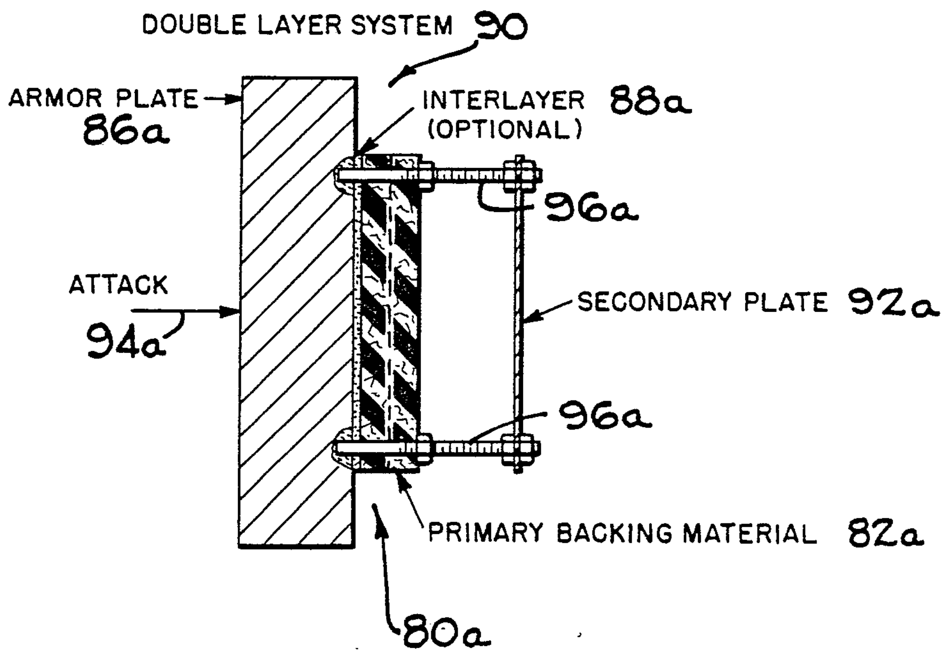
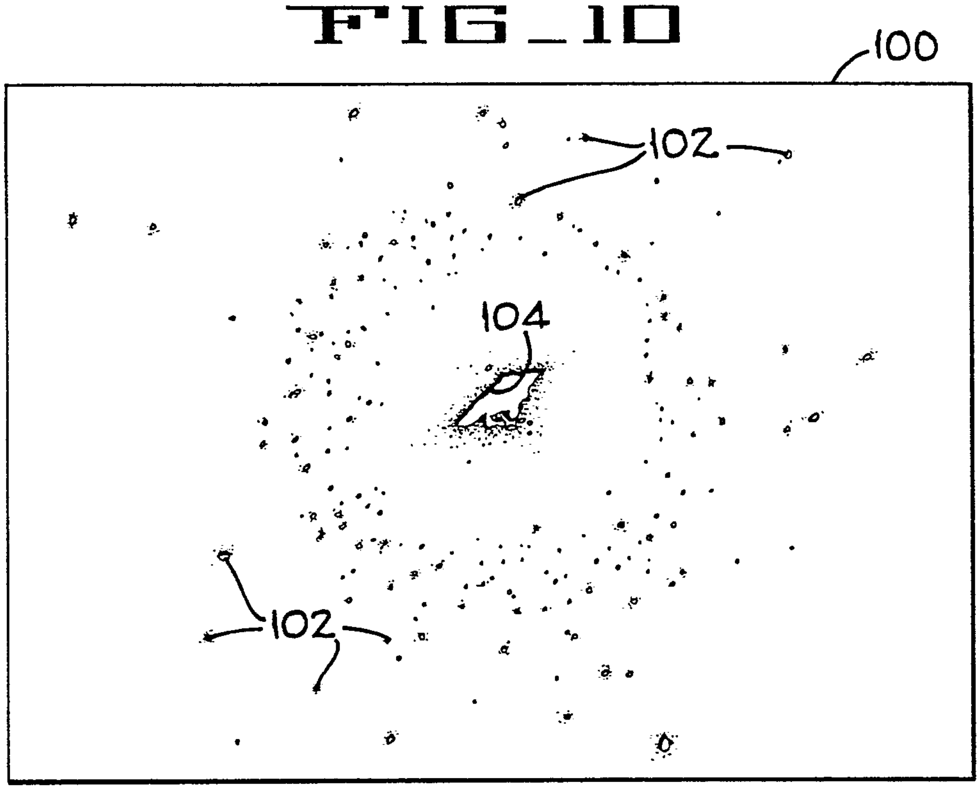
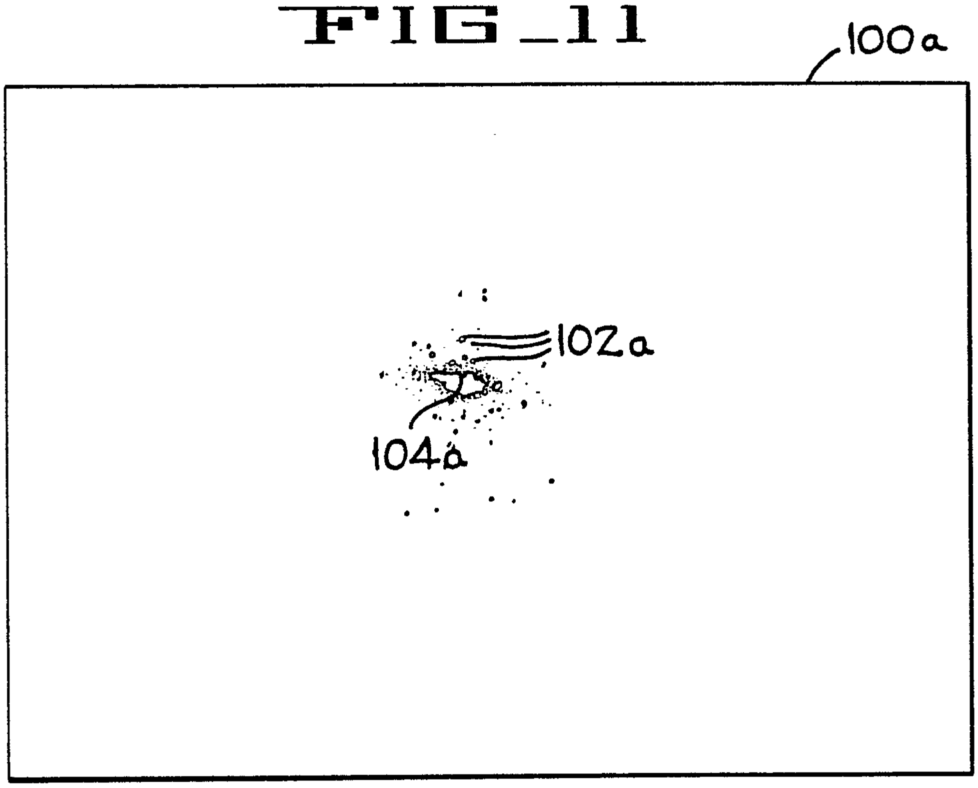

DOUBLE LAYER SYSTEM 90
ARMOR PLATE 86a
INTERLAYER 88a (OPTIONAL)
96a
ATTACK 94a
SECONDARY PLATE 92a
96a
PRIMARY BACKING MATERIAL 82a
80a

FIG_10



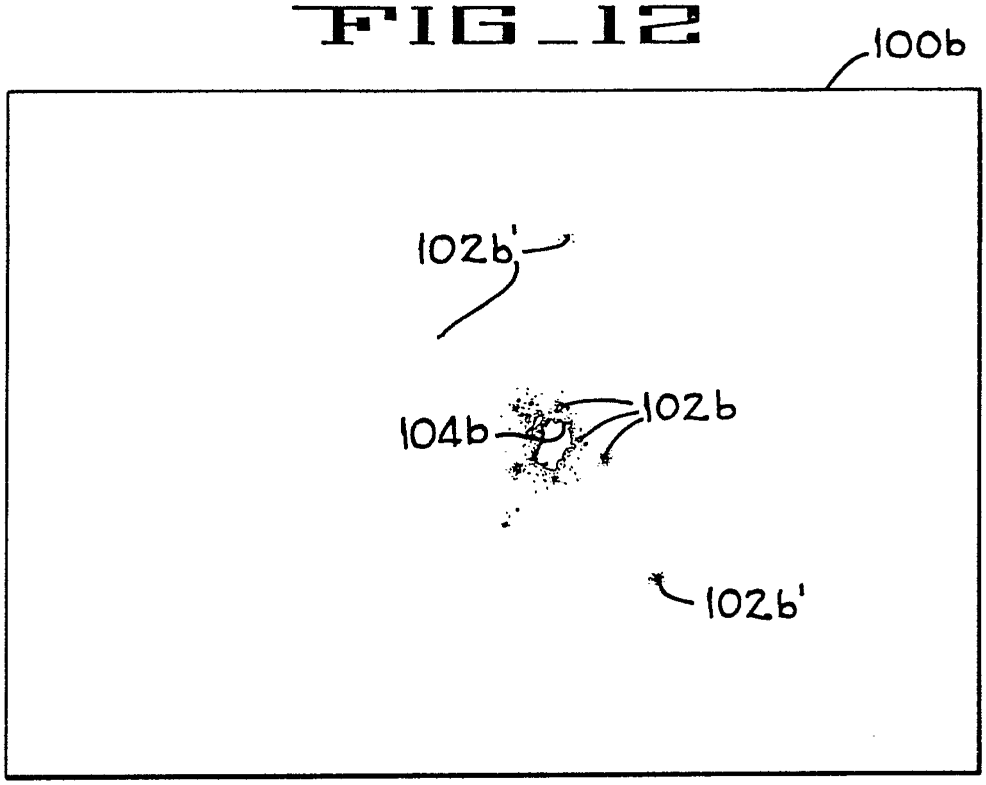
NO BACKING MATERIAL

FIG_11



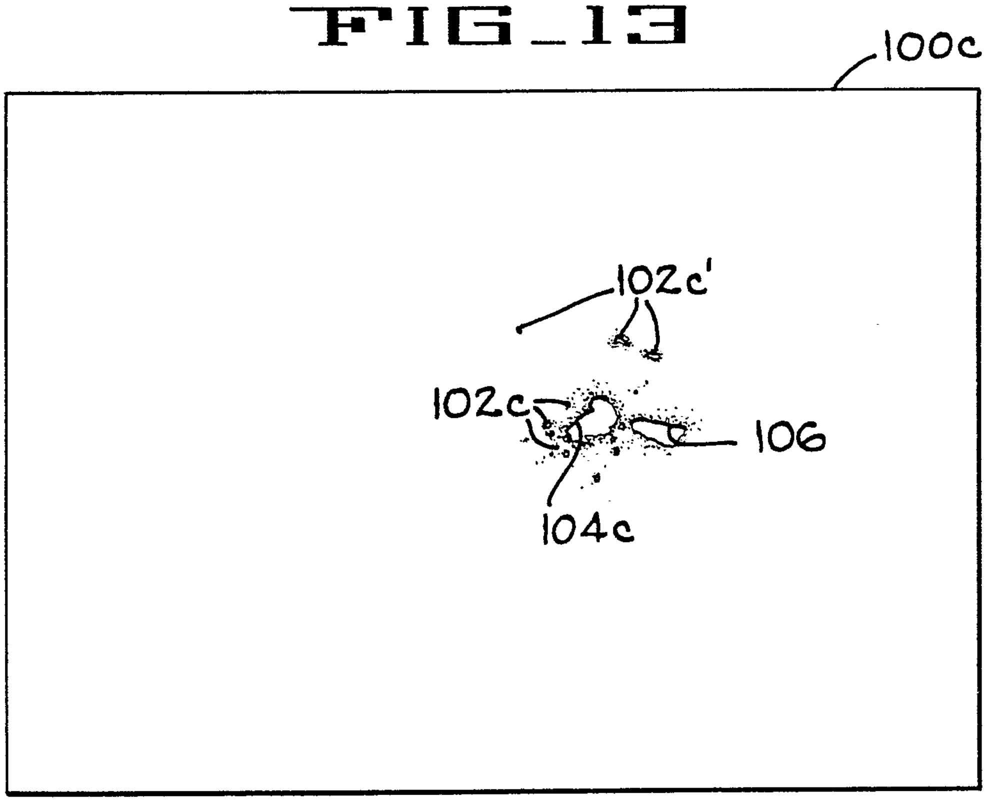
4.5 PSF ARAMID FIBER - 4" SPACING

FIG_12



4.3 PSF SPALL BACKING-SINGLE LAYER

FIG_13



2.8 PSF PRIMARY SPALL BACKING
1.5 PSF ARAMID FIBER-2" SPACING

European Patent Office

EUROPEAN SEARCH REPORT

Application Number

EP 89 10 4961

DOCUMENTS CONSIDERED TO BE RELEVANT

Category	Citation of document with indication, where appropriate, of relevant passages	Relevant to claim	CLASSIFICATION OF THE APPLICATION (Int. Cl.4)
Y Y	FR-A-2 461 232 (KRAUSS-MAFFEI) * Page 1, lines 11-19,31-38; page 2, lines 1-18,38; page 3, lines 1-19; page 4, lines 8-11; figures *	1-4,6-12,14,16,18-21,23-24,28-32,35-39-44,47,49	F 41 H 5/04
Y Y	GB-A- 746 371 (UNITED STATES RUBBER) * Page 1, lines 20-30,61-68; page 2, lines 24-123; page 3, lines 10-75; page 4, lines 19-29 *	1-4,6-12,14,16,18-21,23-24,28-32,35-39-44,47,49	
Y	US-A-4 061 815 (POOLE) * Column 2, lines 45-68; column 3, lines 1-20,41-61; column 4, lines 1-60; column 5, lines 1-47; figures 1-3 *	6,14,16,24,41,42	**TECHNICAL FIELDS SEARCHED (Int. Cl.4)**
Y	US-A-4 186 648 (CLAUSEN) * Column 3, lines 28-64; column 4, lines 63-68; column 5, lines 1-42; column 6, lines 27-35; column 7, lines 43-68; column 8, lines 1-52; column 9, lines 30-68; column 10, lines 1-11; figures 1-5,11 *	12,14,18,31,32,43,49	F 41 H

-/-

The present search report has been drawn up for all claims

Place of search	Date of completion of the search	Examiner
THE HAGUE	08-06-1989	VAN DER PLAS J.M.

CATEGORY OF CITED DOCUMENTS

X : particularly relevant if taken alone
Y : particularly relevant if combined with another document of the same category
A : technological background
O : non-written disclosure
P : intermediate document

T : theory or principle underlying the invention
E : earlier patent document, but published on, or after the filing date
D : document cited in the application
L : document cited for other reasons

& : member of the same patent family, corresponding document

EPO FORM 1503 03.82 (P0401)

European Patent Office

EUROPEAN SEARCH REPORT

Application Number

EP 89 10 4961

DOCUMENTS CONSIDERED TO BE RELEVANT

Category	Citation of document with indication, where appropriate, of relevant passages	Relevant to claim	CLASSIFICATION OF THE APPLICATION (Int. Cl.4)
E,D	EP-A-0 307 672 (FMC CORP.) * Page 7, lines 45-58; page 9, lines 5-17; page 12, lines 55-58; page 13, lines 13-33; page 25, lines 52-56; page 29, lines 25-32,48-50,54-58; page 30, lines 1-21,35-45; page 31, lines 29-54 *	1,3,4,7,28-32,35-37,39,40-42	
X	US-A-4 704 943 (McDOUGAL) * Column 1, lines 30-68; column 2, lines 1-16,33-59; column 11, lines 48-68; column 12, lines 1-27; column 13 lines 21-68; column 14; column 15, lines 1,2; figures 9-13 *	1,3,4,28-32,37	
A	US-A-4 664 967 (TASDEMIROGLU) * Column 1, lines 12-38,65-68; column 2, lines 1-15,31-51; figures 1-4 *	1	
A	GB-A-1 081 464 (FELDMÜHLE) * Page 1, lines 66-82; page 2, lines 1-3,32-71 *	1,14,18,20	TECHNICAL FIELDS SEARCHED (Int. Cl.4)
A	GB-A-1 151 441 (AEROJET) * Page 1, lines 25-39; page 2, lines 1-21; page 3, lines 18-47; page 4, lines 1-17 *	2,16,18,20	
A	FR-A-2 425 046 (INSTITUT FRANCO-ALLEMAND) * Page 1, lines 24-32; page 2, lines 28-35; page 3, lines 1-13; figure *	1,2,42,49	
A	US-A-3 563 836 (DUNBAR) * Column 3, lines 47-75; column 8, lines 9-34 *	1,2,6,14,16,24,34,53	

--- -/-

The present search report has been drawn up for all claims

Place of search	Date of completion of the search	Examiner
THE HAGUE	08-06-1989	VAN DER PLAS J.M.

CATEGORY OF CITED DOCUMENTS

X : particularly relevant if taken alone
Y : particularly relevant if combined with another document of the same category
A : technological background
O : non-written disclosure
P : intermediate document

T : theory or principle underlying the invention
E : earlier patent document, but published on, or after the filing date
D : document cited in the application
L : document cited for other reasons

& : member of the same patent family, corresponding document

EPO FORM 1503 03.82 (P0401)