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Chang

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[54] **EXPLOSIVE CLADDING ON GEOMETRICALLY NON-UNIFORM METAL MATERIAL**

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[52] **U.S. Cl.**.....**29/470.1**

[51] **Int. Cl.**.....**B23k 21/00**

[58] **Field of Search**.....29/421 E, 470.1, 29/486, 497.5

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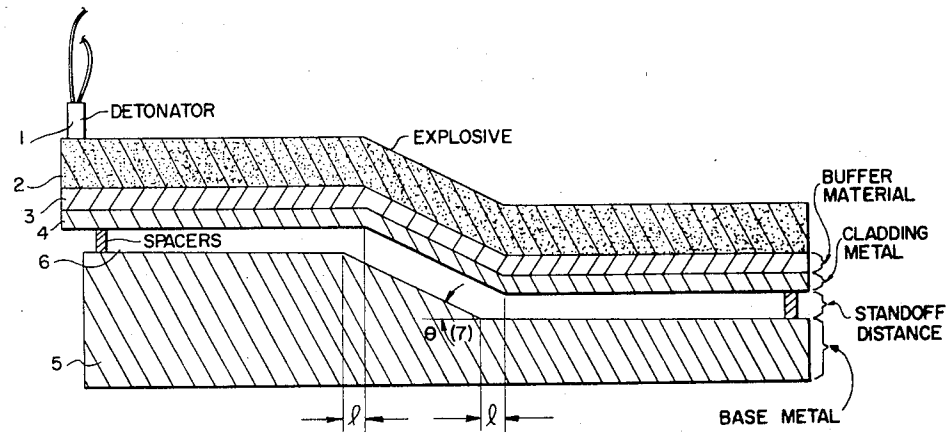
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Assistant Examiner—Ronald J. Shore
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[57] **ABSTRACT**

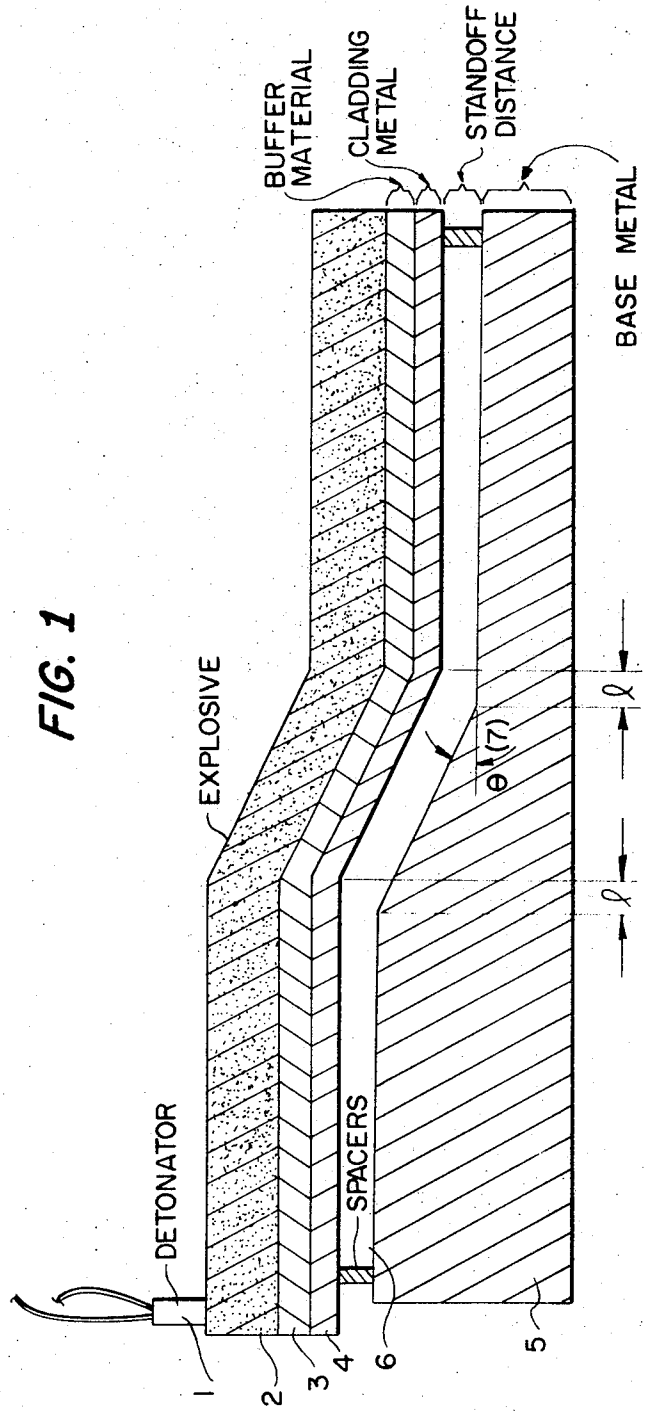
A method for explosively cladding one metal having a non-linear surface on another metal having a similar non-linear surface. A metal base member is spaced from a metal cladding plate an an explosive is positioned over the cladding plate whereby ignition of the explosive forces the cladding against the metal base to create a metallurgical bond.

10 Claims, 6 Drawing Figures



3 Sheets-Sheet 1

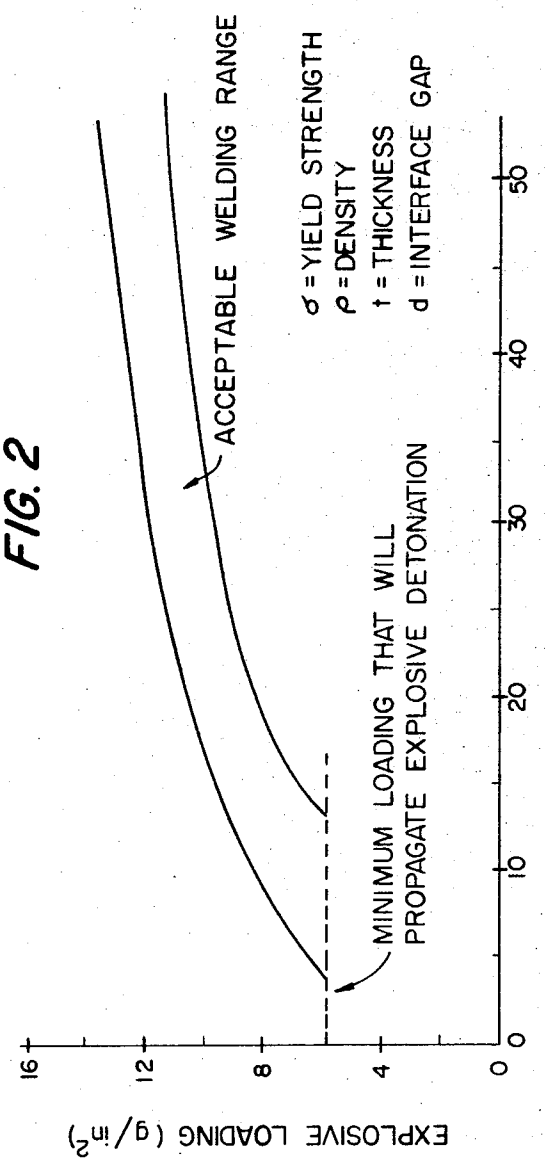
FIG. 1



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FIG. 2



RELATIONSHIP OF THE IMPORTANT PROCESS VARIABLES FOR EXPLOSIVE BONDING WITH A LOW-DETONATION-VELOCITY EXPLOSIVE.

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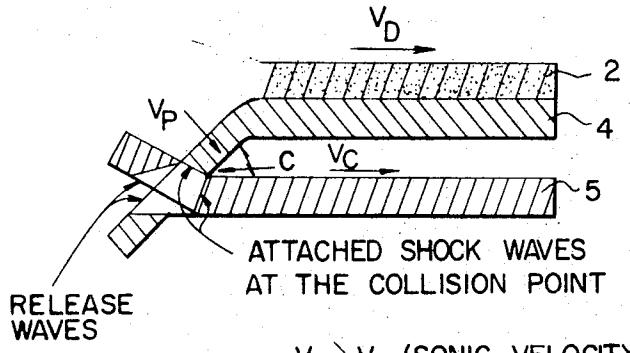
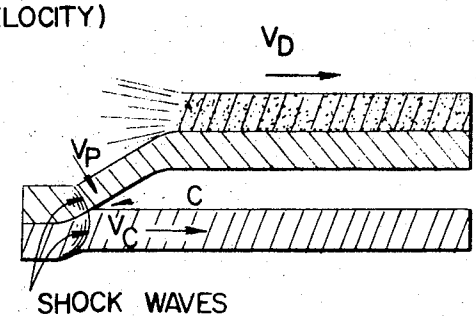


FIG. 3a

$V_C > V_S$ (SONIC VELOCITY)

FIG. 3b



$V_C \simeq V_S$

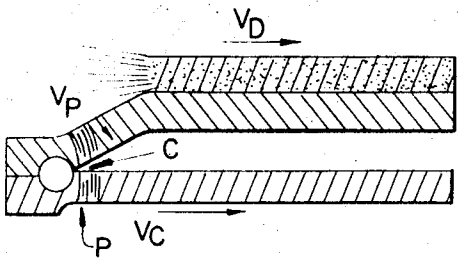
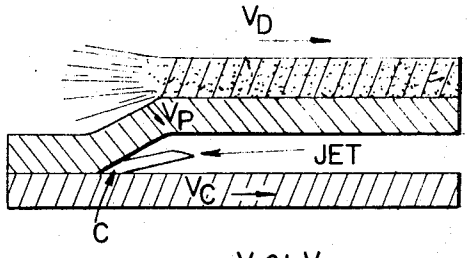


FIG. 3c

$V_C < V_S$

FIG. 3d



$V_C \simeq V_S$

HIGH VELOCITY JET EMANATING
THE COLLISION POINT

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EXPLOSIVE CLADDING ON GEOMETRICALLY NON-UNIFORM METAL MATERIAL

This invention relates to the cladding of metals upon other metals, and more particularly to a method of cladding one metal upon another by means of explosives.

In factories and plants many facilities are operated in various corrosive environments. As a result, the surfaces of these facilities must be clad with corrosive resistant metals. For example, containers, tanks and conduits of chemical plants or pharmaceutical plants are clad inside with either stainless steel, titanium alloy, lead or the like, for these cladding materials can withstand an acidic or alkaline corrosive environment. In general, corrosion-resisting metal is more expensive than corrodible metal, and to prevent the latter metal from being corroded, the portion of the metal exposed to and in contact with corrosives should be clad with corrosion-resisting metal in an appropriate thickness.

Cladding on metallic surfaces has been made by various methods, such as metalizing process, electrolytical or electrochemical deposition, and mechanical forming by rolling or other means of distortion.

The aforesaid methods heretofore employed for cladding one metal upon another have generally served the purpose but have not been satisfactory under all conditions of service. For example, the aforementioned methods are usually carried out by dipping the base metal into the molten cladding material. This necessitates close controls of the condition of the base metal and over the cladding process itself. The absence of surface oxides, contaminants and the like is a critical factor in obtaining the desired adherence between the base metal and the protecting metal to be clad thereon. Especially, brittle intermetallic compounds of compatible metals and thermal stress pose problems in this mechanism.

The mechanical cladding technique to achieve a metallurgical bond between two pieces of metal by deforming the two materials also has similar disadvantages. In this technique, it is very hard to achieve an intimate bond between the cladding material and the base metal. For example, the residual stress produced by rolling work is prone to deteriorate the bond between the two materials.

Although explosives have been used for several centuries and metals have been welded by various techniques for many more centuries, it has been only recently that explosives have been used to perform welding. Strong metallurgical bonds can now be produced over metal combinations which cannot be welded by other methods.

Explosive welding (bonding) is carried out by bringing together properly prepared metal surfaces with a high relative velocity, high pressure, and proper orientation, so that a large amount of plastic interaction occurs between the surfaces. The dynamics of this high-velocity collision are extremely complex. Only in the last few years have instances of explosive bonding been reported in the literature by numerous workers and in trade journals. Better quantitative relationships are now being developed to predict more reliably the results of explosive welding operations. Until such confident control of the process is achieved practical applications will continue to depend upon empirical

knowledge and experience, or upon rigidly standardized welding operations using special explosive-charge components or explosive welding machines.

The present state of the art of explosive welding techniques allows production of uniform flat clad plate of unique metal combinations and properties. In fact, commercial size clad plates are now being produced and marketed, and many companies in the world are currently developing new products for commercial application.

Although cladding techniques for flat plates have been well developed and the flat clad plates are commercially available, cladding on a geometrically non-uniform base plate has not been accomplished successfully. The effects on the mechanics of explosive bonding of a geometrically non-uniform surface and of the variation in direction of explosive detonation on a non-uniform surface have also not been determined.

It is, therefore, an object of this invention to provide a solution to the technical problems involved in the above-mentioned cladding methods.

A second object is to provide a method of achieving a metallurgical bond between two pieces of metal by use of explosives.

A third object is to provide an explosive cladding method for commercial applications on a broad scale.

A fourth object is to provide a method of achieving a metallurgical bond between two pieces of metal having geometrically non-uniform or non-linear surfaces.

Additional objects and advantages of the invention will be set forth in part in the description which follows, and in part will be obvious from the description, or may be learned by practice of the invention. The objects and advantages are realized and attained by means of the instrumentalities and combinations particularly pointed out in the appended claims.

The accompanying drawings, which are incorporated in and constitute a part of this specification, illustrate an example of a preferred embodiment of the invention and together with the description serve to explain the principles of the invention.

In the drawings:

FIG. 1 is a schematic illustration of an arrangement of explosive cladding embodied in this invention;

FIG. 2 shows the relationship of the important process variables for explosive bonding with a low-detonation-velocity explosive observed in the invention; and

FIGS. 3*a* – 3*d* illustrate the mechanism of explosive cladding as embodied in this invention.

In order to accomplish the objects of this invention, a metallurgical bond between two pieces of metal can be achieved by use of the energy developed by an explosive of proper detonating rate or velocity to collide mating metal surfaces with each other. In general, this process of bonding is achieved by placing the base metal at a fixed location which is kept at a certain distance from the position of the cladding material and by detonating the explosive loaded on the cladding material.

In order to achieve the metallurgical bond between the cladding material and the base metal, as embodied in this invention, it is necessary to bring atoms of the cladding material sufficiently close to atoms of the base metal so that their normal forces of interatomic attrac-

tion may act to produce a bond. However, the surfaces of metal and alloys often are covered naturally with films of oxides, nitrides and absorbed gases, and in the presence of such films or coatings, mating metal surfaces will not bond even under a very high pressure. Removal or effacement of interrupting surface films is, therefore, necessary to achieve the desired bond.

In the present invention, it has been observed that the dynamic angle between the colliding surfaces must be maintained within critical limits, as a result of properly controlled explosive-bonding parameters, to make a jet, or a portion of the colliding surfaces, which is expelled so as to achieve a metallurgical bond. The unwanted films on colliding surfaces are removed or broken up because of severe deformation and extension of the colliding surfaces and the resulting jet, and film-free surfaces remain and are pressed into intimate contact so that the mating surfaces can be metallurgically bonded.

It has been also observed in the invention that the collision velocity and detonation velocity have a great influence on the bonding process. In a collision between two pieces of metal, pressure disturbances are developed and propagated, and their types are dependent on the collision velocity and the detonation velocity.

When the collision velocity Vc exceeds the sonic velocity Vs of the cladding material, attached shock waves at the collision point C are generated into each metal, as illustrated in FIG. 3*a*. The shock front moves with the collision point and subjects the atoms to high pressures. These pressures are dependent on the collision velocity and physical properties of the metal. However, when expansion waves, which originate at the outer surfaces, reach the interface, they destroy the high pressure waves, causing the metal to separate.

If the collision velocity is approximately equal to the sonic velocity, the shock waves become detached and move ahead of the collision point. Detached shock waves are also formed when the collision angle β exceeds some critical values at a given collision velocity, and the critical angle is proportional to the detonation velocity.

When the collision velocity is less than the sonic velocity of the cladding material, no shock waves appear, since the pressure is spread ahead of the collision point as shown in FIG. 3*c*.

If the pressure ahead of the collision point, as in the cases of detached and non-shock waves, is great enough to cause plastic deformation of both metal surfaces, a flow of metal in the form of a jet will be initiated to remove or break up the unwanted films on the colliding surfaces, with the result that the mating metal surfaces are subjected to great pressures to achieve a metallurgical bond.

The proper detonation velocity as developed in the example of this invention is approximately 10,000 feet/sec. If the velocity exceeds excessively this limit, the velocity at the collision point will be larger than the sonic velocity of the cladding material to generate shock waves with no resulting jet, as described above, and if the velocity is less than the limit, pressures will decrease to fail in achieving good bonding.

In this invention, an empirical relationship developed by the Battelle Memorial Institute of U. S. A. was used that relates the identified material and process variables to the quality of explosive bonding. This was developed in terms of an energy-balance method during the experimental work at Battelle Memorial Institute.

The relationship is as follows: $L\alpha(t\rho\sigma y)/d$

where

L = weight of explosive per unit area of cladding plate

t = cladding - plate thickness

ρ = cladding - plate density

σy = cladding - plate yield strength

d = interface gap (standoff distance)

Using this relationship as a guide, different values of the factor $(t\rho\sigma y)/d$ were selected and tried with different values of L to establish limits on the value of L which would give good bonding. This effort resulted in a successful graphical relationship by plotting the explosive loading L against the factor $(t\rho\sigma y)/d$, as illustrated in FIG. 2. This graph is valid only for a particular explosive; in this case, a non-nitroglycerine dynamite, "T70C, a product of the Trojan Powder Company, was used at a vibratory-packed density of 1.0g/cc, and it had a detonation velocity of approximately 10,000 feet per second. This graph can normally be used to determine either the standoff distance or explosive loading for particular values of σy,ρ and t.

For the experiment in this invention, "T70C" explosive was used, as described above, and the explosive loading L was determined with the following values of σy,ρ,t and d.

$\sigma y = 56{,}000$ psi

$\rho = 6.286$ lb/in^3

$t = 1/8$ in

d = 1/8 in

As a result of calculation for L, a value of approximately 9 grams per in^2 was obtained.

As a result of this invention, cladding on various non-linear metal plates is now possible. Commercial size clad plates of stainless steel, carbon steel and titanium steel, etc., have been produced for use in explosive methods. Also, the cylindrical explosive cladding technique has been applied in welding tubes and tube plates of heat exchangers. However, the explosive cladding techniques developed hitherto are limited to flat plates and cylinders where the explosive detonation front moves in a linear direction. However, the method embodied in this invention can apply explosive cladding on a broader scale and includes explosive cladding when the explosive detonation front moves in a non-linear manner.

As illustrated in FIG. 1, a base metal **5** is so placed as to maintain a certain distance **6** (standoff distance) from a cladding material **4**, which has a certain thickness. A buffer material **3** is laid on the cladding material to protect the surface of the cladding material from harmful explosion products and to prevent cracking of the cladding material due to thermal stress. An explosive **2**, with a detonation velocity of approximately 10,000 ft/sec, is spread out in a certain density on the buffer material. The required density value of explosive can be obtained from the factor $(t\rho\sigma y)/d$ and FIG. 2. The distance between bending knots **7** is determined by the formula of $l = d \tan \theta/2$

where

l = distance between bending knots of base metal and cladding material

d = standoff distance between cladding metal and base metal

θ = bending angle

in order to maintain a constant standoff distance.

After all the necessary components are arranged as described above, a detonator 1 is detonated to blast the explosive. Approximately half of the energy generated in the explosive detonation is propagated to the cladding material through the buffer material to bend the cladding material in a certain slope so as to collide with the base metal at a very high velocity to achieve explosive bonding according to the mechanisms described above. When the explosive detonation front moves to the bending portion, the direction of detonation front changes to make the detonation unstable but the detonation direction is soon normalized to achieve good explosive cladding.

Although in the experiment of this invention specimens were so arranged as to make the direction of explosive detonation front change twice, the direction can change several times, and explosive cladding can be made as satisfactorily on non-linear behavior plates as well as on flat plates. The direction of detonation can be as shown in FIG. 1, e.g., down the slope or it can be in the opposite direction, up the slope. Either direction of detonation provides the desired bonding.

This invention is not limited to the conditions and requirements described above; it can be so modified within the scope of the methods, which are claimed in this invention, as to be made applicable to various conditions and requirements depending on the situation.

What is claimed is:

1. A method of explosively cladding one non-linearly shaped metal upon another non-linearly shaped metal, comprising the steps of:

providing a metal base member, having a non-linear shape formed by at least two planar surfaces to be explosively clad, including a first planar surface at an angle to and joined with a second planar surface and forming a first bending knot at the point where the two planar surfaces meet, and positioning said metal base member in a fixed location;

placing a metal cladding plate, having a non-linear shape similar in shape to the non-linear shape of said base member, and formed by at least two planar surfaces including a third planar surface joined with a fourth planar surface at a second bending knot, said third and fourth planar surfaces having the same angle as said first and second linear surfaces, a selected distance away from the base member in a first direction, said first and third surfaces being adjacent one another and separated by an interface gap equal to said selected distance;

positioning a buffer material on the cladding plate with said cladding plate located between the metal base and the buffer material;

placing a predetermined amount of explosive on the buffer material so that the explosive changes its shape and corresponds to the shape of the base member that is to be cladded;

igniting the explosive to cause the explosive to burn at a predetermined detonation velocity and to change its explosive front in accordance with the shape of the base member that is to be cladded;

forcing said planar surfaces of the base member and of the cladding plate together at a selected collision velocity; and

plastically deforming said planar surfaces to create a flow of metal between the surfaces in the form of a jet to remove or break up any unwanted films upon collision of the planar surfaces whereby the surfaces are subjected to great pressures to achieve a metallurgical bond between the base member and the cladding plate.

2. A method as in claim 1 wherein said first bending knot of the base member and said second bending knot of the cladding plate are spaced from each other in a second direction perpendicular to said first direction, and the distance in said second direction is determined by the formula of $l = d \tan \theta/2$ where

l = distance in said second direction between said first and second bending knots of the base member and the cladding plate

d = distance of the interface gap between the base member and the cladding plate, and

θ = bending angle between said first and second planar surfaces and between said third and fourth planar surfaces.

3. A method as in claim 1 wherein the predetermined amount of explosive used is determined by the following formula of $L\alpha(t\rho\sigma y)/d$

where

L = weight of explosive per unit area of cladding plate

t = cladding plate thickness

ρ = cladding plate density

σy = cladding plate yield strength and

d = interface gap (standoff distance)

4. A method as in claim 3 wherein the collision velocity is equal to or less than the sonic velocity of the cladding plate material.

5. A method as in claim 4 wherein the detonation velocity of the explosive is no greater than 10,000 feet per second.

6. A method as in claim 1, wherein said base member includes a fifth planar surface joined to said second planar surface at a third bending knot and parallel with said first planar surface, and said cladding plate includes a sixth planar surface joined to said fourth planar surface at a bending knot and parallel to said third planar surface.

7. A method as in claim 6 wherein said first bending knot of the base member and said second bending knot of the cladding plate are spaced from each other in a second direction perpendicular to said first direction, and the distance in said second direction is determined by the formula of $l = d \tan \theta/2$ where

l = distance in said second direction between said first and second bending knots of the base member and the cladding plate

d = distance of the interface gap between the base member and the cladding plate, and

θ = bending angle between said first and second planar surfaces and between said third and fourth planar surfaces,

and said third and fourth bending knots are spaced from each other in said second direction at a distance equal to the distance l between said first and second bending knots.

8. A method as in claim 1 wherein the collision velocity is equal to or less than the sonic velocity of the cladding plate material.

9. A method as in claim 8 wherein the detonation velocity of the explosive is no greater than 10,000 feet per second.

10. A method as in claim 9 wherein the predetermined amount of explosive used is determined by the following formula of $L \alpha (t\rho\sigma y)/d$

where

L = weight of explosive per unit area of cladding plate

t = cladding plate thickness

ρ = cladding plate density

σy = cladding plate yield strength and

d = interface gap (standoff distance).

* * * * *