United States Patent [19]
Hanson et al.
[11] 3,744,119
[45] July 10, 1973

[54] METHOD FOR EXPLOSIVELY BONDING TOGETHER METAL LAYERS AND TUBES

[76] Inventors: **Ivor G. Hanson,** 7530 Teller St.; **George Herbst,** 6777 Vivian St., both of Arvada, Colo. 80002; **Jerry M. Lewis,** 721 Mead St., Louisville, Colo. 80027

[22] Filed: **Nov. 28, 1969**

[21] Appl. No.: **880,822**

[52] **U.S. Cl.** **29/470.1,** 29/474.3
[51] **Int. Cl.** **B23k 21/00**
[58] **Field of Search** .... 29/421 E, 470.1, 29/486, 497.5, 474.3

[56] **References Cited**

UNITED STATES PATENTS

3,140,537	7/1964	Popoff	29/421 X
3,346,946	10/1967	Riegelmayer	29/421 X
3,364,561	1/1968	Barrington	29/470.1
3,364,562	1/1968	Armstrong	29/470.1
3,417,455	12/1968	Pearson	29/470.1
3,434,197	3/1969	Davenport	29/421 X
3,503,110	3/1970	Berry et al.	29/470.1 X
R26,858	4/1970	Chudzik	29/421 X
3,535,767	10/1970	Doherty, Jr. et al.	29/470.1
3,397,444	8/1968	Bergmann et al.	29/470.1

OTHER PUBLICATIONS

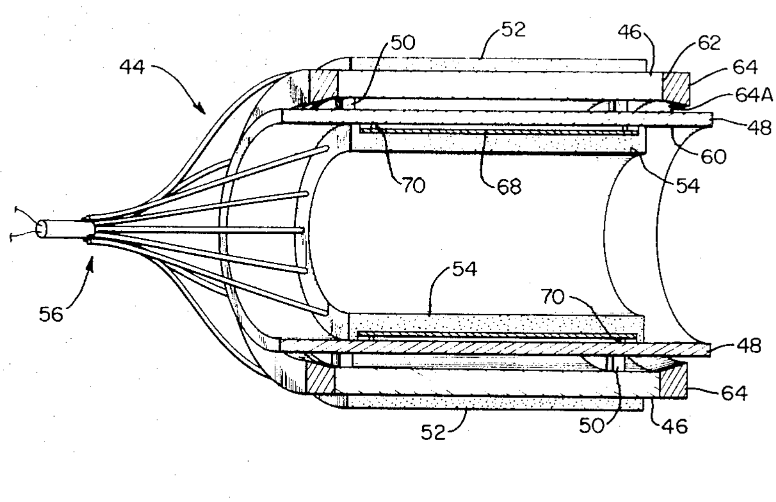
"Zirconium Grade 11," Alloy Digest, published by Engineering Alloys Digest, Inc., Upper Montclair, New Jersey, 2 pages, 10/64.

Primary Examiner—J. Spencer Overholser
Assistant Examiner—Ronald J. Shore
Attorney—Sheridan, Ross and Burton

[57] **ABSTRACT**

Method and assembly for welding a flyer metal tube to a parent metal tube, comprising assembling a flyer metal tube and a parent metal tube in concentric disposition with the outer surface of one of said tubes being disposed in parallel, spaced-apart relation with the inner surface of the other metal tube, selecting and matching two layers of explosive which will, during simultaneous detonation thereof, produce a general balance of forces along the resulting detonating fronts in a direction normal to said layers of explosive and, following detonation of the layers of explosive, maintain a pressure differential between the released and expanding gases generated by the detonation of the two layers of explosive below a predetermined amount, placing a first one of said layers of explosive about the outer surface of the outer metal tube and placing a second layer of explosive about the inner surface of the inner metal tube, and simultaneously detonating said layers of explosive along a common, generally planar front so that the detonation is propagated parallel to the longitudinal axis of said tubes. The loading of the layer of explosive disposed about a surface of the flyer metal layer is sufficient to produce a pressure greater than the elastic limit of the metal tube in the assembly having the higher elastic limit and to effect bonding between the metal tubes. The loading of the layer of explosive disposed about a surface of the parent metal tube is sufficient to preclude movement of the parent metal tube relative to the flyer metal layer in a manner that would prevent welding together of said metal tubes. The method and assembly relate to the use of a flyer metal tube having a resistance factor of at least approximately $1.5(10)^{-4}$ psi and which is spaced apart from the parent metal layer by a distance equaling at least approximately 0.05 times the thickness of the flyer metal layer, and also to the use of a flyer metal tube having a resistance factor of at least approximately $2.5(10)^{-4}$ psi and which is spaced apart from the parent metal tube by a distance equaling at least approximately 0.1 times the thickness of the flyer metal tube. The method and assembly also relate to the welding together of metal layers sandwiched between two layers of explosive in which the flyer metal layer has a resistance factor of at least approximately $2.5(10)^{-4}$ psi and the distance separating said metal layers, prior to bonding, equals at least approximately 0.1 times the thickness of the flyer metal layer. The article of manufacture produced comprises a flyer metal layer bonded to a parent metal layer in which the flyer metal layer, prior to bonding, has a resistance factor of at least approximately $2.25(10)^{-4}$ psi, and also a flyer metal tube bonded to a parent metal tube in which the flyer metal tube, prior to bonding, has a resistance factor of at least approximately $2.5(10)^{-4}$ psi.

12 Claims, 14 Drawing Figures



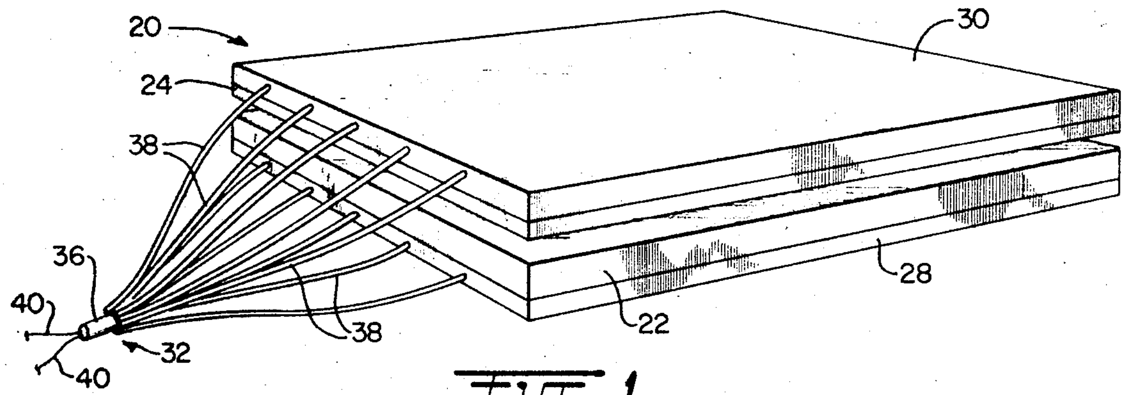


FIG. 1

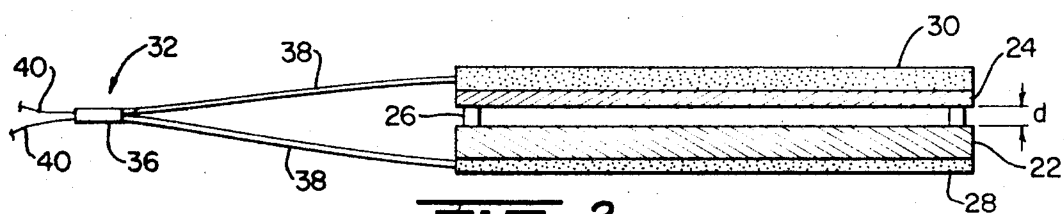


FIG. 2

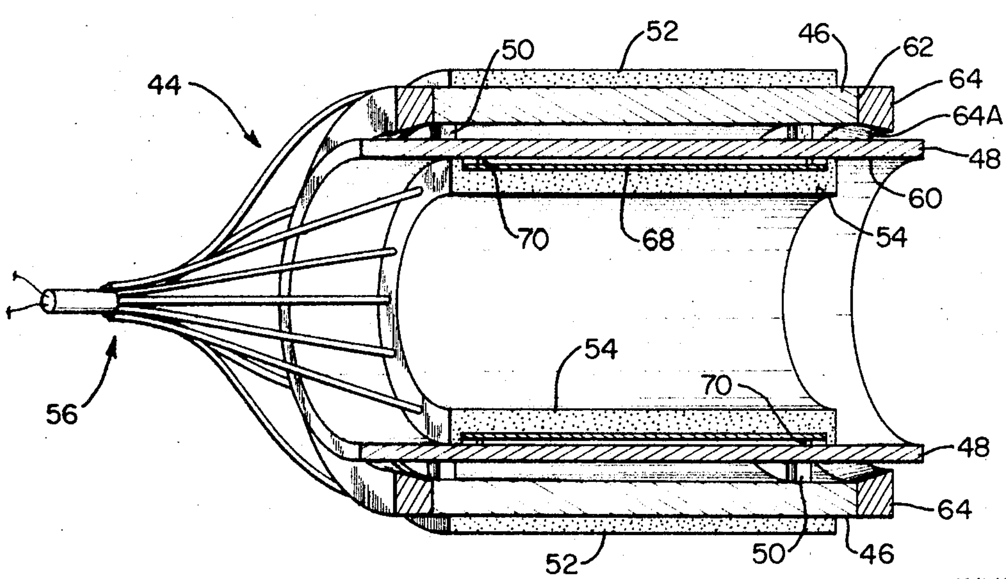


FIG. 3

INVENTORS
IVOR G. HANSON
GEORGE HERBST
JERRY M. LEWIS
BY Sheridan, Ross & Burton
ATTORNEYS

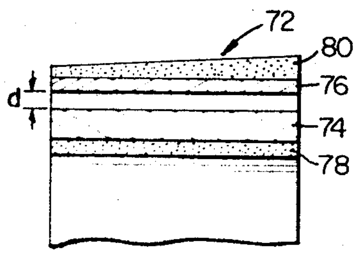


FIG. 4

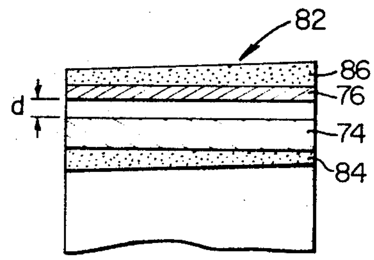


FIG. 5

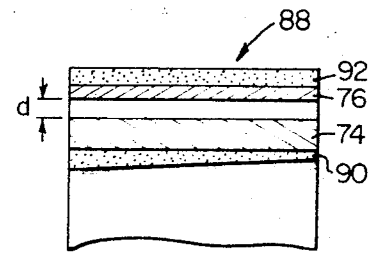


FIG. 6

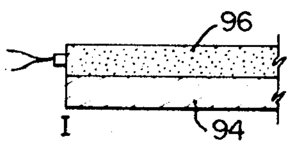


FIG. 7A

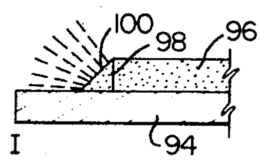


FIG. 7B

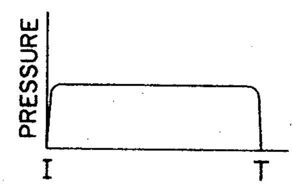


FIG. 7C

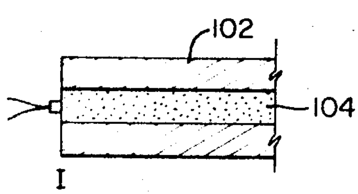


FIG. 8A

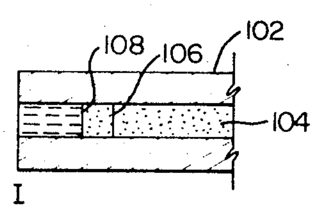


FIG. 8B

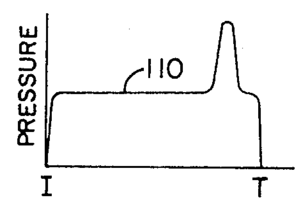


FIG. 8C

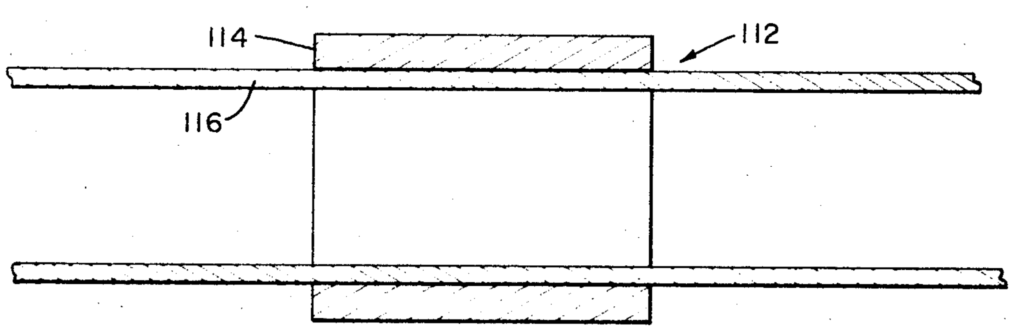


FIG. 9

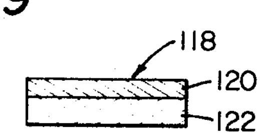


FIG. 10

INVENTORS
IVOR G. HANSON
GEORGE HERBST
JERRY M. LEWIS

BY Sheridan, Ross & Burton

ATTORNEYS

METHOD FOR EXPLOSIVELY BONDING TOGETHER METAL LAYERS AND TUBES

BACKGROUND OF THE INVENTION

Heretofore, a considerable amount of effort had been expended in perfecting methods of explosively welding together metal plates, tubes and the like. For example, some of the very early explosive welding work was done by Vasil Philipchuck as reported in pages 80–86 of the August, 1958 issue of *Steel*. Subsequent work done by Philipchuck is disclosed in U.S. Pat. No. 3,024,526. Other early pioneer work done in this field is disclosed in U.S. Pat. Nos. 3,031,746; 3,036,374 and 3,060,874. Subsequent work done in this field is disclosed in U.S. Pat. Nos. 3,137,937 and 3,140,537. All of the aforementioned work related to the use of a single layer of explosive disposed against a relatively thin metal layer to weld said thin metal layer to another layer of metal. In connection with the above-referenced work and the work reported herein, the layer of metal against which the layer of explosive was disposed may be considered and is hereafter referred to as the "flyer" metal layer. The other metal layer, which may be considered and is hereafter referred to as the "parent" metal layer, was disposed upon a relatively rigid supporting surface or die member. In all of this work, there was a predetermined standoff or distance separating each of the metal layers prior to detonation of the layer of explosive.

Based upon the teachings contained in the above-referenced publication and patents, particularly U.S. Pat. No. 3,137,937 which not only disclosed and claimed that bonding of metal layers can be obtained by placing a layer of explosive on the outside of one of the metal layers but also showed in Examples **2** and **3** the use of mild steel plates of 0.75 inch and 1 inch, it was thought that relatively thick metal layers could be welded to each other (or a relatively thick metal layer could be welded to a relatively thin metal layer) through the use of a single layer of explosive disposed adjacent a surface of said relatively thick metal layer merely by increasing the amount of explosive sufficiently such that the layer of explosive, upon detonation thereof, would deform the flyer metal layer and drive same against the parent metal layer. However, it was found that this did not work. As a matter of fact for the conditions specified, it was found that no weld could be obtained for certain thicknesses of flyer metal layers (such as 0.75 inch and 1 inch thick mild steel plates) and that only inconsistent results, i.e., no welding or poor or inferior welds, were obtained for flyer metal layers of slightly less thickness. Based upon a careful review of the factors and circumstances relating to the work done with thicker flyer metal layers, it was concluded that either the amount of explosive required to deform the relatively thick flyer metal layer to drive same against the parent metal layer was so great that the parent metal layer could not be stabilized or rigidized sufficiently to permit a permanent weld or a weld of acceptable quality to form between the two metal layers and/or the parent metal layer moved, during detonation of the explosive, relative to the flyer metal layer in a manner that prevented welding together of said layers. In an attempt to overcome this problem, the mass or size of the support member for the parent metal layer was substantially increased. However, this did not solve the problem.

Since the amount of explosive required to deform the flyer metal layer and to drive same against the parent metal layer in bonding or welding engagement is dependent upon certain strength characteristics of the flyer metal layer, an analysis of the above-referenced work was made to determine the size of flyer metal layers or tubes which could be welded to another metal layer or tube through the use of a single layer of explosive. It was found that a flyer metal tube could not be permanently welded to a parent metal tube where the resistance factor of the flyer metal tube was at least approximately $2.5(10)^{-4}$ psi, and that only inconsistent results (either no welding or welds of reduced or inferior quality) were obtained where the resistance factor varied between approximately $1.5(10)^{-4}$ to slightly less than $2.5(10)^{-4}$ psi, i.e., $2.25(10)^{-4}$ psi. It was also found that a flyer metal layer could not be permanently welded to a parent metal layer where the resistance factor of the flyer metal layer was at least approximately $2.25(10)^{-4}$ psi, and that only inconsistent results (as aforesaid) were obtained where the resistance factor varied between approximately $1.5(10)^{-4}$ psi to slightly less than $2.25(10)^{-4}$ psi, i.e., $2(10)^{-4}$ psi. The resistance factor referred to herein is determined from the following formula:

$$R_f = \sigma t \epsilon \div E$$

σ = the yield strength (in psi) of the flyer metal layer or tube

t = thickness (in inches) of the flyer metal layer or tube

ϵ = the density (in lbs/in.^{3}) of the flyer metal layer or tube

E = Young's Modulus (in psi) for the flyer metal layer or tube.

In essence, the resistance factor is basically a measure of the degree of resistance a particular member would have to deformation necessary for explosive bonding.

SUMMARY OF THE INVENTION

It has been unexpectedly discovered that relatively thick flyer metal layers or tubes can be welded to parent metal layers or tubes through the use of two layers of explosive, one layer of explosive being disposed adjacent the flyer metal or tube and the other layer of explosive being disposed adjacent the parent metal layer or tube, where (in the case of metal tubes) the layers of explosive are matched such that they will, during simultaneous detonation thereof, produce a general balance of forces along the resulting detonating fronts in a direction normal to said layers of explosive and, following detonation of the layers of explosive, maintain a pressure differential between the released and expanding gases generated by the detonation of the two layers of explosive below a predetermined amount. Additionally, the loading of the layer of explosive disposed adjacent a surface of the flyer metal layer or tube must be sufficient to produce, upon collision of the metal layers or tubes, a pressure greater than the elastic limit of the metal layer or tube (involved in the welding operation) having the higher elastic limit and sufficient to cause bonding between said metal layers or tubes. Also, the loading of the layer of explosive disposed adjacent the parent metal layer or tube must be sufficient, upon collision with said flyer metal layer or tube, to preclude movement of the parent metal tube relative to the flyer metal layer or tube in a manner that would prevent welding together of said metal layers or tubes. It has also been discovered that where the resistance factor of the flyer metal tube varies between approximately $1.5(10)^{-4}$ psi to slightly less than $2.5(10)^{-4}$ psi, i.e., approximately $2.25(10)^{-4}$ psi, the standoff or distance separating the tubes should equal at least approximately 0.05 times the thickness of the flyer metal tube, and where the resistance factor of the flyer metal tube equals at least approximately $2.5(10)^{-4}$ psi, the standoff or distance separating the tubes should equal at least approximately 0.1 times the thickness of the flyer metal tube and preferably between approximately 0.2 to 0.4 times the thickness of the flyer metal tube. Where the resistance factor of the flyer metal layer varies between approximately $1.5(10)^{-4}$ psi to slightly less than $2.25(10)^{-4}$ psi, i.e., approximately $2(10)^{-4}$ psi, the standoff or distance separating the layers should equal at least approximately 0.05 times the thickness of the flyer metal layer, and where the resistance factor of the flyer metal layer equals at least approximately $2.25(10)^{-4}$ psi, the standoff should equal at least approximately 0.1 times the thickness of the flyer metal layer and preferably between approximately 0.2 to 0.4 times the thickness of the flyer metal layer.

One of the principal objects of this invention is to provide a method and assembly for explosively bonding or welding together metal layers and tubes and a novel article produced as a result thereof.

Another object of this invention is to provide a method of welding a flyer metal tube to a parent metal tube comprising assembling a flyer metal tube and a parent metal tube in concentric disposition with the outer surface of one of said tubes being disposed in parallel, spaced-apart relation with the inner surface of the other metal tube so that the distance separating said opposed surface equals at least approximately 0.001 inch; selecting and matching two layers of explosive which will, during simultaneous detonation thereof, produce a general balance of forces along the resulting detonating fronts in a direction normal to said layers of explosive and, following detonation of the layers of explosive, maintain a pressure differential between the released and expanding gases generated by the detonation of the two layers of explosive below a predetermined amount; placing a first one of said layers of explosive about the outer surface of the outer metal tube and placing a second one of said layers of explosive about the inner surface of the inner metal tube; and simultaneously detonating said layers of explosive along a common, generally planar front so that the detonation is propagated parallel to the longitudinal axis of said tubes; the loading of said layer of explosive disposed about a surface of said flyer metal tube being at least sufficient to produce, upon collision of the metal tubes, a pressure greater than the elastic limit of the metal tube in the assembly having the higher elastic limit and sufficient to cause bonding between said metal tubes; the loading of a layer of explosive disposed about a surface of said parent metal tube being sufficient, upon collision with said flyer metal tube, to preclude movement of the parent metal tube relative to the flyer metal tube in a manner that would prevent welding together of said metal tubes.

Another object of this invention is to provide a method as aforedescribed in which the step of assembling includes assembling together two tubes of unequal length with one of said tubes being disposed concentrically within the other of said tubes, and restraining at least a portion of the longer tube disposed adjacent and axially outwardly from one end of said shorter tube, during detonation of said layers of explosive, to control the bulging radially outwardly thereof.

Another object of this invention is to provide a method as aforedescribed in which the step of assembling includes assembling two tubes of unequal lengths with one of said tubes being disposed concentrically within said other of said tubes, and insulating at least one of the ends of said shorter tube against damage from shock waves reflected from said end of said shorter tube.

Another object of this invention is to provide a method as aforedescribed in which the step of selecting and matching two layers of explosive includes selecting a first layer of explosive of substantially uniform thickness and selecting a second layer of explosive which, adjacent the plane of initial detonation, has a maximum thickness equal to the thickness of the first layer of explosive and, proceeding in a direction parallel with the direction of propagation of the layers of explosive, has a reduced thickness.

Another object of this invention is to provide a method of welding a flyer metal layer to a parent metal layer comprising selecting a flyer metal layer having a resistance factor varying between approximately $1.5(10)^{-4}$ psi and $2.25(10)^{-4}$ psi and assembling said flyer metal layer and a parent metal layer in parallel, spaced-apart relation so that the distance separating said layers equals at least approximately 0.05 times the thickness of the flyer metal layer; selecting two layers of explosive; sandwiching said assembled metal layers between said layers of explosive so that each of said layers of explosive is disposed adjacent a surface of a corresponding one of said metal layers; and simultaneously detonating said layers of explosive along a common, generally planar front so that the detonation is propagated parallel to said metal layers in a direction generally perpendicular to said planar front; the loading of said layer of explosive disposed adjacent a surface of the flyer metal layer being at least sufficient to produce, upon collision of the metal layers, a pressure greater than the elastic limit of the metal layer in the assembly having the higher elastic limit and sufficient to cause bonding between said metal layers; the loading of the layer of explosive disposed adjacent a surface of said parent metal layer being sufficient, upon collision with said flyer metal layer, to preclude movement of the parent metal layer relative to the flyer metal layer in a manner that would prevent welding togeher of said metal layers.

Another object of this invention is to provide a method as aforesaid described in which the step of assembling includes selecting a flyer metal layer having a resistance factor of at least approximately $2.25(10)^{-4}$ psi and assembling same with a parent metal layer so that the distance separating said metal layers equals at least approximately 0.1 times the thickness of the flyer metal layer.

Another object of this invention is to provide an assembly for welding together two metal layers, said assembly comprising a parent metal layer; a flyer metal layer having a resistance factor varying between approximately $1.5(10)^{-4}$ psi and $2.25(10)^{-4}$ psi; means for supporting said metal layers in parallel, spaced-apart relation so that the distance separating said metal layers equals at least approximately 0.05 times the thickness of the flyer metal layer; two layers of explosive, said metal layers being sandwiched between said layers of explosive, a first one of said layers of explosive being disposed adjacent a surface of said flyer metal layer and a second one of said layers of explosive being disposed adjacent a surface of said parent metal layer, the loading produced by said first layer of explosive being sufficient, upon detonation thereof, to drive the flyer metal layer in collision with said parent metal layer and to cause bonding between said metal layers, and the loading of said second layer of explosive being sufficient, upon detonation thereof simultantously with the detonation of said layer of explosive, to preclude movement of the parent metal layer relative to the flyer metal layer in a manner that would prevent welding together of said metal layers; and means for simultaneously detonating said layers of explosive along a common, generally planar front whereby the detonation is propagated parallel to said metal layers in a direction generally perpendicular to said planar front.

Another object of this invention is to provide an assembly as aforesaid described in which said flyer metal layer has a resistance factor of at least approximately $2.25(10)^{-4}$ psi and the distance separating said metal layers equals at least approximately 0.1 times the thickness of the flyer metal layer.

Another object of this invention is to provide an assembly for welding together two metal tubes in which the assembly comprises a parent metal tube; a flyer metal tube; means for supporting said metal tubes in concentric disposition with the outer surface of one of said tubes being disposed in parallel, spaced-apart relation with the inner surface of the other metal tube so that the distance separating said opposed surfaces equals at least approximately 0.001 inch; two matched layers of explosive which will, during simultaneous detonation thereof, produce a general balance of forces along the resulting detonating fronts in a direction normal to said layers of explosive and, following detonation of the layers of explosive, maintain a pressure differential between the released and expanding gases generated by the detonation of the two layers of explosive below a predetermined amount, one of said layers of explosive being disposed about the outer surface of the outer metal tube and the other one of said layers of explosive being disposed about the inner surface of the inner metal tube, the loading produced by the layer of explosive disposed about a surface of said flyer metal tube being sufficient, upon detonation thereof, to drive the flyer metal tube into collision with said parent metal tube and to cause bonding between said metal tubes, and the loading produced by the layer of explosive disposed about a surface of said parent metal tube being sufficient, upon detonation thereof simultaneously with detonation of the other layer of explosive, to preclude movement of the parent metal tube relative to the flyer metal tube in a manner that would prevent welding together of said metal tubes; and means for simultaneously detonating said layers of explosive along a common, generally planar front whereby the detonation is propagated parallel to the longitudinal axis of said tubes.

Another object of this invention is to provide an assembly for welding together two metal tubes as aforesaid described in which said flyer metal tube has a resistance factor of at least approximately $1.5(10)^{-4}$ psi and the distance separating said tubes equals at least approximately 0.05 times the thickness of said flyer metal tube.

Another object of this invention is to provide an assembly for welding together metal tubes as aforesaid described in which said flyer metal tube has a resistance factor of at least approximately $2.5(10)^{-4}$ psi and the distance separating said tube equals at least approximately 0.1 times the thickness of said flyer metal tube.

Another object of this invention is to provide an assembly for welding together metal tubes as aforesaid described in which the metal tubes are unequal in length and one of said tubes is disposed concentrically within the other of said tubes, the longer of said tubes having a part extending axially outwardly from one end of the shorter tube, and restraining means for controlling the bulging radially outwardly of a portion of said part of the longer tube disposed adjacent and axially outwardly from said one end of said shorter metal tube.

Another object of this invention is to provide an assembly for welding together metal tubes as aforesaid described in which the metal tubes are unequal in length and one of said tubes is disposed concentrically within the other of said tubes, the longer of said tubes having a part extending axially outwardly from one end of the shorter tube, and means for insulating at least one of the ends of said shorter tube against damage from shock waves reflected from said end of said shorter tube.

Another object of this invention is to provide an article of manufacture comprising a flyer metal layer explosively bonded to a parent metal layer, the flyer metal layer, prior to bonding, having a resistance factor of at least approximately $2.25(10)^{-4}$ psi.

Another object of this invention is to provide an article of manufacture as aforedescribed in which the parent metal layer, prior to bonding, has a resistance factor of at least approximately $1.5(10)^{-4}$ psi.

Another object of this invention is to provide an article of manufacture comprising a flyer metal tube explosively bonded to a parent metal tube, one of said metal tubes being concentrically disposed within the other of said metal tubes, the flyer metal tube, prior to bonding, having a resistance factor of at least approximately $2.5(10)^{-4}$ psi.

Further objectives, advantages, and salient features will become more apparent from the description to follow, the appended claims, and the accompanying drawings.

BRIEF DESCRIPTION OF THE DRAWINGS

FIG. 1 is a perspective view of an assembly of two metal layers formed in accordance with this invention;

FIG. 2 is a longitudinal, cross-sectional view of the assembly shown in FIG. 1;

FIG. 3 is a longitudinal, cross-sectional view of an assembly of metal tubes formed in accordance with this invention;

FIGS. 4–6 are partial longitudinal, cross-sectional views of two assembled metal tubes showing two matched layers of explosives;

FIGS. 7A–C show a representative pressure gradient generated by the detonation front of a layer of explosive as same travels from the point of initial detonation to the point of termination of detonation, said layer of explosive being disposed above the metal layer;

FIGS. 8A–C show a representative pressure gradient generated by the detonation front of an explosive charge as same travels from the point of initial detonation to the point of termination of detonation, said charge being disposed within said metal tube; and

FIGS. 9 and 10 are cross-sectional views of articles of manufacture produced in accordance with the method of this invention.

DESCRIPTION OF THE PREFERRED EMBODIMENTS

It is to be understood that where two layers of explosive are used, both metal layers can be considered as a flyer metal layer; however, it will normally be found that for various reasons, such as dimensional stability of the finished article or the configuration of the parts involved, one metal layer will be considered either as the flyer metal layer or the primary flyer metal layer while the other metal layer will be considered as the parent metal layer or the secondary flyer metal layer. Unless otherwise specified, the use herein of the term "parent" metal layer or tube shall also include those layers or tubes which are "secondary" flyer metal layers or tubes as specified above.

It is to be also understood that the layer of explosive need not be disposed in direct contacting engagement with the appropriate surface of the layer or tube, although such is preferred in many instances, and that a sheath or layer of buffer material may be disposed intermediate said surface and the layer of explosive. Consequently, the use herein of the terms "adjacent" and "about" encompasses those conditions where the layer of explosive is disposed in direct contact with the surface of the metal layer or tube as well as spaced apart therefrom.

Referring now to the drawings and particularly to FIGS. 1 and 2, an assembly 20 for welding together two metal layers is shown comprising a parent metal layer 22, a flyer metal layer 24 having a resistance factor of $1.5(10)^{-4}$ psi or more, means 26 (see FIG. 2) for supporting the flyer metal layer 24 above the parent metal layer 22 in a horizontally disposed, parallel, spaced-apart relation, two layers 28 and 30 of explosive, and means 32 for simultaneously detonating said layers of explosive along a common, generally planar front whereby the detonation is propagated parallel to the metal layers 22 and 24 in a direction generally perpendicular to the planar front.

The standoff or distance d separating the metal layers equals at least approximately 0.05 times the thickness of the flyer metal layer. It has been found, however, that the distance *d* must be increased where thicker flyer metal plates 24 are involved. For example, the use of flyer metal layers having a resistance factor of at least approximately $2.25(10)^{-4}$ psi requires the use of a standoff or distance d equaling at least approximately 0.1 times the thickness of the flyer metal layer or plate. It has been found that the increase in the standoff or distance *d* is not directly proportional to the increase in the thicknes of the flyer metal layer. Baeed upon test results it has been found that for layers having a resistance factor at $2.25(10)^{-4}$ psi or more the standoff or distance *d* preferably should vary between approximately 0.2 to 0.4 times the thickness of the flyer metal layer.

The means 26 for supporting the flyer metal layer 24 in parallel, spaced-apart relation with respect to the parent metal layer 22 comprises a plurality of cube-shaped metal blocks as shown. However, it will be understood that other suitable means may be used for mounting the metal layers in this manner.

The layer 30 of explosive disposed upon the upper surface of the flyer metal layer 24 must produce a loading which, upon detonation thereof, is sufficient to drive the flyer metal layer 24 into collision with the parent metal layer 22 and to cause bonding or welding between said metal layers. The layer 28 of explosive disposed beneath the lower surface of the parent metal layer 22 must produce, upon detonation thereof simultaneously with the detonation of the layer 24 of explosive, a loading sufficient to preclude movement of the parent metal layer relative to the flyer metal layer in a manner that would prevent welding together of said metal layers.

For a metal layer having a resistance factor of at least approximately $1.5(10)^{-4}$ psi to slightly less than $2.25(10)^{-4}$ psi, i.e., approximately $2(10)^{-4}$ psi, it is believed that the layer 28 of explosive disposed adjacent the parent metal layer 22 must produce a loading sufficient to stabilize the parent metal layer to prevent movement of same away from the flyer metal layer 24 in a manner or at a rate that prevents welding together of said layers. For a metal layer having a resistance factor of $2.25(10)^{-4}$ psi or more, it is believed that the layer 28 of explosive disposed adjacent the parent metal layer 22 must produce a loading sufficient to move the parent metal layer toward the flyer metal layer 24 in a manner or at a rate that enables or effects welding together of said layers.

As shown in FIGS. 1 and 2, the explosive layer 30 is thicker than the explosive layer 28. However, it is to be understood that the thickness of explosive layer 28 may vary from that as shown and may have the same thickness as the explosive layer 30. As a general rule, the thickness of the explosive layer 28 is held to a minimum. The thickness of the explosive layer 28 is primarily dependent upon the thickness of the flyer metal plate, i.e., the thicker the flyer metal layer used, the thicker will be the explosive layer 28. Additionally, the thickness of the explosive layer 28 is affected to a lesser extent by the thickness of the parent metal layer 22, i.e., as the thickness of the parent metal layer 22 increases the thickness of the explosive layer 28 may decrease somewhat. It is to be understood that the amount of explosive contained in explosive layer 28 must be sufficient either to prevent movement of the parent metal layer 22 relative to the flyer metal layer 24 in a manner that would prevent welding together of said layers or to cause the parent metal layer 22 to be driven into colliding engagement with the flyer metal layer 24.

The means 32 shown in FIGS. 1 and 2 for simultaneously detonating the layers of explosive along a common, generally planar front comprises an electric blasting cap 36 and a plurality of identical lengths of detonating fuse 38. One end of each of the detonating fuses 38 is connected to the blasting cap 36. The other end of half of the detonating fuses 38 is connected to predetermined, laterally spaced-apart points of the layer of explosive 30 along one end thereof. The other end of the remaining half of detonating fuses 38 is connected to predetermined, laterally spaced-apart points of the layer 28 of explosive along one end thereof. It has been found that a detonating fuse known in the trade as

Primacord, a trademark of the Ensign-Bickford Company of Simsbury, Connecticut, may be used with good results. The Primacord detonating fuse has a detonating velocity of approximately 21,000 feet per second. Since identical lengths of detonating fuses are used, it is possible to initiate accurately and, for all practical purposes, simultaneously detonation of the layers of explosive along a generally planar front, i.e., along the left end of the layers of explosive as shown in FIGS. **1** and **2**. The electric blasting cap **36** is connected by wires **40** to a suitable source of electrical power (not shown).

Referring now to FIGS. **3** and **4**, an assembly **44** for welding together two metal tubes is now described. The assembly **44** comprises a parent metal tube **46**, a flyer metal tube **48**, means **50** for supporting said metal tubes in concentric disposition with the outer surface of the inner metal tube **48** being disposed in parallel, spaced-apart relation with the inner surface of the outer metal tube **46** so that the distance separating said opposed surface equals at least approximately 0.001 inch, two matched explosive layers **52** and **54**, one layer **52** of explosive being disposed about the outer surface of the outer metal tube **46** and the other layer **54** of explosive being disposed about the inner surface of the inner metal tube **48**, and means **56** for simultaneously detonating said explosive layers **52** and **54** along a common, generally planar front.

The criteria controlling the standoff or distance d separating the metal tubes is similar to that set forth above with respect to the metal layers shown in FIGS. **1** and **2**. More specifically, the standoff *d* must be increased where thicker flyer metal tubes are involved. For example, the use of flyer metal tubes having a resistance factor of at least approximately $1.5(10)^{-4}$ psi to slightly less than $2.5(10)^{-4}$ psi requires the use of a standoff or distance *d* equaling at least approximately 0.05 times the thickness of the flyer metal tube. Where a flyer metal tube having a resistance factor of at least approximately $2.5(10)^{-4}$ psi is used, the standoff *d* should equal at least approximately 0.1 times the thickness of the flyer metal tube. As is the case with the metal layers, it has been found that the increase in the standoff or distance *d* is not directly proportional to the increase in the thickness of the flyer metal tube. Test results have shown that the standoff d for metal tubes having a resistance factor of at least approximately $2.5(10)^{-4}$ psi should vary between approximately 0.2 to 0.4 times the thickness of the flyer metal tube.

The means **50** for supporting the metal tubes in parallel, spaced-apart relation comprise a plurality of cube-shaped metal blocks as shown. However, this invention is not limited to the use of metal cubes since other suitable means may be used for mounting the metal tubes in the specified manner.

The explosive layers **52** and **54** must, during simultaneous detonation, produce a generaly balance of forces along the resulting detonating fronts in a direction normal to the layers of explosive and, following detonation of the layers of explosive, maintain a pressure differential between the released and expanding gases generated by the detonation of the two layers of explosive below a predetermined amount. Thus, the problem involved in selecting and matching two layers of explosive is twofold. First, the opposed pressures produced along the detonating fronts must be fairly accurately balanced, in a direction normal to the disposition of the explosive layers, if damage or destruction to the metal tubes is to be avoided. It will be understood that if a substantially greater pressure is produced along the detonating front of the explosive layer **54** than is produced along the detonating front of the explosive layer **52**, the metal tubes will be expanded radially outwardly by an excessive amount thereby damaging or destroying said tubes. Conversely, if the pressure produced by the explosive layer **52** along its detonating front exceeds that produced by the explosive layer **54** along its detonating front, the metal tubes will be crushed or driven radially inwardly by an excessive amount thereby damaging or destroying the tubes. Consequently, the amount of pressure generated along the detonating front of the explosive layer disposed adjacent the flyer metal tube must not exceed the amount of pressure generated by the other layer of explosive along its detonating front plus the amount of pressure required to expand excessively or crush the metal tubes.

As previously stated, the selection and matching of the explosive layers requires maintaining below a predetermined amount the pressure differential occuring between the released and expanding gases generated by the detonation of the two explosive layers. Although further discussion of this particular matter is found hereinafter with respect to FIGS. **7** and **8**, it has been found that, following detonation, there is a buildup of pressure within the inner tube **48** which may exceed considerably the pressure existing adjacent the outer surface of the outer tube **46**. Consequently, it has been found that the pressure, due to the released gases, existing within the inner tube **48** must not exceed the pressure, due to the released gases, existing adjacent the outer surface of the outer tube **46** plus the amount of pressure required to expand excessively or destroy the metal tubes.

The explosive layer **52** disposed adjacent the flyer metal tube **46** must produce a loading which, upon detonation thereof, is sufficient to drive the flyer metal tube **46** into collision with the parent metal tube **48** and to cause bonding and welding between said metal tubes. The explosive layer **54** is disposed adjacent the inner surface of the parent metal tube **48** must produce, upon detonation thereof simultaneously with the detonation of the explosive layer **52**, a loading sufficient to preclude movement of the parent metal tube **48** relative to the flyer metal tube in a manner that would prevent welding together of said metal tubes.

Where there is involved a flyer metal tube having a resistance factor of at least approximately $1.5(10)^{-4}$ psi to slightly less than $2.5(10)^{-4}$ psi, i.e., approximately $2.25(10)^{-4}$ psi, it is believed that the explosive layer disposed adjacent the parent metal tube must produce a loading sufficient to stabilize the parent metal tube to prevent movement of same away from the flyer metal tube in a manner or at a rate that prevents welding together of said metal tubes. Where there is involved a flyer metal tube having a resistance factor of approximately $2.5(10)^{-4}$ psi or more, it is believed that the explosive layer disposed adjacent the parent metal tube must produce a loading sufficient to move the parent metal tube toward the flyer metal tube in a manner or at a rate that enables or effects welding together of said metal tubes.

A number of explosives, as follows, have been found to be suitable for use in the method and assembly of this invention:

Explosive	Detonation Velocity (fps)
70% Gelex* dynamite	18,400
40% Extra* dynamite	10,400
Trojamite** "A" dynamite	10,600
Trojamite** "B" dynamite	10,100
Trojamite** "C" dynamite	9,600

*A trademark of E. I. DuPont de Nemours & Co., Wilmington, Delaware.

** A trademark of the Trojan Powder Company, Allentown, Pennsylvania.

The means **56** shown in FIG. **3** is similar to the means **32** shown in FIGS. **1** and **2** and functions in the same manner.

As shown in FIG. **3,** the metal tubes **46** and **48** are unequal in length. The inner metal tube **48** is longer than the outer metal tube **46** and has a part **60** extending axially and outwardly from the end **62** of the shorter metal tube **46.** The assembly **44** includes a restraining means **64** for controlling bulging radially outwardly of a portion of the part **60** of the longer metal tube **48.** The means **64** also insulates the end **62** of the shorter tube **46** against damage from shock waves which are traveling axially along metal tube **46** and which would be reflected from the "free" end **62** thereof except for the use of the means **64** as aforedescribed. As shown, the means **64** has a conically shaped inner surface **64A.** The diameter of surface **64A** disposed adjacent the end **62** of the tube **46** is substantially equal to the inner diameter of the tube **46.** Proceeding in a direction away from the end **62** of tube **46,** the diameter of surface **64A** preferably decreases. Since the longer metal tube **48** extends axially and outwardly from both ends of the shorter metal tube **46,** it will be appreciated that another means **64** is also used adjacent the other end **66** of the metal tube **46.** As the resistance factor of the flyer metal tube increases, the more critical is the requirement that a suitable means be used to prevent radial bulging for the longer of the tubes and to insulate the ends of the shorter tube against damage from shock waves reflected from the free end of the shorter tube. It has been found that failure to use such means as aforedescribed may result in either damage or failure to the part **60** of the longer tube and/or free ends of the shorter tube.

The assembly **44** also shows the use of a metal sleeve **68** and means **70** for supporting the metal sleeve in parallel, spaced-apart relation with respect to the inner surface of the inner metal tube **48.** The use of the metal sleeve **68** has for its purpose to provide a coating of metal, if desired, about the inner surface of the inner metal tube **48.** Thus, through the use of the metal sleeve **68** mounted as shown, it is possible to clad a layer of metal about the inner surface of the inner metal tube **48.**

FIGS. **4–6** show partial longitudinal, cross-sectional views of two assembled metal tubes and their associated matched layers of explosives. In each of these views, the direction of propagation of detonation proceeds from the left to the right. In FIG. **4** is shown a partial assembly **72** comprising an inner metal tube **74,** an outer metal tube **76,** an explosive layer **78** disposed about the inner surface of the inner metal tube **74,** and an explosive layer **80** disposed about the outer surface of the outer metal tube **76.** The explosive layers **78** and **80** are selected and matched as aforedescribed. More specifically, the inner layer of explosive **78** has a substantially uniform thickness while the outer explosive layer **80** has, adjacent the plane of initial detonation, a minimum thickness equal to the thickness of the explosive layer **78** and, proceeding in a direction parallel with the direction of propagation of the explosive layers, the thickness thereof increases to a predetermined maximum.

In FIG. **5** is shown another partial assembly **82** comprising an inner metal tube **74,** an outer metal tube **76,** an explosive layer **84** disposed about the inner surface of the inner metal tube **74,** and an explosive layer **86** disposed about the outer surface of the outer metal tube **76.** The explosive layers **84** and **86** are selected and matched as aforedescribed. The explosive layer **86** has a thickness which, adjacent the plane of initial detonation, has a minimum thickness and, proceeding in a direction parallel with the direction of propagation of the layers of explosive, increases in overall thickness. The explosive layer **84** has a maximum thickness adjacent the plane of initial detonation and, proceeding in a direction parallel with the direction of propagation of the layers of explosive, decreases in overall thickness.

In FIG. **6** is shown another partial assembly **88** comprising an inner metal tube **74,** an outer metal tube **76,** an explosive layer **90** disposed about the inner surface of the inner metal tube **74,** and an explosive layer **92** disposed about the outer surface of the outer metal tube **76.** The explosive layers **90** and **92** are selected and matched as aforedescribed. The explosive layer **92** has a substantially uniform thickness. The explosive layer **90** has a maximum thickness, adjacent the plane of initial detonation, equal to the thickness of the first layer of explosive and, proceeding in a direction parallel with the direction of propagation of the layers of explosive, decreases in overall thickness.

As previously indicated, the explosive layers must be selected and matched one to the other such that following detonation thereof a pressure differential will be maintained below a predetermined amount between the released and expanding gases generated by the detonation of the two layers of explosive. The criteria associated wijth this requirement will be more readily understood by examining FIGS. **7** and **8.** In FIGS. **7A** and **7B** is shown a metal layer **94** having an explosive layer **96** disposed upon the upper surface thereof. Explosive layer **96** is initially detonated at I and the propagation of detonation proceeds from left to right to the termination of detonation T, see FIG. **7C.** As shown in FIG. **7B,** the detonation front is represented by the number **98** while the gases which are being generated as a result of detonation of the explosive layer **96** are being released along the release front **100.** The velocity of the release front **100** is about two-thirds the velocity of the detonation front **98** and, thus, the release front trails or follows behind the detonation front. As indicated in FIG. **7B,** the gases, which are essentially unconfined, are released generally obliquely with respect to the upper surface of the metal layer **94.** As shown in FIG. **7C,** the amount of pressure generated by the detonation of the explosive layer **96** is substantially constant immediately following the point of initiation I until immediately prior to the termination of detonation T. In FIGS. **8A** and **8B** is shown a metal tube **102** substantially filled with a charge of explosive **104.** In FIG. **8B** the detonating front is represented by the number **106** and the release front is represented by the number **108.** Due to the confinement exerted upon the released gases by the cylindrically shaped inner surface of the metal tube **102,** the gases are released in a direction generally parallel to the longitudinal axis of the metal tube **102.** As a result, there exists a substantial pressure to the left of the release front **108** due to the fact that the released gases are confined as aforesaid. Adequate compensation must be made for the buildup of pressure due to the released and expanding gases if damage or failure of the tube **102** is to be prevented. As previously stated, it has been found that the pressure (due to the released and expanding gases) existing within the inner tube must not exceed the pressure (due to the released and expanding gases) existing adjacent the opposed outer surface of the outer tube plus the amount of pressure required to expand excessively or crush the metal tubes. In FIG. **8C** is shown a pressure profile curve **110** representative of the pressure generated by the detonation of the charge of explosive **104.** Since the velocity of the release front **108,** as detonation takes place, is approximately two-thirds that of the velocity of the detonation fron **106,** it has been found that a rapid buildup in pressure occurs somewhere upstream from the termination of detonation T, in some instances about five-sixths of the distance from points I to T. This occurs at the point of intersection of the release front **108** with the reflection of the shock waves which are reflected from the right end of the metal tube **102** back toward the left end. Of course, where the charge of explosive **104** is replaced by an annular layer of explosive (as contrasted to a cylindrically shaped charge that substantially fills the inner tube), there will be less confinement of the released and expanding gases and the amount of pressure buildup will be correspondingly reduced. However, it will be readily appreciated that due to the buildup of pressure occurring from the intersection of the release front and the reflection of the shock waves as aforesaid, it becomes quite important to select and match the layers of explosives and/or the confinement aspects (such as by the use of an annular die) exteriorly of the outer tube in order to compensate for this condition.

In FIG. **9** is shown a cross-sectional view of an article of manufacture produced in accordance with the method of this invention. More specifically, in FIG. **9** is shown an article of manufacture **112** comprising a flyer metal tube **114** bonded to a parent metal tube **116,** said flyer metal tube having, prior to bonding, a resistance factor of at least approximately $2.5(10)^{-4}$ psi. The parent metal tube **116** included in the article of manufacture **112** preferably has, prior to bonding, a resistance factor of at least approximately $1.5(10)^{-4}$ psi. Due to the scale involved, no attempt is made to show the weld or bond between the tubes **114** and **116.**

In FIG. **10** is shown a cross-sectional view of another article of manufacutre produced in accordance with the method of this invention. More specifically, in FIG. **10** is shown an article of manufacture **118** comprising a flyer metal layer **120** bonded to a parent metal layer **122,** said flyer metal layer having, prior to bonding, a resistance factor of at least approximately $2.25(10)^{-4}$ psi. The parent metal layer **122** included in the article of manufacture **118** preferably has, prior to bonding, a resistance factor of at least approximately $1.5(10)^{-4}$ psi. Due to the scale involved, no attempt is made to show the weld or bond between the layers **120** and **122.**

In view of all of the foregoing, it will be readily appreciated that a new and novel method and assembly for explosively welding together metal layers and tubes has been described as well as a new and novel article produced by said method and assembly. The method and assembly of this invention permits the welding together of relatively thick metal layers or tubes through the use of a pair of layers of explosives. Through the practice of the method and assembly of the subject invention, flyer metal tubes having a resistance factor in excess of $10(10)^{-4}$ psi have been explosively welded to a parent metal tube. Not only does the method and assembly of this invention permit the welding together of relatively thick metal layers and tubes but also it permits same to be done in an economical, safe and rapid manner. From a position of hindsight, it now appears that the knowledge and information gained from explosively bonding together flat metal plates can be translated to metal tubes and the like on a somewhat logical basis although such was not at all apparent until a considerable amount of inventive development had been done in this area.

It is to be understood that this invention is not limited to the exact methods, assemblies and articles of manufacture shown and described as various other forms and modifications will be apparent to those skilled in the art. For example, it will be understood that acceptable results will be obtained even though the opposed surfaces of the metal layers and tubes are not truly disposed in a parallel manner since quite acceptable results can be obtained even though true parallelism is not maintained. Additionally, it is to be understood that the terms metal layers and metal tubes may also encompass other metal configurations such as conically shaped members, and similarly configured metal layers which may have arcuately shaped, mating boss and recess portions formed in a portion thereof.

We claim:

1. A method of welding a flyer metal tube to a parent metal tube comprising:

a. assembling a flyer metal tube and a parent metal tube in concentric disposition with the outer surface of one of said tubes being disposed in parallel, spaced-apart relation with the inner surface of the other metal tube so that the distance separating said opposed surfaces equals at least approximately 0.001 inch; b. selecting and matching two layers of explosive which will, during simultaneous detonation thereof, produce a general balance of forces along the resulting detonating fronts in a direction normal to said layers of explosive and, following detonation of the layers of explosive, maintain a pressure differential between the released and expanding gases generated by the detonation of the two layers of explosive below a predetermined amount;

c. placing a first one of said layers of explosive about the outer surface of the outer metal tube and placing a second one of said layers of explosive about the inner surface of the inner metal tube; and

d. simultaneously detonating said layers of explosive along a common, generally planar front so that the detonation is propagated parallel to the longitudinal axis of said tubes; the loading of said layer of explosive disposed adjacent a surface of said flyer metal tube being at least sufficient to produce, upon collision of the metal tubes, a pressure greater than the elastic limit of the metal tube in the assembly having the higher elastic limit and sufficient to cause bonding between said metal tubes; the loading of the layer of explosive disposed adjacent a surface of said parent metal tube being sufficient, upon collision with said flyer metal tube, to preclude movement of the parent metal tube relative to the flyer metal tube in a manner that would prevent welding together of said metal tubes.

2. A method as described in claim **1** in which the step of assembling includes assembling a flyer metal tube having a resistance factor of at least approximately $1.5(10)^{-4}$ psi in parallel, spaced-apart relation with the parent metal tube so that the distance separating said metal tubes equals at least approximately 0.05 times the thickness of the flyer metal tube.

3. A method as described in claim **1** in which the step of assembling includes assembling a flyer metal tube having a resistance factor of at least approximately $2.5(10)^{-4}$ psi in parallel, the spaced-apart relation with the parent metal tube so that the distance separating said metal tubes equals at least approximately 0.1 times the thickness of the flyer metal tube.

4. A method as described in claim **1** in which the step of assembling includes assembling together two tubes of unequal length with one of said tubes being disposed concentrically within the other of said tubes, and restraining at least a portion of the longer tube disposed adjacent and axially outwardly from one end of said shorter tube, during detonation of said layers of explosive, to control the bulging radially outwardly thereof.

5. A method as described in claim **4** in which the step of assembling includes assembling a flyer metal tube having a resistance factor of at least approximately $2.5(10)^{-4}$ psi in parallel, spaced apart relation with the parent metal tube so that the distance separating said metal tubes equals at least approximately 0.1 times the thickness of the flyer metal tube.

6. A method as described in claim **1** in which the step of assembling includes assembling together two tubes of unequal lengths with one of said tubes being disposed concentrically within the other of said tubes, and insulating at least one of the ends of said shorter tube against damage from shock waves reflected from said end of said shorter tube.

7. A method as described in claim **6** in which the step of assembling includes assembling a flyer metal tube having a resistance factor of at least approximately $1.5(10)^{-4}$ psi in parallel, spaced-apart relation with the parent metal tube so that the distance separating said metal tubes equals at least approximately 0.05 times the thickness of the flyer metal tube.

8. A method as described in claim **1** in which the step of assembling includes assembling together two tubes of unequal lengths with one of said tubes being disposed concentrically within the other of said tubes, and insulating the ends of said shorter tube against damage from shock waves reflected from said ends of said shorter tube.

9. A method as described in claim **8** in which the step of assembling includes assembling a flyer metal tube having a resistance factor of at least approximately $2.5(10)^{-4}$ psi in parallel, spaced-apart relation with the parent metal tube so that the distance separating said metal tubes equals at least approximately 0.1 times the thickness of the flyer metal tube.

10. A method as described in claim **1** in which the step of selecting and matching two layers of explosive includes selecting a first layer of explosive of substantially uniform thickness and selecting a second layer of explosive which, adjacent the plane of initial detonation, has a maximum thickness equal to the thickness of the first layer of explosive and, proceeding in a direction parallel with the direction of propagation of the layers of explosive, has a reduced thickness.

11. A method as described in claim **1** in which the step of selecting and matching two layers of explosive includes selecting a second layer of explosive of substantially uniform thickness and selecting a first layer of explosive which, adjacent the plane of initial detonation, has a minimum thickness equal to the thickness of the second layer of explosive and, proceeding in a direction parallel with the direction of propagation of the layers of explosive, has an increased thickness.

12. A method as described in claim **1** in which the step of selecting and matching two layers of explosive includes selecting a first layer of explosive having a thickness which, adjacent the plane of initial detonation, has a minimum thickness and, proceeding in a direction parallel with the direction of propagation of the layers of explosive, increases in overall thickness; and selecting a second layer of explosive which, adjacent the plane of initial detonation, has a maximum thickness and, proceeding in a direction parallel with the direction of propagation of the layers of explosive, has a reduced thickness.

* * * * *