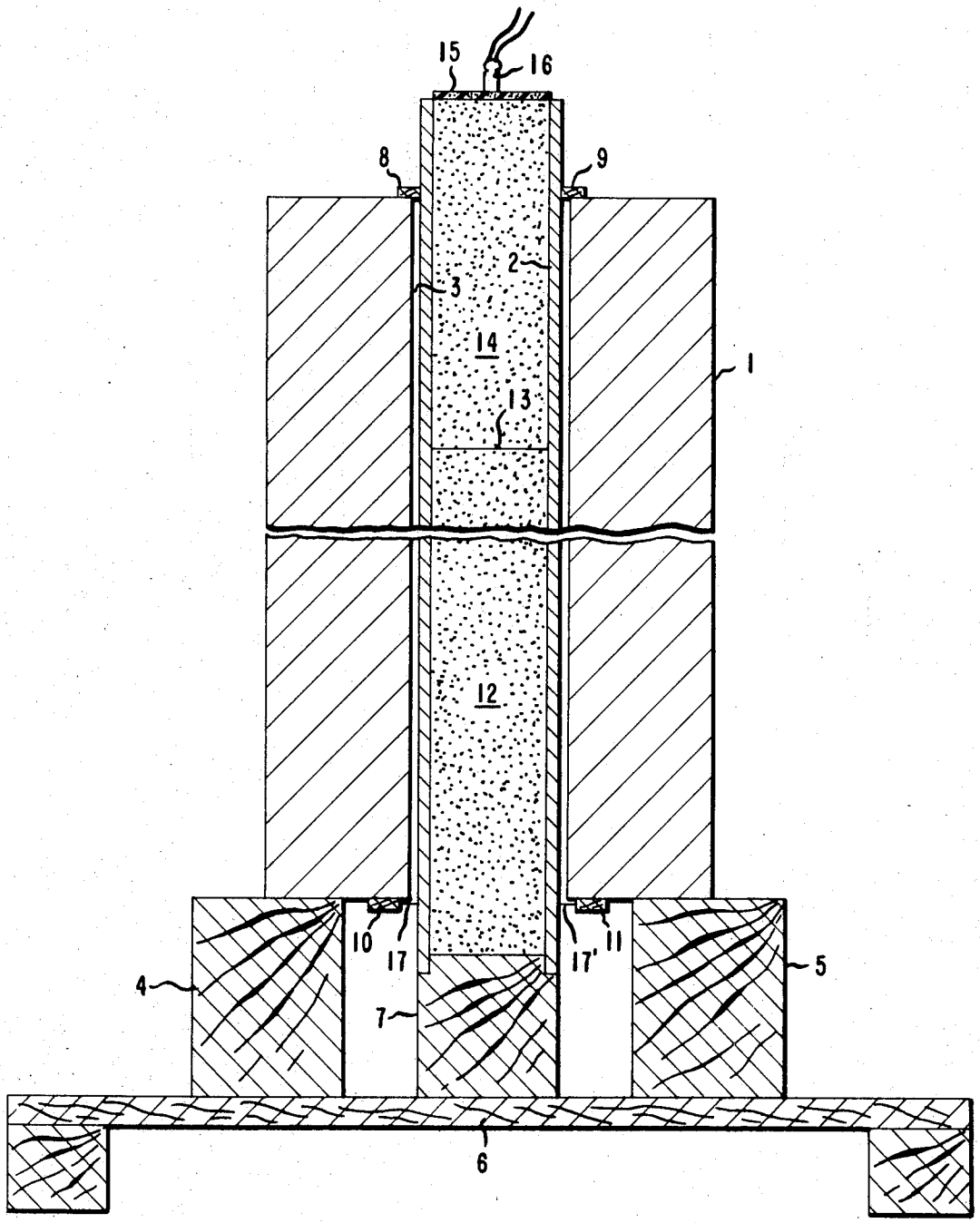
Feb. 16, 1971 J. BUCHWALD 3,562,897

EXPLOSION BONDING OF TUBES

Filed Nov. 27, 1968




*INVENTOR*
JOSEPH BUCHWALD

BY L. A. Burrows Jr

*ATTORNEY*

United States Patent Office 3,562,897 Patented Feb. 16, 1971



3,562,897

# EXPLOSION BONDING OF TUBES

Joseph Buchwald, Philadelphia, Pa., assignor to E. I. du Pont de Nemours and Company, Wilmington, Del., a corporation of Delaware

Continuation-in-part of application Ser. No. 740,671, June 27, 1968. This application Nov. 27, 1968, Ser. No. 786,533

Int. Cl. B23k 21/00

U.S. Cl. 29—470.1 11 Claims

## ABSTRACT OF THE DISCLOSURE

In the process for metallurgically bonding a lining tube to the inside surface of a second tube by propelling the lining tube into a progressive collision with the second tube by detonating an explosive charge within the lining tube, improved bonding at the initially colliding tube ends is obtained by employing, at the initiation end of the explosive charge, an explosive which has a higher detonation velocity and/or explosive loading than the explosive which extends through the remaining length of the lining tube.

## CROSS-REFERENCE TO RELATED APPLICATION

This application is a continuation-in-part of my prior copending application Ser. No. 740,671, filed June 27, 1968.

## BACKGROUND OF THE INVENTION

This invention relates to an explosion-bonding process for producing a metallurgical bond between adjacent surfaces of coaxial metal tubes.

The past few years have witnessed the development and commercial acceptance of metallurgically bonded clad products made by certain explosion-bonding processes. Briefly, such processes involve spacing metal layers from each other, placing a layer of detonating explosive adjacent to the outer surface of at least one of the metal layers, and detonating the explosive in a manner such that the metal layers are caused to collide progressively at a velocity which is below 120% of the sonic velocity of the metal in the system having the highest sonic velocity. See, for example, U.S. Pats. 3,137,937; 3,140,537; and 3,397,444, and copending, coassigned U.S. patent application Ser. No. 965,506, filed Jan. 3, 1968, and now abandoned in favor of continuation-in-part application Ser. No. 756,704, filed July 30, 1968. These copending applications and U.S. 3,397,444 describe improved methods of carrying out the processes of the other aforementioned patents, wherein the metal layers are caused to collide progressively at a velocity within the range where relatively small amounts of solidified melt are produced at the resulting interface, with collision velocities that give low-melt-content wavy bonds being particularly preferred. Clad products having these type bond zones have improved strength and ductility.

Often it is desirable to explosion-bond the outside surface of one tubular metal layer (the lining tube) to the inside surface of a second, and usually thicker, tubular layer of different metal. In such cases, the lining tube, whose outer diameter is somewhat smaller than the inner diameter of the second tube, is positioned substantially coaxially inside the second tube; the explosive is positioned substantially coaxially within the lining tube and over the length thereof to be bonded to the second tube; and the explosive is initiated at one end in such a manner that detonation is propagated in a direction substantially parallel to the tube's axis. In this "inside-out" tube bonding technique, the explosive charge can



occupy a portion of the inner tube's diameter or it can span the tube, depending on the explosive load required, the density of the explosive used, and the inner diameter of the tube. With larger inner diameters, the tube may not be spanned and the explosive can be in the form of an axially disposed solid linear charge spaced from the tube wall, with or without an intervening medium between charge and wall; or a tubular layer of explosive can be positioned coaxially within the metal tube and contacting or spaced from the tube wall.

As previously indicated, explosion bonding of metal layers such as tubes preferably is carried out at a collision velocity which results in the production of relatively small amounts of solidified melt at the bond zone, with collision velocities that produce low-melt-content wavy bonds being particularly preferred. Examples of such wavy bonds are those which contain, by interfacial area, at least about 70% direct metal-to-metal bond, the remaining bond being periodically spaced regions of solidified melt that bond the parent metals and are separated from each other by areas of such direct bonding. Although the collision velocities, hence detonation velocities, required to give preferred type bond zones depend on the particular tubular layers being bonded, they generally will be from about 1800 meters per second to about 65% of the sonic velocity of the metal in the system having the highest sonic velocity. It has been found, however, when inside-out tube bonding with an explosive having a detonation velocity less than about 3000 meters per second, that an amount of explosive which gives good wavy bonding over the majority of the tubes' interfacial area often does not give the desired type bonding at the initially colliding ends of the tubes, i.e., the ends where the explosive is initiated. Apparently because the explosive at the initiation end is unconfined, it generates, over about the first 2 to 10 inches of tube length, a substantially lower pressure impulse than the remainder of the charge, and therefore fails to establish the collision conditions required to give the desired bonding. (The term "pressure impulse" is used in the conventional sense to denote the integral of P over the interval of time, $t$; P being the pressure generated by the explosive, and $t$ being the interval of time over which the explosively generated pressure accelerates the object in question. As applied in the present case, $t$ is the interval of time over which the inner tube is accelerated prior to its collision with the outer tube.) It is known that, other conditions being equal, pressure impulse determines the velocity of the inner tube, hence the angle it forms with the second tube, at the moment of collision, and it is this collision angle that determines the type of bonding produced at a given collision (detonation) velocity.

From the foregoing, it is seen that there is need for an inside-out tube bonding process employing an explosive charge that will produce a low-melt bond zone with a minimum area of poor bonding at the initially colliding ends of coaxial tubular layers.

## SUMMARY OF THE INVENTION

This invention provides an improved process for metallurgically bonding the outside wall or surface of a lining or cladding tube to the inside surface of a second tube of different metal by means of the progressive collision of the tube surfaces effected by the detonation of an explosive positioned substantially coaxially within the lining tube over the length thereof to be bonded to the second tube. In particular, an improved degree of low-melt-content bonding is obtained by employing as the explosive (a) a first explosive component having a detonation velocity in the range of about from 1800 to 3000 meters per second and extending from one end of the lining tube to within about from two to ten inches from its opposite end, and (b) a second explosive component extending from

the first component to said opposite end of the lining tube and having a detonation velocity at least as high as the first component's but less than about 3500 meters per second, the detonation velocity and loading of the second component being sufficient, in combination, to generate a substantially higher pressure impulse than the first component under the same conditions, i.e., if similarly located and initiated in the same manner; and initiating the outside end of the second explosive component so that its detonation propagates in a direction substantially parallel to the tubes' axis, and hence causes them to collide at a rate substantially equal to its detonation velocity.

The "loading" of the second component is the weight of active explosive ingredient it contains per unit (e.g., square inch) of its exterior cylindrical surface area, "exterior" meaning farthest from its axis of rotation.

The terms "tube" and "tubular metal body" as used denote a metal body having a substantially cylindrical passage therethrough and includes, e.g., elongated cylinders ranging from thin-walled tubes to thick-walled pipes, such as those employed as nozzles on reaction vessels. All tubes, with the optional exception of the outermost tube, are substantially cylindrical. The shape of the outermost tube is immaterial provided it contains a substantially cylindrical passage or bore that is to be clad with a lining tube. Thus, e.g., the outermost tube can be a pierced billet of square or rectangular cross-section having one or more substantially cylindrical bores which are to be simultaneously or sequentially clad with lining tubes. Such clad billets are extruded into tubular products of various shapes. The "lining" or "inner" tube refers to the innermost tube and is the tube within which the explosive is placed and which is propelled by the detonation so as to cause it to collide with the second tube.

The "opposite end" of the lining tube, or the location to be considered in defining the length of the second explosive component, denotes an effective end, or a surface lying in the same plane as the corresponding end of the second tube, i.e., the location where the tube surfaces first collide. For reasons which will be explained later, the true ends of the lining tube may project beyond the ends of the second tube, and the explosive may extend to the true ends. However, these portions of the lining tube and the explosive are not considered in the definition of the parameters employed in the present process. In the same sense, the "outside end" of the second explosive component is a surface lying in the same plane as the end of the second tube.

## BRIEF DESCRIPTION OF THE DRAWING

The accompanying drawing illustrates a vertical cross-sectional view of an assembly which can be used to carry out a preferred process of the present invention.

## DETAILED DESCRIPTION OF THE INVENTION

According to the present process, two or more tubes to be bonded are positioned coaxially in a nesting arrangement with a standoff spacing between them and the innermost tube is propelled into a progressive collision with the surrounding tube by an explosive charge which has a higher detonation velocity and/or explosive loading over a prescribed distance at its initiation and then it does through the remainder of its length within the innermost tube. It will be understood that a number of coaxial inner tubes can be caused to collide with a surrounding outer tube by detonating an explosive in the innermost tube so as to form a multilayered tubular composite. However, for ease of description, a two-tube collision will be described, and the tubes referred to as inner (or lining) tube and the second or surrounding tube.

The tube which is to serve as the lining tube is positioned coaxially within a tube to be lined so that a substantially uniform standoff distance is provided between the facing surfaces of the tubes. The explosive charge



components are positioned within the lining tube. They are cylindrical in shape, i.e., their surface which contacts or faces the wall of the lining tube substantially conforms to the wall surface. With large-diameter lining tubes, the charge components may be solid or hollow cylinders, in contact with or spaced from the lining tube wall. With smaller-diameter tubes, the charge components will most likely be solid cylinders and in contact with the tube wall or with a thin protective layer or coating, e.g., of plastic, which may be applied to the tube wall in certain instances. The charge components abut so that the charge is continuous. Any explosive which has the requisite detonation velocity may be used, and solid, liquid, as well as semi-solid explosives are suitable. A solid explosive may be self-supporting, e.g., a flexible sheet explosive in the form of a rod or tubular layer, or granular. For loading into long tubes of relatively small diameter, readily pourable compositions, e.g., free-flowing granular compositions, are preferred. The two-component cylindrical charge extends throughout the length of the tube where bonding is desired, and usually substantially fills the tube when the inner diameter is small.

The first component of the explosive charge usually extends from one end of the inner tube to a position about from 2 to 10 inches short of the tube's opposite end. This component detonates at a velocity of about from 1800 to 3000 meters per second. For any given metals system, detonation velocity and explosive loading normally will be chosen to give a wavy metallurgical bond comprising, by area, at least about 70%, and preferably at least about 90%, direct metal-to-metal bonding, the remainder being periodically spaced regions of solidified melt that bond the parent metals and are separated from each other by areas of such direct bonding. For this purpose, the detonation velocity preferably will not exceed about 2800 meters per second. Detonation velocities below about 1800 meters per second generally are not employed because of the possibility they will not generate sufficient pressure impulse to give optimum bonding between the surrounding portions of the tubular layers.

The second explosive component extends from the first component to the opposite end of the lining tube, i.e., it extends the remaining length of the inner tube that is to be bonded to the surrounding tube. The purpose of the second component is to provide substantially the same bond morphology over about the initial 2 to 10 inches of tube length, i.e., at the initiation end, that is obtained over the remaining length of the tubes by using the first explosive component. As previously explained, such bonding does not occur at the initiation end of the tubes when the first explosive component extends the full length of the tube, the reason being that it generates insufficient pressure impulse, as measured by the integral of P over the interval of time $t$; P being the pressure generated by the explosive, and $t$ being the interval of time over which the explosively generated pressure accelerates the tube prior to the collision. Consequently, the second explosive component must generate a substantially higher pressure impulse than the first component under the same conditions. By this it is meant that the pressure impulse is substantially greater than would be produced if an explosive charge of the same composition and loading as the first component replaced the second component on an equal volume basis. Thus, the second component at the initiation end of the tubes makes up for a deficiency of impulse which would prevail there with the first component. Preferably, when in their respective positions in the lining tube, the two explosive components generate substantially the same pressure impulses.

Since detonation pressure P increases with increasing detonation velocity, and the time over which P falls to a specified fraction of its peak value increases with increasing explosive loading at a given detonation velocity, it is seen that the substantially greater pressure impulse required for the second component can be obtained by

using an explosive having a detonation velocity, explosive loading or both, higher than the corresponding values for the first explosive component. The detonation velocity alone can be higher with the explosive loading of the second component about the same as that of the first, or the explosive loading alone can be higher with the same detonation velocity. The latter will not often be the case, however, since an increase in loading often will be accompanied by an increase in detonation velocity, e.g., when loading is increased by using a higher-density explosive. Also, in the event it is practical to increase the loading by increasing the total volume of the second component, the resulting larger diameter may cause the detonation velocity of the second component to be higher than that of the first unless an explosive composition can be employed which detonates at a lower velocity than the first in the same diameter.

The magnitude of the increase in pressure impulse required in any particular case, and therefore the differential in detonation velocity and/or explosive loading required between the charge components, depends, of course, on the magnitude of the deficiency in impulse at the initiation end of the tube assembly. The lower the explosive-to-lining metal weight ratio and the detonation velocity of the first component, and the smaller the standoff between metal tubes, the greater the deficiency in impulse at the initiation end is likely to be and accordingly the greater the increase in impulse which will be needed. As a rule, the pressure impulse will be increased sufficiently if the second component has a detonation velocity at least about 500 meters per second higher than the first component. An explosive loading for the second component at least about 25% higher than that of the first is the minimum increase that ordinarily will be employed when the detonation velocity remains constant or is increased solely by the increase in loading. To avoid bonds containing substantial amounts of solidified melt, the detonation velocity of the second component should not exceed about 3500 meters per second. Excessive increases in impulse should be avoided to prevent tube distortion and the formation of large amounts of solidified melt. Depending on the impulse deficiency, pressure impulse increases generally up to about 75% are employed.

Within the foregoing limits the specific detonation velocity of each component depends on such factors as the yield strength of the lining metal and the ratio of explosive loading to lining metal weight ($E/M$ ratio), velocities near the higher end of each range being employed with higher-yield-strength metals, lower $E/M$ ratios, and systems which do not form brittle intermetallic compounds. As a rule, the lowest velocity that will assure the desired bonding will be employed.

Typical explosive compositions useful in the present process are described in aforementioned U.S. Pat. 3,397,444 and copending U.S. patent applications Ser. Nos. 695,506 and 756,704, the disclosures of which are incorporated herein by reference. To achieve different detonation velocities, the two components of the explosive charge may be two explosives having different compositions, or they may be the same explosive composition packed to different densities (this also results in different loadings), or having different particle sizes. Different loadings also can be provided by using two different diameters, which may also result in a difference in detonation velocities, or by using a hollow cylindrical charge as the first charge component and a solid cylindrical charge (coaxial with the first) as the second component. Where a hollow cylindrical charge is employed as the first component, it may be advantageous for the second component to be a hollow charge having a conical cavity with its apex positioned substantially coaxial with the tubes and at their initiation end and with the base of the cone having about the same diameter as the inner diameter of the first component.

The higher-impulse explosive component usually extends into the lining tube for a distance of about from two to ten inches from one end, shorter distances resulting in a possible unbonded portion, and longer distances giving a higher-melt-bond-zone portion. Within the specified range of distances, the lower the detonation velocity of the second component, the longer its length will usually be. Preferably, the second component does not extend into the lining tube for more than about eight inches from its effective end, nor more than about one-third of its length. Although it is not intended that the invention be limited by theoretical considerations, it is believed that when inside-out bonding long tubes, the results obtained are dependent on the different conditions of confinement of the explosive existing at the tube ends as contrasted to the more central sections, the higher-pressure-impulse explosive being needed until the confinement condition prevailing within the tube becomes effective. Thus, it is with longer tubes, e.g., tubes longer than about 10 inches, that the present invention finds its greatest advantage. With shorter tubes, e.g., 5–10 inch long tubes, the difference in confinement is not as pronounced, and the explosive producing the higher pressure impulse can be used throughout the length when required, although use of the dual-component charge as in the present process is advantageous in that it gives greater assurance of a low-melt bond zone throughout. With these shorter tubes, the maximum length of the second component is correspondingly shorter, generally about 4 inches, shorter lengths being employed with shorter tubes.

In order to achieve uniform bonding, the adjacent surfaces of the tubes should collide substantially simultaneously in any cross-sectional plane perpendicular to their axis, and the magnitude of the pressure generated by the collision shoud be substantially uniform throughout the collision region. For this reason, the explosive charge is initiated at its entire outside end surface substantially simultaneously, i.e., the second component is surface-initiated at its outside end. A convenient way of surface-initiating the charge is by means of a thin circular disc of a cap-sensitive, high-velocity sheet explosive positioned at the end of the charge in contact therewith and initiated at its center by means of a blasting cap. Alternatively, a plane wave initiator such as one of those described in U.S. Pats. 2,887,052; 2,999,458; and 3,016,831 may be employed.

For a more complete understanding of the invention, reference is now made to the drawing in which **1** is a thick-walled metal tube to the inside wall of which a thin metal linear is to be metallurgically bonded to form a composite tube. Metal lining tube **2** having approximately the desired wall thickness is positioned coaxially within tube **1**. The inner diameter and wall thickness of tube **2** are such as to provide a desired standoff between the facing surfaces of tubes **1** and **2**, and the length of tube **2** exceeds that of tube **1** so that it projects from the bore in tube **1** at both ends for a distance, for example, of at least about one inch. Tube **1** rests on wooden blocks **4** and **5** which in turn are supported on wooden pallet assembly **6**. Tube **2** is maintained at its desired level with respect to tube **1** by means of cylindrical wood support **7**, which also is supported on pallet assemby **6**. Support **7** can be taped in place, if desired. Standoff **3** is maintained by four small wooden blocks glued 90° apart to each end of tube **1**. At the top end of the vertical assembly, the standoff blocks, two of which, **8** and **9**, are shown, are seated against the outer surface of tube **2**. At the bottom end, the standoff blocks, two of which, **10** and **11**, are shown, are set back from the inner wall of tube **1**, and tube **2** is held in place by means of small nails **17** and **17'**, one of which is driven into each standoff block and seated against the outer surface of tube **2**. This permits the unobstructed egress of gases and jetted material from the collision region.

A granular explosive **12** is introduced into tube **2** and packed to a density such as to provide the desired loading and a detonation velocity in the range specified above for

the first component of the charge. Explosive **12** extends to line **13**, which is about from two to ten inches from the top of tube **1**. Loaded directly on top of explosive **12** and extending to the top of tube **2** is granular explosive **14** which is packed to a higher density and/or provides a higher detonation velocity, as specified above for the second component of the charge. A thin circular disc of a high-detonation-velocity explosive **15** is in contact with the outer edge of explosive component **14**, and a blasting cap **16** is affixed to the center of disc **15**. Detonation of disc **15** by actuation of blasting cap **16** initiates explosive **14**, thereby propelling tube **2** outwardly. When the detonation reaches the plane in which the upper end of tube **1** lies, the tubes begin to collide, and the collision progresses through the initial two to ten inches of axial length at a rate substantially equal to the detonation velocity of explosive **14**. Beginning at **13**, the collision velocity will be substantially the same as the detonation velocity of explosive **12**.

The impact angle produced on collision has an effect on the geometry of the bond zone, i.e., on the amplitude of the waves in the wavy interface produced under the preferred conditions described in the aforementioned copending patent applications, wave size increasing with increased impact angle. The impact angle increases as the explosive-to-lining-metal weight (*E/M*) ratio and the ratio of standoff between facing tube surfaces to lining metal weight (*S/M* ratio) increase. Thus, for a given lining tube, the impact angle can be increased by increasing the explosive loading (e.g., by increasing the packing density of a given explosive composition) and/or the standoff. Generally, a standoff of at least about 0.150 inch is required to achieve a proper collision angle when *E/M* is about 1.0 or less and lower-impulse, low-detonation-velocity explosives are employed. In selecting a standoff, consideration is given to the thinning of the lining tube occurring as a result of the expansion of its diameter. For a given system, increasing the standoff results in an increase in thinning. Since, under most circumstances, little variation is desired in the thickness of the lining metal before and after bonding, standoffs at the low end of the operable range for the system in question are preferred. Standoffs up to the maximum which corresponds to the maximum percent elongation of the lining metal without fracture under dynamic loading can be used, however, if the resulting change in tube thickness is acceptable. With small-diameter tubes, large standoffs are undesirable since, for a given lining thickness and inner diameter of the outer tube, the necessarily smaller inner diameter of the lining tube would lower the explosive loading possible. Also, to achieve a given range of impact angles, a lower range of standoffs usually is employed for thinner liners with a given explosive load, i.e., *S/M* is decreased as *E/M* increases.

The present process finds its greatest utility in tube bonding situations where *E/M* is low, e.g., less than about 1.0. Ratios as low as about 0.2 can be employed. As specified above, the lower this ratio, the higher the detonation velocities of the explosive components and/or the larger the standoff in order to compensate for the lower impulse obtained. Since lower *E/M* ratios are dictated by space limitations when the inner diameter of the lining tube is smaller, the present process is most advantageous when used to bond lining tubes of small inner diameter, e.g., about four inches or less. However, the process can be employed to improve the impulse at the initiation end even with larger-diameter tubes, where a low *E/M* ratio is not required by a volume restriction.

Although not critical to the present process, extension of the lining tube so that it projects beyond the outer tube at the end of the assembly where the explosive is initiated, or at both ends of the assembly, and providing explosive substantially throughout the entire length of the lining tube, allows more complete bonding in the region where the collision begins and ends. A one- or two-inch extension is effective in most cases. In some metal systems, it may be desirable to notch the lining tube circumferentially at the outside in line with the outer tube edge to cause the extension(s) to shear cleanly. Where the assurance of a completely bonded product is necessary, it may be desirable to weld an annular extension also to the end of the outer tube and to initiate the collision at the extension pieces so that the desired conditions are fully established by the time the collision reaches the tubes to be bonded.

While the position of the bonding assembly per se has no effect on the process, it is preferred to use a vertical arrangement, such as is depicted in the drawing, when the explosive is a granular material. Uniformity of explosive loading, which is a prerequisite for uniformity of bond quality, is difficult to achieve with granular explosives in a horizontal arrangement. The tube assembly can be maintained in position by any means available, the combination of wooden blocks and pallet shown in the drawing being an especially convenient one. An open construction beneath the outer tube in the path of the standoff is desirable to permit easy egress of jetted material and gases.

The means employed to maintain the standoff is not critical to the present process provided it does not interfere with the collision of the layers or introduce into the bond zone a material which deleteriously affects the properties of the bonded composite. While any of the means heretofore described, e.g., in U.S. Pat. 3,360,848, may be employed, support means between the surfaces are not required in the preferred vertical arrangement since the standoff-maintaining elements are not required to support any significant compressive load. Blocks such as those depicted in the drawing, extending from the outer tube edge to the outer wall of the inner tube may be used, as well as cardboard or plywood collars around the inner tube, etc. The standoff-maintaining elements should not block egress of material from the standoff spacing, however.

The present process is employed to line tubes of any required length, usually at least about ten inches long to make effective use of the dual component feature. There is no maximum length of tubes which may be employed beyond that imposed by problems associated with the handling and assembling of long tubes, especially heavy-wall outer tubes. In some systems, e.g., when the outer tube wall is thin and/or the metals are extremely ductile, it may be desirable to provide confinement around the tube assembly to prevent deformation. Types of confinement which might be employed include metal castings, metal rings, split dies, metal straps, reinforced concrete, etc. However, when the wall of the outer tube is relatively thick, e.g., about two inches or more, additional confinement usually is not required.

The process of this invention is applicable to the bonding of a wide variety of metals including, for example, iron, titanium, zirconium, aluminum, columbium, tantalum, nickel, and copper, as well as alloys based on one or more of these metals but additionally containing minor amounts of alloying elements. The lining metal should be sufficiently ductile (e.g., percent elongation of at least about 25) so that the lining tube can undergo expansion without cracking or fracture.

The following examples serve to illustrate specific embodiments of the process of this invention. However, they will be understood to be illustrative only and not as limiting the invention in any manner.

## EXAMPLE 1

A Type 347 stainless steel tube having a length of 35 inches, an outer diameter of 2.875 inches, and a wall thickness of 0.250 inch is positioned coaxially within a cavity in a vertically positioned cylindrical A–105 steel forged nozzle having a length of 30 inches, an outer diameter of 9 inches, and an inner diameter of 3.250

inches in a manner such that the inner tube projects 3 inches from the top of the nozzle and 2 inches from the bottom, and there is about a 0.200 inch standoff between the facing surfaces of the tube and nozzle. The support assembly, tube closure means, and standoff-maintaining means specified above in the description of the drawing are employed. A granular explosive composition consisting, by weight, of 36% ammonium nitrate, 9% trinitrotoluene, and 55% sodium chloride (i.e., a uniform mixture of 45% grained 80/20 amatol and 55% table salt) is poured incrementally into the tube to a height of 24 inches, i.e., 8 inches from the top of the nozzle, or 11 inches from the top of the tube, the explosive being tamped heavily after about each 1–2 inch addition. The particle size of the ammonium nitrate used to make the amatol (hence the particle size of the amatol) and the density of the explosive composition are such that the mixture detonates at a velocity of 2650 meters per second. Then the remainder of the tube is filled in the same manner with explosive of the same composition but having amatol prepared from a finer ammonium nitrate and therefore detonating at a velocity of 3350 meters per second. The weight of explosive used is such as to give an *F/M* ratio of 0.326. The explosive is covered with a 0.1-inch-thick circular disc of a flexible explosive composition of U.S. Pat. 2,999,743 detonating at a velocity of about 7200 meters per second. The diameter of the disc is equal to the inner diameter of the inner tube. An electric blasting cap is positioned at the center of the disc. The blasting cap is actuated to initiate the explosive disc and, in turn, the explosive in the tube. The projecting ends of the lining tube are sheared off. In the composite obtained, the stainless steel lining tube is metallurgically bonded to the nozzle over 98% of the interfacial area by a wavy bond containing at least about 90% direct metal-to-metal bond.

Substantially the same results are obtained when the wall thickness of the liner is 0.276 inch, and the other parameters remain the same.

## EXAMPLE 2

The procedure described in Example 1 is repeated with the exception that the lining tube is 20 inches long; the nozzle is 15 inches long; the lower-velocity composition extends for a distance of 13 inches, i.e., to within 4 inches from the top of the nozzle (weight: 1 lb., 13 oz.) and detonates at a velocity of 2150 meters per second; and the higher-velocity composition occupies the upper 7 inches of the tube (weight: 1 lb., 6 oz.) and detonates at a velocity of 3150 meters per second. Substantially complete bonding with the desired bond morphology is obtained.

## EXAMPLE 3

The procedure of Example 1 is repeated with the following exceptions:

(a) The nozzle is 15 inches long and the lining tube 20 inches long.

(b) The explosive composition used in the top portion of the tube in Example 1 (containing finer ammonium nitrate) is used throughout, the powder being poured loosely into the tube without tamping to a height of 13 inches, i.e., to within 4 inches from the top of the nozzle, and tamped into the tube, as described in Example 1, for the remaining 7 inches. The tamped composition detonates at a velocity of 3130 meters per second and the untamped composition at 2350 meters per second. The total weight of explosive is about 4 pounds.

(c) A 1-inch-high low-carbon-steel ring having a 7-inch outer diameter and 3.250-inch inner diameter is positioned coaxially around the top end of the inner tube and welded to the top end of the nozzle to provide a one-inch extension on the nozzle.

The lined nozzle obtained is metallurgically bonded over substantially the entire interface with the preferred type of bond zone.



## EXAMPLE 4

A 2-inch inner diameter lined nozzle is made by the procedure described in Example 1 with the following variations:

(a) The nozzle is made of HD4142 steel, is 20 inches long, and has an outer diameter of 5.75 inches and an inner diameter of 2.45 inches (1.65-inch wall). The liner is 25 inches long and has an outer diameter of 2.125 inches and an inner diameter of 1.75 inches (0.187-inch wall).

(b) The standoff is 0.160 inch.

(c) The higher-velocity explosive detonates at 3300 meters per second and occupies the upper 8 inches of the tube (i.e., 5 inches of the tube measured from the top of the nozzle).

Good bonding is achieved over substantially the entire interface.

## EXAMPLE 5

The procedure described in Example 1 is employed to metallurgically bond a Grade II titanium liner having a 2.875-inch outer diameter and 0.203-inch wall thickness to a 15-inch-long A–105 steel nozzle having a 9-inch outer diameter and 3.250-inch inner diameter. The explosive composition in the bottom 12 inches of the 20-inch-long lining tube detonates at a velocity of 2150 meters per second, and that in the upper 8 inches (5 inches measured from the nozzle top) at a velocity of 2950 meters per second. The weight of the lower charge is 2 lb., 14 oz.; that of the upper charge is 1 lb., 11 oz. Bonding is complete with the exception of about 0.5 inch on each end.

## EXAMPLE 6

The procedure described in Example 5 is followed to produce a 3-inch inner diameter steel nozzle lined with "Inconel" 600. A single explosive composition is employed throughout as described in Example 3, the tamped upper portion in this case detonating at a velocity of 3150 meters per second and being 7 inches long (4 inches from nozzle top). An extension ring on the nozzle, as is described in Example 3, is employed. Complete bonding is obtained.

What is claimed is:

**1.** In a process for metallurgically bonding a metal lining tube to the inside surface of a second tube of different metal by progressively propelling the lining tube against said inside surface by detonating an explosive positioned substantially coaxially within the lining tube over the length thereof to be bonded to the second tube, the improvement comprising employing as the explosive (a) a first explosive component which has a detonation velocity of about from 1800 to 3000 meters per second and extends from one end of the lining tube to within about from two ten inches from its opposite end, and (b) a second explosive component which extends from the first component to said opposite end of the lining tube and has a detonation velocity at least as high as the first component's but less than about 3500 meters per second, the detonation velocity and loading of the second component being sufficient, in combination, to generate a substantially higher pressure impulse than the first component under the same conditions; and initiating the outside end of the second explosive component so that its detonation propagates in a direction substantially parallel to the tubes' axis.

**2.** A process of claim **1** wherein the second explosive component generates substantially the same pressure impulse over said two to ten inches as the first component does over substantially the remaining length of the lining tube.

**3.** A process of claim **1** wherein said tubes are at least about ten inches long.

**4.** A process of claim **3** wherein said substantially higher impulse is generated by using as the second com-

ponent an explosive whose detonation velocity is higher than that of the first component.

5. A process of claim 4 wherein the detonation velocity of the second component is at least about 500 meters per second higher.

6. A process of claim 5 wherein the first and second explosive components fill the lining tube.

7. A process of claim 1 wherein the first and second components are of the same composition and said substantially higher pressure impulse is generated by using in the second component a higher loading of explosive than is employed in the first component.

8. A process of claim 7 wherein the first and second components fill the lining tube and said higher loading is provided by packing the second component to a higher density than the first component.

9. A process of claim 8 wherein said tubes are at least about ten inches long and the ratio of explosive loading to lining metal weight is below about one.

10. A process of claim 9 wherein the second component has at least about a 25% higher loading than the first component.



11. A process of claim 9 wherein the pressure impulse generated by the second component is up to about 75% higher than would be generated by the first component under the same conditions.


**References Cited**

UNITED STATES PATENTS

| | | | |
|---|---|---|---|
| 3,263,324 | 8/1966 | Popoff | 29—486 |
| 3,364,561 | 1/1968 | Barrington | 29—470.1 |
| 3,409,969 | 11/1968 | Simons et al. | 29—421(E) |
| 3,434,197 | 3/1969 | Davenport | 29—470.1 |
| 3,439,408 | 4/1969 | Bergmann et al. | 29—470.1 |



JOHN F. CAMPBELL, Primary Examiner

R. J. SHORE, Assistant Examiner

U.S. Cl. X.R.

29—479, 486