This invention relates to a novel process for producing a metallicurgical bond between a tubular metal lining and a metal tube or pipe. The use of lined tubes and pipes has been a well-established practice for many years. Such compositions consist of a tube or pipe, usually fabricated from a relatively inexpensive metal, to the inside wall of which is bonded a lining of a second metal which possesses certain desirable properties, e.g., high corrosion or oxidation resistance, not characteristic of the first metal. In most instances, the metal which forms the lining is considerably more expensive than is the metal to which it is applied. Hence, a substantial economic saving is made possible by the use of thinly lined tube or pipe rather than thick-walled tube or pipe of the costlier metal. Naturally, this saving is greatly increased when lined tubes or pipes are employed in the construction of large masses of equipment such as pipelines for transporting large quantities of chemicals.

A second advantageous feature of the use of composite tubes and pipes results from the fact that frequently the metal possessing the desired corrosion resistance or other property is lacking in the necessary tensile strength, thermal properties, or compression strength to enable it to be employed per se in applications where stresses would be encountered. Thus, in addition to the economy provided by the use of the less expensive metal, the structural strength, heat transfer properties, and rigidity which it may impart to the composite system represent important and valuable factors in composite assemblies.

A variety of methods exist for providing metal tubes and pipes with metal linings to form composite assemblies; however, these methods suffer from certain disadvantages which cause them to be inconvenient, or wholly unsuitable, under certain circumstances.

The processes which involve application of a molten metal to the inner wall of a tube or pipe are limited to the bonding of gases which are contained in, or which are formed, by the application of heat to a material not of relatively low melting point. The molten metal is often difficult to handle, and must be protected from oxidation by working with the metal in an inert or reducing atmosphere or in a vacuum. The lining produced is often of nonuniform thickness, rough, and nonductile due to the presence of deleterions, brittle intermetallic phases formed at elevated temperatures. A route of compromise heat treatments must often be utilized due to possible noncompatibility of the physical natures of the dissimilar metals involved in the assembly; this would limit the usefulness of such an assembly to certain operations wherein the corrosive environments would not impose stringent demands upon the performance of the metals involved. Composite pipes fabricated by hot-dipping and centrifugal casting may be satisfactory for soil and waste disposal services but unsatisfactory for processes which might require high-pressure services.

Methods of producing lined tubes or pipes such as drawing or extruding often suffer from the same disadvantages as do methods involving molten metals with respect to limitations on the metals bonded, formation of brittle intermetallic phases, and use of elevated parameter processes which may require welding under protective atmospheres and the use of elaborate, expensive equipment. In many cases, a mechanical, rather than a metallurgical, bond between the lining metal and the outer tube or pipe is effected, lowering the heat transfer properties, the mechanical strength, and the ductility of the composite system.

Deposition of linings, for example by electroplating, electrolytic plating and vapor deposition, is time-consuming and expensive. The extensive preparation of the surface to be coated and precise control of conditions required make lining tubes or pipes of large diameter by this method uneconomical. The linings may be porous, brittle, or too thin to withstand, for example, a severely corrosive atmosphere. Deformation of the composite system may necessitate extensive machining operations, and there are limitations upon the number of metals which may be bonded under the pertinent conditions of a given process; for example, an alloy lining can not be deposited by electroplating or by electrolytic plating of the lining of one metal can be metallurgically bonded to a tube or pipe of another metal. Such a process would enable fabrication of composite tubes or pipes from metals which heretofore could not be effectively bonded together.

The disadvantages of older commercial methods are overcome by the inventive process for lining a metal tube which comprises the positioning of a first metal tube concentrically inside a second metal tube or pipe, the outside wall of said first tube being spaced from the inside wall of said second metal tube, a distance at least 0.001 inch, positioning concentrically said first metal tube a linear charge of a detonating explosive having a velocity of detonation less than 120% of the velocity of sound in that metal having the higher sonic velocity, and thereafter initiating said explosive charge. Usually, it is desirable to use an explosive having a detonation velocity not greater than the velocity of sound in that metal with the higher sonic velocity, and this represents the preferred embodiment of the invention. The adjacent walls of the two metal tubes must be separated at the minimum spacing which I have found will consistently be adequate. The maximum separation allowable is dependent upon the reduction of velocity of the propellent tube caused by air between the adjacent surfaces of the two tubes, and upon the physical condition and properties, e.g., ductility, of the metals involved. By increasing the explosive loading or by evacuating the space between the adjacent walls of the two tubes, spacings much greater than 0.001 inch are feasible. In general, however, separation of more than 0.5 inch is not convenient or necessary.

For more complete understanding of the invention, reference is now made to the attached drawings in which FIGURE 1 represents a longitudinal, cross-sectional view of an assembly which might be used to practice the invention and FIGURE 2 represents a schematic view illustrating the mechanics of bonding.

In FIGURE 1, metal tube 1 is positioned concentrically inside metal tube 2, using tape 3 to maintain an air annulus 4 between the outer wall of the first tube and the inside wall of the second tube. The taped assembly is inserted into the vertical bore of a steel block 5 which
is supported by steel blocks 6 and a steel slab 7. The vertical bore of the steel block 5 is lined with a layer of petrolatum 8 for ease of insertion of the taped assembly and prevention of bonding of the outside wall of the second metal tube 2 to the steel block 5. A linear charge of a detonating explosive 9 is positioned concentrically inside the first metal tube 1 and is supported in place by cardboard spacers 10 glued to the ends of the taped assembly. To the upper end of the linear charge of detonating explosive 9 is attached initiator 11 having lead wires 12.

When electric current is supplied through lead wires 12, initiator 11 is actuated and initiates explosive 9. The shock pressure impulse moving radially from the detonation of explosive 9 impinges on the inside wall of tube 1, the pressures impelling that portion of the tube at high velocity against the inner surface of tube 2. The confinement of block 5 prevents excessive expansion of tube 2. The bonded assembly is readily removed from block 5; in fact, the bonded assembly is frequently ejected by the gases formed by the detonation.

An essential and critical characteristic of the present invention concerns the nature of the metallic bonds which secure the metal lining to the metal tube or pipe. This bond is an uninterrupted metal-to-metal bond which extends uniformly over the entire area of the adjacent surfaces of the two tubes.

In this respect the bond formed according to the present invention is superior to metal-to-metal bonds formed between concentric tubes or pipes by means of explosives up to the present time. For example, explosives may be used to join ends of pipes within a metal sleeve in which case a mechanical bond between the outside walls of the pipes and the inside wall of the sleeve is formed. In other instances in which bonding between concentric tubes or pipes effected by means of explosive is claimed, the components are deformed by the explosive pressure so that they are not readily separated by mechanical means and/or the bond between the components is not uniform.

Generally, the strength of the bond formed according to the present invention will be greater than the strength of the weaker metal. The ductility of the bonded material is also comparable to that of the non-bonded tubes and may oftentimes be increased by mild heat treatment.

A particularly surprising and advantageous feature of the present invention is that the continuous bonding zone joining the tubes will be of essentially homogeneous composition throughout. In conventional bonding methods, the metallurgically bonded zone is composed of a gradated sequence of compositions which are progressively richer in the metal of the tube that is closer and, conversely, progressively poorer in the metal of the tube which is farther away. If the metals being joined form a brittle intermetallic compound there is often a region in the cross-section of this heterogeneous bonding zone comprising essentially the brittle intermetallic compound alone which exerts a deleterious effect on the ductility of the composite system.

Although I do not intend to be limited by any theory of operation, I believe the formation of the homogeneous bonding zone described above is attributable to the "jetting" action which occurs schematically as illustrated in FIGURE 2. When linear explosive charge 9 is initiated (13 representing the gaseous detonation products), the detonation proceeds throughout the remainder of the linear charge at the detonation velocity of the explosive composition. The pressures produced by the detonation thus act progressively on the inner metal tube 1 to propel it toward the outer metal tube 2. If the outside wall of the inner tube 1 is parallel to the inside wall of the outer tube 2, the portion of the outside wall of the inner tube 1 nearest the point of initiation will make contact with the inside surface of the outer tube 2 while other portions are either stationary or enroute to the surface (as shown in FIGURE 2). If the conditions are appropriate, a "jet" 13 composed of portions of the adjacent surfaces will be produced, this jet being directed into the as yet unoccupied space between the walls of the two tubes. The jetted material is recirculated to give intimate mixing of the metallic portions of the adjacent surfaces. The removal of these metallic portions of the adjacent surfaces and the confluence under high pressure of previously underlying metal results in the desired bonding, as at 15.

In order to achieve the desired result, an explosive charge must be initiated so that the detonation is propagated essentially parallel to the wall of the inner tube. The progressive impact of the inner tube on the outer tube will cause the formation of a "jet" along the line of intersection. This "jetting" will not occur if the entire charge is detonated simultaneously. Naturally, the dimensions of the explosive charge must be such as to extend over the entire length of the inner tube which is to be bonded to the outer tube.

An essential and critical feature of the present invention is the use of an explosive having a detonation velocity not greater than about 120% of the velocity of sound in that metal of the system having the highest sonic velocity. By "metal" in the present sentence, we mean metallic component or tube of the system which in any instance may be either a solid elemental metal or a solid mixture of elemental metals, i.e., an alloy. When the detonation velocity of the explosive exceeds this limitation, oblique shock waves ensue which interfere with the "jet" phenomenon referred to above and prevent formation of a good metal-to-metal bond. Also, in those cases where a jet does form, pronounced secondary effects often result, such as distortion of the parts and cracking of the bonded zone.

While I have referred above to the "velocity of sound" of metals, those skillled in the art will recognize that these terms have somewhat different meanings in differing circumstances. For example, these terms will have a different significance to the physicist when dealing with plastic shock wave phenomena in solids as contrasted with elastic shock wave phenomena. It is the former with which I am concerned for purposes of the present invention. The terms "velocity of sound" and "sonic velocity" as used throughout this application in connection with metals and metallic systems refer to the velocity of a plastic shock wave which forms when an applied stress just exceeds the elastic limit for unidimensional compression of the particular metal or metallic system involved. The value of this sonic velocity may be obtained by means of the relation

\[ V = \sqrt{\frac{K}{\gamma}} \]

where \( V \) is the sonic velocity in cm./sec., \( K \) is the adiabatic bulk modulus in dynes/cm.\(^2\), and \( \gamma \) is the density in g./cm.\(^3\). Values of \( K \) may be obtained from values of Young's modulus, \( E \), and Poisson's ratio, \( \gamma \), by means of the relation

\[ K = \frac{E}{(1-\gamma^2)} \]

Values of \( E \) and \( K \) or \( E \) and \( \gamma \) are readily available in the literature (see for example American Institute of Physics Handbook, McGraw-Hill, New York, 1957). Alternatively, the sonic velocity may be ascertained from published values of the velocity of the plastic shock wave as a function of the particle velocity imparted to the metal by the shock wave in the manner described by G. McQueen, S. P. Marsh, Journal of Applied Physics, 31 (7), 1253 (1960).

In those cases where literature data are unavailable, values of \( V \) may be obtained by carrying out shock wave measurements as described by R. G. McQueen and S. P. Marsh (loc. cit.) and in references cited by them. Alternatively \( V \) may be ascertained from the relation

\[ V = \sqrt{C_s^2 \left(\frac{4}{3}C_p^2\right)} \]

where \( C_s \) is the velocity of elastic compressional waves and \( C_p \) is the velocity of elastic shear waves in the metal.
The required velocities of the elastic waves may be measured by well-known methods. For illustration purposes, sonic velocity values as used herein for representative metals are set forth in the following table:

<table>
<thead>
<tr>
<th>Metal</th>
<th>Sonic velocity, m/sec.</th>
</tr>
</thead>
<tbody>
<tr>
<td>Zinc</td>
<td>3000</td>
</tr>
<tr>
<td>Copper</td>
<td>4000</td>
</tr>
<tr>
<td>Magnesium</td>
<td>4500</td>
</tr>
<tr>
<td>Niobium</td>
<td>4500</td>
</tr>
<tr>
<td>Austenitic stainless steel</td>
<td>4500</td>
</tr>
<tr>
<td>Nickel</td>
<td>4700</td>
</tr>
<tr>
<td>Titanium</td>
<td>4800</td>
</tr>
<tr>
<td>Iron</td>
<td>5200</td>
</tr>
<tr>
<td>Molybdenum</td>
<td>5200</td>
</tr>
<tr>
<td>Aluminum</td>
<td>5500</td>
</tr>
<tr>
<td>“Monel”</td>
<td>4400</td>
</tr>
<tr>
<td>Bronze</td>
<td>4000</td>
</tr>
<tr>
<td>“Hastelloy”</td>
<td>4400</td>
</tr>
</tbody>
</table>

In addition to the limitation on the maximum detonation velocity of the explosive used, we have found that the latter must have a minimum detonation velocity of at least about 1200 meters per second. Explosive compositions which detonate at velocities lower than this will often fail to develop the energy necessary for formation of the “jet” postulated above, and will thus fail to firmly bond the metals within the sense and scope of the present invention.

The following examples illustrate some of the various modifications of the assembly which can be used in the practice of this invention. They are intended as illustrative only, however, and are not to be considered as exhaustive or limiting. Any desired composite metallic system may be obtained by a suitable adjustment of conditions.

Example 1

The explosive employed in this example was an extruded cord of a flexible explosive composition comprising 20% very fine pentaerythritol tetranitrate (PETN), 70% red lead, and, as a binder, 10% of a 50/50 mixture of butyl rubber and a thermoplastic terpene resin (mixture of polymers of β-pinene of formula (C_{10}H_{16})_n), commercially available as “Piccolyte” S-10 (manufactured by the Pennsylvania Industrial Chemical Corporation). Complete details of this composition and a suitable method for its manufacture are disclosed in co-pending application Serial No. 65,012, filed October 5, 1960, in the name of Cyril J. Breza and having a common assignee with the present application. The composition is readily extruded into cord and detonates at a velocity of about 4100 meters per second.

A type 304 stainless steel seamless tube, 8 inches long, 1.75 inches outside diameter, and 0.028 inch wall thickness, was placed concentrically inside a carbon steel seamless tube 8 inches long, 2.75 inches outside diameter, and 0.420 inch wall thickness. Both ends of the assembly were taped in order to maintain an air annulus of 0.060 inch between the walls of the two tubes. The assembly was inserted into a 12-inch vertical bore, 0.020 inch oversize with respect to the outside diameter of the carbon steel tube, in a type 1045 steel block, 10 inches in diameter by 12 inches long, supported by four steel blocks and a steel slab. The 0.020-inch annulus was filled with petrolatum for ease of insertion of the assembled tubes and prevention of bonding of the outside wall of the carbon steel tube to the steel block. A cord of the above-described explosive, about 0.5 inch in diameter and 10 inches long, having a weight distribution of 150.5 grams per linear foot, was positioned concentrically inside the stainless steel tube, extending about 1 inch beyond each end of the tube assembly, and supported in place by two cardboard spacers glued to either end of the tube assembly. The explosive was subsequently initiated using a No. 6 electric blasting cap positioned at the upper end of the cord. After detonation, the stainless steel lining and the carbon steel tube were found to be firmly and uniformly bonded together to form a composite assembly. Microscopic examination revealed excellent metallurgical bonding.

Example 2

The materials, technique, and explosive composition of Example 1 were used in Example 2, a pressure transfer medium of air, as described in Example 1, or of water, as described in Example 2, and a weight distribution of the above-described explosive of between approximately 150 and 200 grams per linear foot, firmly and uniformly bonded composite assemblies may be prepared of the following metals: carbon steel, alloy steel, stainless steel, “Hastelloy”, “Monel”, “Inconel”, “Stellite”, “Nichrome”, aluminum, aluminum alloy, copper, copper alloy, molybdenum, molybdenum alloy, tungsten, tungsten alloy, titanium, titanium alloy, molybdenum, magnesium alloy.

The novel bonding process is applicable to a wide variety of metals, such as iron, niobium, chromium, cobalt, nickel, beryllium, tantalum, vanadium, zirconium, silver, platinum, gold, and their alloys, and other metals, many of which are very difficult to bond by any of the conventional techniques. Two or more concentric tubes may be bonded together to form a multimetallic composite assembly. Each of the tubes may be of a single metal or of an alloy of two or more individual metals, or each of the tubes may be a composite of two or more single tubes.

This process is suitable for the preparation of composite tubes and pipes from seamless or seamless individual tubes and pipes. By tube or pipe I mean an object of such a configuration that the transverse cross section of the surface to be bonded according to the present invention is essentially circular. By this definition I do not exclude objects having relatively small irregularities in the surface to be bonded. In commercial practice, one or more of the component parts of the composite system will often be an implement or unit of equipment; for example, a lining may be bonded to the wall of the cylindrical bore of a nozzle to be used on a pressure vessel according to the present invention. The method of the present invention can be used for the simultaneous fabrication and lining of tubes of difficultly weldable material; for example, one or more of the component parts of the assembly to be bonded may comprise a sheet of a metal rolled into a cylindrical configuration in such a manner that an overlap and an air space between the overlapping edges are provided. The composite system prepared according to the present invention can be of approximately final dimensions, or, for example, a pierced billet with a relatively thick lining suitable for subsequent drawing or extruding to the desired dimensions. Theoretically, there are no limitations on the length nor on the diameter of the composite system which can be fabricated by the method of the present invention.

The method employed to provide the required gap between the walls of the component tubes is not critical. As I have shown, in a vertical assembly the tubes may be positioned concentrically and taped in place in order to maintain an air annulus between their adjacent surfaces. Also, small projections in one or both of the adjacent surfaces function quite satisfactorily. Obviously, the sup-
porting means should not shield large areas of the adjacent surfaces of the tubes. It is desirable that the walls of the tubes be relatively free of surface impurities. Where surfaces are unclean, usually cleaning of the surfaces with a mild abrasive followed by flushing with a solvent is adequate to remove any impurity which would impair adhesion or result in brittle areas. However, the intense and elaborate cleaning operations required for other bonding methods are not necessary for the present process.

Rigid supporting means for the tube assembly is not critical to the practice of the invention; however, the presence of a supporting medium aids in avoiding distortion of the composite formed. A supported forged steel block with a suitable bore, because of its shock resistance and its relatively low cost, represents a satisfactory supporting means. Among the practicable alternatives are a hinged or solid steel die, reinforced concrete, a combination of steel and reinforced concrete, and a combination of any of the aforementioned supporting means with sand, rock, earth, or water. The assembly may be arranged vertically, as shown, or horizontally.

The parting composition used to separate the outside wall of the outer tube from the supporting means, and as a lubricant between these adjacent surfaces, is not critical. Some alternatives to the petrolatum shown are other lubricating materials such as Vaseline, greases, and graphite.

In some cases it is advantageous to provide a layer of inert or buffer material between the linear explosive charge and the inside wall of the inner tube. This layer of inert or buffer material may comprise, for example, water, a polystyrene plastic foam, a polyester film, or tape.

The linear explosive charge need not be positioned absolutely concentrically with respect to the tube-assembly and the explosive composition used is not critical. Among the alternatives to the pentaerythritol tetranitrate composition described in the examples are granular trinitrotoluene, sensitized ammonium nitrate, e.g., various mixtures of ammonium nitrate and trinitrotoluene and soda ash, and some dynamites confining in a linear configuration.

The explosive charge may be initiated by any conventional initiating device, for example, blasting cap, detonating fuse, exploding wires, etc. The location of the initiating source on the liner charge is not critical provided that the entire length is not simultaneously initiated. The amount of explosive used is not critical, provided a sufficient loading is present to propel the inner tube with adequate velocity to achieve the desired bonding. The particular amount and loading of explosive suitable in any case will be readily apparent to one skilled in the art considering such factors as type of explosive, wall thickness of the metal tubes, etc. Obviously, excessive explosive will cause undesirable deformation and should be avoided.

In addition to the aforementioned uses, lined tubes and pipes have specific application in oil well tubing, automobile bearings and radiators, heat exchangers, missile fuel and gas tanks, radio tubes, waveguide tubing, rocket nozzle rings, and tubing for gas, mineral acid, power reactors, and cryogenic services. These composite assemblies, e.g., stainless steel, "Inconel" C-276, and titanium-clad carbon steel, are desirable as fittings, such as nozzles and transition joints, for clad vessels of the same composite structures.

The invention has been described in detail in the foregoing. However, it will be apparent to those skilled in the art that many variations are possible without departure from the scope of the invention. I, therefore, to be limited only by the following claims.

I claim:
1. A process for bonding the outside wall of a first metal tube to the inside wall of a second metal tube by a continuous metallurgical bond characterized by the presence of a homogeneous mixture of the metals of the two tubes to form a lined tube which comprises positioning said first metal tube essentially concentrically inside said second metal tube, the outside wall of said first metal tube being spaced from the inside wall of said second metal tube by a distance of at least 0.001 inch, positioning essentially concentrically inside said first metal tube and throughout the length of said tubes to be bonded a linear charge of a detonating explosive having a velocity of detonation of at least 1200 meters per second but less than 120% of the velocity of sound in the metal in the system having the highest sonic velocity, and initiating said linear charge of explosive in such a manner that detonation is propagated in a direction essentially parallel to the longitudinal axis of said first metal tube and said second metal tube over the length of said first metal tube and said second metal tube to be bonded.

2. A process according to claim 1 wherein said linear charge of a detonating explosive is spaced from the inside wall of said first metal tube so as to form an annulus, said annulus being provided with a layer of a buffer material.

3. A process according to claim 1 wherein said linear charge of a detonating explosive is spaced from the inside wall of said first metal tube so as to form an annulus, said annulus being filled with air.

4. A process for bonding the outside wall of a first metal tube to the inside wall of a second metal tube by a metallurgical bond characterized by the presence of a homogeneous mixture of the metals of the two tubes which comprises positioning said first metal tube substantially concentrically inside said second metal tube, the outside wall of said first metal tube being spaced from the inside wall of said second metal tube by a distance of about from 0.001 to 0.5 inch, positioning substantially concentrically inside said first metal tube, spaced apart from the inside wall thereof and substantially throughout the length of said tubes to be bonded a linear charge of a detonating explosive having a velocity of detonation of about from 1200 to 5000 meters per second but less than the velocity of sound in that metal in the system with the highest sonic velocity, initiating said linear charge at one end thereof so that detonation is propagated in a direction substantially parallel to the longitudinal axis of said first metal tube and said second metal tube over the length of said first metal tube and said second metal tube to be bonded.

5. A process of claim 4 wherein said first metal tube is a stainless steel tube and said second metal tube is a carbon steel tube.

References Cited in the file of this patent

UNITED STATES PATENTS
3,024,526 Philipchuk et al. __________ Mar. 13, 1962
3,038,374 Williams __________ May 29, 1962