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AN EXPERIMENTAL INVESTIGATION INTO TUBE TO TUBE-PLATE WELDING USING THE IMPACTOR METHOD

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Industrial Summary

A study has been carried out to explore the explosive welding of tubes to tube-plates, considering various metals and using a parallel set-up employing an impactor and high detonation-velocity explosive material. The parameters for the securing of an acceptable weld have been found experimentally and have been compared with equivalent theoretical values. The technique has been extended to the employment of simultaneous detonation at multiple locations and successful welds have been realised without appreciable distortion.

1. Introduction

Techniques for welding tubes to tube plates employ a small explosive charge, which on detonation effects their high velocity collision, whereupon under controlled conditions, a good bond is secured between the two. Basically, there are two different geometries available: (i) using a high detonation-velocity explosive material; and (ii) using a low detonation-velocity explosive material.

The geometry using a high detonation-velocity explosive material has a mutual inclination between the tube and the tube-plate, which is obtained either by tapering the tube-plate hole (Fig. 1) over part of the tube-plate thickness,

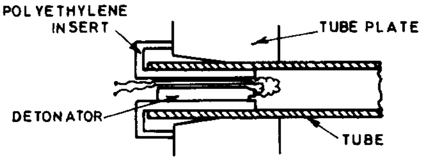

Fig. 1. Angular geometry.

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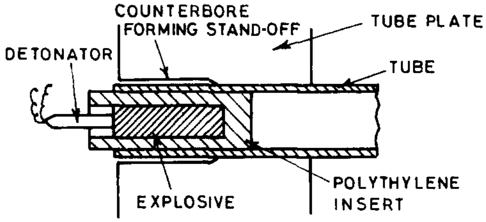

Fig. 2. Parallel geometry.

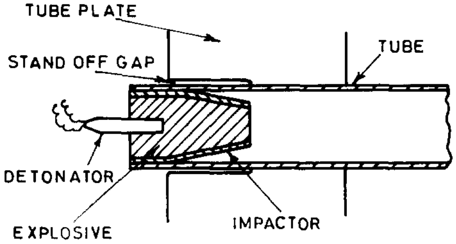

Fig. 3. Angular bonding with an impactor.

or by machining/swaging the outer surface of the tube whilst maintaining the tube-plate hole parallel.

The other geometrical arrangement, where the surfaces to be welded are kept parallel to each other and at a short distance apart (Fig. 2), requires an explosive material having a detonation velocity that is less than the sonic velocity of the materials being welded. As a low detonation-velocity explosive material produces pressures that are much smaller than those arising from the use of a high detonation-velocity explosive material, its use requires the employment of greater stand-off distances in order that a given tube velocity can be generated. Another disadvantage of using a low detonation-velocity explosive material is that the collision-point velocity, which is equal to the corresponding detonation velocity, may not be equal to the optimum collision-point velocity of the materials to be welded.

One of several methods of achieving suitable welding conditions using a high detonation-velocity explosive material is to use an impactor and parallel geometry. An explosive-welding technique (Fig. 3) using an impactor has been described by Chadwick [1]. The parallel set-up with an impactor is preferred because use can be made of high detonation velocity explosive materials, which are generally more consistent in detonation, more compact and more easily handled than low detonation-velocity explosive materials [2].

2. Theoretical considerations

More obvious variables of the explosive-welding process are the detonation velocity of the explosive material V_D, the sonic velocity of the material of the 'parent' plate (the tube-plate) V_{SP}, the sonic velocity of the material of the 'flier' plate (the tube) V_{SF}, the cone angle of the impactor α, the yield strength of the materials to be welded σ_S, the dynamic angle of collision of the tube and the tube-plate β, the velocity of expansion of the tube V_t and the velocity of the collision-point of the flier-plate and the parent-plate V_W.

(1) Tube velocity

A minimum tube velocity is necessary in order that the contact pressure required to obtain a satisfactory weld can be generated. Similarly, the minimum kinetic energy imparted to the flier plate must be such that the strain energy necessary to cause dynamic yield in the stronger of the two materials being welded is exceeded. An upper limit of impact energy is imposed by phenomena such as the formation of intermetallic compounds in particular combinations, or excessive melting at the interface, which lead to weakening of the joint [2].

A critical value of impact energy is thus required to achieve welding. However, a unique value of impact energy does not exist for all thicknesses of flier plate: for constant impact energy the weld quality decreases with decreasing flier plate velocity [3].

To establish a relationship between the minimum kinetic energy and the dynamic yield stress for an acceptable weld, it has been assumed [3] that the kinetic energy is directly proportional to the strain energy required for dynamic yield of the stronger of the materials being welded.

$$\textit{Kinetic energy} = \frac{K_m \sigma_D^2}{2E} \tag{1}$$

where σ_D is the dynamic yield stress, E is Young's modulus and K_m is a constant.

The value of K_m is determined empirically by equating the kinetic energy and the strain energy of dynamic yield in a case where an acceptable weld has been achieved. The value of K_m can thus be obtained from

$$\frac{K_m \sigma_D^2}{2E} = \frac{\rho t V_t^2}{2} \tag{2}$$

where ρ, t and V_t are the density, the thickness and the velocity of the tube, respectively.

Using this value of K_m for other materials, the minimum value of V_t can be calculated. The relationship between the charge-to-metal mass ratio C/M and the tube velocity has already been established [4]:

$$V_t = K_V V_{Di} [2R/(2+R)]^{1/2} \tag{3}$$

where V_D is the ideal detonation velocity[1], K_V is a constant and R is the C/M ratio.

Values of σ_D for various materials are not easily available and hence the relationship as given below can be used [3]:

$$\frac{\sigma_D}{\sigma_s} = 5.98 - 2.42 \log_{10} [(\sigma_s) \times 0.65] \tag{4}$$

where σ_D is the dynamic yield strength and σ_s is the 0.2% proof stress.

(2) Collision-point velocity

For optimum welding conditions, the collision-point velocity must be kept well below the sonic velocity and within a range appropriate to the materials and the flier velocity being used. When the collision-point velocity falls below a particular value, the weld interface becomes flat, whilst with increasing collision-point velocity, the volume of trapped jet[2] increases, which suppresses the formation of waves. At intermediate collision-point velocities, the jet behaviour is regular, a steady-state wave pattern at the interface is established and the maximum bond strength is obtained. The value of the collision-point velocity at which the interface just becomes flat is known as the transition velocity V_{WT} [2], its value depending upon the particular properties of the metals being welded and being given by the relationship [4]:

$$V_{WT}^2 = \frac{2(H_T + H_{TP})\mathrm{Re} \times 10^7}{(\rho_T + \rho_{TP})} \tag{5}$$

where Re is the value of Reynolds number appropriate to the flow process (10.6 ± 1.73), H is the hardness (kgf/mm^2), ρ is the density (kg/m^3) and subscripts T and TP refer to the tube and tube-plate, respectively.

In general, welds obtained at a collision velocity V_W equal to 1.25 V_{WT} are found to be satisfactory [4]. The collision-point velocity depends upon the tube velocity, the detonation velocity and the dynamic angle of collision.

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[1] The ideal detonation velocity is a value representative of the detonation velocity V_D of an explosive material, and is a characteristic property of the explosive material, like the Gurney constant. For the explosive material "Trimonite No. 1", for example the following relationship holds [4]:

Gurney constant $\cdot\, (2E_0)^{1/2} = 0.9 V_{Di}$

where E_0 is the explosive energy liberated per unit mass (J/kg) and V_{Di} has the units m/s.

[2] At the collision point of the flier and the parent plates, a "jet" is ejected, constituting a thin layer from the surface of the two plates, the resulting virgin surfaces being more amenable to pressure welding [4]. If the collision-point velocity is below a particular value which is characteristic of each of the two plates to be welded, free jetting or unimpeded escape of the jet takes place. With increasing collision-point velocity, the collision point overtakes and traps a large part of the jet, the effective velocity of which is reduced. Jet material trapped ahead of the collision point can suppress the formation of "waves" and rarely will the joint be satisfactory [2].

(3) Dynamic angle

This angle is dependent upon the material conditions, the detonation velocity, the initial angle of obliquity, the tube velocity and the collision-point velocity, and has been related to these parameters by the relationships (5):

$$\beta_{\text{min}}=K_1\sqrt{H_{\text{V}}\times 10^7/V_{\text{W}}^2} \tag{6}$$

$$\beta_{\text{max}}=2\sin^{-1}(K_2/t^{0.25}V_{\text{W}}^{1.25}) \tag{7}$$

where β is in radians, K_1 is a constant based on surface quality, H_{V} is the Vicker's hardness (kgf/mm^2), t is the tube thickness (m), V_{W} is the collision-point velocity (m/s), K_2 is a constant determined[3] at V_{W} when it is equal to 0.5 $(K/\rho)^{0.5}$, K is the bulk modulus of the material and ρ is the density of the material.

(4) Stand-off distance

In practice, a finite distance is required between the flier plate and the parent plate when using an impactor, to allow steady-state bending to become established in the flier plate, at the angle required for jetting. For greater tube wall thickness, the stand-off requirement increases, to allow for steady-state bending of the plate. It is preferable to have the tube velocity at around 0.7 of its terminal velocity [1] in order to have some residual pressure to counteract the separating action of the (tensile) stress wave arising from the reflection of the initial compressive shock wave upon its arrival at the opposite face of the plates [6].

(5) Ligament[4] distortion in tube to tube-plate welding

The impact of the tube on the tube-plate is a dynamic situation, in which the tube-plate attains a velocity following impact by the tube: this brings about the distortion of the tube-plate. The kinetic energy is found to be the most important parameter in dictating ligament distortion. If the ligament is thin, more displacement will occur, thus causing a greater loss in impact pressure, so that it is sometimes below the minimum required for welding. Ligaments thinner than about 6 mm necessitate the use of geometries other than that of a tapered hole, or require the presence of removable ligament-supporting plugs in the surrounding holes [6].

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[3] V_{W} is limited by the compressive wave velocity given by K and ρ. Once the value of K_2 is established experimentally at a value of V_{W} equal to half the compressive wave velocity then, for any value of V_{W} with a particular flier plate thickness, the value of β_{max} is given by eqn. (7) and the upper boundary can be plotted in the β-V_{W} plane [5].

[4] The ligament is the solid portion between adjacent holes, i.e., the pitch distance minus the counterbore diameter (see Figs. 2–4).

3. Experimental set-up

Experiments were carried out to study the technique of welding a tube to a tube-plate using a parallel set-up, an impactor (polythene insert) and a high detonation-velocity explosive material (Fig. 4).

Monel, Incoloy, copper and stainless steel tubes were welded to stainless steel tube-plates (Table 1). The tube-plates used were of 75 mm diameter and 40 mm thickness, having eight holes. The ligament width was 5.2 mm and the stand-off was equal to 0.52 mm. Conical impactors machined from polyethelene were used. Simultaneous detonation of assemblies set within each of the eight holes was carried out. A military plastic explosive with a detonation velocity of 7000 m/s was used. The tubes were welded at one end. Measurements of tube-expansion velocities and collision-point velocities were carried out in another set of experiments, using the pin–oscilloscope technique, as shown in Fig. 5. The set-up consists of a wooden pin-probe holder, nine pin-probes, a metal tube with a tapered insert containing the explosive charge, and an R–C network and oscilloscope. The common probe is kept in touch with the tube surface, whilst the rest of the pins are mounted at different but accurately

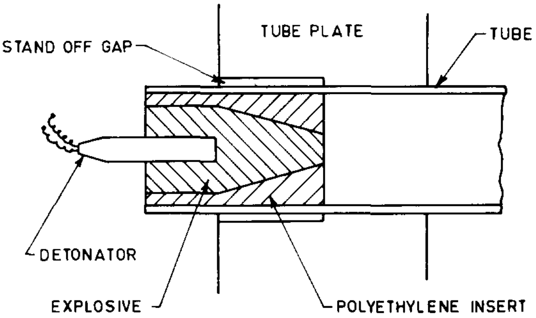

Fig. 4. Angular bonding using a charge-tapering polythene insert.

TABLE 1

Tube details/mechanical properties

Tube material	Tube dias. od/id (mm)	H_V (kgf/mm^2)	σ (g/cm^3)	E (ref. [7]) (kgf/mm^2 $\times 10^3$)	σ_s (kgf/mm^2)	σ_D (kgf/mm^2)
Monel	12.6/10.2	129	8.83	15.9	23.40	73.45
Incoloy	12.6/10.2	130	7.95	20.0	33.62	92.72
Copper	12.5/9.5	122	8.96	12.3	36.10	118.27
Stainless steel	12.6/9.2	164	7.80	20.8	24.50	75.92

1 kgf/mm^2 = 9.81MPa.

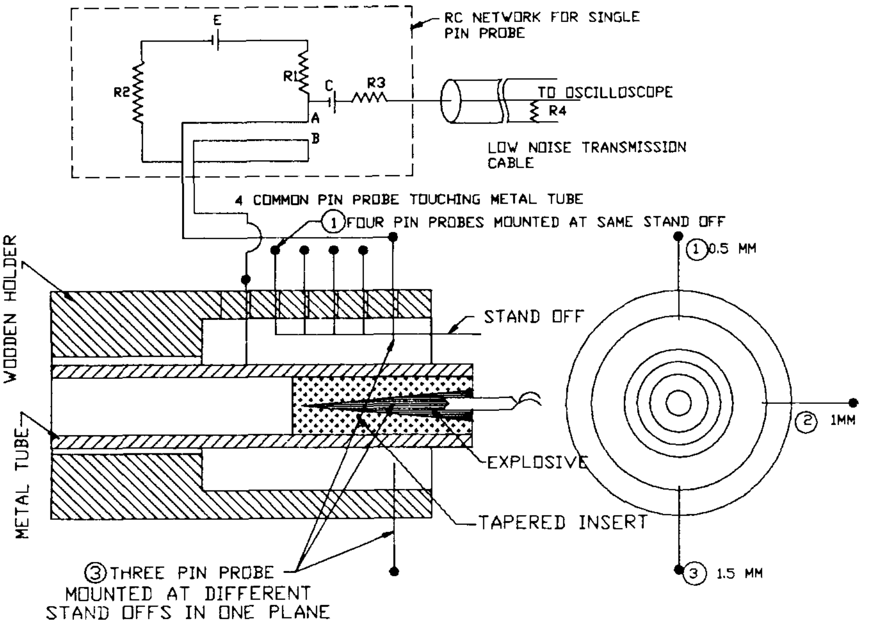

Fig. 5. Experimental set-up for the measurement of expansion velocity V_t and collision-point velocity V_W.

measured (by slip gauge) stand-offs from the surface of the tube. Four pins mounted at the same stand-off but at different axial locations are used to measure V_W, whilst three pins mounted at the same axial location but at different stand-offs are used to measure V_t. Non-continuity exists between each stand-off probe and the common probe and the far ends of the stand-off probes and the common probe are connected to a resistance–capacitance (R–C) network charged to 30V. The R.C. network is designed to generate pulses of only nano-second duration so that there is no inter-mixing of successive pulses. The output of these probes is fed to a digital storage oscilloscope of 200 MHz bandwidth through low-noise cable. When the explosive charge is detonated by an electrical detonator, each element of the metal tube is accelerated progressively and touches the probes successively in the direction of the propagation of detonation. Each probe, on touching the accelerated element of the tube, becomes shorted, which results in the discharging of capacitor ‘C’ and the generation of a sharp electrical pulse of only nano-second duration, which is recorded on the oscilloscope. As the charges were tapered, their masses were determined by weighing of the impactors. Values of σ_s and H_V were obtained by actual testing and measurement. In order to secure reliable results, all of the components were checked for dimensional accuracy.

4. Results and discussion

Photomicrographs of a representative joint for each combination of metals are presented as Figs. 6(a)–(d). For each combination, 50 tubes were welded and for each tube 10 velocity measurements were carried out.

Ultrasonic examination and sectioning for metallographic evaluation showed welding of all except two S.S. tubes in their respective tube-plates. The distortions (1–2 mm) in the bores of the tubes were confined to the mouth, the rest of the bores being found to be tapering smoothly by a maximum of 0.5 mm from the mouth inwards. The results confirm the fulfilment of the conditions for welding. The measured expansion velocities (Table 2) are in agreement with the values calculated on the basis of average C/M values. Since eqn. (3) is for constant C/M ratios, the actual V_t values are observed to be both higher and lower than calculated values. All of the measured collision-point velocities are observed to be above the calculated transition velocity and also above 1.25 V_{WT}, except in the case of stainless steel (Table 3). The microstructures, however, show a typical wavy interface for all of the four combinations. The conical

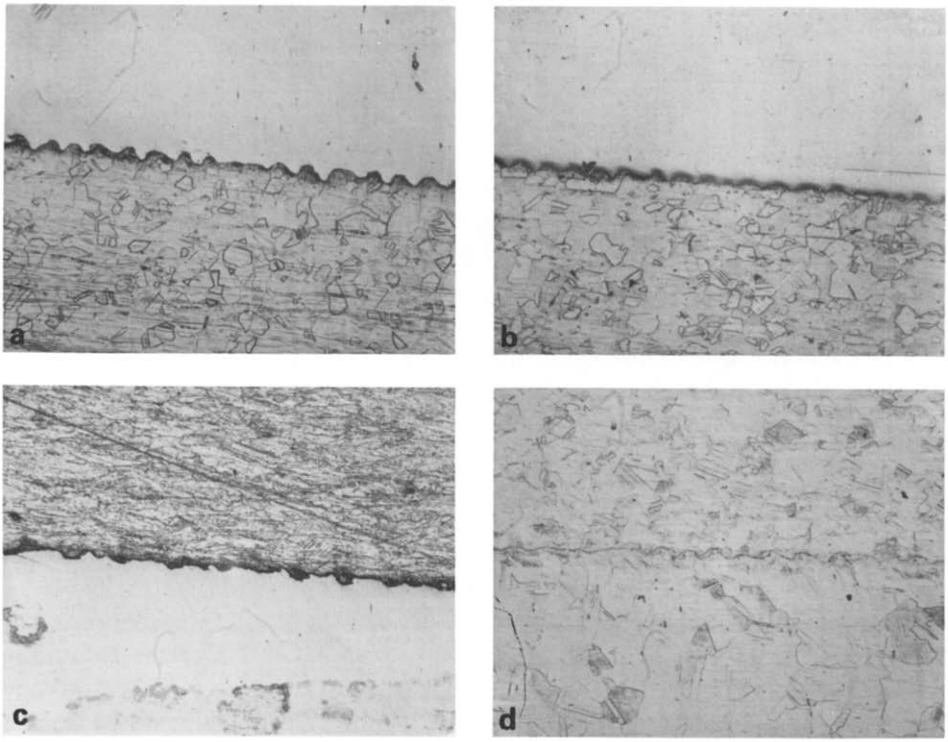

Fig. 6. Photomicrographs of welded joints. The tube-plate (bottom) is stainless steel in each case, whilst the tube (top) is: (a) Monel; (b) Incoloy; (c) Copper; (d) Stainless steel. (×51).

TABLE 2

Tube expansion velocities

Tube	Average C/M	Calculated V_t (m/s)	Measured V_t (m/s)	
			max	min
Monel	0.15	291	300	130
Incoloy	0.15	291	330	130
Copper	0.10	267	360	220
Stainless steel	0.10	256	380	

TABLE 3

Transition collision-point velocity

Tube-plate material	Tube material	Calculated V_{WT} (m/s)	Measured V_W (m/s)	V_W/V_{WT}
S.S. 304 L 75∅×40 mm H_V 223	Monel	2120	3250	1.53
	Incoloy	2180	3820	1.75
	Copper	2090	3660	1.75
	Stainless steel	2295	2570	1.12

TABLE 4

Calculated range of dynamic angles β

Tube	β_{min} at $K_1=0.60$ (°)	β_{max} at $K_2=595$ (°)
Monel	4.00	15.00
Incoloy	3.64	12.25
Copper	3.30	12.20
Stainless steel	6.00	18.00

TABLE 5

Values of K_m and K_3 obtained from impact energy calculations using data from the present investigation

Tube	K_m	K_3
Monel	2.706	0.544
Incoloy	2.312	0.651
Copper	1.528	0.966
Stainless steel	6.830	1.060

impactor is of definite advantage in reducing the effective detonation velocity of the explosive to within the requirement of the collision-point velocity. Values for the dynamic angle ($\beta_{\min}$ and $\beta_{\max}$) have been calculated (Table 4) and found to be in agreement with values found in various published works [4,7], although the actual values have not been confirmed experimentally.

Two approaches have been used to estimate K_m and K_3, one being based on the dynamic yield strength and the other on the relationship [4]:

$$\textit{Collision energy} = \frac{K_3(H_T + H_{TP})^2}{4(E_T + E_{TP})} \tag{8}$$

where the collision energy is equal to the energy of deformation, H is the hardness, E is Young's modulus, subscripts T and TP refer to the tube and the tubeplate, respectively, and K_3 is a constant.

It may be noted that in this investigation the values of K_m and K_3 reported (Table 5) relate to various levels of impact energy.

5. Conclusions

(1) The impactor technique for welding tubes to tube-plates using a parallel-geometry set-up and high detonation-velocity explosive material is basically feasible.

(2) The kinetic energy of the impacting tubes and the distortion of the tubeplate are important factors in securing satisfactory welding.

(3) A stand-off of around one-half of the wall thickness of the tube appears to be adequate.

(4) Based on values of K_m and K_3, the process of explosive welding using the parallel technique can be designed theoretically.

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