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The use of explosion-bonded transition joints for the joining of aluminium superstructures to steel hulls

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SYNOPSIS

This article discusses the joining of aluminium superstructures to steel hulls in ships. It examines the background to the adoption of explosion-bonded transition joints, and a complete review is given of the need for the material, the method of its manufacture, the techniques employed during fabrication, evaluation of the joints by mechanical testing, corrosion resistance and possible problems associated with its use. The results of a survey of aluminium/steel joints used in the Royal Navy are presented.

INTRODUCTION

Recent advances in ship technology have resulted in increased top weight which, together with lighter propulsion systems, have caused a stability problem. This has been overcome by the use of aluminium alloy for parts of the superstructure. At 2700 $kg \cdot m^{-3}$, the density of aluminium compares with approx. 7870 $kg \cdot m^{-3}$ for steel. Thus, aluminium is 37% as dense. *HMS Amazon* (Fig. 1) was the first Royal Navy ship to be built with a significant amount of aluminium alloy superstructure. Aluminium alloy is used extensively in the Hong Kong Patrol Vessels (HKPVs); it is also used in the Type 22 and, to lesser degree, the Type 23 frigates.

The joining of aluminium to steel is not especially easy. Conventional welding technology is not suitable for joining aluminium to steel because of the widely differing temperatures required for each metal. Most plain carbon steels require temperatures of approx. 1500–1600°C, whilst aluminium alloys are often welded at 700–800°C. Even if the difficulties of temperature can be overcome, the tendency to form large quantities of brittle iron/aluminium intermetallics poses a serious problem to the mechanical properties of the resulting joint.

A second problem is that, in a marine environment, the coupling of aluminium to steel is an unwise engineering practice because of the galvanic potential which is established when an electrolyte (sea water) is present. In the marine engineering industry at large, aluminium is used in the form of sacrificial anodes to protect steel structures[1]. Aluminium is the anode and corrodes, whilst the steel is the cathode and is protected. Furthermore, aluminium usually undergoes pitting corrosion in sea water because of local galvanic action at breaks in the protective film of aluminium oxide[2,3]. Pitting corrosion is a particularly insidious form of corrosion because the depth of penetration can be considerable and the consequent reduction in strength quite large for apparently little damage. Thus, the accelerating effect of the bimetallic couple when aluminium-to-steel joints are used is potentially serious.

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Traditional practice has been to attempt to insulate the two metals with a rubber or plastic seal. In R.N. ships where aluminium superstructures are rivetted to steel, a neoprene rubber insulator is used to separate the two dissimilar metals. The rubber has proved to be susceptible to mechanical damage and deteriorates with age, leaving the bimetallic joint open to corrosion. Initially, joints were made with rivets, but the development of an explosion-bonded transition joint in the 1960s made available a new method of ship construction.

At the Royal Naval Engineering College, the authors have made a detailed investigation of the extent of the use of aluminium alloys in ship superstructures. In particular, the authors have studied the use of explosion-bonded joints and their mechanical and corrosion properties. This paper reviews the current situation.

Figs. 1(a)–1(d). Ships of the Royal Navy using aluminium/steel joints

Fig. 1(a). *HMS Amazon*, the first of the Type 21 class

Fig. 1(b). *HMS Starling*, one of the Hong Kong patrol vessels, and one of the first class of R.N. ships to use explosion-bonded transition joints

USE OF RIVETS

Although other methods of mechanical fastening are available, including bolts and adhesives, rivets have been used exclusively for the aluminium/steel joints in the Royal Navy up to and including *HMS Beaver* in 1984 when the method of using explosion-bonded joints was universally adopted. Naval Engineering Standard NES 768[4], based on information provided by the Aluminium Federation[5], describes the recommended techniques for rivetting aluminium to steel. Fig. 2 shows the geometrical arrangement of a rivetted joint in which a neoprene rubber gasket is supposed to insulate the steel from the aluminium, thus eliminating the possibility of dissimilar metal corrosion. It should be noted that, unless the neoprene extends along the shank of the rivet also, the insulation is not effected because electrical contact exists through the rivet. Aluminium coatings are often applied to steel rivets, apparently to increase the corrosion resistance, though it is doubtful if this practice is effective. In the vicinity of the holes complex stress regimes are also introduced which increase the likelihood of delamination of a corroded joint. All these problems – the introduction of stress, the complicated arrangement necessary to effect complete insulation, together with the care needed to protect the joint in service – make the arrangement unsatisfactory in practice. Evidence of this is clearly visible in the fleet survey reported below.

EXPLOSION-BONDED TRANSITION JOINTS

In acknowledgement of the problems associated with joining aluminium to steel by means of rivets, the decision was made to use an explosion-bonded trimetallic composite transition joint. 'Kelomet' is the trade name given to any metal composite consisting of two or more dissimilar metals which are bonded together using explosives. The particular material used, known as Kelocouple, is one such explosively clad plate and consists of:

low-carbon manganese steel, BS 1501-224-400A substrate;
aluminium alloy, BS 1470, grade 5083 cladding;
commercial purity aluminium, BS 1470, grade 1200 interlayer.

The original concept of Kelocouple was to produce a continuous, crevice-free joint of high strength and low corrosion rate which provides an easy method of joining aluminium alloy to steel. This was to be achieved by means of the cladding technique known as explosion welding.

Explosion welding

Explosion welding was first observed during World War I when pieces of bomb shells stuck to metallic objects in the vicinity of the explosion. At the time, explosives experts did not recognize the industrial potential of this. In 1962, a U.S. process patent was issued to Philipchuk and Bois. This patent covered a method for using explosive detonation to weld metals together in spots along a linear path. The method in use today resulted largely from work carried out in the laboratories of Du Pont which culminated in 27 U.S. process patents being issued to Du Pont starting in June 1964. U.S. Patent 3233312 was issued in February 1966 and covered a wide variety of products made by explosive cladding. The process patents U.S. 3397444 and U.S. 3493353 set the standard for worldwide

Fig. 1(c). *HMS Boxer*, a Type 22 frigate using rivetted joints

Fig. 1(d). *HMS Norfolk*, first of the Type 23 class (artist's impression)

explosion cladding. Over 300 dissimilar metal combinations have been joined in such a manner, as well as a large number of similar metal combinations. Explosion clad methods are used in the aerospace, nuclear and cryogenic industries and in the manufacture of chemical process vessels[6].

Explosion welding[7] uses the controlled energy of detonating an explosive to create a metallurgical bond between two or more dissimilar metals, no intermediate filler being required to promote bonding. Metals that are difficult to weld by other methods can be joined by using explosion welding. Initially, large sheets of the metals are superimposed, the cladding metal being placed at a closely controlled distance from the thicker backing metal. Explosives, spread uniformly on the cladding metal, are detonated driving the cladding metal down across the intervening air gap between the two materials with pressures in the region of 1 million atmospheres (Fig. 3). Detonation continues radially and a composite jet of surface metal is expressed from the apex of the collapse angle formed, which removes any contamination from the surfaces producing the characteristic wave-like form[8]. Once bonded, the sheets are cut into strips of various sizes depending upon the required application. Finally, the composite is ultrasonically tested for bond continuity, the manufacturers guaranteeing 95% of the maximum.

Explosion-clad materials are useful for a number of reasons. A metallurgical, high-quality bond can be formed between similar and dissimilar metals, including those metals classified as incompatible for joining by fusion and diffusion methods[9]. In addition, explosion cladding can be achieved over areas limited only by the size of the cladding plate and the amount of the explosion that can be safely tolerated. At present, sizes have ranged from 0.5 mm to >90 m. Metals with widely differing melting points can be clad with relative ease and high-quality wrought metals can be clad without altering the chemical composition of the metals. Furthermore, multiple-layered composite sheet plate can be bonded in a single explosion.

There are, however, some limitations. The inherent difficulty of storing the explosives used in the process is a factor which limits the process to those manufacturers possessing the technical capability. The process is not easily automated because it is labour-intensive and alloys of high strength are difficult to bond, as also is the case when metals have greatly differing densities.

Explosion-welded materials usually exhibit a regular, wavy bond zone interface (Fig. 4a), though this has been almost eliminated in the most recent forms of Kelocouple (Fig. 4b). The wave formation is analogous to fluid flowing around an obstacle[8]. When the fluid velocity is low, the fluid flows smoothly, but above a certain velocity, the flow causes turbulence. The obstacle in the explosion welding is the point of highest pressure in the collision region. The pressures are many times higher than the dynamic yield strength of the metals and so the metals flow plastically. The bond represents the frozen flow pattern of the plastic metal flow during bond formation. Under optimum conditions, the metal flow around the collision is unstable and oscillates producing the characteristic wavy interface.

The weld quality is related to the size of the solidified metal pockets along the interface. It is necessary to keep the number of such pockets containing the intermetallics to a minimum.

Fabrication techniques

Explosion-bonded joints were first used in the Royal Navy in the construction of *HMS Peacock* in 1982. After this time, the use of rivets was abandoned and all joints were made with Kelocouple.

Various geometries are possible for the assembly process. Fig. 5 illustrates the usual method of joining used in the Royal Navy. Transition strips can either be welded to a steel coaming which is then scribed, cut and welded to the deck, or the strip can be welded directly to the deck. The weld between the aluminium bulkhead and the transition joint can be welded before or after the steel weld. As a general guide, the thickness of the transition joint should be 4-times the thickness of the aluminium that is to be used. This value is generally conservative and is dependent on the magnitude of the stresses that will be encountered in the application. However, if the thickness ratio is decreased, care has to be taken to ensure that the

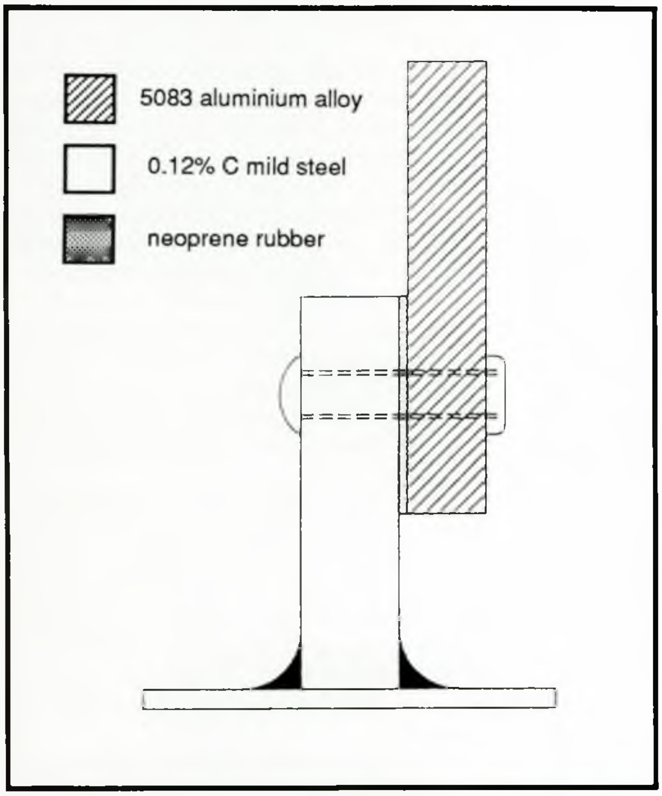


Fig. 2. Geometrical arrangement of a conventional rivetted joint

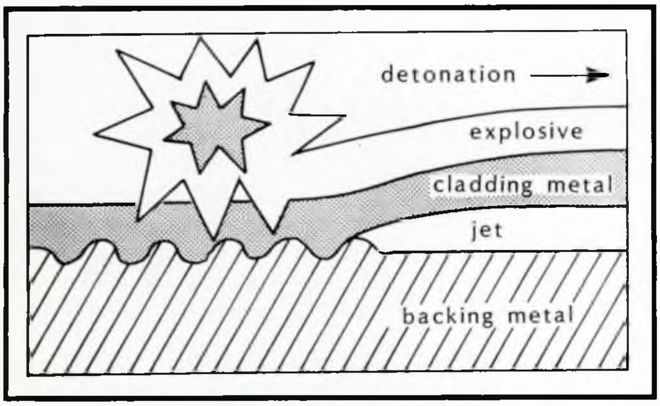


Fig. 3. The explosion welding process

temperature of the interface during welding does not exceed the recommended value[10]. The material can be cut to the required length, but because of the problem with temperature control, only mechanical methods can be used. Guidelines for joining the joint to itself and the ship are available on request from the manufacturer[11,12].

NES 706[13] covers the welding and fabrication of ship structure. It mentions the use of explosion cladding but does not supply information on aluminium/steel joints. The Naval Engineering Standard concerned with the fabrication and welding of aluminium and its alloys is NES 768[4]. At the time of writing, it exists only in draft form, but contains details for the use of Kelocouple. Shipyards provide their own recommendations for fabrication with Kelocouple based on information supplied by ICI.

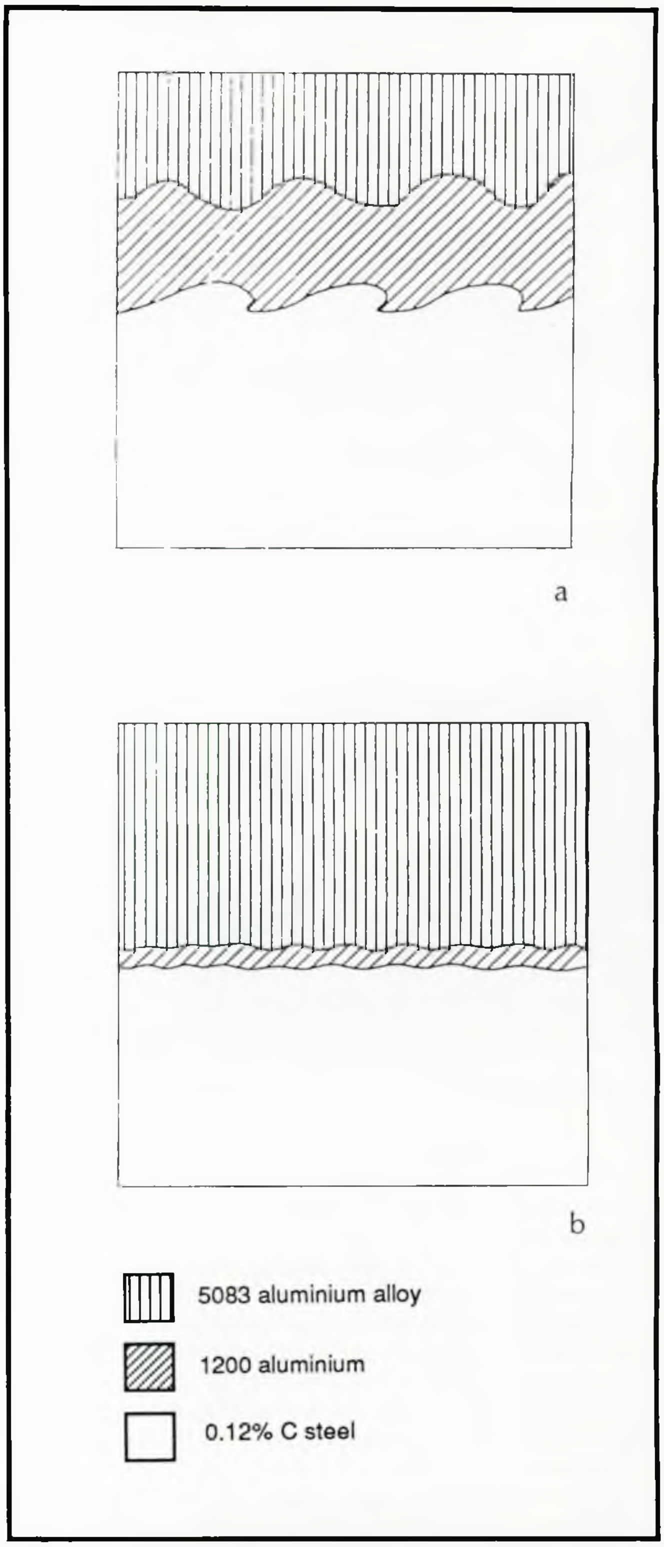


Fig. 4(a). Section through Kelocouple I, an explosion-bonded transition joint
Fig. 4(b). Section through Kelocouple II

The following paragraphs summarize the main points for good shipyard practice when using explosion-bonded transition joints.

1. Welding may be performed using MIG. In the case of aluminium, the shield gas is argon.
2. A type NG6 electrode is recommended for the aluminium weld with an approved 0.12% carbon content steel electrode for the steel weld.

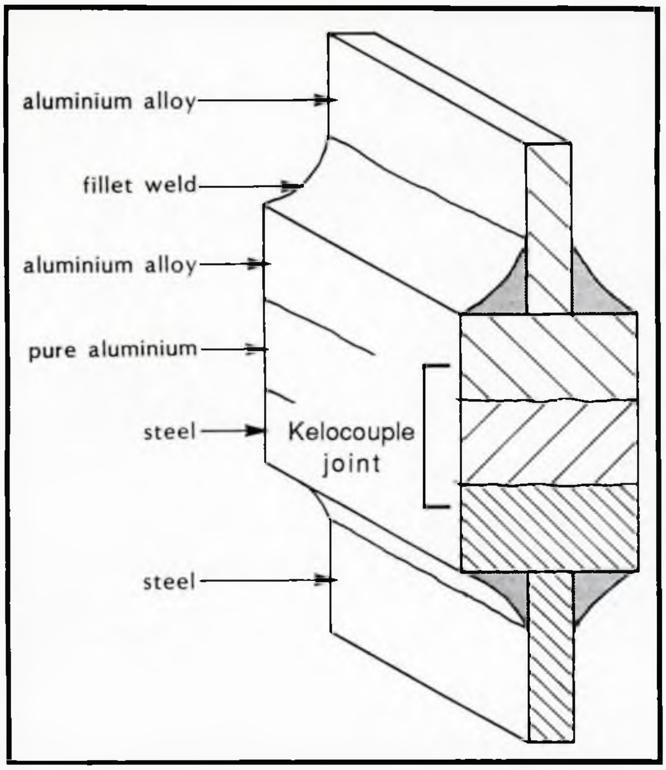


Fig. 5. Geometry for the assembly of structures by means of explosion-bonded transition joints

3. A major factor is temperature control at the aluminium/steel interface which should be kept below 315°C. Above this temperature, brittle intermetallics may form at the interface which may contribute to a reduction in the performance of the transition joint. The use of 'Tempilsticks' is recommended for temperature monitoring.
4. The steel should be welded first, using conventional techniques for performing fillet welds. The weld should be completed in several short passes to ensure the interface temperatures are kept to a minimum.
5. It is recommended that if a transition joint is to be bent, the radius should not be less than 8-times the joint width in the horizontal plane.
6. If a corner is required and there is not enough room to bend the joint in the recommended way, the joint should be mitred to another.
7. Weld deposit should on no account be laid across the interface of the joint. This would produce a very high concentration of brittle intermetallics which, combined with very high localized thermal stresses produced as the metals re-solidify, can lead to weakening and failure of the bond.
8. Care has to be taken that any contraction of the bulkhead after welding does not over-stress the transition joint.
9. When the Kelocouple butts against a single metal, a sealant is required in the same way as for rivets, but this situation should be avoided if possible.

THE PERFORMANCE OF EXPLOSION-BONDED TRANSITION JOINTS

Corrosion resistance

Table 1 lists the manufacturer's data concerning the corrosion performance of both painted and unpainted joints. The results showed that after the initial penetration in the first 3 months of the test any further penetration was negligible in the unpainted joint. The manufacturer suggests that this is due to the formation of an aluminium oxide hydrate, an inert corrosion product whose volume is greater than the original metal, which arrests further corrosion. The manufacturer also supplies recommendations for painting Kelocouple being used in a marine environment.

An investigation was carried out by McKenney & Banker[14] into the corrosion resistance of the transition joint. They found that the aluminium begins to corrode at the interface with the formation of a slight penetration. Rather than acting as a point of high ion concentration (which accelerates the corrosion) the area fills with hydrated aluminium oxide and corrosion is reduced to a negligible state. Tests at Wrightsville Beach, North Carolina, demonstrated this phenomenon and produced results that compared favourably with the original manufacturer's data. Accelerated salt spray tests were used to simulate years of exposure to a marine environment and once again showed that corrosion becomes negligible after the initial build-up of corrosion products. Identical tests were carried out on painted specimens with a localized paint failure and the results showed that the solid metallurgical bond restricts the electrolytic penetration of the interface with the corrosion product, once again stopping extensive pitting.

Considerable testing in salt spray conditions has been carried out at RNEC. Pask & Mohammet[15] showed that penetration of the 1200 aluminium could be far greater than quoted in the manufacturer's literature (Table 1). One problem experienced in making an assessment of the corrosion performance was a variable thickness of the 1200 aluminium layer. Scott[16] found that the steel suffered very shallow pitting over large surface areas, whereas the aluminium alloy became pitted to a great depth with a smaller surface area. Pits did not form in the pure aluminium which suffered serious general dissolution. This was attributed to the small anode/cathode ratio. Recent studies[17] at RNEC showed that the accelerated corrosion, was severe in the unpainted condition. However, taking the quoted scale factor of 16 h exposure = 1 year in service[14], the observed corrosion had occurred over a period representing a complete ship lifetime. It was also found that, in agreement with McKenney & Banker[14], the corrosion rate slowed after the initial build-up of corrosion products, and that the application of paint coatings considerably improved the performance[16,17].

Mechanical testing

Before a method of joining can be accepted for shipbuilding it has to be approved by the register of shipping concerned. Mechanical testing of Kelocouple was first carried out for

Table 1. Corrosion resistance of painted and unpainted Kelocouple specimens
Manufacturers' data, reproduced with permission.

Specimen condition	Exposure duration (months)	Depth of penetration (mm)
Unpainted	3	0.67
	12	0.82
	27	1.05
	60	1.57
Painted	12	0.00
	34	0.00

Lloyd's Register of Shipping in 1980. Since then, Kelocouple has also been tested by the U.S.S.R. Register of Shipping and Det Norske Veritas and has been accepted in all cases.

Fig. 6 shows some of the mechanical tests carried out and Table 2 lists results obtained. Fatigue tests on both transition and rivetted joints have also been carried out by the manufacturers. The results are shown in Table 3. A wide range of values was obtained, from which was determined minimum guaranteed values for mechanical properties of the aluminium/steel interface, i.e. a minimum shear value of 5.6 $kgf{\cdot}mm^{-2}$ (55 MPa) and a minimum tensile value of 7.0 $kgf{\cdot}mm^{-2}$ (69 MPa).

The tests described appear to be the only currently acceptable methods of obtaining absolute values of mechanical properties, illustrating the difficulty of testing such a material. At present there are no British Standards which cover the testing of trimetallic composites. This considerably limits the quantitative data available. Some tests have been devised by interested parties in an attempt to produce an absolute set of values rather than a qualitative comparison of properties. At present, the only standard test is the ASTM A264 interface shear test for a clad material in which a specimen can be designed to enable testing of any part of the bond (Fig. 6c).

The tests carried out so far do not give much information on how Kelocouple will perform when in use in a ship at sea. The ideal research project would be to set up a test which would subject the test specimen to loads and forces experienced at sea in the working environment. This itself creates problems because of the complex nature of the forces and is very difficult to model. One area of research is the use of finite element analysis which enables models to be set up in which the material is subject to more complex loading. Attempts have been made in this area at RNEC, with some success[17].

Figs. 6(a)–6(d). Some methods for the mechanical testing of explosion-bonded transition joints (Specimens not to scale.)

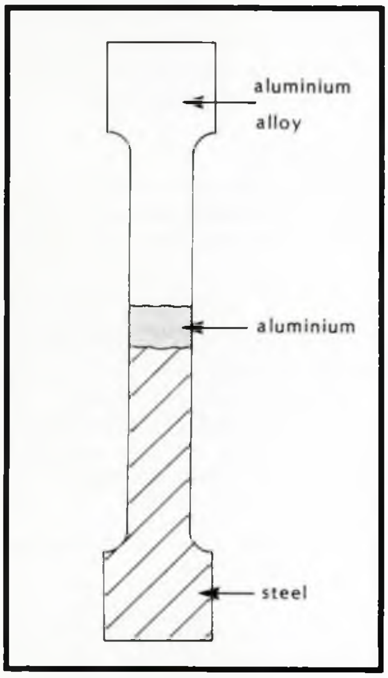


Fig. 6(a). Specimen for Hounsfield No. 12 test

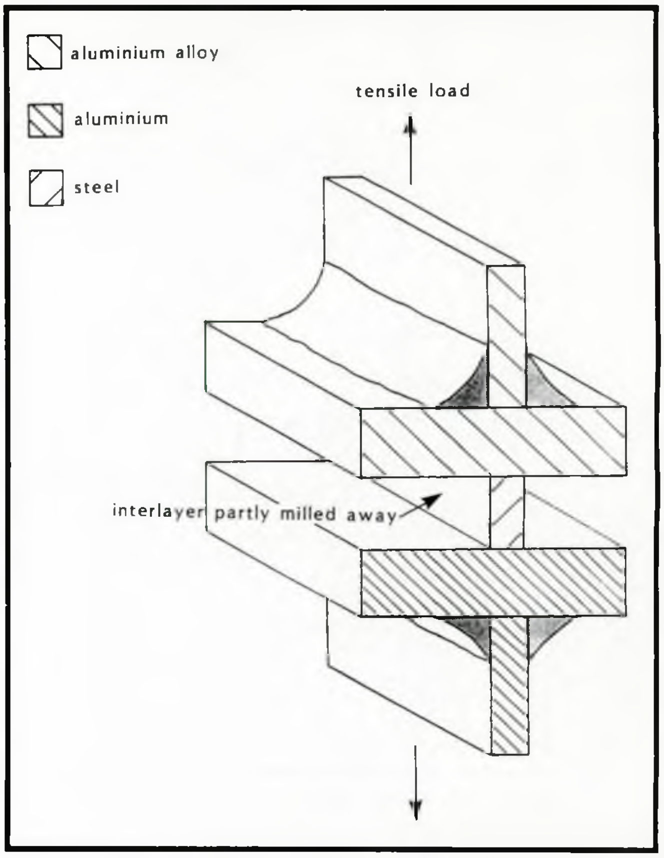


Fig. 6(b). Tensile test specimen

Recent developments

The excessive use of low-strength 1200 aluminium has already been highlighted by ICI as a drawback[18]. Recent improvements in the technique of explosion welding have enabled a reduction in the amount of 1200 aluminium, together with virtual elimination of the wave-like interface; reduction of the intermetallic content has not been achieved however. Fig. 4(b) illustrates the latest version, known as Kelocouple II. Tests[18] have shown a greater mechanical shear strength at the aluminium/steel interface, but no corrosion tests have been carried out. (These tests will have to be carried out before the material can be acceptable to the shipbuilding industry.)

A further development is to use different interlayer materials instead of the 1200 aluminium. The metal selected needs to possess a similar mechanical strength to the 1200 aluminium when bonded, but better performance in a marine environment. ICI have produced an aluminium alloy/steel joint with a titanium interlayer, but as yet no tests have been carried out for mechanical or corrosion properties[18].

APPLICATIONS OF KELOCOUPLE

The Royal Navy

At the Royal Naval Engineering College, a fleet survey was carried out during the period August–December 1987. In this section, the results are presented, in context with other information obtained during a study carried out by one of the authors[17]. Table 4 summarizes data for the ships concerned and Fig. 7 shows the extent of use of Kelocouple.

Of the shipyards which build ships for the Royal Navy, Hall

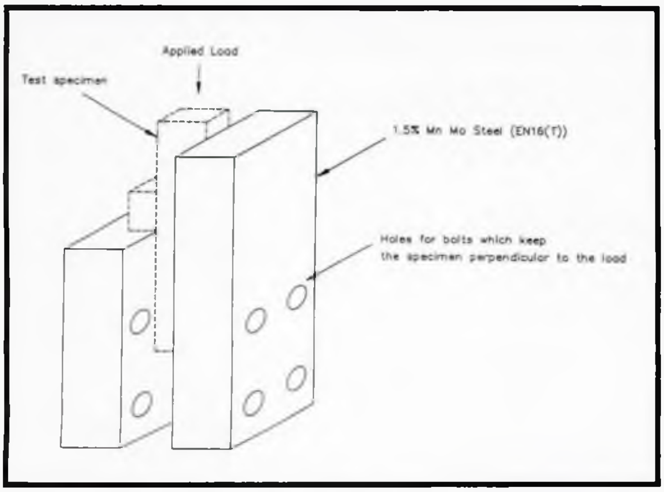


Fig. 6(c). Shear test, ASTM A264

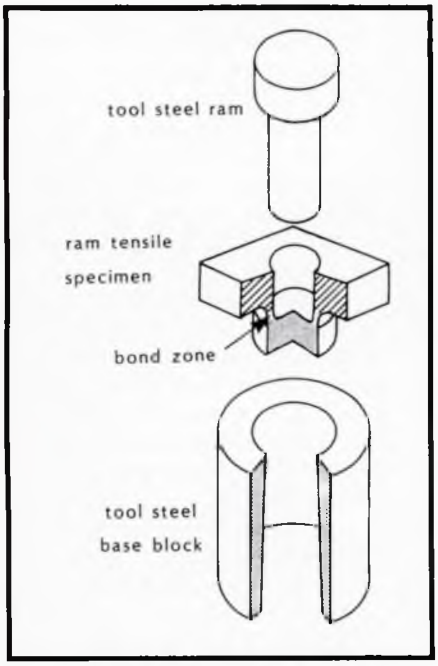


Fig. 6(d). Ram tensile test

Table 2. Results of mechanical tests carried out for Lloyd's Register
Manufacturers' data, reproduced with permission.

Test type	Specification	Result	
		kgf mm^{-2}	MPa
Shear (longitudinal)	ASTM A264	9.12	89.5
Shear (transverse)	ASTM A264	7.69	75.4
Ram tensile		12.72	124.8
Ram tensile		13.36	131.0
Tensile		10.63*	104.3
Tensile		8.42*	82.6
Tensile	Hounsfield No. 12	10.82	106.1

* Material failed in aluminium weld tail.

Russell, Yarrow and Swan Hunter Shipbuilders use Kelocouple. Shipyards first became aware of Kelocouple joints from technical data supplied by ICI. The use of Kelocouple was not originally specified by the Ministry of Defence, but was introduced by the shipyards after initial acceptance trials to meet requirements. Shipyards then used the 'follow build' principle within ship classes. This principle entails the use of plans and technical information supplied by the lead yards. Once accepted by MOD(N), Kelocouple was used thereafter for all aluminium/steel joints.

The survey highlighted the serious problems currently being experienced with rivetted joints and the need for a different method of jointing. The following reports were obtained from ships of the Bird Class.

HMS Peterel. Breakdown of the neoprene layer occurred in areas where the coach housing was joined to the upper deck. Corrosion ensued and corrosion products forced the aluminium/steel interface apart.

HMS Sandpiper. Similar to *Peterel* but, additionally, the joint was reported to have lost watertight integrity. Local reinforcement was required in the worst areas.

HMS Cygnet. Corrosion occurred at five rivetted areas and watertight security was lost. Replacement of damaged sections was necessary during refit.

The problems were not limited just to the Bird Class vessels, but were reported in Batch 1, Type 22 frigates also.

HMS Battleaxe. The after corners of the bridge wings, where joined to the steel deck, suffered cracking caused by the build-up of corrosion products which forced the aluminium/steel joint apart.

HMS Broadsword. As for *Battleaxe*, but rivets in the same area had corroded to such an extent that they were no longer joining the two metals together.

HMS Boxer. Corrosion was reported in all aluminium/steel joints because of breakdown of the neoprene insulation. Voluminous corrosion products had caused excessive tensile loading on the rivets, some of which had fractured.

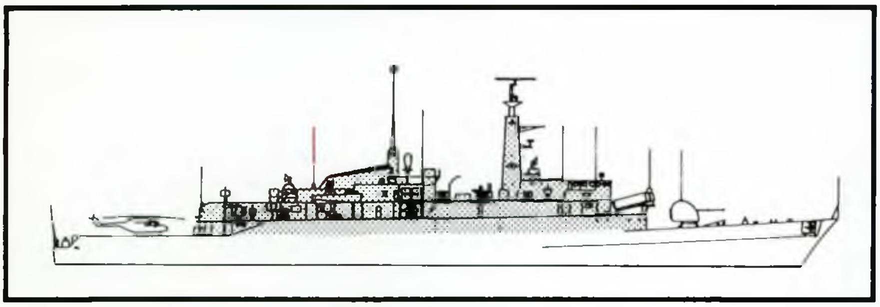
HMS Brilliant. Similar to *HMS Boxer.* Damaged sections had to be replaced with new rivetted joints during refit.

The first class of ship to be built using Kelocouple was the HKPV. All five were constructed at Hall Russell in Aberdeen, beginning with *HMS Peacock* in 1983. Together with *Plover, Starling Swallow*, and *Swift*, all have shown signs of slight rust at the transition joint, but not to an extent that could cause failure in the joint. Problems have occurred only because of damage to the protective paint scheme on and near the joint. For example, slight corrosion occurred in *HMS Starling* where the paint scheme had been damaged by chemical spillages. Use of anti-rust treatments was reported to have minimized the damage. At present, no defects have been officially reported with reference to the performance of the joint.

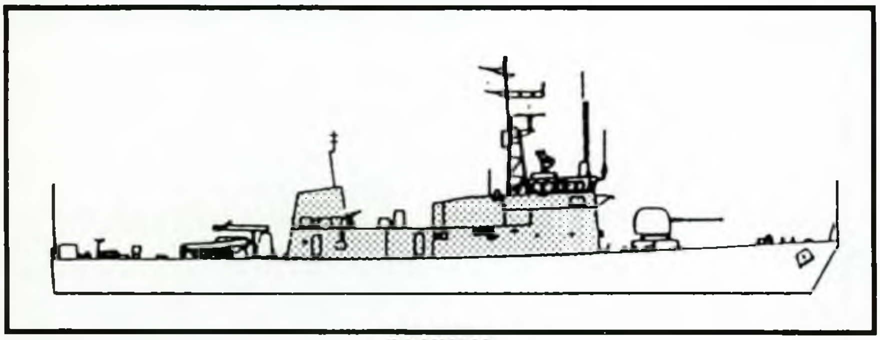
Yarrow has been involved with aluminium/steel jointing since the start of the Type 21 build programme (*HMS Amazon*), and until the Batch 1 Type 22, conventional rivetting techniques were used. Yarrow won the contract for the Batch 2, Type 22 and introduced Kelocouple in 1984 in the build of the third ship of the type, *HMS Brave*. Yarrow is the lead yard in the Batch 2

Table 3. Fatigue resistance data comparison for Kelocouple and rivets
Manufacturers' data, reproduced with permission.

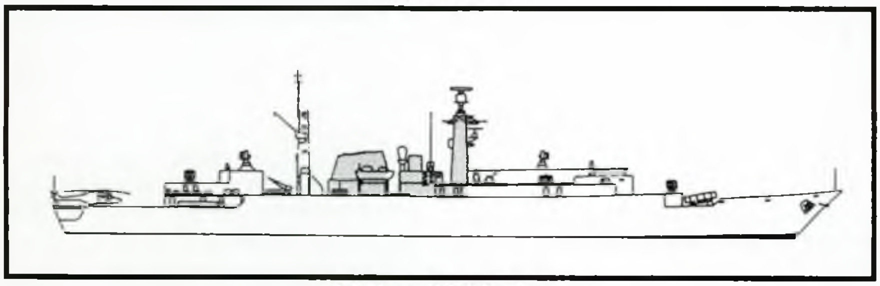
	Stress in web			
Specimen	Compression kgf mm^{-2} (MPa)	Tension kgf mm^{-2} (MPa)	Cycles to failure	Comments
Transition joint	10.5 (103) 10.5 (103) 7.0 (69)	3.5 (34) 0.7 (7) 2.1 (21)	395,000 721,500 1,267,400	All failed in HAZ of aluminium
9 mm rivets	10.5 (103) 10.5 (103)	3.5 (34) 3.5 (34)	31,600 63,300	Rivet fractured



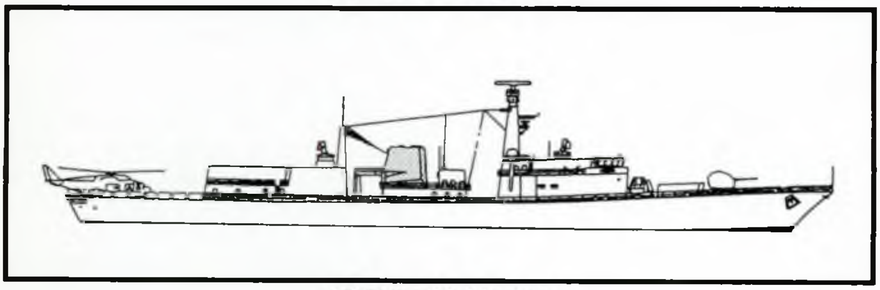
(a) Type 21 frigates



(b) HKPVs



(c) Type 22 frigates



(d) Type 23 frigates

Fig. 7. The extent of use of aluminium/steel joints in R.N. ships
Adapted from *Janes Fighting Ships* and used with permission.
Shaded areas represent aluminium superstructure.

and 3, Type 22 and 23 programmes with *Boxer*, *Cornwall* and *Norfolk* as lead ships of each class. Swan Hunter are the 'follow yard' in all the above programmes and have therefore used Kelocouple because it was specified by Yarrow. The only problems experienced during build were caused by porosity of the aluminium/steel interface in a particular batch of Kelocouple, which was subsequently replaced by ICI.

Batch 2 and Batch 3, Type 22 frigates are too new to have experienced corrosion problems during service. Some problems have been reported during fabrication and are listed below.

HMS Brave. Splitting occurred between the bonded surfaces due to an incomplete butt weld. The offending section was ground out and replaced during a maintenance period. As a temporary measure to prevent further crack propagation, the ends of the cracks were drilled to relieve the stress at the crack tips.

HMS Coventry. During preliminary inspection of the bridge area, it was noticed that the aluminium/steel interface had cracked because of excessive heat. The section was cut out and replaced.

The only other way in which Kelocouple is being used in the Royal Navy at present is in the new Type 23 frigate. As yet, *HMS Norfolk* is the only ship of this type to be close to having the Kelocouple used and it will be a long time before any results are available on the performance of the joint in service.

It is interesting to note that Kelocouple is, so far, used only at build and not to replace corroded rivet sections when a ship is in refit.

The United States Navy

The Spruance Class destroyer of the U.S. Navy is often referred to as a 'hot rod'. The ship includes four marine gas turbine engines with a deckhouse of aluminium. This use of aluminium has relieved the ship of 100 tons and so the maximum speed of the ship has been increased significantly[19]. This application used Detacouple, the original form of transition joint manufactured by Du Pont

Table 4. Results of fleet survey into the use of aluminium/steel joints (1987)

Pennant no.	Name	Class	Batch	Yard	Date*	Method†
F88	*Broadsword*	22	I	2	5/79(C)	R
F89	*Battleaxe*	22	I	2	3/80(C)	R
F90	*Brilliant*	22	I	2	5/81(C)	R
F91	*Brazen*	22	I	2	7/82(C)	R
F92	*Boxer*	22	II	2	11/84(C)	R
F93	*Beaver*	22	II	2	12/84(C)	R
F94	*Brave*	22	II	2	7/86(C)	K
F95	*London*	22	II	2	6/87(C)	K
F96	*Sheffield*	22	II	3	88(C)	K
F98	*Coventry*	22	II	2	88(C)	K
F99	*Cornwall*	22	III	2	12/87(C)	K
F85	*Cumberland*	22	III	2	88(C)	K
F86	*Campbeltown*	22	III	4	2/89(C)	K
F87	*Chatham*	22	III	3	10/89(C)	K
F169	*Amazon*	21		5	74(C)	R
F171	*Active*	21		5	77(C)	R
F172	*Ambuscade*	21		2	75(C)	R
F173	*Arrow*	21		2	76(C)	R
F174	*Alacrity*	21		2	77(C)	R
F185	*Avenger*	21		2	78(C)	R
F230	*Norfolk*	23		2	6/87(L)	K
F231	*Marlborough*	23		3	12/87(LD)	K
F232	*Argyll*	23		2	4/87(LD)	K
F233	*Lancaster*	23		2	9/87(LD)	K
P239	*Peacock*	HKPV		1	7/84(C)	K
P240	*Plover*	HKPV		1	7/84(C)	K
P241	*Starling*	HKPV		1	8/84(C)	K
P242	*Swallow*	HKPV		1	10/84(C)	K
P243	*Swift*	HKPV		1	5/85(C)	K
P260	*Kingfisher*	Bird		6	10/75(C)	R
P261	*Cygnet*	Bird		6	7/76(C)	R
P262	*Peterel*	Bird		6	2/77(C)	R
P263	*Sandpiper*	Bird		6	9/77(C)	R

KEY

Yard:
1. Hall Russell
2. Yarrow
3. Swan Hunter
4. Cammell Laird
5. Vosper Thornycroft
6. R. Dunston Ltd., Hessle

*Date: (LD) = laid down; (L) = launched; (C) = commissioned.
†Method: K = Kelocouple; R = rivets.

which is now manufactured under licence in the U.K. by ICI. After data was collected on the material, it was approved by the American Bureau of Shipping and U.S. Coast Guard commercial. The U.S. Navy have found that crevice corrosion problems within the rivetted system are virtually eliminated by the use of Detacouple. Virtually all shipyards which use explosion-bonded transition joints have reported it to be easier and more economical to install than mechanically fastened systems.

Detacouple has also been used extensively in the Todd-built FFG-7 Class patrol frigates. The use of aluminium superstructures has relieved the ships of some 200 tons weight. Centre of gravity is lowered and ship's stability is consequently improved.

Commercial shipbuilding

Kelocouple was first used in the fishing industry by the Crail (Fife) blacksmith, Robert Miller and Son. Aluminium deckhouses were joined to steel decks, and although installation costs were found to be slightly higher than with conventional methods, a much better joint was produced. The joints have also been used by the Campbeltown Shipyard which reported similar findings to those of Miller's. Other shipbuilders are assessing its potential role in the fishing industry. It is said that this advance in technology has increased the efficiency and long-term value of the fishing fleet[20].

The Royal National Lifeboat Institution has used Kelocouple in the Arun Class lifeboats. The construction of this vessel is interesting because of the need to use a double-hulled structure to provide adequate buoyancy. With the use of a steel main hull, aluminium superstructure and deck, plus aluminium bulkheads and inner hull sections, this has led to an extremely complicated structure. The decision was taken at an early stage to confine the use of Kelocouple to mainly internal joints, retaining conventional rivetting for attaching decks to the hull. This has led to some unnecessarily complicated interfaces between Kelocouple and aluminium decks. Seal welds have been required in unusual positions because of the requirement for absolute water-tight integrity. These welds have run normal to the bond interface across the whole depth of the joint. In most cases this has occurred at the end of a Kelocouple strip where it butts onto a flat plate, causing a short length of bond to delaminate. Examination showed that all the delamination resulted from welding carried out in a manner contrary to the manufacturer's recommendations and that none of the jointing was faulty.

Fairey Marinteknik are using Kelocouple in the Arun Class lifeboat, the Protector Class Patrol Craft for the Bahamas Police, and the Tyne Class lifeboats; a total of nine in all. To date, no major problems have been experienced.

CONCLUDING REMARKS

The importance of the aluminium/steel joint cannot be overstated. It is used to secure large parts of a ship's superstructure to the deck and needs to be structurally sound, as well as providing good corrosion resistance. Experience in the use of riveted joints has shown clear deficiencies in performance.

In instances where explosion-bonded transition joints have been used, problems so far encountered have generally occurred because manufacturer's guidelines have not been followed. Deviations from the guidelines can lead to a severe reduction in corrosion resistance and strength. Performance in service has so far been satisfactory, although the material is still relatively new. It is likely that, with the introduction of newly developed transition joint materials, the in-service performance will be further improved.

Research methods for examination of mechanical and corrosion properties remain somewhat inadequate. In particular, methods of providing reliable mechanical test data need to be established. More detailed study of the use of fillers is required to increase understanding of the corrosion mechanisms and protection of the join across the interface.

The use of explosion-bonded transition joints will, if implemented in the correct manner, provide an economical and efficient method of securing aluminium to steel in modern ships. These joints have already been accepted by the major shipping registers of the world and it seems that the only thing that prevents use on an even wider scale is the reluctance of shipbuilders to entrust such important work to a relatively new construction method. As more use is made of the material and the confidence of the shipbuilders is increased, a greatly increased application in future building projects will be found.

ACKNOWLEDGEMENTS

The authors are most grateful to Mr. D. G. Nowell and Mr. R. Hardwick of the Metal Cladding Department, Nobel's Explosives Company Limited, Stevenston, Ayrshire, and to Lieutenant Commander S. J. Bates, B.Sc., C. Eng., M.I.Mar.E., R.N. for considerable help given in the preparation of this article.

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Discussion

K. R. Trethewey (RNEC) I would like to point out that my experience of explosion-bonded transition joints is limited to the work described in the paper. R. Hardwick and D. G. Nowell from ICI Nobel's Explosives Co. Ltd., who are experts in the production and fabrication of the material, will assist in answering questions relating to this topic.

R. Hardwick (ICI Nobels) Dr. Trethewey invited comment on the variability of shear and other mechanical test results. An accurate qualitative result of bond strength of Kelocouple is difficult to achieve particularly in the case of Kelocouple I. This is because of the limitations of each testing procedure that he has already indicated but compounded by the physical characteristics of the particular bond, namely a 5 mm or so wavelength on this interface. As the sample width itself is only of this same order of dimensions, the location of the sample area with respect to the wave can be very significant. In the case of the shear test the lug width may contain an individual wave vortex which is predominantly intermetallic, thus adversely affecting the result. A shear lug site omitting a wave vortex would give a correspondingly enhanced result. The testing procedure should seek to minimize the effects of the sample site. This can be achieved more simply in Kelocouple II where the wavelength is only of the order of 1–1.5 mm, and a typical shear lug area can contain a greater number of waves thereby giving a sample area which is more representative of the plate properties generally.

R. Hardwick (ICI Nobels) In the light of the accelerated corrosion test results, is there any economic justification for developing a transition joint using an alternative interlayer to that of pure aluminium which would:

1. reduce the potential drop between the aluminium alloy and steel thereby reducing corrosion;
2. give an enhanced joint strength;
3. make the joint less heat sensitive?

Joint cost would probably increase due to the relative cost of the interlayer materials (perhaps 10–15%).

Is there a case to be made for more extensive use in aluminium superstructures to reduce the top weight of ro-ro ferries and improve stability to reduce the potential for capsizing?

Has consideration been given to abutting Kelocouple to the face of rivetted structures to facilitate welding of a shield to seal off corrosive media from the structure, as shown in Fig. 1 below?

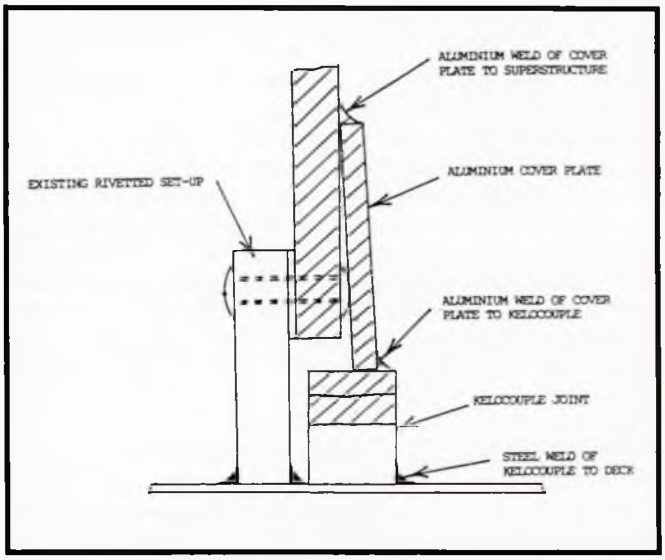

Fig. 1. Suggested method of excluding sea water from the rivetted joint construction of an existing ship
Modifications to accommodate other alternative constructions will be apparent.

K. R. Trethewey (RNEC) Our results show that, at present, Kelocouple seems to be meeting admirably the needs of the maritime industry. Corrosion has not proved to be anything like the problem we envisaged when we set out on our test programmes and all the experience of the Royal Navy indicates satisfactory performance so far. Whether this continues to be the case during the next 20 years remains to be seen. It is doubtful, therefore, whether any justification could be found for producing more expensive explosion-bonded joints with different interlayers unless other constraints changed, such as the design lifetime, or an application in which a smaller joint thickness was essential. Obviously, I express an opinion only about the marine industry; other industries have vastly different needs. I think the point about the use of aluminium superstructures on ro-ro ferries is a good one, but I do not know enough about the constraints of the ferry operators to offer more than that opinion. The question about the use of Kelocouple for improvement of the existing rivetted structures is an excellent one and I see no reason why the Ministry should not adopt the practice illustrated in the diagram supplied by Mr. Hardwick (Fig. 1 above). There is certainly a good amount of current repair work of rivetted structures being carried out. The suggested method would almost certainly prove to be quicker than the present cut out and replacement policy.

F. D. Petit (The Crown Agent for Overseas Administrations) Firstly I would like to congratulate the authors on an interesting and clearly presented paper.

1. Could the authors suggest a simple site inspection check for Kelocouple I and II before fabrication?
2. Can Kelocouple II be more readily bent than Kelocouple I?
3. Can Kelocouple II strips be used in fuel tanks?
4. What tests, other than corrosion, are required before Kelocouple II can be used, and when will it be available for use?
5. Can aluminium alloy be explosion-bonded to stainless steel?

K. R. Trethewey (RNEC) I am afraid I am not able to suggest a simple site inspection check. I would like to refer the remaining questions to Mr. Nowell and Mr. Hardwick.

D. G. Nowell (ICI Nobels) Kelocouple can be used for fuel tanks but we would recommend internal sealing over the joint interface. Porosity across the interface would then not be a problem. Kelocouple II would pose less problems in this respect due to the smaller wavelength and amplitude which limits the size of any porous intermetallic associated with the wave vortices. We would however, still recommend the use of a sealant layer within the tank.

The smaller wavelength and amplitude would not cause Kelocouple II to bend more readily but it is reasonable to expect a better result after bending and perhaps a tighter radius might be viable before the onset of problems.

R. Hardwick (ICI Nobels) We confirm, in response to the question, that stainless can be joined to aluminium, but a product similar to Kelocouple in these materials would require development. Certainly, explosively bonded stainless steel–aluminium alloy transition joints have been used in the aerospace industry, demonstrating the viability of bonding the two materials. We have suggested that such a product might be viable in response to a query concerning the suitability of Kelocouple II as rubbing strake attached to the keels of shore launched lifeboats. The use of stainless in this case would avoid the rusting of the comparable carbon–steel component which would arise when paint was removed from the steel during launching.

S. J. Bates (Royal Navy) I wish to thank the authors for a most interesting paper. I was particularly interested in the lucid and topical summary of the applications of Kelocouple, especially in the Royal Navy.

The authors will know that my involvement with this material dates back to 1985 when Lt. Cdr. Trethewey and I co-supervised R. Pask and S. Mohammet's work (ref. 15 of the paper). At that time, R. Pask and S. Mohammet visited a commercial shipyard at which a Batch III Type 22 frigate was being built. These authors reported some examples of 'out of specification' butt welding of Kelocouple to Kelocouple, particularly in inaccessible areas. We concluded at that time that such sites provided likely areas of galvanic attack in a marine environment. The author's fleet survey has not indicated any such problems so far, but I wish to emphasize the remark in the paper that Batch II and III Type 22s have not been sufficiently long in service to enable a full comparison between rivetted designs such as Type 21s and Kelocouple designs such as the later Type 22s.

When welded in accordance with ICI (Nobel) recommendations, I must agree that Kelocouple appears to be a superior alternative to the rivetted/neoprene sealed type of joint but would caution against over-optimism until the Kelocouple-built frigates have had a few more years at sea.

K. R. Trethewey (RNEC) The poorly welded joints reported in the Pask and Mohammet work to which Lt. Cdr. Bates refers were indeed cause for concern at the time, especially when taken in the context of the serious pitting corrosion being observed in salt spray exposure tests. However, it would appear that the combination with paint provides a greatly reduced chance of pitting corrosion, and all I can say is that there is no present evidence of in-service problems. I agree with Lt. Cdr. Bates that it may be too early to say that there will be no problems in the future, but there seems little doubt that Kelocouple performs much better than the rivetted joints and will result in significantly reduced maintenance.

R. Hardwick (ICI Nobels) To add comment to Dr. Trethewey's response, we have found that many of the dubious welding practices which do occur in shipyards when attaching Kelocouple are the result of the welder not being aware of the correct welding practice. The welding guidelines for installation of Kelocouple supplied by ICI have not been issued to the welder in any cases and, therefore, he is in no position to know whether the procedure he is adopting is correct or incorrect.

A solution to this problem adopted by some companies is to transfer the fundamentals of the ICI guidelines onto the drawings applicable to the specific construction being undertaken by the welder.

K. S. Harvey (The Salvage Association) I congratulate the authors and thank them for what I have found to be an extremely interesting and informative paper which will be a valuable contribution to the Institute's Transactions.

There are several points which I would like to comment on and concerning which I request the authors' assistance.

Referring to Fig. 5 of the paper, it would appear that the strength of the explosion-bonded joint is a function of the strength of the pure aluminium, and I wonder if the pictorial view presented is to scale. It seems that the width of the transition as well as the thickness is about 4-times that of the alloy attachments but perhaps this could be confirmed.

Concerning item 6, under 'Fabrication techniques', a joining of joints is mentioned. May I suggest that it would be helpful if the authors could elaborate on this aspect in their reply to the discussion as regards mitre joints or other types of joint involving the abutment of pure aluminium.

Can the authors advise from the results of tests, if any, carried out to define the corrosion/fatigue characteristics, i.e. what role the corrosion plays towards reduction of fatigue with respect to the transition joint in specific terms?

In Table 3 of the paper there appears to be a great variance between the results of two rivet tests. Are the figures as typed correct? When the transition joint test results are transposed into a log stress–log N graph this does not produce a straight line gradient. Can the authors comment please?

Finally have any comparisons been made between the explosion-bonded transition joint method and friction welding?

K. R. Trethewey (RNEC) You are correct in stating that the strength of the joint is a function of the strength of the aluminium, despite our best effort to cause failure at the interface, even with corroded ones. Fig. 5 of the paper does indeed represent the relative recommended thicknesses. With reference to the request for a diagram of the mitre joints, I apologize for the omission of this Figure from the paper; this was for technical reasons. I would refer Mr. Harvey to ref. 12 of the paper, obtainable from Nobel's Co., which contains full details of the information requested. In response to Mr. Harvey's questions about the mechanical tests, I can only repeat that our experience is that the reliability of data is unsatisfactory when compared with similar mechanical test data for single materials. Despite a considerable amount of work carried out in our laboratories, our own data was quite inconclusive about any corrosion effects on the fatigue life of the joints and this is the reason why we did not include it in the paper. Mr. Hardwick has already supported our comments about the nature of the interfacial region interferring with the performance of the joints under test. This is probably part of the reason for the discrepancies noted by Mr. Harvey about the data in Table 3, but I must point out that this was not our data. (I confirm that the data for the rivets is typed correctly.) Finally, I do not know of any comparisons between explosion bonding and friction welding.

R. Hardwick (ICI Nobels) In response to Mr. Harvey, concerning the proportions of the Kelocouple strips relative to the thickness of the principle components, we confirm that the widths of the strips recommended by ICI are 4-times that of the thickness of the component. This recommendation, as Mr. Harvey rightly deduced, is related to the weaker aluminium interlayer whose tensile strength is typically 25% of that of the alloy being jointed. Consequently, the width of 4-times the component thickness effectively ensures the tensile strength of the joint equates with that of the parent component. As Mr. Harvey also inferred, the thickness of the interlayer is also significant in relation to the shear strength of the joint and for this reason the thickness of the interlayer of Kelocouple II is only 2 mm compared with the 10 mm of Kelocouple. Consequently, the shear strength of Kelocouple II, as indicated by test results, is some 33% greater than that of Kelocouple. We should point out in view of the various questions relating to Kelocouple II, that this product is not commercially available at this stage as the product is currently being qualified for the various relevant inspection bodies.

M. H. P. Hembling (LR) I thank the authors for a most interesting paper. It is noted that several references are made to temperature restrictions at the aluminium/steel interface and in this respect I would like to comment on the recommendations on shipyard practice given in the paper as follows.

The use of GMAW(MIG) for the steel connection permits a relatively high heat input. From the practical aspect, this is easier to control if MMAW is used as the size of electrode supplied to the welder can be restricted.

It is virtually impossible to measure the temperature at the interface and therefore the figure quoted is of little practical use. In order to use Tempilsticks for control purposes, a corresponding surface temperature would be required. It is presumed that a back-step or similar method of welding is used and if this were put down in several small runs, then the interpass temperature control may cease to be important.

It was seen during the slide presentation that staggered intermittent welding was being used on the Al–alloy connections. It is presumed that, due to the lower welding temperature, this is less critical than the steel connection but confirmation, or otherwise, of the acceptability of this practice would be appreciated.

More specific information about temperature and, better still, heat input restrictions would be most useful in establishing weld procedures for the use of this transition joint.

Finally, with regard to the butt and mitre joints shown during the presentation, has consideration been given to the possible application of adhesives to a scarped or joggled joint?

K. R. Trethewey (RNEC) We have no experience in the use of adhesives for such joints. This may be a fruitful area for further research. I would like to thank Mr. Hembling for his constructive comments on welding practice with which I agree. I would also point out that in our test programme we have found no evidence to support the view that overheating causes problems. This is not to say that there are no problems, but is more a reflection of the difficulty of obtaining reproducible mechanical test data. However, I know that Mr. Nowell has had some problems in this area.

D. G. Nowell (ICI Nobels) Dr. Trethewey, in response to the effects of overheating the joint, has referred to their experimental results which certainly do indicate that the effects of overheating might be exaggerated. It is also interesting and gratifying to note that his research has not revealed any case of joint separation attributable to overheating. Dr. Trethewey rightly suspects that ICI might be erring on the side of caution but this is because we do ourselves know of such an experience where, in bonding Kelocouple to an aluminium Helipad, thick weld runs were being put down on the aluminium side of the joint with no heat sink at the steel side. The problem was compounded by weld runs taken over the interface. We therefore suggest that a welder, like ourselves, should err on the side of caution as joint separation can occur in extreme cases. The earlier comment by Mr. Hembling, recommending the obligatory use of smaller rod sizes to prevent an excessive rate of weld deposition and associated high heat input, is certainly one we would endorse.

E. Y. Fewster (Frear Pty Ltd.) The authors should be congratulated on a well researched and delivered paper dealing with a recent technological development.

In the preprint of the paper, Fig. 5 (Geometry for the assembly of structures by means of explosion-bonded transition joints) shows the geometry of the assembly, and the author showed a slide of the preparation for a butt weld.

No doubt the bevel angles of the butt preparation would be the standard bevels for the three types of materials. Would the author indicate the sequence of welding the three elements, bearing in mind the difference in fusion temperatures required? Further, would he indicate the preferred welding technique, that is stick, TIG, MIG, for both butt welds and the longitudinal welds? Would he also indicate the off-the-shelf stock sizes available for length of strip, together with the cross-sectional dimensions which are readily available?

The paper outlines mechanical testings (Fig. 6a). Can the author comment on forms of non-destructive quality control during manufacture to guard against the possibility of non-bonded pockets, or tendency to lamination?

K. R. Trethewey (RNEC) Bearing in mind the comments made by Mr. Hembling, details regarding the welding processes are to be found in the manufacturer's guide (ref. 12 of the paper). This states that both aluminium and steel welding may be performed by the MIG process. Where MIG is not available, metal arc or TIG may be used. For the aluminium welds, an argon shielding gas should be used. The steel welds should be completed first; several short passes should be made to minimize bond zone temperatures.

D. G. Nowell (ICI Nobels) Each plate is ultrasonically tested over its full area and a sample is taken for an appropriate destructive test to be made. Subject to a satisfactory result, the plate is then trimmed and cut into strips of appropriate width as required by the customer. Individual strips are then visually examined and each end of the strip is subjected to a chisel test to confirm that failure at that point occurs in the aluminium and not at the bond. Standard widths are 16, 25, and 30 mm from stock but strips can be cut to any width up to that of full plate size or indeed any shape of component can be produced for a given customer demand.