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State-of-the-Art Survey of Joinability of Materials for OTEC Heat Exchangers

R. J. Beaver

OAK RIDGE NATIONAL LABORATORY
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R. J. Beaver

ABSTRACT

Literature and industrial sources were surveyed to assess, on the basis of apparent economics and reliability, the joinability of both shell-and-tube and compact ocean thermal energy conversion (OTEC) heat exchangers. A no-leak requirement is mandatory to prevent mixing seawater and the ammonia working fluid. The operating temperature range considered is 7 to 28°C (45 to 82°F).

Materials evaluated were aluminum, titanium, copper-nickel, AL-6X austenitic stainless steel, singly and in combination with steel and concrete. Many types of welding and brazing processes, roller expansion, magnaforming, O-ring sealing, and adhesive bonding were considered.

The automatic gas tungsten-arc welding process and explosion welding processes are the only two joining processes that now appear to offer the high reliability required of no-leak shell-and-tube heat exchangers. Of these two processes, the gas tungsten-arc welding process appears to be the more economically attractive.

Because of the no-leak requirement, the selection of a process for joining compact heat exchangers is more uncertain than for the shell-and-tube heat exchangers. Mechanical joining by gasketing has been reported as successful in preventing interleakage and under such circumstances would appear to be a most attractive process; however, the compatibility of gasketing material with anhydrous ammonia is questionable. Welding is a possibility, but, depending on the design requirements, control of distortion may not be feasible. Resistance seam welding has been reported as successful in joining honeycomb structures. Although somewhat costly at present, electron beam and laser welding processes should not be overlooked. Fluxless soldering and brazing have successfully joined relatively small modules. In the case of fluxless soldering, the 95 Zn-5 Al filler commonly used is not likely to be compatible under the OTEC environmental conditions. In the case of fluxless brazing, although relatively small modules have been manufactured to no-leak requirements, the reliability with the scale-up to the modular size indicated for OTEC compact heat exchangers is uncertain. Adhesive bonding of joints cannot be discarded as a possibility; however, the long-term tests needed to demonstrate reliability under OTEC

environmental conditions and the higher costs entailed in controlling quality during processing are complicating factors.

Results of development and experience indicate that joining aluminum, titanium, or copper-nickel to steel is feasible if proper procedures are followed. Structural joints of metals to concrete appear conceivable if the metals are encapsulated into and bonded to the concrete.

INTRODUCTION

The present base-line design concept for the OTEC (Ocean Thermal Energy Conversion) power system operating in the temperature range of 7 to 28°C (45 to 82°F) uses ammonia (NH_3) as the working fluid. The expected electrical output is 25 MW(e) per power module in a 100 MW(e) plant. Plants of this size require heat exchange equipment having large heat transfer areas. For example, in one conceptual design[1] for a 25 MW(e) module an aluminum shell-and-tube heat exchanger required a heat transfer area of 1.057×10^5 m^2 (1.38×10^6 ft^2) [approximately 40,000 tubes 64 mm OD by 13.0 m long (2.5 in. by 42.5 ft)]. In another example,[2] the design of a plate-fin heat exchanger for a 26 MW(e) plant indicated that the module was 16 m (52 ft) high overall and consisted of 144 submodules. In each submodule the NH_3 channel was 4.1 mm (0.16 in.) high and approximately 13 mm (1/2 in.) wide.

Leakage of seawater into the NH_3 will quickly deteriorate the NH_3 working fluid and adversely affect economics of operation.[3] Therefore, a mandatory requirement of OTEC designs is that no leakage occurs.[4] Reliability of joints (leaktightness, mechanical integrity, corrosion resistance, etc.) that separate the working fluid from seawater is therefore of paramount importance. The selection of a joining technique must be based primarily on these as well as economic considerations. Thus, this report represents the "state of the art" in the joinability of materials presently under consideration. These materials are aluminum, titanium, copper-nickel alloys, and AL-6X, a recently developed austenitic stainless steel. Design considerations also involve joining dissimilar materials, such as aluminum to steel, titanium to steel, and metal to concrete. The following joining methods have been examined in establishing the present state of the art: roller expansion, O-ring seals, magnaforming, fusion welding, brazing, soldering, explosion welding, and adhesive bonding.

References

1. Lockheed Missiles and Space Company, Inc., *OTEC Heat Exchanger Design and Producibility Study, Part A — Sections 1 and 5*, LMSC-D507632 (Part A) (Oct. 28, 1976), p. 81.

2. W. B. Suratt et al., "Plastic Heat Exchangers for Ocean Thermal Energy Conversion," pp. 138–41 in *Proceedings, Third Workshop on Ocean Thermal Energy Conversion (OTEC)* APL/JHU-SR-75-2 (August 1975).

3. Lockheed Missiles and Space Company, Inc., *OTEC Heat Exchanger Design and Producibility Study, Part C — Appendixes G Thru J*, LMSC-D507632 (Part C) (Oct. 28, 1976), p. I21.

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1. JOINABILITY OF ALUMINUM

Gas Tungsten-Arc Welding (GTAW)

This welding process has been used effectively for joining aluminum.[1] Alloys under consideration for OTEC systems at present are limited to 3003 and the 5XXX Series, with the 5XXX Series favored by the Lockheed Missiles and Space Company as the reference material for shell-and-tube heat exchangers.[2] Alloy 3003, however, offers an economic advantage because it can be welded autogenously.[3] The following alloys in these series are reported[4] as "readily weldable:"

In the 3XXX Series: 3003 and 3004

In the 5XXX Series: 5005, 5050, 5052, 5083, 5086, 5254, 5454, 5456, 5652

The filler metals commonly used for the alloys in these series are identified and rated[4] with respect to ease of welding in Table 1.1. Filler 4043 should not be used on the higher magnesium alloys 5086, 5083, or 5456, since excessive quantities of magnesium-silicon eutectics can develop in the weld structure and decrease ductility and increase crack sensitivity.[5]

Apparently the best all-around filler metal for the high strength alloys 5083, 5086, and 5456 is filler metal 5356, but filler metals 5556 and 5183 provide slightly higher strength with moderate sacrifice in ductility and ease of welding.[6] The crack sensitivity of aluminum-magnesium alloys during welding tends to decrease as magnesium content is increased above 1.5%, at which level cracking sensitivity is the greatest.[6] It has been reported[6] that when the magnesium content exceeds 2.5 to 3%, the crack sensitivity is low enough so that the alloy is easily welded. It has also been reported[7] that GTA welds in 5083 and 5086 alloys made with 5183 filler metal exhibit joint efficiencies of 80 to 100%, depending on the base metal temper, and that the average transverse weld tensile strengths of 5083 and 5086 weldments were 293 and 267 MPa (42.5 and 38.7 ksi), respectively.

Table 1.1. Ratings of Filler Metals Commonly Used in Arc-Welding Aluminum Alloys of Interest to OTEC[a]

Alloys to be Welded	Rating for Each Filler Metal																							
	Ease of Welding						Strength of Welded Joint (as-welded)[b]						Corrosion Resistance[c] Filler Alloy						Ductility[d]					
	1100	4043	5654	5356	5554	5556	1100	4043	5654	5356	5554	5556	1100	4043	5654	5356	5554	5556	1100	4043	5654	5356	5554	5556
To weld alloy 3003 to:																								
3003, alclad 3003	A	A	–	B	–	B	C	B	–	A	–	A	A	A	–	e	–	e	A	D	–	B	–	C
3004, alclad 3004	–	A	–	B	–	B	–	B	–	A	–	A	–	A	–	e	–	e	–	C	–	A	–	B
5005, 5050	B	A	–	B	–	B	C	B	–	A	–	A	A	A	–	–	–	–	A	D	–	B	–	C
5052	–	A	–	B	–	B	–	B	–	A	–	A	–	A	–	–	–	–	–	C	–	A	–	B
5154	–	A	C	B	C	B	–	B	A	A	A	A	–	C	A	B	A	B	–	C	A	A	A	B
5454	–	A	–	B	C	B	–	B	–	A	A	A	–	C	–	B	A	B	–	C	–	A	A	B
5083, 5086, 5456	–	A	–	A	–	A	–	B	–	A	–	A	–	B	–	A	–	A	–	C	–	A	–	B
To weld alloy 3004 to:																								
3004, alclad 3004	–	A	C	B	C	B	–	D	C	B	C	A	–	A	B	e	B	e	–	C	A	A	A	B
5005, 5050	–	A	–	B	–	B	–	B	–	A	–	A	–	A	–	–	–	–	–	C	–	A	–	B
5052	–	A	–	B	–	B	–	C	–	B	–	A	–	A	–	–	–	–	–	C	–	A	–	B
5154	–	A	C	B	C	B	–	D	C	B	C	A	–	C	A	B	A	B	–	C	A	A	A	B
5454	–	A	–	B	C	B	–	D	–	B	C	A	–	C	–	B	A	B	–	C	–	A	A	B
5083, 5086. 5456	–	A	–	A	–	A	–	C	–	B	–	A	–	B	–	A	–	A	–	C	–	A	–	B
To weld alloy 5005 or 5050 to:																								
5005, 5050	C	A	–	B	–	B	–	B	–	A	–	A	A	A	–	–	–	–	A	D	–	B	–	C
5052	–	A	–	B	–	B	–	B	–	A	–	A	–	A	–	–	–	–	–	C	–	A	–	B
5154	–	A	C	B	C	B	–	B	A	A	A	A	–	C	A	B	A	B	–	C	A	A	A	B
5454	–	A	–	B	C	B	–	B	–	A	A	A	–	C	–	B	A	B	–	C	–	A	A	B
5083, 5086 5456	–	A	–	A	–	A	–	B	–	A	–	A	–	B	–	A	–	A	–	C	–	A	–	B
To weld alloy 5052 to:																								
5052	–	A	B	A	C	A	–	D	C	B	C	A	–	C	B	–	B	–	–	C	A	A	A	B
5154	–	A	B	A	C	A	–	D	C	B	C	A	–	C	A	B	A	B	–	C	A	A	A	B
5454	–	A	B	A	C	A	–	D	C	B	C	A	–	C	B	B	A	B	–	C	A	A	A	B
5083, 5086 5456	–	–	–	A	–	A	–	–	–	B	–	A	–	–	–	A	–	A	–	–	–	A	–	B
To weld alloy 5083 or 5456 to:																								
5154	–	–	B	A	B	A	–	–	C	B	C	A	–	–	A	A	A	A	–	–	A	A	A	B
5454	–	–	–	A	B	A	–	–	–	B	C	A	–	–	–	B	A	B	–	–	–	A	A	B
5083, 5086 5456	–	–	–	A	–	A	–	–	–	B	–	A	–	–	–	A	–	A	–	–	–	A	–	B
To weld alloy 5086 to:																								
5154	–	–	B	A	B	A	–	–	C	B	C	A	–	–	A	A	A	A	–	–	A	A	A	B
5454	–	–	–	A	B	A	–	–	–	B	C	A	–	–	–	B	A	B	–	–	–	A	A	B
5086	–	–	–	A	–	A	–	–	–	B	–	A	–	–	–	A	–	A	–	–	–	A	–	B
To weld alloy 5154 to:																								
5154	–	–	B	A	B	A	–	–	C	B	C	A	–	–	A	–	A	–	–	–	A	A	A	B
5454	–	–	B	B	B	A	–	–	C	B	C	A	–	–	A	B	A	B	–	–	A	A	A	B
To weld alloy 5454 to:																								
5454	–	–	B	A	B	A	–	–	C	B	C	A	–	–	B	B	A	B	–	–	A	A	A	B

[a]Ratings A, B, C, and D are relative, in decreasing order of merit, and apply only within a given block. Combinations having no rating (-) are not recommended

[b]Rating applies particularly to fillet welds. All filler alloys rated will develop presently specified minimum strengths in butt welds.

[c]Rating based on continuous or alternate immersion in fresh or salt water.

[d]Rating based on free-bend elongation of weld.

[e]Filler metals 5356 and 5556 are not recommended for corrosion resistance in welding alloy 3003 or 3004 to bare 3003 or 3004, but are rated B for welding alloy 3003 to alclad 3003 or 3004 and C for alloy 3004 to alclad 3004.

Gas Metal-Arc Welding (GMAW)

Gas metal-arc welding (GMAW) is feasible for automatic welding of aluminum alloys.[4] Examples of automatic welding include a 1.8-m-diam by 24-m-long (6 by 80 ft) heat exchanger of alloy 5083-0, where 23 weld passes were made in some joints; an amphibious fighter made of alloy 5083; joints of alloy 5154 to alloy 6063-T42 in a cylindrical pressure vessel; a truck radiator grill of alloy 5052 welded to alloy 6063; and a pressure vessel of alloy 5254.

Gas Welding

Although this method offers the economical advantage of simple, low-cost equipment, the disadvantages are (1) flux residue, which must be removed; (2) a wide heat-affected zone; and (3) lower welding speeds compared with the gas shielded arc processes.[5]

Electron-Beam Welding

The welds are characterized by deep, straight-sided, and narrow penetration, and distortion and shrinkage are minimal.[5] The mechanical properties of electron-beam welds in the 3XXX and 5XXX Series are virtually the same as obtained by the gas tungsten-arc process.[4] This method offers the potential of welding the 5XXX Series autogenously as exemplified by a shell of a sequential timer in which alloy 5052-H32 was welded to alloy 5052-H22.[4]

Laser Welding

A recent review by the United Technologies Research Center[8] of the status of laser welding of aluminum indicated the following:

1. Aluminum alloys are the most difficult to laser weld because of their high initial surface reflectivity for CO_2 laser radiation.
2. The main difficulty in the formation of laser welds in aluminum alloys has been the generation of porosity.

3. Some success has been achieved in laser welding of 2219 and 5456 alloys. Both these materials have been welded in thicknesses up to 9.5 mm (0.375 in.) with acceptable bead geometry and microstructure, but it has not yet been possible to completely eliminate porosity.

4. Room-temperature tensile tests indicate that the ultimate tensile strength of the welds is essentially the same as that of the base metal.

Resistance Welding

The 3XXX and 5XXX Series aluminum alloys are weldable by resistance welding, and the fusion and heat-affected zones "are not selectively attacked by corrosion," a phenomenon that occurs, for example, in the 2XXX and 7XXX Series.[5] Resistance seam welding is therefore a very conceivable process for obtaining leaktight joints in compact heat exchangers (e.g., fin-plate type). Typical settings for seam welding the the 3XXX and 5XXX alloys have been identified,[5] and the more important conditions for seam welding alloy 5052-H34 using a conventional single-phase seam welding machine are given[4] in Table 1.2. The quality control during production is limited principally to qualification of the entire process and strict control during manufacturing. Development of ultrasonic inspection techniques for possible weld imperfections would improve the assurance of leaktight joints before subsequent pressure testing.

Table 1.2. Pertinent Parameters in Making Gastight Resistance Seam Welds in Sheet Thicknesses of Alloy 5052-H34 of Interest to OTEC[a]

Sheet Thickness		Spots		Total Weld Time, Cycles[b]	Wheel Speed		Heat Time, Cycles[d]		Electrode Force		Welding Current, (A)	Width of Weld	
(mm)	(in.)	per m	per in.		mm/s	fpm[c]	min	max	kN	lb[e]		(mm)	(in.)
0.81	0.032	630	16	5.5	17	3.4	1	1.5	3.07	690	29,000	3.3	0.13
1.63	0.064	394	10	11.5	13	2.6	2	3.5	4.27	960	38,500	4.8	0.19
2.59	0.102	315	8	20.5	9	1.8	4	6.5	5.45	1230	43,000	6.6	0.26

[a]60-cycle single-phase direct-energy welding machines. Electrode and work metal must be cooled with water at 0.13 to 0.2 liter/s (2–3 gpm).

[b]Heat time plus cool time.

[c]Wheel speed is adjusted to give desired number of spots per unit length.

[d]Heat time must be set at full-cycle setting if total time is set at full-cycle setting.

[e]Electrode force and welding current are adjusted to give desired width of weld.

Cold Welding

Cold welding is a solid-state welding process wherein coalescence is produced by the external application of mechanical force alone.[5] The effect of cast structure produced when metals are melted and the heat produced during high-temperature joining operations are eliminated by this method.

Cold welding is generally limited to butt-welding and lap-welding, surface preparation must be strictly controlled, and pressures ranging from 1.0 to 3.5 GPa (150×10^3 to 500×10^3 psi) (depending on temper of the alloy) are required to obtain a metallurgical bond.[5] Excellent lap-welds of the 3XXX Series have been obtained, but alloys containing more than 3% Mg (which are among the 5XXX Series) are not readily lap-welded.[5]

Explosion Welding

Explosion welding is a process in which a force obtained from the detonation of an explosive drives the two parts together and creates a metallurgical bond with minimum distortion. The bonded region is typified by a rippled interface, which increases metal-to-metal bond surface.[5] Under the proper conditions, the following aluminum alloys can be explosion welded:[9]

Alloy 1100	Alloy 5083-H24
Alloy 2024-T3 and -0	Alloy 6061-T6
Alloy 2214-T6	Alloy 7178-0
	Alloy 7075-T6

Soldering and Brazing

Soldering and brazing processes offer the advantage of metallurgically bonding all joints simultaneously at a temperature below the melting temperature of the base metals. Therefore, compared with welding, the potential for dimensional control as a consequence of less distortion is improved. For these reasons, soldering or brazing of compact OTEC heat exchangers is worthy of consideration.

The use of flux in the soldering or brazing process is not recommended for OTEC heat exchangers. Fluxes usually contain chemical elements that can have harmful effects on other parts of a plant system if the flux is trapped or not completely removed in cleaning.[4] In addition, entrapped flux can be a source of a leak that may develop during operations. As an example, the flux used for brazing aluminum usually consists of mixtures of alkali and alkaline earth chlorides and fluorides, sometimes containing aluminum fluoride or cryolite and, where necessary, small amounts of chlorides of Sb, Cd, Cr, Co, Cu, Fe, Pb, Mn, Ni, Si, Sn, Zn, precious metals, or rare earths.[4]

Fluxless soldering, which uses ultrasonics to remove the oxide from aluminum surfaces by vibratory motion of the molten solder, has been developed and used to join the tubular elements in the tube-fin heat exchanger coils.[10-12] The soldering alloy commonly used as a reference alloy is 95 Zn-5 Al, but the corrosion resistance of this alloy under OTEC environmental conditions is questionable.[13]

The principal techniques developed for fluxless brazing of aluminum are (1) motion brazing and (2) the addition of magnesium in the brazing alloy. Motion brazing includes both vibration brazing and flow brazing.[4] In either technique brazing should be done in the absence of air to obtain consistently sound joints, although simple shapes have been joined in air by flow brazing.[5] Vibration brazing appears to be most adaptable to joints when brazing sheets are used. The brazing-sheet surfaces are held together at a temperature preferably above the liquidus of the brazing alloy. The relative movement between the brazing sheets developed by low or ultrasonic frequencies displaces the oxide film on the semi-liquid contact surfaces.[4] In flow brazing the part to be brazed or the molten filler metal is moved rapidly with respect to the other, causing a mechanical removal of oxide film and the mating of liquid-liquid or solid-liquid interfaces.[4] The motion brazing concept has inherent complications because of the directional vibration, rate and type of motion, supply of premelted filler alloy to the joint, shape of part, and precleaning.[4] Designers of OTEC compact heat exchangers who consider using fluxless brazing must therefore realize that the design must be relatively uncomplicated.

The fluxless process that uses magnesium as an addition to the brazing alloy has been reported as rapidly gaining acceptance as a production-viable, cost-effective joining process.[14] Brazing must be done in the absence of air, and the magnesium in the brazing alloy acts as a flux.[15] Although the brazing operation itself can be done in a dry nitrogen atmosphere, a vacuum before the actual brazing is recommended to minimize contamination by moisture, oxygen, and carbon dioxide.[15] A vacuum of 4 mPa (3×10^{-5} torr) appears necessary when brazing in vacuum.[15] When brazing in an atmosphere of nitrogen, a prior evacuation to 40 mPa (3×10^{-4} torr) is acceptable.[15]

In another fluxless brazing process, which may be of interest, the aluminum is coated with a polymeric material immediately after cleaning to prevent substantial permeation of oxygen from the air to the aluminum surfaces. This coating is thermally degraded and removed from the surfaces in the vacuum furnace before brazing with an Al—7.5% Si alloy.[16] This technique may be questionable for brazing alloy 5052 and aluminum-magnesium alloys with higher magnesium content.

It has also been reported that aluminum alloys of interest to the OTEC program can be fluxless brazed in vacuum with brazing alloys that contain tin and indium and exhibit excellent wettability and flowability characteristics.[17]

Roller Expansion

This method is a common and economical process for joining aluminum tubes to aluminum tubesheets.[18–20] However, the joint is not metallurgically bonded, and the reliability of each joint in an OTEC aluminum heat exchanger to meet the no-leak requirement throughout the operational life of at least eight years intended for these heat exchangers is questionable.

Magnaforming

This magnetic method is principally used for forming metals — not for metallurgically bonding one metal to another. Mechanical bonds can be achieved, and magnaformed joints of aluminum tubes to tubesheets with good strength have been reported.[21] However, the same report indicated that such joints leaked when helium leak tested.

O-Ring Seals

For heat exchangers where a no-leak requirement is mandatory, O-rings do not appear to be reliable sealants. For example, in tests where magnaforming was used to obtain tighter than normal O-ring joints, vapor leak rates ranging from 37 to 59 × 10^{-6} cm^3/s were reported.[21]

Application of Joining Methods in Shell-and-Tube Heat Exchangers

The following examples of joining methods used in manufacturing aluminum heat exchangers were uncovered by this survey:

A Japanese desalination plant includes designs of heat exchanger stages in which aluminum tubing 16.0 mm OD by 1.27 mm wall (0.63 by 0.050 in.), with lengths up to 3.3 m (11 ft) and with as many as 106 tubes in a stage were joined by roller expanding and also by welding.[18] The alloys used were 3004, 5050, 5052, and 6063. The report did not contain specific details of the roller expansion and welding methods used.

In the late 1960s, aluminum heat exchangers were used in a desalination program supported by the Office of Water Research and Technology and involving the Reynolds Metals Company.[22] Alloy 5052 was joined by roller expansion.

The use of rubber grommets to join aluminum tubes to tubesheets has been exploited by Israel Desalination Engineering in the heat exchangers of the desalination plant near Haifa, Israel.[23] The alloy tubes of 1.24 mm (0.049 in.) wall thickness are alloy 5052-H32.

The French have also indicated the application of aluminum in heat exchangers for desalination plants, but the report is not clear on the method used for joining the tubes to the tubesheets.[19]

The literature has revealed the following examples of welding tubes to tubesheets for aluminum heat exchangers:

Prominent as an industrial supplier is Whessoe Ltd., Darlington, England. Personnel of this company report that aluminum alloys that have been most commonly used for heat exchangers are alloy 3003 for the tubes and an Al—5% Mg alloy for the tubeplate.[24] The GTAW process is used, and the addition of "sufficient amount of silicon to the weld pool is necessary to avoid cracking."

As early as 1967 the Germans reported[25] that heat exchangers in air separation plants have been made in "recent years" exclusively from aluminum. Tubeplates, core tubes, outer shell, and curved heads consist of alloys 5154 and 5083 and tubes of pure aluminum as well as alloy 3003. The tubes ranged from 10.0 to 12.7 mm (0.39 to 0.50 in.) OD with a wall thickness of 1.02 mm (0.040 in.). Tubeplates ranged in thickness from 60 to 120 mm (2.36 to 4.72 in.). Joining was by the GTAW process, and the technique consisted of the following: (1) assemble the tube into the tubesheet with a flush fit at the upper edge of the tubeplate, (2) preheat to 150—200°C (302—392°F) to minimize current required, (3) weld with an Al—12% Si filler metal, (4) with a conical cutter eliminate tube constriction caused by weld reinforcement, and (5) use a tube expander to expand the tubes for 90% of the tubeplate length. This report emphasized that the greatest tendency to form cracks exists when the magnesium content of the alloy is in the range of 1 to 2% and the silicon content is in the range of 0.5 to 1%. For this reason the Al—12% Si filler metal was used.

In 1973 the Russians reported[26] development of welding (apparently using the GTAW process) for manufacturing an experimental heat exchanger with the following parameters:

Total surface area, m^2 (ft^2)	12.0 (129)
Number of tubes	44
Dimensions, mm (in.)	
OD	38 (1.5)
Wall thickness	3.0 (0.12)
Length	1980 (78)
Tubeplate thickness	39.9 (1.57)

Five types of joints were evaluated, materials were "AMg3" for the tube and tubeplates, and the filler metal was "SV-AMg3." A defect common to all the joints was the presence of a crack "on the inside of the tube which appeared unavoidably during the formation of a run inside the tube." Cracking was avoided by reduction of the welding current, and the welded joints passed the halide leak test. In the final weld procedure that was apparently established, the arc current was 190 ± 10 A and the preheating temperature was 180 ± 20°C (356 ± 36°F).

In 1968 the Italians reported[27] using aluminum alloys in the construction of heat exchangers approximately 0.9 m diam by 4.4 m long (3 by 14.5 ft) with approximately 500 tubes [80 m^2 (860 ft^2) tube surface area] for use in "chemical substances." Aluminum-magnesium alloys with magnesium contents ranging from 2.5 to 5% were reported as used. It was stated that the filler metal should generally be the same as the base metal. This report also included the application of "braze welding," which consisted of using the common aluminum brazing alloys (5–13% Si) as the filler metal.

Explosive Fabricators reported completing qualification of explosion welding 9.5-mm-diam (3/8-in.) aluminum alloy 3003 tubing, about 0.3 mm (0.012 in.) wall thickness, into 38-mm-thick (1 1/2 in.) aluminum alloy 6061-T6 tubesheets.[28] The exact size of the heat exchanger is not known at the time of this report, but it is expected that the production unit will contain at least 2000 tubes. Qualification trials determined that at least seven tubes can be explosion welded to the tubesheet simultaneously, and it is anticipated that during production hundreds of tubes can be explosion welded to the tubesheet simultaneously. This company claims that because of a specially designed explosive with a velocity of only 2200 m/s, tubes can be explosion welded to tubesheets by joining concentric surfaces, with the part of the tubesheet hole machined to a larger diameter to allow for correct standoff distance. In this process two areas between the tube and the tubesheet are metallurgically bonded: a region closest to the top of the tubesheet and a region closest to the bottom of the standoff region. The total welded area of each joint that this company proposes to guarantee is $4td$ (t = wall thickness, and d = tubing diameter).

Application of Joining Methods in Compact Heat Exchangers

The following examples of joining methods used in manufacturing aluminum compact heat exchangers (e.g., fin-plate type) were uncovered by this survey:

Brazing is not an uncommon method for joining compact heat exchangers, but the units are usually small. Automobile radiators have been brazed with flux,[29] and the Russians reported[30] brazing sheet-ribbed heat exchangers weighing approximately 360 kg (790 lb) in a flux bath. Fluxless brazing eliminates the problem of flux entrapment and contamination. Successful fluxless brazing of aluminum automobile radiators and automobile heat exchangers has been reported.[10] However, fluxless brazing is not likely to be a process of guaranteed leaktight sealing, as exemplified by numerous leaks observed after fluxless brazing of a test heat exchanger for the space shuttle.[31]

It has been reported that all-aluminum tube-fin air conditioner coils are being fluxless soldered in mass production (approximately 40 coils per hour) by the ALCOA 571 Process.[11] Coils are made by assembling hairpins and fins and expanding the hairpins in the conventional fashion. The ends of the hairpins are flared to a prescribed socket geometry to provide a joint area and a friction fit for the inserted return bends. After vapor degreasing, the return bends and other accessories are simply tapped into position to establish circuitry. The joints are preheated to soldering temperature in the inverted position by hot air or gas flame. The coil is then rapidly transferred and lowered into a molten bath of 95% Zn—5% Al solder filler metal and exposed for a few seconds to ultrasonic cavitation. Solder penetrates the annular space between the return bend and the socket, wets the surfaces, and completes the joint. Although the recommended solder composition is 95% Zn—5% Al, the aluminum concentration can vary from 3 to 5% without adversely affecting joint quality. It was emphasized that the heart of a production ultrasonic soldering process is a reliable ultrasonic solder pot.

The Airesearch Manufacturing Company of the Garrett Corporation[32] indicated that no-leak aluminum compact heat exchangers can be successfully brazed in the size range of 0.3 to 0.6 m (1-2 ft) in cross sectional dimension and 0.6 to 0.9 m (2-3 ft) in length. The company expressed concern about consistently obtaining leakfree units much larger than this when all joints are brazed simultaneously because of the inherent question of manufacturing control and, therefore, the higher potential of a more substantial monetary loss in the event of a rejection. They suggested that the prime consideration for joining panels for the ammonia side should be the establishment of a design that would enable welding processes to be used, and that the panels for the seawater side could be joined by other techniques, which might be less complicated and more economical.

Formability and Machinability of Aluminum

The *Metals Handbook* reports excellent formability of aluminum and its alloys.[33] Alloys 5052 and 5052-H32 are in the same formability ranking, whereas alloy 5052-H34 is ranked as somewhat more difficult to form. Another comparison of interest is the variation of the usable elongation with sheet forming practice. The following compares 3003-H14 (indicated to be similar in formability to 5052-H34) with 5052-0 (indicated to be similar in formability to 5052-H32):

	3003-H14	5052-0
Typical elongation, %	8	25
Stretch forming, %	8	15
Skin stretching, %	4	12
Trapped rubber forming, %	8	15
Drop hammer forging, %	8	15

The *Reactor Handbook* reports that wrought aluminum alloys may be readily machined.[34] It was indicated that the non-heat-treatable alloys (e.g., the 3XXX and 5XXX Series) are easier to machine in the full-hard temper as they tend to be gummy in the softer tempers. Standard tools are commonly used. However, tools should be finished with considerably more side and top rake than those for cutting most other metals. This also applies to saws and files. Standard twist drills may be used, although better results are usually obtained with drills having a larger spiral angle. Also, lubricants should be copiously applied.

Lockheed Missiles and Space Company has recently developed high-speed machining of aluminum, which has the capability of reducing machining costs. For example, Lockheed's equipment can machine 43,000 64-mm-diam (2.5-in.) holes in a 50-mm-thick (2-in.) tubesheet to ±0.013 mm (±0.0005 in.) with a 32 RMS finish in approximately 20 s per hole with imperceptible wear of the tool.[23]

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2. JOINABILITY OF TITANIUM

Gas Tungsten-Arc Welding (GTAW)

This process is the most widely used in welding titanium.[1] Procedures and equipment are generally similar to those used for welding austenitic stainless steel or aluminum, except that because titanium is extremely reactive above 590°C (1000°F) more care must be exerted to shield the weld, including the root side, from air and moisture.[1]

Although originally titanium was welded in a chamber filled with inert gas, manual, semiautomatic, and automatic open-air welding (with necessary shielding) has contributed greatly to the expanded use of titanium.[2] Shielding for welding titanium may be divided[1] into primary shielding, secondary shielding, and backup shielding as follows:

1. Primary shielding is provided by a correctly sized torch or gun for protection of the weld puddle and its immediately surrounding area. Gas cup design is important. It should be designed to release a constant gas stream and should be of the largest size consistent with accessibility and visibility during welding. Generally, the size ranges between 13 and 19 mm (1/2—3/4 in.).

2. Secondary shielding is required to protect the solidified and cooling weld bead and the heat-affected zone. The length of the secondary shield is directly proportional to the heat input and the welding speed. Because of the relatively poor thermal conductivity of titanium (0.05 times that of copper), a considerable length of weld bead needs to be protected. The most common secondary shielding for automatic welding is the trailing shield design.

3. Backup shielding is required to protect the hot metal on the side opposite the welding torch. *The root of a full-penetration weld must always be protected.* In welding tubing it is recommended that the interior of the tubing be purged of air, with inert gas used as a replacement (normally the volume of inert gas required is 6 times the volume of air to be displaced).

Examples of shielding designs are illustrated in the Welding and Brazing volume of the *Metals Handbook*[1] and in the *Welding Handbook*.[2]

Only argon or helium is used as shielding gas, with argon more widely accepted, especially in welding thin sections because of economics and availability; however, helium is often used as the shielding gas at the torch in automatic operations.[1] The purity of the shielding gas with respect to air and water has an important influence on the mechanical properties of the weldment, and a −29°C (−20°F) dew point at the weld zone is indicated as the approximate upper moisture limit. However, a −46°C (−50°F) dew point at the weld is often recommended by some authorities.[2] The purity of commercially available welding gases is normally acceptable, but care must be exercised in assuring the quality of the equipment; the dew point of the gas needs to be measured as it is expelled from the weld apparatus or purged from the weld chamber. Bend tests should be made periodically as a process control measure.[2]

In welding commercially pure titanium it is recommended[2] that the filler metal used should be one or two grades lower than the base metal because dilution and a small pickup of interstitials will strengthen the weld [e.g., 552 MPa (80,000 psi) base metal should use 448 MPa (65,000 psi) filler metal]. AWS Specification A5.16-70 encompasses all commercially pure welding wires.

The following power supply requirements are recommended[1] for GTAW of titanium:

1. Transformer-rectifiers are preferred over motor-generator sets because the current can be controlled more closely.

2. The power supply should include accessories for arc initiation because of the danger of tungsten contamination of the weld if the arc is struck by touch starting. For welding in air, controls for extinguishing the arc without pulling the torch away from the workpiece are needed.

Automatic GTAW of titanium and titanium alloys has been done under the conditions listed in Table 2.1, using 1.5-mm (0.060-in.) sheet of Ti—6% Al—4% V alloy in the 1a (flat) position with and without filler wire.[1]

Table 2.1. Conditions for Automatic GTAW of 1.52-mm-Thick (0.060-in.) Ti—6% Al—4% V Sheet in the 1a (Flat) Position

Conditions	With 1.57-mm-diam (0.062-in.) Filler Metal	Without Filler Metal
Electrode diameter, mm (in.)	1.57 (0.062)	1.57 (0.062)
Current, dcsp, A	95	125
Voltage, V	10	10
Welding speed, mm/s (in./min)	4.2 (10)	5.1 (12)
Shielding gas	argon	argon
Shielding gas flow, ml/s (cfh)		
Nozzle	118 (15)	118 (15)
Trailing	236 (30)	315 (40)
Backing	32 (4)	39 (5)

Gas Metal-Arc Welding (GMAW)

This process is appropriate for welding titanium to titanium. It is generally used for joining titanium parts more than 3 mm (1/8 in.) thick and is less costly than the GTAW process, especially when the base metal is greater than 13 mm (1/2 in.) thick.[2] Open-air welding requires the same shielding considerations as with the GTAW process. Arc instability, which can occur in GMAW, is a potential cause of weld contamination and defect formation; also, some users of titanium prefer the GTAW over the GMAW process because it is more uniform, and predictable transverse shrinkage is obtained.[1]

Electron-Beam Welding

Titanium is amenable to electron-beam welding because the normal operating vacuum provides the required purity of atmosphere for welding the reactive titanium, welds can be made in a single pass with no filler metal addition, and the joint mechanical properties are equal to or better than those attainable by the GTAW process.[2] Joint clearances and good fit-up are important, especially in thin material, because the electron beam will form a series of holes if the gap is excessive.[2]

Laser Welding

Recent studies[3,4] in laser welding of the Ti—6% Al—4% V alloy indicate that this process is likely to approach industrial use in joining titanium and its alloys in the near future. It has the capability of combining high speed and automation with acceptable penetration and minimum distortion. Therefore, it may be a promising welding process for joining compact OTEC no-leak heat exchangers. In the program described,[4] the following conclusions, which are of interest in the joinability of compact OTEC heat exchangers, were made:

1. Laser welds free from porosity to the resolution limit of radiographic inspection were produced in Ti—6% Al—4% V specimens that were 3.6 and 5.8 mm (0.140 and 0.230 in.) thick. Weld bead contours were generally acceptable.

2. At a laser power of 5.5 kW using the oscillator-amplifier mode, speeds in the range of 21 to 25 mm/s (50—60 ipm) were optimum for the 5.8-mm-thick (0.230-in.) material, and speeds in the range of 25 to 30 mm/s (60—70 ipm) were deemed optimum for the 3.6-mm-thick (0.140-in.) material.

3. All tensile failures in welds made within the proper speed ranges occurred in the base metal.

4. All weld specimens in the 3.6-mm-thick (0.140-in.) material made with the oscillator amplifier showed fatigue failure initiations in the base metal.

Resistance Welding

Metallurgically, titanium can be considered as weldable by resistance spot as well as the seam welding process since porosity, hot cracking, and cold cracking are rare.[2,5] The welding schedules are similar to those used for austenitic stainless steel, and titanium can be welded with any type of resistance welding machine — single or three-phase, ac or dc.[2] Seam welding is reported to be as easily performed as spot-welding, with speeds up to 0.76 m/s (150 ft/min) attainable, and the spot distance for a no-leak joint is readily obtained by computing the nugget size, wheel speed, and off time.[2] Cleanliness of the surfaces is important because excessive surface oxide can cause nugget embrittlement. For large surface areas, acid pickling is recommended[2] using 30 HNO_3 (70% concentration), 3 HF (49% concentration), bal H_2O. Inert gas shielding is not required for spot welding but is necessary for seam welding, and shielding devices similar to those used for the GTAW process are recommended.

Explosion Welding

As indicated previously in this report, explosion welding has been used in joining metals. Titanium is among those metals reported[6] as compatible to metallurgical bonding by the explosion welding process.

Plasma Arc Welding

This process has been used successfully in welding titanium.[1] Plasma arc welding of titanium is closely related to the GTAW process but takes advantage of the ionization (plasma) in the arc by placing a constriction containing an orifice (nozzle) around the arc, which greatly increases the plasma density and velocity. This results in a higher arc temperature, a more concentrated heat pattern, and a higher arc voltage than can be obtained with a nonrestricted arc. Among the advantages cited[1] for the plasma arc welding process in comparison with the GTAW process are: (1) arc stability is improved, (2) less sensitivity to variations in arc length exists, (3) tungsten contamination is eliminated, and (4) the "keyhole" technique avoids the need for solid backing for complete penetration. Another advantage is that a thicker root can be welded than is possible by the GTAW process, which leaves a smaller groove to be filled by the depositing wire. Three of the main disadvantages are: (1) the higher cost for equipment (generally 2 to 5 times the cost for GTAW equipment), (2) a high rate of inert gas consumption,[1] and (3) the difficulty in reliably completing a circumferential butt weld in tubing or pipe.[7]

Brazing

By 1967 brazing of titanium and its alloys had become relatively well established. Pertinent information is contained in a Defense Materials Information Center report[5] covering work up to 1967. This report emphasized that brazing had been largely used for the fabrication of sandwich structures and the joining of titanium with dissimilar metals. At that time the silver-base alloys had been used with the most success in obtaining satisfactory flowability and wettability. Also in the mid-1960s the titanium-base brazing alloys containing zirconium and beryllium and the palladium brazing alloys containing silver and silicon were developed, especially for use in brazing below the beta transition temperature. It was noted that the Ti-Zr-Be braze metals showed improved crevice corrosion resistance compared with the silver-base alloys without any adverse affect on strength level, strain accomodation ability, peel toughness, and oxidation resistance. Of these alloys, the Ti—47.5% Zr—5.0% Be alloy, developed at the Oak Ridge National Laboratory, was the preferred alloy of 18 Ti-Zr-Be alloys evaluated.[8]

Aluminum and aluminum-base alloys are also used in brazing titanium structures. The recent issue of the *Brazing Manual*[9] reports aluminum alloy 3003 as a useful brazing alloy. Also Al-Si-Mg-Re alloys are marketed as brazing alloys for titanium structures.[10] The composition varies from 4.5 to 11% Si, 0.30 to 1.21% Mg, and 0.75 to 2% Re. Compositional modifications also include additions of Ag, Cu, Sn, Pd, Bi and Ga. Typical chemical compositions of useful braze metals are as follows:

Ag—10% Pd
Ag—9% Pd—9% Ga
Ag 8% Al 3.5% Pd
Pd—15.4% Ag—3.5% Si
Ti—47.5% Zr—5.0% Be
Al—1.5% Mn—0.6% Si—0.7% Fe—0.2% Cu—0.1% Zn
Al—10.0% Si—1.28% Mg—1.00% Re
Al—4.5% Si—0.30% Mg—1.25% Re—2.0% Cu—3.0% Sn

The *Brazing Manual*[9] emphasizes the following salient points for controlling the brazing of titanium and its alloys:

1. Thorough cleaning of the surfaces is extremely important.

2. Pickling solutions for cleaning should contain 20 to 40% HNO_3 plus 2% HF. (At lower nitric acid concentrations, hydrogen may be absorbed by the titanium base metal.)

3. Furnace or induction brazing requires that the titanium base metal be protected by either vacuum or an inert atmosphere. A vacuum of 0.1 Pa (10^{-3} torr) or better is required, and the dew point of inert gas must be -57°C (-70°F) or less to prevent discoloration during brazing in the range 670 to 925°C (1400–1700°F). Argon from cryogenic storage vessels is often preferred because of its inherent excellent purity.

4. Although titanium can be torch brazed in open air with flux (generally mixtures of florides and chlorides of the alkali metals sodium, potassium, and lithium), maintaining the quality of the brazed joint is difficult in torch brazing.

Weld-Braze Combination

Combining resistance spot welding with brazing was reported[11] by R. G. Hocker of the Northrup Corporation, Aircraft Group, Hawthorne, California, as a method useful for joining titanium aircraft structures. It is worthy of consideration as a joining method for compact heat exchangers. The "weldbrazing" concept involves the establishment of lap joints of titanium, which are initially joined together by resistance spot welds at periodic intervals [e.g., 13 mm. (0.5 in.)] along the length, followed by filling the unwelded portions with aluminum by the fluxless brazing process. The proper welding parameters were readily established for resistance spot welding combinations of lap joints that included sheet thicknesses of 0.5, 1.0, and 1.6 mm (0.020, 0.040, and 0.063 in.). Hocker also stated that brazing titanium with aluminum in a partial pressure of argon results in better filleting of filler metal than is obtained by brazing in vacuum, and that better metal flow is obtained when titanium foil shielding is placed around the lap joints to act as a getter of any contamination that may exist in the brazing environment. An optimum brazing cycle was reported as follows:

1. Heat the part in vacuum to 316°C (600°F).

2. Backfill with argon to a partial pressure of 40 kPa (300 torr).

3. Heat to braze temperature.

4. Hold for 5 min.

5. Furnace cool to below 316°C (600°F) before flowing argon for rapid cooling.

The braze metals that were thoroughly examined in that project included aluminum alloys 4043, 1100, 3003, and 5052. Joints brazed with all these alloys showed evidence of attack in salt fog tests (5% NaCl) except for a joint brazed with alloy 3003 that had been anodized before the corrosion test. These results question the reliability of titanium joints brazed with aluminum to retain leaktightness throughout the long-term exposure (at least 8 years) anticipated for OTEC heat exchangers. This indication does not negate the "weldbraze" concept as a potentially acceptable method for joining compact OTEC heat exchangers. It is likely that the brazing temperature required for other braze alloys will be higher than for aluminum, necessitating higher capital equipment costs.

Roller Expansion

This method has been commonly used in joining titanium tubes to tubesheets for desalination plants.[12] However, for OTEC no-leak heat exchangers, it was suggested[12] that the roller expansion method be supplemented with seal welding because of the questionable reliability of each roller expansion joint meeting the no-leak requirement through the 30-year operational life intended for OTEC titanium shell-and-tube heat exchangers.

Application of Joining Methods to Shell-and-Tube Heat Exchangers

The Nooter Corporation[13] reports extensive experience in autogenous welding titanium tubes to clad titanium tubesheets for shell-and-tube heat exchangers using an automated Gas Tungsten-Arc Welding (GTAW) process in air with specially designed inert atmosphere trailers to protect the titanium during welding. The joint design requires that the thickness of the tubesheet side of the joint match the wall thickness of the tubing. This is done by machining a radiused groove around each hole in the tubesheet. This suggests that by using such a welding practice OTEC shell-and-tube heat exchangers can be manufactured to a no-leak requirement. An example cited[13] was a heat exchanger containing 3400 19-mm-diam (3/4-in.) ASME SB-338 Grade 2 titanium tubes welded into 1.4-m-diam (57-in.) Monel tubesheets clad with titanium to permit welding of the titanium tubes. The maximum tubesheet diameter preferred by the Nooter Corporation appears to be 3 m (10 ft), and heat exchangers as long as 22 m (72 ft) have been reported.[14]

In 1974 Gulf General Atomic Company reported[15] welding a shell-and-tube heat exchanger containing 1820 tubes for a low-activity waste boiler with a reject and repair rate of less than 1.5%. The tubing was ASME SB-338 grade 3 titanium, 19 mm (3/4 in.) OD by 3.40 mm (0.134 in.) wall thickness by 3.7 m (12 ft) long, welded to ASME SB-375 grade 2 titanium tubesheets 19 mm (3/4 in.) thick. The welding head was designed to consistently make welds, by the GTAW process, that would meet the *ASME Boiler and Pressure Vessel Code* as supplemented by the Department of Energy's (DOE) RDT specifications. Pertinent welding process information is as follows:

1. Welding process

   Shielded automatic GTAW using a Hobart 800 series programmed power unit.

   Welding position — 1-G.

   95 A pulsating, dcsp.

   Root pass — fusion.

   Two passes following root pass, each with 1.14-mm-diam (0.045-in.) filler metal AWS Type ERTi-2.

2. Joint design

   Tubesheet near holes "grooved to specifications."

   Tubesheet hole diameter: 19.20 to 19.35 mm (0.756–0.762 in.).

   Tube OD: 19.05 ± 0.10 mm (0.750 ± 0.004 in.).

   Tube ends: within ± 0.51 mm (0.020 in.) on top surface of tubesheet.

3. Sequence

   The welded structure was fixtured in a structural steel cage to allow positioning vertically for tube-to-tubesheet welding and for positioning horizontally for welding tubesheets to the steel sheet as well as liquid-penetrant inspection of the welds.

(a) Assemble tubes, tubesheets, and baffles in the steel cage (apparently in the horizontal position).

(b) Rotate to vertical position and fusion weld 1820 tube-to-tubesheet joint root passes.

(c) Rotate 180° and fusion weld the 1820 tube-to-tubesheet joint root passes at the opposite end.

(d) Rotate fixture to horizontal position and liquid-penetrant inspect 3640 root welds.

(c) Clean thoroughly and return fixture to vertical position.

(f) Complete welding of the 1820 welds.

(g) Rotate 180° and complete welding of the 1820 welds on the opposite end.

(h) Position horizontally and liquid-penetrant inspect 3640 welded joints.

Yorkshire Imperial Metals, Leeds, England, reports[16] joining four calandrias with 50-mm-OD by 1.63-mm-wall (2 by 0.064-in.) titanium tubes explosion welded to type 321 stainless steel tubesheets. The total number of joints explosion welded was 9600 (2400 per calandria). This relatively recent article reported the following parameters of importance in the design of explosion welding:

1. Ligament thickness. This parameter (the thickness between tubesheet holes) is governed principally by the wall thickness of the tube being explosion welded in that the thicker the wall of the tube the greater the momentum caused by the greater mass of the tube during the explosion, and thus the greater the ligament thickness must be to avoid distortion. Distortion of the ligament should be avoided because it reduces the collision pressure. However, where appropriate, ligament distortion can be offset by support plugs in adjacent tubesheet holes that remain to be welded.

2. Geometrical arrangement. Two basic geometrical arrangements are used in explosive welding. In the first of these, the two surfaces

that are to be welded lie parallel and a short distance apart. However, if the two components are to be welded successfully, the explosive used must have a detonation velocity below the sonic velocity of the materials being welded. In the second geometrical arrangement, the two surfaces to be joined are inclined to each other. Its principal advantage over the parallel system is that the detonation velocity of the explosive is less critical, and detonation velocities in excess of the sonic velocities of the materials can be used. Its principal disadvantage is that because of the inclination of the two surfaces before welding the increasing distance between them can become excessive, and there is therefore an upper limit to the areas of the surfaces which can be welded.

3. Explosive charge. The explosive charge must provide enough force to exceed the yield strength of the tube material. Additional evidence suggests that the explosive charge is also related to the melting point of the material (e.g., material with relatively low yield strength but high melting point seems to require a higher explosive charge than normally expected from consideration of yield strength alone).

4. Surface finish. The surface finish is related to the explosive charge. As the explosive charge is increased, the depth of surface removed during the process becomes greater. For dissimilar metals where entrapment of intermetallic may occur because of roughened surfaces [e.g., 7.6 μm (300 microinches)] a mirror finish is preferred, but a compromise of 3.0 μm (120 microinches) is generally acceptable.

The explosion welding process in comparison with the other welding processes offers the potential for ultrasonic inspection of the welded region of the joint design. This technique has been reported[16] as used during production by Yorkshire Imperial Metals. Also, any joints found to be unbonded can be readily plugged by the explosion welding process.[16]

Application of Joining Methods to Compact Heat Exchangers

Through the past 20 years brazing has been the prominent method for joining "compact" heat exchangers and similar designs, such as honeycomb sandwich structures. The *Brazing Manual*[9] shows a lightweight honeycomb sandwich of titanium for a supersonic plane wing panel, 7.3 m (24 ft) long brazed with aluminum alloy 3003. The Boeing Commercial Airplane Company reports[17] additional details on the development of aluminum-brazed titanium honeycomb sandwich structures.

Honeycomb structures also have been produced by automated resistance seam welding by ASTECH, Santa Ana, California (a Division of the TRE Corporation). On the basis of its experience, ASTECH[18] indicated that it could produce leak-free compact titanium heat exchangers of the fin-to-plate type. For such a design, a panel width of 3 m (10 ft) can readily be considered, with greater widths quite conceivable; however, the length of the fin-to-plate weldment would be limited to 1.3 m (4 ft) by existing equipment limitations.

Formability and Machinability

The *Metals Handbook*[19] reports the following on the formability of titanium sheet:

> The combination of titanium's low modulus and high yield strength results in greater springback during forming than shown by aluminum and steel. The greater the springback, the more the difficulty in compensating for it in tool design. The allowable bend radius of titanium in comparison with aluminum shows that for 1.6-mm (0.063 in.) sheet, the allowable bend radius for titanium is 4.8 mm (3/16 in.), compared with 1.6 mm (1/16 in.) for 5052-0 or 5052-H32. Titanium sheet, 0.51 mm (0.020 in.) thick, would have an allowable bend radius of 1.6 mm (1/16 in.). Formability of titanium can be increased by elevated-temperature forming. As a rule of thumb, this increase is approximately 25%.

The *Reactor Handbook*[20] reports the following salient features relative to the machinability of titanium: the machinability of titanium appears to depend on its hardness or strength; the higher the strength the more difficult it is to machine. In some ways titanium machining is similar to machining stainless steel. The type of chip formed when titanium is machined resembles that formed with stainless steel. Also, tool designs that have been successful for machining austenitic stainless steels have proven satisfactory for machining titanium and its alloys. Carbide-tipped tools are preferred. Typical machining practice is:

	Roughing Cuts	Finishing Cuts
Speed, surface m/s (ft/min)	0.23–0.30 (45–60)	≈0.35 (70)
Minimum feed mm/rev (in./rev)	0.76 (0.030)	0.38 (0.015)
Depth of cut, mm (in.)	1.52 (0.060)	0.38 (0.015)

Cutting speeds of more than 1.5 surface m/s (300 sfm) have been found satisfactory in lathe, milling, drilling, and broaching operations when liquid CO_2 is sprayed on the cutting edge of the tool. Generally, cutting lubricants consist of cutting oils with added chlorinated solvents. It is important to keep the work and tool as cool as possible. It is also mandatory in the interest of preventing galling and prolonging tool life to not disengage the feed while the tool is moving in contact with the work.

Grinding should be done wet to keep the work cool and to prevent burning or explosion of titanium dust. The recommended abrasive is alumina used at slow wheel speeds [10–15 surface m/s (2000–3000 ft/min)]. In any event, grinding of titanium is expensive because of the high rate of wheel wear, estimated to be 2.5 volumes of abrasive for each volume of titanium removed.

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3. JOINABILITY OF COPPER-NICKEL ALLOYS

Copper-nickel alloys with the compositional limits[1] given in Table 3.1 are readily joined by welding and brazing processes.

Table 3.1. Composition Limits of Copper-Nickel Alloys That Are Readily Joined by Welding or Brazing

Designation[a]	Range, wt %		Maximum, wt %			
	Ni	Fe	Zn	Mn	Pb	Cu
CA 706	9.0–11.0	1.0–1.8	1.0	1.0	0.05	86.5
CA 710	19.0–23.0	0.5–1.0	1.0	1.0	0.05	74.0
CA 715	29.0–33.0	0.4–1.0	1.0	1.0	0.05	65.0

[a]By Copper Development Association.

The GTAW Process

The gas tungsten-arc welding process (GTAW) is preferred for joining copper-nickel alloys in thicknesses up to 1.6 mm (1/16 in.) and may be used for greater thicknesses.[2] Automatic GTAW has been used to weld tubes to tubesheets.[2] The nominal conditions[2] for automatic GTAW of CA 706 alloy 3.2 mm (1/8 in.) thick with grooved butt joint (no root opening) are as given in Table 3.2. The preferred electrode material

Table 3.2. Nominal Conditions for Automatic GTA Butt-Welding 3.2-mm-Thick (1/8 in.) CA 706

Current, dcsp, A	310–320
Electrode diameter, mm (in.)	4.8 (3/16)
Travel speed, mm/s (in./min)	6.3–7.6 (15–18)
Welding rod	RCuNi
Welding rod diameter, mm (in.)	1.6 (1/16)
Argon flow rate, liter/s (cfh)	0.20–0.24 (25–30)
Number of passes	1
Preheat	not necessary

is EWTh-2, and Filler Metal RCuNi must be used during welding. Although special compositions of thin-sheet CA 706 and CA 715 alloys that contain titanium can be welded without filler metal, filler metal RCuNi, which contains 0.20 to 0.50% Ti, is otherwise necessary since it acts as a deoxidizer, helps minimize porosity, and eliminates the possibility of oxygen embrittlement within the weld metal or heat-affected zone.[2]

The Gas Metal-Arc Welding (GMAW) Process

This welding process is preferred[2] for welding copper-nickel alloys thicker than 1.6 mm (1/16 in.). The filler wire[2] most commonly used is ECuNi (65% Cu, 32% Ni, and 0.20 to 0.50% Ti). No preheating or postheating is needed; the interpass temperature should be less than 66°C (150°F). This process is most frequently automated for use in butt-welding pipe.

Resistance Welding

The copper-nickel alloys are readily spot and seam welded with relatively low welding current, and generally do not alloy with the electrode material and cause electrode pickup.[2] Alloy CA 706 rates good in its joinability by spot welding; CA 715 is indexed as being weldable but not as easily as steel.[2]

Electron-Beam Welding

The copper-nickel alloys can be welded without any unusual problems, and the welding is influenced by the same factors that affect arc welding of these alloys.[2]

Explosion Welding

The copper-nickel alloys have been reported[3] as having been explosion welded with no unusual problems.

Brazing

Copper-nickel alloys have been brazed with copper and copper-phosphorous brazing filler metals, but the silver filler metals (BAg) series are most often employed.[4] The copper filler metal requires a high brazing temperature, and excessive alloying with the base metal is possible; and, although the CA 706 alloy can be brazed with the copper-phosphorous filler metal, this filler metal is not recommended for the CA 710 and CA 715 alloys.[4] In addition, the base metal must be free of sulfur or lead, either of which can cause cracking during the brazing cycle.[4] To prevent cracking caused by the susceptibility of the copper-nickel alloys in the stressed condition to intergranular penetration by the molten filler metal, it is recommended that the copper-nickel alloys be stress-relieved before brazing, and stresses should be avoided during brazing.[4]

Flux brazing is not recommended because flux entrapment or flux residue of flux-brazed components could contaminate the OTEC plant system. Copper-nickel alloys can be fluxless brazed in dry, nonoxidizing protective atmospheres with the lithium-containing filler metals such as BAg-8a and BAg-19 because lithium in the brazing alloy acts as a flux.[2] The chemical composition and brazing temperatures of these alloys[2] are listed in Table 3.3.

Table 3.3. Brazing Alloys for Copper-Nickel Alloys

Brazing Alloy	Content, %			Brazing Temperature, °C (°F)	
	Ag	Cu	Li	Solidus	Liquidus
BAg-8a	72.0	27.8	0.2	766 (1410)	766 (1410)
BAg-19	92.5	7.3	0.2	779 (1435)	891 (1635)

Roller Expansion

The joining of copper alloy tubes to tubesheets by roller expansion has proved perfectly satisfactory for the oil industry, but seal welding as a supplement to expansion is normal in severely corrosive environments[5] (presumably because the mechanical expansion alone results in a tight but not metallurgically bonded seal).

Application of Joining Methods to Shell-and-Tube Heat Exchangers

The *Metals Handbook*[2] cites an example where heat exchangers were fabricated in which 1.22-mm-wall (0.048-in.) CA 715 tubes 19 mm (3/4 in.) OD were welded automatically to 25-mm-thick (1-in.) CA 715 tubesheets by the GTAW process. Originally the welding had been done manually but was unproductive, and the weld quality was questionable. The automatic welding process provided joint strengths equal to or greater than the minimum tensile strength of the base metal, and production rates were 2 to 6 times as fast as manual welding. The joint consisted of a hole through the sheet for insertion of the tube with an 82° (included angle) countersink 1.02 mm (0.040 in.) deep on the face of the sheet, and with the tube end swaged outward into the countersink to lock it in place. Equipment used in welding consisted of a mandrel, which was inserted into the end of the tube; a welding torch; and rotary equipment that caused the electrode to trace a circle around the mandrel, and thus around the tube, when the control circuit was closed. The diameter of the welded circle could be adjusted to suit the workpiece. In welding, controlled circuitry initiated a timed gas prepurge, and the arc was started with a high-frequency pulse. Welding was at full current around the 360° joint and an additional 20° overlap. A current decay was used to avoid crater cracks when the arc was broken.

In April 1975 approximately 6300 explosion welds of CA 706 tubes to steel tubesheets were made in nine feedwater heat-tube bundles for the CEGB Willington Power Station.[6] The tubes were 19 mm (3/4 in.) OD by 1.22 mm (0.048 in.) wall thickness. All joints were leaktight after three years' service.

Formability and Machinability

The copper-nickel alloys are included with those copper alloys that cold form readily and work harden slowly; however, it is recommended that they be annealed (with a specified grain size after the anneal) for cold working operations such as deep drawing, coining, and flanging.[7] The machinability of the copper-nickel alloys is similar to that of copper; for example, the machinability index of both CA 706 and CA 715 is 20 (free-cutting brass = 100).[7]

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4. JOINABILITY OF THE AUSTENITIC STAINLESS STEEL AL-6X

Within recent years an austenitic stainless steel developed by the Allegheny Ludlum Company and identified as AL-6X appears to have the corrosion resistance in seawater required of OTEC heat exchangers.[1] Its nominal composition[1] is listed below:

Element	Wt %
C	0.025
Mn	1.50
P	0.025
S	0.010
Si	0.050
Ni	20.25
Cr	24.50
Mo	6.25

This composition resembles type 310 stainless steel with the exceptions of the molybdenum addition of 6.25 wt % and the restriction of the carbon content to 0.025 wt %. These changes offer the potential for improved corrosion resistance in seawater applications, and tests conducted[2] to date indicate that crevice corrosion encountered with other austenitic stainless steels in seawater appears to be insignificant with AL-6X.

AL-6X is reported[1] to have the following characteristics:

1. Physical properties are shown in Table 4.1.
2. Room-temperature mechanical properties are described in Table 4.2.

3. In comparison with types 304 and 316 stainless steel, the AL-6X alloy passed 200-h chloride stress-corrosion cracking tests in boiling solutions of 33% LiCl and 20% NaCl, whereas types 304 and 316 failed. In addition, the AL-6X alloy passed the Wick test,[3] which is respected in industry for its reliability in predicting performance in the field under similar environmental conditions.

4. When the alloy is held in the 593 to 1093°C (1100–2000°F) range, a molybdenum-containing sigma phase forms on slow cooling from the annealing temperature and is suspected to be detrimental to corrosion resistance in seawater when present in significant amounts.

The correct annealing temperature for the AL-6X alloy is reported[2] as 1200°C (2200°F).

Table 4.1. Physical Properties of AL-6X

Melting point, °C (°F)	1371 (2500)
Density, Mg/m^3 ($lb/in.^3$)	8.11 (0.293)
Specific gravity	8.0
Linear Coefficient of thermal expansion, $°C^{-1}$ ($°F^{-1}$)	
20–100°C (68–212°F)	15.3×10^{-6} (8.5×10^{-6})
20–500°C (68–932°F)	16.0 " (8.9 ")
20–1000°C (68–1832°F)	18.0 " (10.0 ")
Thermal conductivity from 20 to 100°C (68–212°F)	
W/m K	13.8
cal/s °C cm	0.033
Btu in./hr °F ft^2	95.0
Magnetic permeability at 20°C (68°F) (annealed strip)	1.01
Electrical resistivity at 20°C (68°F), μΩ m	0.95

Table 4.2. Room-Temperature Tensile Properties and Hardness of AL-6X[a]

Cold Reduction (%)	Yield Strength 0.2% Offset		Tensile Strength		Elongation in 50.8 mm (2 in.) (%)	Typical Hardness[b]
	(MPa)	(psi)	(MPa)	(psi)		
Annealed	312	45,200	641	93,000	46.0	80 R_B
20	795	115,300	874	126,700	14.0	25 R_C
50	1044	151,400	1117	162,000	4.5	
60	1095	158,800	1200	174,100	4.0	33 R_C

[a]The tests were prepared from sheet material of 1.65 mm (0.065 in.) starting gage and pulled at a rate of 0.005/min to yield and 0.5/min from yield to fracture. Modulus of elasticity of annealed material is 200 GPa (29×10^6 psi).

[b]Data on cold-rolled stock are included as a fabricating guide to indicate the effects of cold working operations such as drawing and forming.

Gas Tungsten-Arc Welding Process

The automatic GTAW process for autogenous welding of AL-6X welded tubing has been developed. The bulk of the experience is with lighter gage tubing (22–24 BWG), with very little experience on heavier gages, where there is a tendency to form sigma.[4]

Roller Expansion

The joining of AL-6X alloy tubes to tubesheets has been limited to the roller expansion process for applications in saltwater environments under steam condenser operating conditions.[5]

Other Joining Processes

Alloy AL-6X is susceptible to precipitation of molybdenum-bearing phases during heat treatment. This causes degradation of its corrosion resistance in seawater.[2] This phenomenon is likely to occur when the cooling rate after welding or subsequent heat treatment is insufficient for these phases to be retained in solution, and must be recognized in considering the acceptability of welding and brazing processes for joining AL-6X. Experience in autogenously welding Al-6X strip[6] using the GTAW process indicates that with proper joint design AL-6X tubes can be welded to austenitic stainless steel tubesheets. Tubing of AL-6X should also be amenable to joining to austenitic stainless steel tubesheets by explosion welding according to its chemical and physical similarity to type 310 stainless steel.

Application of Joining Methods in Shell-and Tube Heat Exchangers

Approximately 1.2 Mm (4,000,000 ft) of AL-6X welded tubing has either been installed or ordered for seawater heat exchanger applications.[2] Apparently all installations used the roller expansion method of joining the tubes to the tubesheets.[5]

Application of Joining Methods in Compact Heat Exchangers

The brazed core of the Heavy Duty Gas Turbine Regenerator developed by Airesearch Manufacturing Co. of California (a Division of the Garrett Corp.) for the Cactus-Reynosa Gas Pipeline Booster Stations is an example of a large fin-plate stainless steel heat exchanger in which all joints are simultaneously brazed.[6]

The weight of the brazed core is about 1360 kg (3000 lb) and requires one of the largest brazing furnaces in the United States [1.8 m by 0.75 m by 3 m (6 ft by 2 1/2 ft by 10 ft)]. Brazing is done under a protective atmosphere using a nickel-base braze alloy containing chromium. The brazed core is not required to be leaktight, but the specification does have a restriction on leak rate.

Formability and Machinability

It is expected that the formability of AL-6X would be similar to type 310 stainless steel. The *Metals Handbook* reports[7] the following:

1. Type 310 stainless steel is satisfactory for 90° bends, but when the bend is increased to 180° and 10% stretch is added, type 310 may be borderline.

2. Type 310 stainless steel is no different from type 304 in its ability to withstand a free bend of 180° over a radius equal to one-half the thickness.

3. In stretch forming, type 310 stainless steel, as with the other series 300 alloys except type 301, which is more formable, is limited to 35% max.

4. Type 310 stainless steel rates the poorest of all series 300 alloys in cuppability, although it is capable of being cupped.

The *Metals Handbook* also reports[7] on the machinability of series 300 stainless steels as follows:

1. In machining the series 300 stainless steels the most important factor is work hardening, and techniques must be used that will produce the chip before the steel sticks to the tip of the tool. With the series 300 stainless steels heavier feeds and slower speeds are

preferred. When machining the higher alloys (type 310), where the chips are exceptionally tough and stringy, chip curler tools are recommended.

2. Types 310 and 316 stainless steel are in the same machining class. The machining speeds for pertinent operations are indicated in Table 4.3.

Table 4.3. Machining Speeds Recommended for Various Operations on Type 310 Stainless Steel

Operation	Machining Speed	
	(surface ft/min)	(surface m/s)
Automatic screw machine[a]	60–80	0.3–0.4
Heavy-duty single or multiple spindle[a]	60–80	0.3–0.4
Turret lathe[a]	60–80	0.3–0.4
Automatic screw machine[b]	80–120	0.4–0.6
Milling[c]	30–50	0.15–0.25
Reaming:		
Smooth finish at 0.08 to 0.19-mm (0.003 to 0.0075 in.) feed[c]	15–40	0.08–0.2
Work sizing at 0.08 to 0.19-mm (0.003 to 0.0075-in.) feed[c]	40–80	0.2–0.4
Threading[d]	10–25	0.05–0.13
Tapping[d]	10–25	0.05–0.13
Drill press[d]	30–50	0.15–0.25
Single-point turning:		
Carbide tooling:		
Roughing	130–180	0.65–0.9
Finishing	150–300	0.75–1.5
High-cobalt or cast alloy tooling:		
Roughing	100–130	0.5–0.65
Finishing	100–150	0.5–0.75
Tungsten or molybdenum high-speed tooling:		
Roughing	60–90	0.3–0.45
Finishing	100–120	0.5–0.6

[a]Based on tungsten or molybdenum high-speed tooling (rates may be increased 15 to 30% with high cobalt or cast alloys).

[b]Based on use of tools made of sintered carbide or cast cobalt-chromium-tungsten-base alloy.

[c]Based on tungsten or molybdenum high-speed steel tooling. Greatly increased rates are obtainable with carbide tooling.

[d]Based on tungsten or molybdenum high-speed steel tooling.

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5. MECHANICAL JOINING OF COMPACT HEAT EXCHANGERS

The American Heat Reclaiming Corporation reports[1] that its Mixed Plate Design can be mechanically joined by gaskets cemented into tracks with no interleakage. Materials of construction include aluminum, titanium, copper-nickel, and austenitic stainless steel. Gasket materials identified by this company include natural rubber, Buna-N (nitrile rubber), Buna-S (styrene rubber), resin cured butyl, Neoprene, asbestos, EPDM (Nordel), fluorocarbon (Viton), and Hypalon. The largest module size indicated is approximately 3.0 m (9.8 ft) in height, 1.4 m (4.6 ft) in width, and 7.9 m (26 ft) in maximum length. Experience has been cited[2] in seawater applications using titanium. Thickness of the titanium sheet and the passageways between the sheets were 0.6 to 0.8 mm (0.02 to 0.03 in.) and 5 to 6 mm (0.20 to 0.24 in.), respectively. The compatibility of gasketing material with ammonia is unknown.

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6. JOINABILITY OF DISSIMILAR MATERIALS

Explosion Welding

This section is prefaced by emphasizing that the explosion welding process is one of the most desirable processes in joining essentially all dissimilar metals when it is necessary to circumvent the presence of brittle intermetallic compounds at the metallurgically bonded interface between dissimilar metals. One of the most common products of explosion-welded dissimilar metals is a clad tubesheet (e.g., titanium clad to Monel). Such combinations are used extensively in the fabrication of shell-and-tube heat exchangers to conserve expensive and often strategic materials and in the interest of being able to weld similar materials (e.g., titanium tubes to the titanium cladding).[1] The trademarks of such products include DYNACLAD (Explosive Fabricators, Inc., Louisville, Colo.); DETACLAD (Dupont, E. I. deNemours and Co., Inc., Wilmington, Del.); and KELOMET (Nobel's Explosives Co., Ltd., Stevenston, Ayrshire). All three companies probably produce most all combinations of clad-plate material. A typical example is the following published[2] list of materials available bonded to aluminum, copper, steel, or titanium, either as cladding or substrate.

- Alloy steel
- Aluminum alloy
- Carbon steel
- Copper alloys
- Gold
- Hafnium
- Hastelloys
- Lead
- Nickel alloys
- Niobium
- Palladium
- Platinum
- Silver
- Stainless steel
- Stellites
- Tantalum
- Titanium
- Vanadium
- Zinc
- Zirconium

The maximum tubesheet diameter preferred by shell-and-tube heat exchanger fabricators[3] appears to be 3 m (10 ft) and apparently explosion clad plate is readily obtained in this size. In one case reported,[4] because titanium could not be obtained in one piece in the size needed, 1.5 m (5 ft) diam, it was necessary to electron-beam weld titanium segments together into the size required before explosion welding to the single-piece steel section. Although it has been reported that in the near future clad plates 6 m (20 ft) wide and 9 to 12 m (30 to 40 ft) long may be possible,[5] it is unlikely that shell-and-tube heat exchanger fabricators currently can fabricate the material into tubesheets that are very much larger in diameter than 3 m (10 ft) because of equipment limitations. It therefore is likely that in the fabrication of large tubesheets the fabricators would resort to welding clad tubesheet segments together using batten strips.[1]

Normally, shell-and-tube heat exchanger fabricators make every attempt to avoid welding processes in which dissimilar metals are melted together (e.g., the Nooter Corp. indicated that in welding titanium-clad Monel tubesheets to a Monel shell, the titanium cladding was machined away from the joint, allowing welding of the Monel portion of the tubesheet to the Monel shell).[1] Whenever welding dissimilar metals cannot be avoided, the use of a transition joint in which the dissimilar metals are joined by explosion welding offers the reliability enjoyed by welding similar metals together (e.g., the titanium side of a titanium-steel transition joint to the titanium part and the steel side of the transition joint to the steel part). All the explosion welding fabricators indicated previously should have the capability of producing explosion welded transition joints. For example, Explosive Fabricators offers DYNAWELD transition materials of the same combinations cited for clad plate in various shapes, which include plates, bars, cylinders, and rings, single clad or double clad for structural, electrical, and tubular transition joints.[6]

Aluminum to Steel

It is common knowledge today that aluminum can be joined to steel, although design for structural applications must consider the effects of formation of the iron-aluminum intermetallics at the bonded interface and the wide difference in the coefficient of thermal expansion between aluminum and steel. Pertinent information[7] summarizing work through 1967 is as follows:

1. It is generally agreed that the strength of aluminum-to-steel joints is highly dependent on the metal used to coat the steel before welding, the thickness of the coating, and the degree of adherence between the coating and the steel surface.

2. Aluminum-magnesium alloys have been welded to low-carbon steel that had been precoated with any of the following metals: Cu, Ni, Cd, Sn, Al, Ag, and brass. The most effective metals in producing sound joints were electrodeposited or hot-dipped coatings of Sn, Zn, Al, and Ag. Tests indicated that the coating thickness should not exceed 40 to 50 μm (0.0016 to 0.002 in.)

3. Low-carbon steel precoated with a 40-μm (0.0016-in.) layer of zinc was welded by the gas tungsten-arc process to Al—6% Mg alloy, and the endurance limit of the joints was equivalent to that of the aluminum base metal.

4. Joint strengths between various aluminum alloys and zinc-coated low-carbon steel are about 100 to 140 MPa (14—20 ksi), with fracture occurring at or near the steel interface.

5. Additions of 3 to 5% Si, Cu, or Zn to the filler wire decreased the width of the intermetallic layer and increased the strength of the joint to about that of the aluminum base metal, when Al—1.25% Mn and Al—6% Mg alloys were welded to zinc-coated low-alloy steel.

6. Alloys Al—1.25% Mn, Al—3.5% Mg, and Al-Mg-Mn-Si have been welded to mild steel coated with aluminum, zinc, or tin by hot-dipping or electroplating, with an Al—5% Si filler wire used during welding. A secondary flow of shielding gas was reported to be required to prevent oxidation of the coating opposite the side being welded. The mechanical properties of the welds were generally considered adequate. Long-term

thermal treatments indicated that such joints should not be exposed to service temperatures in excess of 300°C (572°F) for extended periods.

7. Lap-shear specimens of aluminum alloy 6061 and AISI 1010 steel brazed with BAlSi-4 filler metal indicated an average tensile-shear strength of 57.5 MPa (8.34 ksi).

8. Cold welding of aluminum to steel requires a deformation ranging from 47 to 81%, and the tensile strength of such joints ranges from about 83 to 97 MPa (12–14 ksi), increasing to 166 MPa (24 ksi) when annealed at 500°C (930°F).

9. Strips of Al–6% Mg or Al–3% Mg have been roll-welded to low-alloy or low-carbon steel after heating to 350 to 450°C (662–842°F) and rolling to a reduction in thickness of about 40 to 70%. The reported shear strength of these joints was 69–90 MPa (10–13 ksi).

10. Aluminum and its alloys have been joined to most types of steels by explosion welding.

11. Friction welding and ultrasonic welding have been used to weld aluminum to steel without an intermediate metal.

The Russians subsequently have reported[8] that "arc welding aluminum to steel is a process that is well mastered" and that butt joints between tubes should be made as telescopic joints. In 1973 the fusion welding of aluminum to steel was covered quite comprehensively by Ryaboy,[9] who substantiates the points made previously.

A transition piece of aluminum explosion welded to steel is an acceptable insert for welding aluminum to steel. Explosion-welded aluminum-steel transition pieces are in increasing demand in shipbuilding.[10] When steel plate is clad with aluminum alloy by explosion welding, pure aluminum is used as an interlayer, and such a structure will operate successfully for "long periods" up to 260°C (500°F); also, when titanium is sandwiched between the aluminum and the steel in the explosion-welded product the "working temperature" is increased to 425°C (797°F).[10] Transition pieces for use in joining tubular aluminum parts to tubular steel parts are reported[11] to have been made by an extrusion process combined with diffusion bonding. Weldments have been made using transition pieces with the following results:[12] butt weldments using a bilayer transition piece with tensile strengths ranging between 138 and 159 MPa (20—23 ksi) and a typical shear strength at the aluminum-steel interface of 69 MPa (10 ksi); corner joints using trilayer transitions with normal strength of the welded aluminum alloy; and one assembly with 32-mm-thick (1 1/4-in.) 7039 aluminum alloy welded to 13-mm-thick (1/2 in.) steel was twisted 180° without any damage to the weldment. The cited article suggested that the temperature at the bonded interface of the aluminum-steel transition piece should be less than 443°C (830°F), which indicates that the minimum thickness of the transition piece that can be tolerated is approximately 6 mm (1/4 in.) on the steel side and 10 mm (3/8 in.) on the aluminum side.[12]

Titanium to Steel

Most of the development work in joining titanium to steel occurred before 1967 and is reported in a DMIC report.[7] Pertinent information in this report is as follows:

1. The solubility of iron in α-titanium is very low, and if the concentration of iron exceeds about 0.1%, TiFe- and $TiFe_2$-type intermetallic compounds are formed. They are very hard and brittle. Such an effect is compounded with any alloyed ferrous material. Therefore, fusion welding of titanium to steel results in joints with essentially zero ductility.

2. Vanadium appears to be a compatible filler in plug-welding titanium to steel. However, care must be taken to avoid formation of vanadium carbide. Molybdenum was considered as an alternate to vanadium but was deemed inferior because of the extreme hardness in the molybdenum-steel zone.

3. Tantalum-copper transition pieces have been used to weld titanium to steel (the titanium to the tantalum side and the steel to the copper side). The joint strength ranged between 480 and 550 MPa (70—80 ksi).

4. Successful joints have been produced by explosion welding.

In 1967 it was reported[13] from Essen, Germany, that Krupp research metallurgists working with explosion experts from Wasag-Chemie AG had perfected an explosion welding technique for use in conventional production workshops, and that this has made it possible to weld titanium to steel directly — a task that "has long been considered impractical." This article reported that the shearing strength of the resulting inter-metal bond lies between 245 and 340 MPa (35 and 50 ksi); also, in tests where plates were folded through 180° with the titanium on both the compressed and stretched sides, no cracks were reported to have appeared.

Explosion welding titanium to steel plate using the Kelomet (British) process, which is similar to the Detaclad (American) process, is described by Anderson,[10] who reports that the second largest use of clad plate is found in the manufacture of tubeplates for heat exchangers. The article describes a titanium-clad steel tubeplate, 1.5 m (4.9 ft) in diameter, that was successfully produced by explosion welding. In this specific work, because of the manufacturing size limitations of the titanium plate, pairs of titanium plates were joined together by electron beam welding to obtain the necessary size and were then explosion welded to one-piece steel backers. It was also noted that the bonding at the peripheral regions of explosion-welded clad plate is suspect, requiring removal of the peripheral areas before use. This article also describes the classical method for joining titanium-clad steel plates to each other by welding, as illustrated in Fig. 6.1.

The work of the Russians[14] in explosion welding titanium to steel indicated that they preferred to explosively weld titanium to steel using intermediate layers of niobium on the titanium side and copper on the steel side [e.g., 11.9 mm (0.47 in.) Ti, 1.0 mm (0.04 in.) Nb, 1.5 mm (0.06 in.) "copper alloy," 20.1 mm (0.79 in.) steel] to achieve and maintain "high and stable strength in heat treatments to 1000°C." They also indicate that because of the work-hardening associated with the explosive impact, the ductility of the joint, even with the intermediate layers, is only about 1%. However, the intermediate layer design permits stress relieving without formation of intermetallic compounds.

Hardwick of the YIMPACT Department, Yorkshire Imperial Metals, Leeds, England, reported[15] that YIMPACT has been successful in explosion welding titanium tubes to type 321 stainless steel tubesheets.

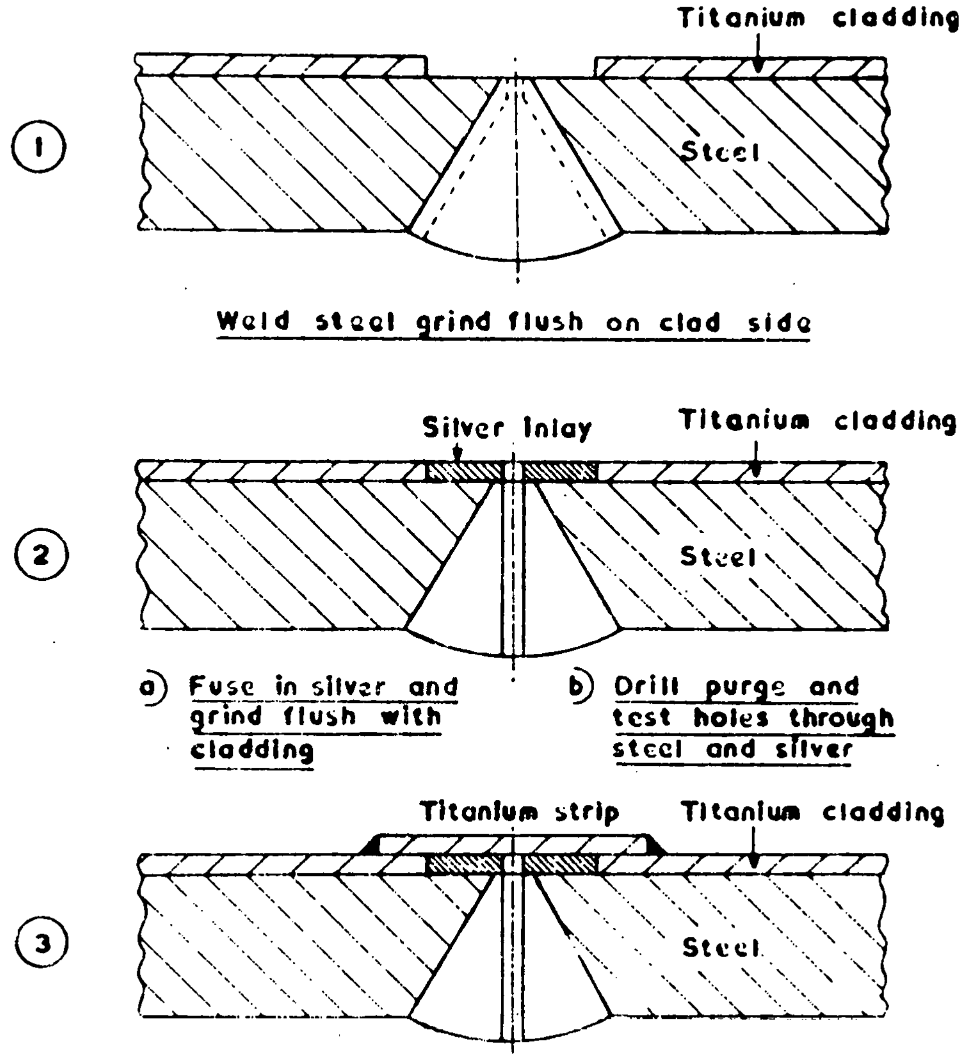

Fig. 6.1. Classical Method of Joining Titanium-Clad Plates. Taken from D. K. C. Anderson, "Industrial Applications of Explosively Clad Metals," paper 18 in *The Use of High-Energy Rate Methods for Forming, Welding, and Compaction,* The University of Leeds, Leeds, U.K., 1973. Reprinted by permission of D. K. C. Anderson, Nobel's Explosives Company Limited, Stevenson, Ayrshire, Scotland.

Titanium can also be brazed to steel either in vacuum or in a high-purity atmosphere.[16] Silver-base alloys wet titanium and most steels quite well, and the reactions between these materials can be controlled satisfactorily.[16]

The filler metals and brazing environments listed in Table 6.1 have been reported[16,17] as used in joining titanium to ferrous alloys.

Table 6.1. Filler Metals Used to Braze Titanium to Ferrous Alloys

Ferrous Base Metals	Filler Metal	Brazing Environment
Type 321 and 17-7 PH[a]	Ag—2% Al	Argon
Type 304L, mild steel, Vascojet-1000	Au—18% Ni	Vacuum
17-7 PH[b]	Ag—5% Al—0.5—1.0% Mn	Argon
Type 304L	Pd—14.3% Ag—4.6% Si	Vacuum
	Ag—9.0% Pd—4.2% Si	Vacuum, 4 mPa (3×10^{-5} torr)
4340 (Ni plated)	Ag—15.5% Cu 16.5% Zn—18% Cd	Argon
Steel	Aluminum	Salt bath
Type 320	Ag—2% Cu	Not identified

[a]Failed after 100 h in salt spray tests.

[b]Withstood 50-h salt spray test successfully.

Copper-Nickel Alloys to Steel

The GTAW, GMAW, and SMAW processes are acceptable processes for welding copper-nickel alloys to steel, with the GTAW favored where rapid rates of deposition are desired.[18] Iron can embrittle copper-nickel alloys and also cause localized corrosion; therefore, the steel should be overlaid first with nickel and then with two layers of the copper.[18] An acceptable practice reported[19] for welding copper-nickel tubes to ferrous tubesheets is to first surface the steel with a high-nickel alloy filler. Welding of components during fabrication of the fishing vessel, the Copper Mariner, exemplify the welding of CA 706 to steel.[20] A variety of joint configurations was used; welding was done by the SMAW process using the ENiCu-2 (65% Ni—30.5% Cu—3.10 Mn) electrode; and, where the weldment was to be immersed in seawater, it was capped or surfaced with ECuNi (65% Cu—32.0% Ni—2.00% Mn). Operational experience with the Copper Mariner has stimulated serious interest in the use of steel plate clad with CA 706 and other copper-nickel alloys for large ships and piping systems.[21] Such clad plate can be furnished to ASTM Standard Specification B 432, and it may be assumed that normally roll-bonding is the process used for cladding the copper-nickel alloy to the steel.[20] To prevent hot-cracking during welding and to prevent embrittlement of the weld bead, control must be exerted to avoid excessive contamination of the steel filler metal by the cladding alloy or nonferrous weld metal.[21] Tolerable levels of nickel and copper in carbon steels[21] are shown in Fig. 6.2. Although limited, the data indicate[21] that problems will not be encountered in seawater when the iron content is less than 10%. Welding filler metals are cathodic to CA 706, and the galvanic protection received from use of the filler may be effective in preventing pitting or generalized corrosion.[21] A typical joint

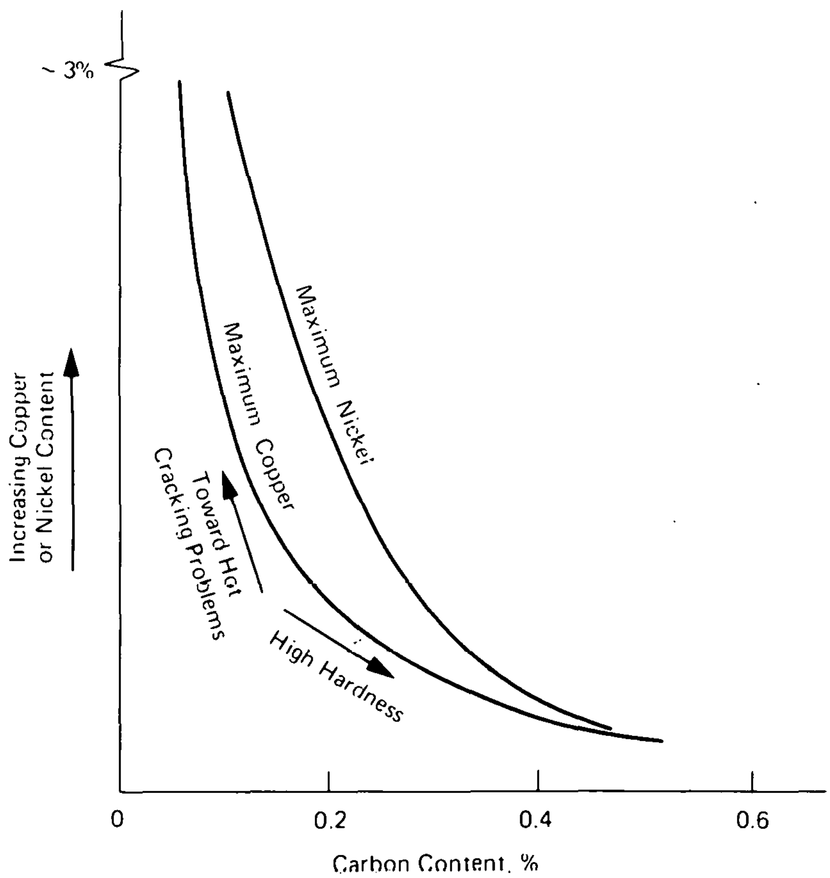

Fig. 6.2. Trend in Tolerance Levels for Copper and Nickel in Steels of Various Carbon Contents. Taken from Copper Development Association data sheet 702/6. Reproduced by permission of the Copper Development Association, Inc.

design[18] for welding plate clad with a copper-nickel alloy is illustrated in Fig. 6.3. Normally the steel side is welded first and the SMAW process is often used throughout. The electrode that has the widest use[18] for the weld overlay as well as the alloy portions of this joint design is ENiCu-2. However, where the joint is to be immersed in seawater, the electrode recommended[20] for the alloy portion would be ECuNi.

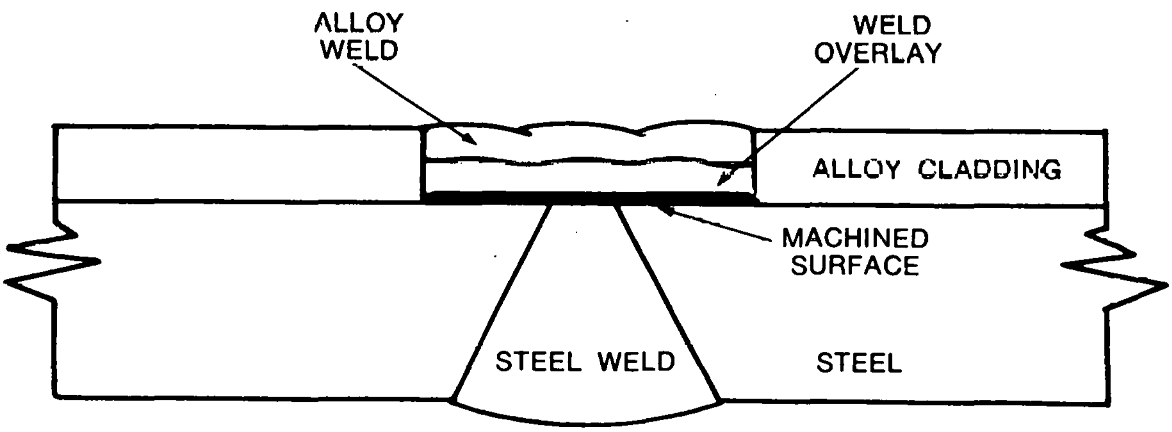

Fig. 6.3. Design Joint in Steel Clad with a Copper Alloy. Reproduced from the *Welding Handbook*, 6th ed., Sect. 4, by permission of the American Welding Society.

Application of electron beam, laser, and similar processes to joining copper-nickel alloys to steel is very limited.[18]

Explosion welding of copper-nickel alloys to various steels was reported[22] as early as 1967. Subsequently, it was reported[15] that the YIMPACT Department of Yorkshire Imperial Metals, Leeds, England, had explosion welded approximately 6300 joints of CA 706 tubes to low-carbon steel tubesheets in nine feedwater heater tube bundles. All joints were reported to be leaktight, and "the units have now been giving trouble-free service over the past three years."

Duplex tubing consisting of CA 706 clad with type 316 stainless stainless steel, 19 mm (3/4 in.) OD by 0.79 mm (0.031 in.) wall was produced by TYCO (now Explosive Fabricators, Louisville, Colo.) for flash distillation plants.[23] Duplex pipe billets, 84.1 mm (3 5/16 in.) diam with a wall thickness of 7.6 mm (0.300 in.) were prepared by explosion welding and sized into the duplex tubing by use of two tube reductions followed by two tube drawing operations.

The AWS *Brazing Manual*[24] reports that dissimilar combinations of copper alloys with steel can be joined by brazing with BAg filler metals. Because of the potential for contamination of an OTEC plant system by flux entrapment or flux residue, fluxless brazing is recommended, using the BAg-8a or BAg-19 brazing alloy described in Table 3.3 of this report.

Metals to Concrete

Adhesive bonding appears to be the only method available for joining metals directly to solid concrete. The literature search, as exemplified by the specification[25] for MMM-A-187, a general-purpose adhesive for repair and bonding of porous materials where high stress or excessive vibration is not imposed, indicates that at best the shear strength would be 10 MPa (1500 psi). In certain design situations, the metal part could be encapsulated into and bonded adhesively to the concrete, but the structural capability of the design and the stability of such a joint under the environmental conditions would have to be fully tested.[26]

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7. JOINABILITY OF METALS WITH ADHESIVES

The use of adhesives in joining metals in engineering structures of interest to the OTEC plant is feasible but may be limited by design considerations, including corrosion resistance under the OTEC plant operating conditions. For example, the ammonia environment has already been expressed[1] as being "very harsh" on adhesives. Joining by adhesives has been a rapidly developing field since the early 1960s, and the present status has been reviewed in a recent program sponsored by the University of Wisconsin, "Selecting and Using Adhesives for Product Assembly." Included in the program were copies of pertinent publications[2–10] deemed informative in updating the status of adhesive bonding. The *Handbook of Adhesive Bonding*[11] is also a relatively recent and highly informative handbook on this subject.

Highlight notes by R. J. Beaver of this sponsored program are as follows:

1. Very few items exist that cannot be bonded to other items with adhesives.

2. No manufacturer will guarantee that his adhesive will meet all the requirements of a specific application time after time. The main reason is that an organic reaction is involved in the making of an adhesive, and no two batches are the same.

3. The selection of the best adhesive for a specific application depends on the following considerations, listed in order of importance:

   a. the service conditions,

   b. the reliability required,

   c. the materials to be bonded,

   d. the care in surface preparation,

   e. the processing limitations,

   f. the allowable cost.

4. ASTM tests that indicate the load-carrying ability of the adhesive are short-time standard idealized tests made at room temperature. The reported values are obtained in practice only under exceptionally controlled conditions.

5. The temperature-load-time requirements must be fully understood to qualify an adhesively bonded joint for a specific application.

6. All adhesively bonded joints will degrade, given enough time. To qualify adhesively bonded joints, testing under exact conditions (joint design, temperature, stress, environment) must be carried out over sufficient time to arrive at predictable life expectancy. Usually this is a time at which first signs of degradation are observed.

7. Adhesively bonded joints withstand loads best in shear. Joints susceptible to cleavage or peel have much lower resistance to such loads. Therefore, structural adhesively bonded joints should always be designed as shear-type joints.

8. "Strong" adhesively bonded joints are those with room temperature lap-shear strength values ranging from 21 to 41 MPa (3000–6000 psi) (depending on the type of adhesive, surface preparation, etc.). Such "strong" joints have practically no resistance to flexure. "Flexible" adhesively bonded joints have shear strengths of about 7 MPa (1000 psi) and resist flexure much better than the "strong" joints. Joints bonded with epoxy are "strong" joints. Joints bonded with silicone are "flexible" joints.

9. Viscosity of the adhesive is one of the important properties in helping to wet the surface of the substrate. It is a property that can be readily monitored for comparing the quality of different batches of adhesive.

10. The aircraft industry is "heads and shoulders" above anyone else in controlling work involving joining using adhesives. The prime reason is because it has given a great deal of thought and trouble in training personnel in understanding the care that must be exercised in controlling the quality of joints bonded adhesively to obtain consistently good results.

11. Moisture is always a potential problem and its presence can lead to poorly bonded joints.

12. The surface condition of the substrate is very important in achieving maximum bond strength. Creating a roughened surface to obtain better mechanical bonding may be detrimental because the adhesive may be too viscous to get into the "valleys" of the roughened surface.

13. Altering the chemistry of the surfaces of difficult-to-bond materials is a technique often used to obtain bonding (e.g., DELRIN is impossible to bond until its surface is treated with sulfuric acid).

Types of Adhesives for Bonding Metals to Metals

A recent publication[6] recommends the following adhesives for bonding any metal to any metal.

Thermosets

epoxy, cyanoacrylate, acrylic

Alloys

vinyl-phenolic, epoxy-phenolic, nitrile-phenolic, epoxy-nylon, neoprene-phenolic

Elastomeric

silicone, urethane, polysulfide

Thermoplastics

polyamide, phenoxy

Table 7.1 gives the pertinent properties of these materials for use as structural adhesives.

Table 7.1. Properties of Structural Adhesives Used to Bond Metals

Adhesive	Service Temperature, (°C)		Shear Strength				Resistance to			Bond Nature
	Max	Min	(MPa)	(ksi)	Peel	Impact	Creep	Solvent	Moisture	
Epoxy-amine	65	−45	20–35	3–5	Poor	Poor	Good	Good	Good	Rigid
Epoxy-polyamide	65	−51	15–30	2–4	Med	Good	Good	Good	Med	Tough, Mod. Flex.
Epoxy-anhydride	148	−51	20–35	3–5	Poor	Med	Good	Good	Good	Rigid
Epoxy-phenolic	176	−253	22	3.2	Poor	Poor	Good	Good	Good	Rigid
Epoxy-nylon	82	−253	45	6.5	V. Good	Good	Med	Good	Poor	Tough
Epoxy-polysulfide	65	73	20	3	Good	Med	Med	Good	Good	Flexible
Nitrile-phenolic	148	−73	20	3	Good	Good	Good	Good	Good	Tough, Mod. Flex.
Vinyl-phenolic	107	−51	15–35	2–5	V. Good	Good	Med	Med	Good	Tough, Mod. Flex.
Neoprene-phenolic	93	−56	20	3	Good	Good	Good	Good	Good	Tough, Mod. Flex.
Polyimide	315	−253	20	3	Poor	Poor	Good	Good	Med	Rigid
Polybenzimidazole	260	−253	15–20	2–3	Poor	Poor	Good	Good	Good	Rigid
Polyurethane	65	−253	35	5	Good	Good	Good	Med	Poor	Flexible
Acrylate acid diester	93	−51	15–30	2–4	Poor	Med	Good	Poor	Poor	Rigid
Cyanoacrylate	65	−51	15	2	Poor	Poor	Good	Poor	Poor	Rigid
Phenoxy	82	−56	17	2.5	Med	Good	Good	Poor	Good	Tough, Mod. Flex.
Thermosetting acrylic	121	−51	20–30	3–4	Poor	Poor	Good	Good	Good	Rigid

Surface Preparation

The importance of surface preparation cannot be overemphasized because bond strength and permanence of an adhesive-bonded joint are highly dependent upon the type of surface that contacts the adhesive, as indicated in Table 7.2.

Table 7.2. Effect of Substrate Pretreatment on Joint Strength

Metal	Adhesive	Shear Strength, MPa (psi), After Selected Substrate Treatments			
		As Received	Vapor Degreased	Grit Blast	Acid Etch
Aluminum	Epoxy	3.06 (444)	5.77 (837)	12.08 (1751)	19.00 (2756)
Aluminum	Vinyl-phenolic	16.83 (2442)	18.90 (2741)		35.66 (5173)
Titanium	Vinyl-phenolic	9.31 (1356)	21.93 (3180)		46.50 (6743)
Stainless steel	Vinyl-phenolic	35.95 (5215)	43.48 (6306)		48.65 (7056)
Cold rolled steel	Epoxy	19.99 (2900)	20.06 (2910)	29.37 (4260)	30.82 (4470)
Copper	Epoxy		12.34 (1790)		16.06 (2330)

Recommended surface preparations for metals of interest are as follows: (numerals indicate alternate methods and letters designate method sequence).

Aluminum and Aluminum Alloys

1 Sandblast or 100 grit emery cloth followed by solvent degreasing. Remarks: medium to high strength; suitable for noncritical applications.

2(a) Immerse 10 min at 77 ± 6°C in commercial alkaline cleaner or solution (parts by wt): sodium metasilicate, 30.0; sodium hydroxide, 1.5; sodium pyrophosphate, 1.5; Nacconol NR (Allied Chemical Co.), 0.5; water (distilled), 128.0.

(b) Wash in water below 65°C and etch 10 min at 68 ± 3°C in solution (parts by wt): sodium dichromate, 1; sulfuric acid (96%, sp gr 1.84), 10; water (distilled), 30.

(c) Rinse in distilled water after washing in tap water, and air dry.

3(a) Etch 20 min at room temperature in solution (parts by wt): sodium dichromate, 2; sulfuric acid (96%, sp gr 1.84), 7.

(b) Rinse thoroughly in deionized water; dry 70°C for 30 min. Remarks: room temperature etch.

Note: Recent communication[12] with ALCOA indicated that in seacoast exposure the mode of bond failure could be best described as undercutting metallic corrosion, which actually undermines the bond line without apparently affecting the adhesive (a one-part heat-cured epoxy). Special surface pretreatments, such as chromate conversion coating and anodizing procedures, that emphasize surface resistance to saltwater corrosion should lead to the most permanent bond.

Titanium and Titanium Alloys

1 Grit, vapor blast, or 100 grit emery cloth, followed by solvent degreasing or scour with a nonchlorinated cleaner, rinse and dry. Remarks: general-purpose bond.

2(a) Etch 5 to 10 min at 20°C in solution (parts by wt): sodium fluoride, 2; chromium trioxide, 1; sulfuric acid (96% sp gr 1.84), 10; water, 50.

(b) Rinse in water and distilled water; air dry at 93°C.

3(a) Etch 2 min at 20°C in solution (parts by vol): hydrofluoric acid (48%), 84; hyrochloric acid (37%), 8.9; orthophosphoric acid (85%, 4.3.

(b) Rinse in water and distilled water. Dry in air at 93°C. Remarks: suitable for alloys bonded with polybenzimidazole adhesives. Bond within 10 min of treatment. ASTM D 2625.

Copper and Copper Alloys

1 Sand, wire brush, or 100 grit emery cloth, followed by vapor or solvent degreasing. Remarks: suitable for general purpose bond; use 320 grit emery cloth for foil.

2(a) Etch 10 min at 66°C in solution (parts by wt): ferric sulfate, 1.0; sulfuric acid (96%), 0.75; water, 8.0.

(b) Wash in water at 20°C and etch in cold solution (parts by wt): sodium dichromate, 5; sulfuric acid (96%), 10; water, 85.

(c) Etch until bright clean surface is obtained. Rinse in water, dip in ammonium hydroxide (sp gr 0.88) and wash in tap water. Rinse in distilled water and dry in warm air. Remarks: for maximum bond strength; suitable for brass and bronze. ASTM D 2651.

3(a) Etch 1 to 2 min at 20°C in solution (parts by wt): ferric chloride (42 wt % solution), 0.75; nitric acid (sp gr 1.41), 1.5; water, 10.0.

(b) Rinse in distilled water after cold water wash and air dry at 20°C. Remarks: room temperature etch. ASTM D 2651.

Stainless Steel

1 Abrade with 100 grit emery cloth, grit or vapor blast, followed by solvent degreasing.

2(a) Solvent degrease and abrade with grit paper.

(b) Degrease again.

(c) Immerse 10 min at 71 to 82°C in solution (parts by wt): sodium metasilicate, 3; tetrasodium pyrophosphate, 1.5; sodium hydroxide, 1.5; Nacconol NR (Allied Chemical Co.), 0.5; distilled water, 138.0.

(d) Rinse in deionized water, air dry at 93°C. Immerse 10 min at 85 to 91°C in solution (parts by wt): oxalic acid, 1; sulfuric acid (sp gr 1.84), 1; distilled water, 8.

(e) Rinse in deionized water, dry at 93°C 10 to 15 min. Remarks: heat resistant bond; alkaline clean alone sufficient for general bonding; commercial alkaline cleaners (Prebond 700, American Cyanimid) available.

3(a) Etch 15 min at 63°C in solution (parts by wt): sodium dichromate (saturated solution), 0.30; sulfuric acid, 10.0.

(b) Remove carbon residue with nylon brush while rinsing in distilled water and dry in warm air at 93°C. Remarks: ASTM D 2651.

4(a) Etch 2 min at 93°C in solution (parts by wt): hydrochloric acid (37%), 20; orthophosphoric acid (85%), 3; hydrofluoric acid (48%), 1.

(b) Rinse in warm water with final rinse in distilled water. Dry in air below 93°C. Remarks: for maximum resistance to heat and environment.

Steel (Mild), Iron, and Ferrous Metals Other than Stainless

1 Abrasion. Grit or vapor blast, followed by solvent degreasing with water-free solvents. Remarks: Xylene or toluene is preferable to acetone and other ketones, which may cause rusting.

2(a) Etch 5 to 10 min at 20°C in solution (parts by wt): hydrochloric acid (37%), 1; water, 1.

(b) Rinse in distilled water after cold water wash, and dry in warm air 10 min at 93°C. Remarks: Bond immediately after etching treatment since ferrous metals rust. Abrasion is more suitable where bonding is delayed.

Design of Adhesive-Bonded Joints

Selection of the type of joint to be used in a given application is influenced by such factors as the type of assembly or structure, the tooling requirements, and the machining costs. In his article, "Designing Adhesive Joints," Chastain[13] emphasizes the following:

1. An adhesive loaded in compression is unlikely to fail, although it may crack at weak spots.

2. In tension the adhesive develops high stresses at the outer edges, and those thin edges bear a disproportionate amount of the load. Although an adhesive bond is very strong in tension, the first small crack that occurs at the weakest area of one of the highly stressed edges propagates swiftly and leads to failure of the joint.

3. The lap joint represents the most widespread joint in adhesive bonding. Overlapping the parts places the load-bearing area in shear, a type of stress that the adhesive bond withstands exceptionally well.

4. Care must be exerted in design to avoid stressing a lap joint in tension, which may introduce cleavage because adhesive bonds are weakest when loaded in cleavage or peel.

5. Types of lap joints are illustrated in Fig. 7.1 along with pertinent comments.

Adhesive Makers and Trade-Name Adhesives

The December 1975 issue of *Tooling and Production*[8] identifies a broad sampling of makers of adhesives, as listed in Table 7.3, and reports experience with specific trade-name adhesives.

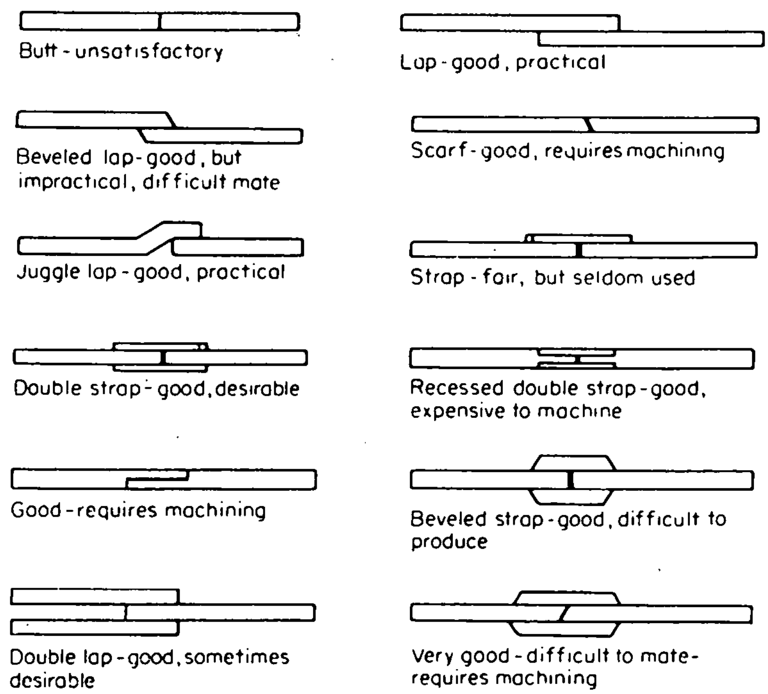

Fig. 7.1. Adhesive Joint Designs. Reprinted from C. E. Chastain, *Appliance Eng.*, 8(4). Reprinted from *Appliance Engineer* magazine, copyright by Dana Chase Publications, 1974.

Anaerobics

The Unbrako anaerobic adhesives of Standard Pressed Steel were reported to resist extremes in temperature and wet or dry environments. They will bond steel, aluminum, titanium, lead, and magnesium. One Unbrako formulation is recommended for mounting bearings, while another is meant for fastening parts to shafts.

A new anaerobic called Adhesive 353 has been developed by the Loctite Corporation. It is noteworthy in that it will bond steel to glass, and it is cured by ultraviolet light. It can be used to bond car windows to brackets and is also intended for use in electrical, optical, and medical industries.

Cyanoacrilates

Permabond International sells a line of these adhesives that are said to be capable of producing bonds with tensile strength of 34 MPa (5000 psi). Automobile manufacturers use it to attach outside trim,

Table 7.3. Manufacturers of Various Types of Adhesives

Adhesive Makers	Anaerobics	Cyanoacrylates	Epoxies	Silicone Gasket
Amicon Corp., Polymer Products Div.			✓	
Aremco Products Inc.			✓	
Chomerics Inc.				✓
Devcon Corp.			✓	✓
The Dexter Corp., Hysol Div.			✓	
Dow Corning Co.				✓
Eastman Chemical Products Inc.		✓		
Epoxy Technology, Inc.			✓	
Formulated Resins Inc.			✓	
Furane Plastics Inc.			✓	
General Electric Co., Silicone Products				✓
Glenmarc Mfg. Co.		✓		
Hapco Mfg. Co. Inc.			✓	
Hardman Inc.			✓	
Loctite Corp.	✓	✓		
Lord Corp., Hughson Chemicals Div.			✓	
MPB Corp.	✓	✓	✓	
ND Industries			✓	
Oneida Electronic Mfg. Inc.		✓		
Permabond International Corp.	✓	✓		
Permatex Co.	✓	✓		✓
Ren Plastics			✓	
Stainless Steel Coatings, Inc.			✓	
Standard Pressed Steel Co.	✓			
Techni-Tool Inc.		✓		
3M Co., Adhesives, Coatings and Sealers			✓	
Tra-Con Inc.			✓	
Vigor Co.	✓	✓		

weather stripping, and scratch bumpers. It can also be used to position motor shafts and gears.

Eastman 910 is capable of bonding steel, aluminum, copper, brass, tin, and other metals. It is useful in both assembly-line and hand-assembly operations.

The Pro-Bond System is made by Glenmarc Manufacturing Company. It consists of two substances, one to bond and one to release the bond. In effect, this makes the system a liquid clamp. It will bond most metals (except titanium) and will hold in either an acid or basic environment.

Epoxies

Tra-Bond 3106T is an adhesive made by Tra-Con Inc. that adheres to wet as well as dry surfaces. It is suited for industrial and electronic applications because of its fast-curing low-shrinkage bonds. It can also be used for repairing pipe and machinery, attaching fixtures, and sealing leaks.

Amicon Corporation makes Uniset 908-58, which is a one-component, fast-curing epoxy. It will bond steel, aluminum, magnesium, titanium, lead and ceramics. Joints have high shear strength and are electrically insulating.

Silicones

Silastic 732 RTV, made by Dow Corning, can be used as a sealer in truck cabs, trailers, and appliance parts.

Chro-Bond 1038 made by Chomerics Inc. will adhere to steel, aluminum, titanium, magnesium, rubber, ceramic, and copper (but not lead). Bonds made with it are flexible and electrically conducting and will dampen vibration.

The chemistry of adhesives can generally be altered to better suit specific applications. This flexibility is exemplified in Table 7.4, where differences between Morton Chemical Company's grades[14] of their MOR-AD thermosetting epoxies are presented.

Applications of Interest for Heat Exchanger Construction

No direct examples were uncovered in the literature where heat exchangers had been joined by adhesives. However, the use of adhesives in joining either shell-and-tube or compact heat exchangers for OTEC plants should not be discounted unless design considerations preclude their use. In the case of tube-to-tubesheet joints, such a joint is similar to hub-mounting, which is one of five design conditions considered appropriate and applicable for adhesive bonding, and the modified (second generation) acrylics are suggested as acceptable low-cost adhesives.[2]

Table 7.4. Guide to the Selection of Some Mor-Ad[a] Thermosetting Epoxy Products Showing Variations in Characteristics

Grade	Service Temperature Range, °C(°F)	Resin-to Hardener Proportions by wt (vol)	Consistency	100-g Pot Life (h)	Curing Conditions				Tensile Shear[b]		Applications
					Temp. °C(°F)	Time, h					
						50%	75%	100%	(MPa)	(psi)	
S-8002	-55 to 82 (-67 to 180)	1.0:1.1 (5:7)	Like syrup	3.5	25(77) 93(200) 160(320)	24 0.17 0.08	72 0.5 0.13	240 1.0 0.25	20.7	3000	Metal to metal, carbon, or galvanized steel, or nonmetals including ceramics; foundation repair; lining ductwork, troughs; stripped fasteners; many applications for corrosion or abrasion resistance.
S-8003	-55 to 149 (-67 to 300)	2.0:1.0 (7:3)	Like caulking	1.5	25(77) 121(250)		24 0.17	48 0.5	25.5	3700	Excellent for aluminum, metal to metal, including carbon or galvanized steel, or many substrates, including polyester fiberglass; ductwork, troughs lined with ceramics; prefabricated furnace arches.
S-8005	-55 to 149 (-67 to 300)	3:1 (3:1)	Like syrup	1.0	25(77) 121(250)		24 0.13	48 0.33	26.5	3850	Metal to metal, especially stainless and nonferrous metals; many nonmetallics, including polyester fiberglass, rubber, malamine-impregnated paper; lining aluminum ducts, stripped stainless bolts; many corrosion resistance applications.
S-8009	-55 to 149 (-67 to 300)	3:1 (7:2)	Like thin syrup	2.3	25(77) 121(250)		4 0.05	24 0.33	26.2	3800	Steel, nonmetallic substrates such as polyester fiberglass, rubber, melamine-impregnated paper, and polystyrene.
S-8019	-40 to 71 (-40 to 160)	2:1 (7:2)	Like putty	0.92	25(77) 93(200) 116(240)	4 0.07 0.05		30 0.2 0.13	23.1	3350	Filling gaps, nonexpanding joints, holes; ducts, troughs, prefabricated furnace arches; castings to be rebuilt; vertical, overhead applications; auto or locomotive body work.
S-8021-1	-55 to 260 (-67 to 500)	3:1 (16:5)	Like syrup	7	25(77) 88(190) 149(300)	does not cure 0.42 0.08		 1.5 0.25	26.9	3900	Requiring strength at high temperatures and extra moisture resistance; metal to metal, metal to nonmetallics, *not* polyethylene, polypropylene, or fluorocarbons.

[a]Trademark of Morton Chemical Co.

[b]Bonding carbon steel at 23°C (73°F).

In the case of compact heat exchangers, construction of adhesive-bonded honeycomb and sandwich structures should be directly related to the construction of compact heat exchangers. Design details for construction of honeycomb structures, with aluminum alloy 5052 as the base material, and for construction of sandwich structures have been established.[15] The types of acceptable adhesives are modified epoxy, epoxy-phenolic, and nylon-epoxy. Also suggested[2] for such structures are the acrylics, including anaerobics, the modified acrylics, and the cyanoacrylates.

HEXCELL[16] indicated that leaktight compact aluminum heat exchangers could be produced with modified epoxy or nitrile phenolic used as the adhesive sealants, but the retention of the leaktightness would be questionable for long-term exposures (e.g., 8 years in seawater) unless the degradation characteristic of a joint in such environment is determined. Room-temperature curing was not recommended because such curing results in a more brittle joint with lower peel strength and likely to degrade more rapidly in seawater than joints heat cured under pressure. The maximum panel size indicated that HEXCELL can produce by heat curing under pressure is 7.3 by 2.4 m (24 by 8 ft).

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8. SUMMARY

As a result of this survey of worldwide literature and applicable industrial contacts, the state of the art of the joinability for OTEC shell-and-tube and compact heat exchangers is summarized as follows:

Tube-to-Tubesheet Joinability

Gas tungsten-arc welding (GTAW) and explosion welding are two methods that appear to offer the highest reliability without extraordinary costs. Other processes appear either unreliable or uneconomical.

1. Gas Tungsten-Arc Welding (GTAW). This process is considered the most attractive because it is well developed, is reliable, lends itself to automation, and has been used in welding tube-to-tubesheet heat exchanger joints. Because aluminum alloy 3003 can be welded autogenously, it is considered superior in cost effectiveness and joint reliability to the 5XXX series.

2. Explosion Welding. This process offers more bonded area in the weldment and lends itself to ultrasonic inspection for internal defects in the welded regions. It has been used in the production of shell-and-tube heat exchangers with materials of interest to OTEC. However, the higher costs indicated for explosion welding tubes to tubesheets may preclude its use.

The following processes do not appear to be applicable to joining tubes to tubesheets for OTEC no-leak heat exchangers:

1. Gas Metal-Arc Welding (GMAW). This process normally offers many of the advantages of the GTAW process, but, for the type of joint design indicated for shell-and-tube OTEC heat exchangers, GTAW is a more favored process.

2. Gas Welding. This method does not readily lend itself to the materials of interest or to automation, and residue from the flux required in this process could contaminate the OTEC system.

3. Shielded Metal-Arc Welding. This method should not be considered for the same reasons expressed for gas welding.

4. Electron-Beam Welding. This method usually requires an evacuated chamber for welding under vacuum, and therefore appears economically unattractive for the thousands of tubes that must be assembled in and welded to the tubesheets.

5. Laser Welding. Although this is a rapidly developing process, its application for welding tubes to tubesheets based on experience to date is uncertain.

6. Resistance Welding. This method appears economically unattractive as an automated process for the tube-to-tubesheet designs.

7. Cold Welding. This method appears unacceptable for the same reasoning expressed for resistance welding.

8. Ultrasonic Welding. This method appears unacceptable for the same reasoning expressed for resistance welding and, in addition, does not appear to have been developed to unquestionable reliability for meeting the no-leak requirement.

9. Brazing and Soldering. These processes do not appear attractive for joining tubes to tubesheets because the costs for soldering or brazing furnaces are probably very expensive, and the reliability appears to be questionable for meeting the no-leak requirement.

10. Adhesive-Bonded Joints. The tube-to-tubesheet joint design is amenable to the shear-type joint recommended for adhesive-bonded joints. However, the reliability of this process to meet the OTEC no-leak requirements must be proven, and the control involved in assuring consistent quality of thousands of joints required makes this process economically questionable for OTEC tube-and-shell heat exchangers.

11. Roller Expansion. Although one of the most popular processes in use for joining tubes to tubesheets, the roller expansion method is suspect in its reliability to meet the no-leak OTEC requirement. It is recommended as a method for obtaining a tight fit between tube and tubesheet before sealing by gas tungsten-arc welding.

12. Magnaforming. This process is not normally used for obtaining metallurgical bonding and is questionable in its reliability to meet the no-leak requirement.

13. O-Ring Seals. This method is also questionable in its reliability to meet the no-leak requirement.

Joinability for Compact Heat Exchangers

1. Resistance Seam Welding. This process is sufficiently well developed to be considered a promising automated process for joining no-leak OTEC compact heat exchangers, but the ability of this method to consistently produce leak-free weldments depends on intense process control during production of the qualified process. The size of currently available equipment for automated resistance seam welding for a fin-plate design appears to be limited to the production of panels 1.2 m (4 ft) long and 3 m (10 ft) wide. Widths considerably greater are conceivable.

2. Fluxless Brazing. This process has been successfully used to produce compact heat exchangers with a no-leak requirement in the size range approximating 0.3 to 0.6 m (1 to 2 ft) in cross-sectional area and 0.6 to 0.9 m (2 to 3 ft) in length. As the size of the module increases beyond this range, the uncertainty of guaranteeing a no-leak requirement and the invested manufacturing costs in the module in the event of a rejection become significant considerations in establishing the most economical modular size for brazed modules.

3. Adhesive Bonding. At first glance adhesive bonding seems to be attractive for joining no-leak OTEC heat exchangers. Ammonia, however, degrades adhesives. Thus it appears likely that adhesively bonded joints would be restricted to a system where leaktight joints are not mandatory, or, if leaktight joints are required for the seawater side, sufficiently long-term tests are conducted to predict the onset of degradation. Design considerations should require lap joints where stress is a consideration. Heat-cured joints offer the most potential for long-term applications, and panels as large as 2.4 by 7.3 m (8 by 24 ft) can be heat-cured.

4. Mechanical Joining. Existing experience indicates that no-leak heat exchangers can be joined by gasketing. The compatibility of the gasketing material with ammonia and scale-up to the sizes indicated for OTEC compact heat exchangers represent uncertainties.

5. Electron-Beam Welding. This process is likely to involve large expenses for fixturing and capital investment, and production rates may

be limited by the need to weld in vacuum or partial vacuum. However, the low distortion involved in welding makes it inherently attractive.

6. Laser Welding. This is a rapidly developing welding process and is a possibility because of its potential for high speed welding with acceptable penetration and minimum distortion.

The following processes do not appear to be applicable to joining OTEC no-leak compact heat exchangers:

1. Gas Tungsten-Arc Welding (GTAW); Gas Metal Arc Welding (GMAW); and Gas Welding. These processes are likely to create adverse distortion, and therefore the reliability for dimensional control is low.

2. Ultrasonic Welding. This process is not developed to the point where it can produce no-leak joints in a consistent reliable manner during production.

3. Explosion Welding. This process does not appear cost-effective because of the apparent lengthy time required for assembling.

4. Soldering. This process is not considered a likely prospect because the corrosion resistance of available soldering alloys is suspect, and the flux residue that may remain could contaminate the entire OTEC plant system.

Joinability of Dissimilar Materials

1. Aluminum to Steel. In joining aluminum to steel it is generally conceded that formation of brittle aluminum-iron intermetallics at the welded interface should be avoided in the interest of retaining ductility. Under strict quality control and careful design, aluminum can be joined to precoated steel (e.g., precoated with zinc or silver) by the GTAW process. Another method that has proven successful is explosion welding, including the preparation of aluminum-steel transition joints. These transition pieces may be used as intermediates in which the steel side is welded to the steel and the aluminum side to the aluminum by the GTAW process. Brazing has also been used in joining copper-coated or aluminum-coated steels.

2. Titanium to Steel. The same considerations for joining aluminum to steel exist in joining titanium to steel; namely, avoiding formation

of brittle titanium-iron intermetallics in the interest of retention of ductility. Tantalum, vanadium, and silver have been used as intermediate barriers between titanium and steel to prevent formation of titanium-iron intermetallics. Tantalum-copper transition pieces have been used in which the steel is welded by the GTAW process to the copper side and titanium to the tantalum side of the transition piece. Titanium can be successfully explosion welded directly to steel, and titanium can be brazed to steel with a silver-base filler metal.

3. Copper-Nickel Alloys to Steel. Copper-nickel alloys can be welded to steel by the GTAW or GMAW processes when the steel is surfaced with nickel or a high nickel alloy. Copper-nickel-clad steel plates can also be welded. Copper-nickel alloys can be explosion welded and also brazed to steel. Application of electron beam, laser, and similar welding processes for joining copper-nickel alloys to steel is very limited.

4. Adhesives for Joining Dissimilar Metals. Adhesives may be considered for successfully joining dissimilar metals, but the subsequent use of such joints is a prime consideration. For example, temperatures as low as 200°C (392°F) that may be encountered during fabrication can destroy the characteristics of many adhesives, and long-term corrosion tests under OTEC environmental conditions would be a necessary qualification. It is also mandatory that the joining process be qualified and strictly followed during production if high reliability is to be achieved.

5. Joinability of Metals to Concrete. Adhesive bonding metals to concrete for structural purposes should be limited to lap joints, and the low strength of the adhesively bonded joint must be recognized. When metals are to be bonded to concrete, encapsulation of the metal into the concrete appears to be necessary for reliability (exemplified by the mechanical embedment of steel reinforcing bars in concrete).

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