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THEIR PRESENT AND FUTURE USEFULNESS

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More sophisticated brazing methods as well as the advent of new structural materials have posed difficult metal joining problems in the electronics, nuclear power, and aerospace industries. Certain of these, particularly in more critical applications, have been successfully solved by the use of gold-based brazing alloys, and this article reviews the present importance and potential scope of such alloys.

Until recently gold-bearing brazing alloys have been used almost exclusively in the jewellery trade. Many alloys of this kind, commonly known as carat gold solders, have been developed over the years not on the grounds of technical necessity but mainly to provide the goldsmith with a wide range of low-melting solders matching the gold content and colour of a large variety of carat golds from which jewellery articles are fabricated. Their usefulness is therefore limited; in general engineering applications they have little to offer that cannot be found in much less expensive silver solders and base metal brazing alloys.

This review is concerned with entirely different materials developed in recent years in response to a demand created by new applications in the electronic, nuclear power, aero-engine, and spacecraft industries. New metal joining problems were posed by the more widespread use of sophisticated brazing methods and



Fig. 1 In the assembly of this Rolls-Royce RB211 turbojet engine a gold-based brazing alloy is being employed because it has excellent high temperature properties and produces joints that meet all the requirements of aerodynamic gas flow. This is important in reducing fuel consumption as well as smoke and noise levels

Table I

Industrial Gold Brazing Alloys

No.	Composition, wt. per cent						Melting range, °C		Specifications	
	Au	Cu	Ni	Ag	Pd	Other	Solidus	Liquidus	B.S. 1845 (UK)	AWS-ASTM (USA)
1	100						1063	1063		
2	94	6					965	970		
3	81.5	15.5	3					~910		
4*	80	20					910	910		
5*	80	19					905	910	Au1	BAu-2
6	75	25					910	914		
7	62.5	37.5					930	940	Au 2	BAu-1
8	50	50					955	970		
9	40	60					975	995		
10	37.5	62.5				1.0 Fe	980	1000	Au3	
11	35	62					973	1029		
12	35	65					970	1005		BAu-3
13	30	70					995	1020	Au4	
14	20	80	3				1018	1040		
15	70		30							
16	60	20	20				1030	1040		
								~845		
17**	82.5		17.5				950	950	Au 5	
18**	68		8.9			1.0 Cr 0.1B	960	980		BAu-4
19	75	22	25				950	990		
20	72		22			6 Cr	975	1038	Au6	
21	65		35				950	1070		
22	92					8		1230		
23	87					13	1180	1300		
24	75					25	1260	1400		
25	70	22				8	1375	~1045		
26	50	25				25		~1121		

*Alloys Nos 4 and 5 are equivalent. A small quantity of iron is added to alloy No. 5 to retard the ordering transformation which takes place in the 80 Au-20 Cu alloy and which is accompanied by volume changes that cause difficulties in the fabrication of this material and may affect the properties of joints it produces (See British Patent Specification No. 681484).

** Alloy No. 18 is a recently developed, less expensive equivalent of alloy No.17 with comparable wetting and free-flowing properties and high-temperature strength and oxidation resistance (British Patent Application No. 39805/68).

by the appearance of new structural materials whose improved mechanical properties and resistance to various environmental influences had to be matched by suitable joining materials. Solutions to some of these problems were found in specially designed base metal brazing alloys; in many critical applications, however, designers and metal fabrication engineers were forced to take recourse to alloys based on noble metals, among which gold brazing alloys occupy an important place. Commercially available brazing alloys in which gold is the major constituent are listed

in Table I, in which data on their composition and melting ranges are given. For the sake of completeness the table also lists pure gold which is sometimes used for low-temperature brazing of diffusion seals and for joining tungsten.

Gold-Copper Alloys

In formulating alloys listed under Nos 2 to 14, use was made of the rather unusual character of the gold-copper system. The equilibrium diagram of this system, reproduced in Fig. 2, shows that, although

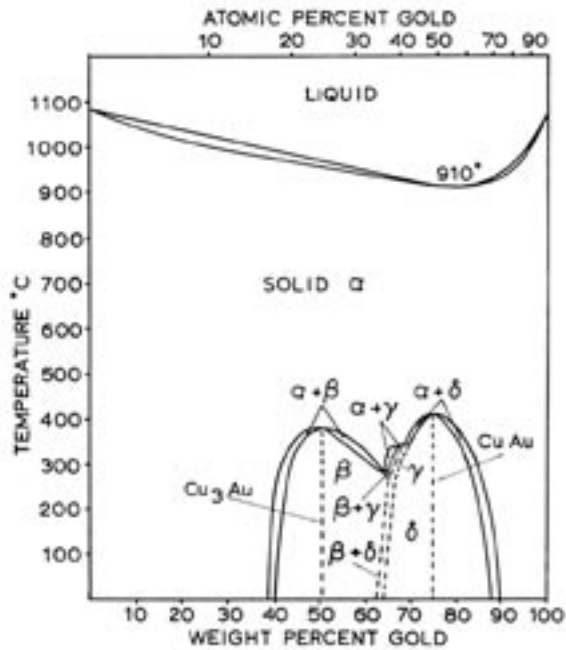


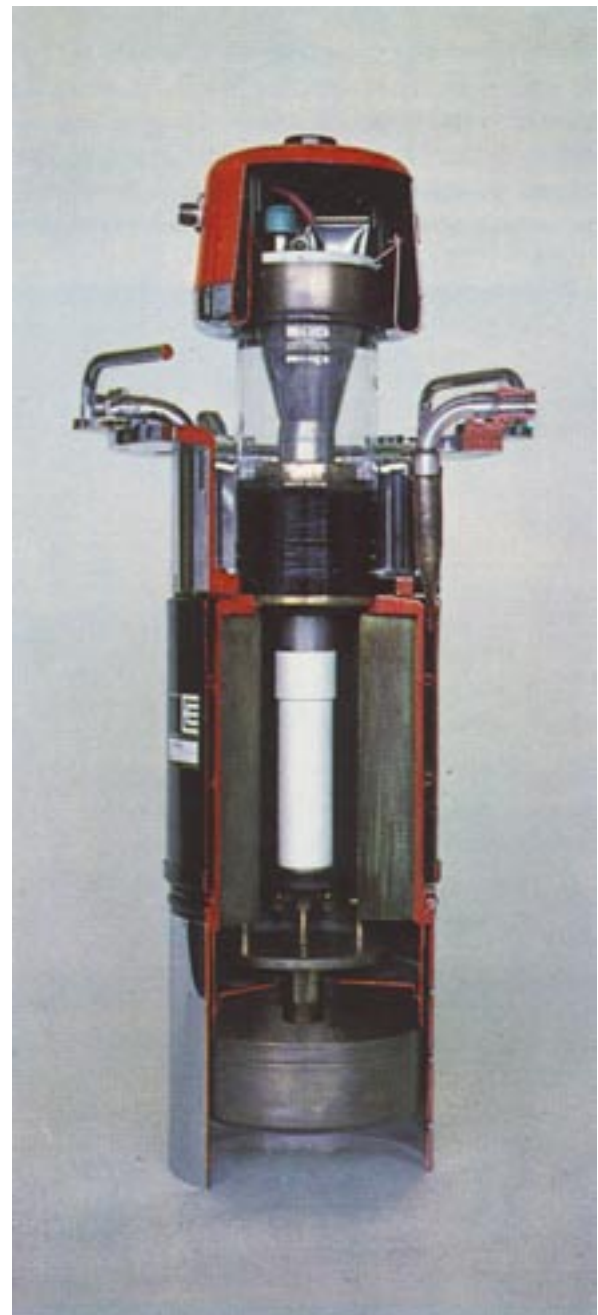
Fig. 2 The constitutional diagram of the gold-copper system. It will be seen that all alloys in the system have narrow melting ranges and are therefore potentially useful brazing materials

it forms a continuous series of solid solutions, the liquidus and solidus temperatures of gold-copper alloys do not follow the additivity law. On the contrary, the melting point of each of these metals is reduced by the addition of the other. Moreover, the liquidus and solidus curves converge near the 80 per cent gold—20 per cent copper composition, which means that this single-phase binary alloy has no melting range. This property is often important from the brazing point of view because it is usually associated with high fluidity and ability to fill narrow joint gaps and to form small radius fillets. Other useful properties of gold-copper brazing alloys include the following:

- (i) Ability to wet copper, nickel, iron, cobalt, molybdenum, tantalum, niobium, tungsten, and their alloys.
- (ii) Ability to produce ductile joints without excessive inter-alloying. The latter factor is important in cases when excessive erosion of the work piece by molten brazing alloy could affect the dimensional accuracy of brazed parts or unduly weaken thin-walled structures.

Fig. 3 A cut-away view of an English Electric Valve Co magnetron. Its assembly involves a large number of sequential brazing operations, the first joint being made with pure platinum and the last with a tin-lead solder. The intermediate stages are carried out with gold-copper, gold-silver, and gold-copper-silver brazing alloys

- (iii) Freedom from volatiles and from constituents that form refractory oxides. The former is important when brazing is used to fabricate parts that operate in vacuum at elevated temperatures; freedom from elements that form refractory oxides makes for easy brazing without a flux in reducing and neutral atmospheres or in vacuum.
- (iv) Exceptional resistance to corrosion, especially in the case of gold-rich alloys.
- (v) Ability to be produced in wrought forms such as foil, strip, and wire. This is an important consideration in furnace brazing applications



in which the brazing alloy must be preplaced in or near the joint area before brazing; shims and wire preforms often provide the most convenient means of doing it.

The largest consumer of gold-copper brazing alloys is the electronic industry where they are widely used in the fabrication of wave guides, electron tubes, valves, radar equipment, and vacuum devices. The reasons why these and other noble metal brazing alloys are especially useful in these applications can be best illustrated by reference to joining problems encountered in the manufacture of magnetrons (1).

The cavity magnetron (see Fig. 3) is a thermionic valve for generating microwaves. It is claimed to be one of the most complex mass-produced brazed assemblies. It comprises a large number of parts made of such diverse materials as copper, nickel, molybdenum, tungsten, brass, Monel, and a nickel-cobalt-iron alloy. Its design and fabrication creates special problems because of the need for high precision, close proximity of joints to one another, difficulty of bonding some of the materials, high degree of vacuum in which the valve operates, intense localised temperatures in operation and long life expected of this type of valve.

The assembly of this device involves about a dozen brazing and soldering operations. These cannot be carried out simultaneously so that it is necessary to apply the so-called step-by-step brazing technique. In this technique each successive joint is made with a brazing alloy that has a melting point lower than that of the alloy used in the preceding operation; in this way the danger of the previously made joints being damaged by heat at any given stage is eliminated.

In this particular case the first joint (between the final turn of a coiled thoriated-tungsten heater and a molybdenum support) is made with pure platinum melting at 1770°C and the last (between copper cooling fins, nickel-plated mounting plate and silver-plated output assembly) with a tin-lead solder melting at 199°C. Brazing operations in the intermediate temperature range (850 to 1400°C) can be performed with any of the brazing alloys listed in Table I, though (as already stated) gold-copper, gold-silver, and gold-copper-silver alloys are most often used in applications of this kind. Which alloy is used in a given case depends on the specific requirements relating to its

Fig. 4 The constitutional diagram of the gold-nickel system on which oxidation-resistant brazing alloys are based. Alloys near the 80 gold-20 nickel composition are mostly used in brazing applications because they have narrow melting ranges and therefore good flowing characteristics

Table II
Typical Values of Mechanical and Physical Properties of Two Gold-Copper Brazing Alloys

Property	Alloy composition	
	80 Au— 20Cu	62.5 Au— 37.5 Cu
Melting range, °C	910	930—940
U.T.S., tons/sq. inch	30	27
Elongation, per cent	17	38
Hardness (D.P.N.)	250	112
Electrical resistivity, microhm—cm	14.2	13.9
Density	17.25	15.2

melting point and other pertinent properties. A general idea about some room temperature characteristics of these materials can be gained from data cited for two gold-copper alloys in Reference 2 and reproduced in Table II.

Gold-Nickel Alloys

The next important group of gold brazing alloys is based on the gold-nickel system which, as shown in Fig. 4, is metallurgically analogous to the gold-copper system.

The number of binary gold-nickel alloys that are potentially useful as brazing media is relatively small and limited to alloys near the 82.5 Au—17.5 Ni composition which, like its counterpart in the gold-

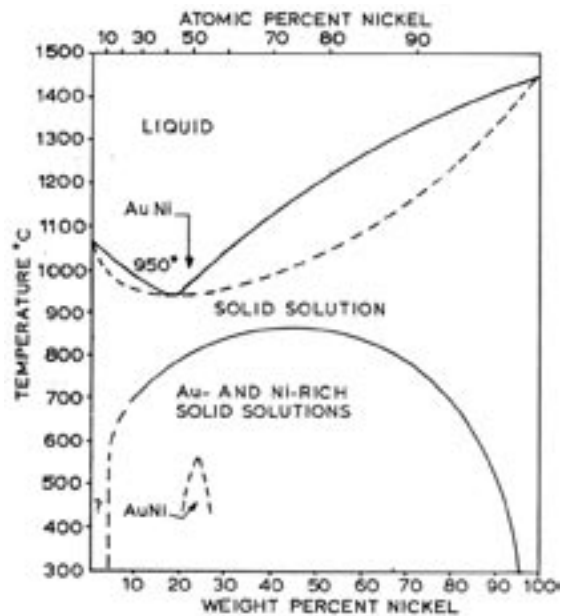


Table III
Comparative Data on the Corrosion and Oxidation Resistance of Gold-Nickel and Gold-Copper Brazing Alloys (3)

Test conditions*	Degree of damage	
	82.5 Au—17.5 Ni alloy	80 Au—20 Cu alloy
100 hours in a NaF—ZrF ₄ —UF ₄ mixture at 815°C	Braze fillet unaffected	Braze fillet unaffected
100 hours in NaOH at 815°C 100 hours in NaOH at 593°C	Braze fillet attacked to a depth of 0.001 inch No attack	Braze fillet attacked to a depth of 0.003 inch No attack
500 hours at 815°C in static air with 220 cools to room temperature	Less than 0.001 inch attacked 0.001 inch attacked	Complete oxidation Complete oxidation
In static air at 815°C for: 200 hours 500 hours 1,300 hours In static air at 926°C for: 200 hours 500 hours	Less than 0.001 inch attacked Less than 0.001 inch attacked 0.01 inch attacked 0.002—0.005 inch attacked 0.002—0.005 inch attacked	0.002—0.005 inch attacked Complete oxidation — Complete oxidation Complete oxidation

* The tests were carried out on brazed specimens.

copper system, is distinguished by having a single melting point. No gold-nickel alloys containing more than 35 per cent nickel are at present used because they have relatively inferior joint filling properties due to their wide melting ranges and high viscosity.

Brazing alloys based on the gold-nickel system have all the useful properties of gold-copper alloys. Where they score heavily over the latter materials is in their high-temperature strength and their resistance to oxidation at elevated temperatures. These differences are clearly illustrated by data reproduced

from Hoffman and his co-workers (3) in Table III which, incidentally, show also that both gold-copper and gold-nickel alloys are very resistant to corrosion by molten fluoride mixtures.

Additional information on the oxidation resistance of joints brazed with a gold-nickel alloy is given in Table IV, while selected data, all from Chang (4), on certain mechanical properties, determined at both room and elevated temperatures of joints brazed with this alloy are reproduced in Tables V and VI.

The reader may be puzzled by the fact that a figure of

Table IV
The Effect of Oxidation at 815°C on Room-temperature Tensile Properties of Joints Brazed with 82.5 Au—17.5 Ni Alloy in Steel AISI 347 ("Zero" joint clearance) (4)

Oxidation Time weeks	U.T.S. tons/sq. inch	Elongation per cent	Reduction in area per cent	Location of failure
0	39.3	50	63	Steel
1	42.0	52	64	Steel
2	41.0	57	56	Steel
4	41.0	51	57	Steel
8	40.5	39	31	Joint and steel

39.3 tons/in² is cited in Table IV for room temperature strength (U.T.S.) of joints made with the 80 Au—20 Cu alloy in one grade of steel, while a figure of 85 tons/in² was recorded for the U.T.S. of similar joints made in a different steel. This is because brazed joint properties depend not only on the inherent strength of brazing alloys but also on the composition and properties of the materials brazed, on the joint design, and on brazing conditions (5). In this connection it should also be borne in mind that mechanical properties of brazed joints working at elevated temperatures may undergo substantial changes due to structural transformations and diffusion phenomena. The magnitude of this effect varies from case to case; in certain circumstances a complete loss of adhesion may occur (6).

High-temperature properties of gold-nickel alloys can be modified by the introduction of alloying elements. For instance, chromium added to these alloys increases their oxidation resistance (at the expense of their free-flowing characteristics) and confers on them the ability to wet graphite. Alloying can be used also to reduce the noble metal content (and therefore the intrinsic cost) of materials of this kind without losing any of their useful properties; this, incidentally, was the reason for developing the alloy listed in Table I as No. 18.

This material (an Au-Cu-Ni-Cr-B alloy) was developed in the Johnson Matthey Research Laboratories (7) to provide a less expensive equivalent of the standard 82.5 Au—17.5 Ni alloy used in relatively large quantities in the aircraft industry, which is the largest consumer of heat-resistant brazing alloys. The reasons for which gold-nickel alloys with their exceptional properties have been found indispensable in this field are again best illustrated by reference to a specific application.

The case in question was the fabrication of a modern aero-engine of the type shown in Fig. 1. One of its components in which brazing had to be used as the joining method is the H.P. compressor module. The brazing alloy used in this case had to possess the following properties.

- (i) Ability to wet, and to produce sound joints on, "Jethete" (a heat-resistant steel containing up to 0.45 per cent C, 0.5—0.9 per cent Mn, 11—12.5 per cent Cr, 2—3 per cent Ni, 0.25—0.4 per cent V and 1.5—2.0 per cent Mo).
- (ii) A melting point below 1000°C. ("Jethete" parts were brazed in a heat-treated condition; heating them above 1000°C during brazing would have destroyed the beneficial effects of the heat treatment).
- (iii) Freedom from volatile constituents, to permit brazing to be carried out in vacuum.

Table V
The Effect of Temperature on the Tensile Properties of Joints Brazed with 82.5 Au—17.5 Ni Alloy in Steel AISI 410. ("Zero" joint clearance; tests carried out on specimens in the as-brazed condition) (4)

Test temperature °C	UTS. tons/sq. inch	Elongation per cent
20	85.0	8.0
260	85.0	6.0
540	47.0	2.0
650	18.0	10-0

- (iv) Freedom from a tendency to erode the parent metal due to excessive interalloying. Joint fillets and the adjacent areas, which could not be dressed after brazing, had to be perfectly smooth because of aerodynamic gas flow considerations; this factor is important from the point of view of reducing the fuel consumption, and smoke and noise levels.
- (v) High strength and oxidation resistance at temperatures of up to 500°C.
- (vi) Ability to be produced in the form of powder, wire, strip, and foil for ease of preplacement.

The only materials that could satisfy all the above requirements were the Au-Ni and Au-Cu-Ni-Cr-B alloys.

Another interesting application of brazing with the 82.5 Au—17.5 Ni alloy is the fabrication of the lunar module of the Apollo spacecraft system (8). The

Table VI
The Results of Charpy V-notch Impact Tests on Specimens Brazed with the 82.5 Au—17.5 Ni Alloy (4)

Parent metal	Joint clearance*	Test Temperature °C	Impact strength, ft lb
Steel AISI 347	"Zero"	20	48
	"Zero"	650	62
	0.004 inch	20	32
	0.004 inch	650	45
Steel AISI 410 (tempered after brazing)	"Zero"	20	7
	"Zero"	650	45
	0.004 inch	20	45
	0.004 inch	650	45

* Joint clearances cited in Tables II to IV are the clearances in the test-pieces as assembled for brazing; the actual braze thickness was approximately 0.002 inch larger.

propulsion and reaction control systems in this vehicle comprise 1046 joints in stainless steel tubing (3/16 to 2 in diameter, 0.016 to 0.057 in wall thickness) carrying fuel, oxidiser (N_2O_4) and helium at pressures of up to 3000 psi. The gold-nickel alloy is used because of its resistance to N_2O_4 ; the brazing is done with a portable clamp-on induction coil under an inert gas shield.

The same alloy is one of three filler materials used in the brazing of the thrust chamber of the F-1 engine powering the first-stage Saturn V launch vehicle of the Apollo spacecraft system (9). Each thrust chamber, which must be fabricated to exceptionally high reliability standards, has 178 primary tubes and 356 secondary tubes and is constructed mainly of a high-temperature nickel alloy (Inconel X-750). The joints are made by a three-step furnace brazing process.

When complete freedom from oxidation is required in addition to all the useful characteristics of gold-nickel alloys, gold-palladium alloys can be used. These materials, some of which have relatively high melting points (up to 1400°C), and gold-palladium-nickel alloys are often found useful in the first (i.e., high-temperature) stages of step-by-step brazing.

Detailed published information on the performance of joints made with gold brazing alloys in various structural materials for service in a wide range of working media and under diverse conditions of stress and temperature is unfortunately scarce. Nevertheless,

the few applications described in this article show quite clearly the importance, the present scope and the potential future uses of materials of this kind.

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