GOLD PLATING OF CRITICAL COMPONENTS FOR SPACE APPLICATIONS: CHALLENGES AND SOLUTIONS

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Ensuring the maximum reliability of the gold plating on lightweight alloys used in space applications is a difficult and challenging task. In this article, the authors describe the processes that they have found to meet requirements.

Aluminium, magnesium, titanium and their alloys are increasingly used as the lightweight structural materials in aircraft and space applications, where lightness is always at a premium. To meet the end requirements (e.g., for improving corrosion and wear resistance, for increasing surface conductivity, for thermal control, etc.) surface coatings are applied to modify the surface properties.

Unfortunately, plating on these lightweight structural materials is difficult. These metals and alloys belong to the group of difficult-to-plate materials. The basic problem stems from their high electrochemical potential in aqueous solution and their consequent high reactivity in air even at room temperature. As a result, they are always covered with a tenacious surface oxide film which prevents metal-to-metal bonding, thus leading to poor adhesion.

For space applications, the reliability of the plating should be 100 %. This means that the adhesion should be excellent and high quality deposits should be produced. Defective plating is unacceptable as it seriously affects the launching and/or functioning of the spacecraft. Stripping the defective deposits without damaging the sensitive components also poses problems. Hence it is mandatory to control deposit characteristics with very high reliability by surface preparation procedures, by careful selection and control of bath composition and operating conditions, and by post-plating handling procedures.

Gold coatings are always the preferred choice in the space programmes. Gold's high conductivity, stable surface resistivity, tarnish resistance, and resistance to chemical corrosion and high temperature oxidation contribute to its high reliability in performance in the space environment.

At the National Aeronautical Laboratory, Bangalore, space quality gold plating on critical components fabricated from aluminium and magnesium alloys and from stainless steel has been developed and these components have been used successfully in Indian space programmes. Work of the authors in this field is briefly summarised in this article.

GOLD PLATING ON 6061 ALUMINIUM ALLOY WAVEGUIDES

Figures 1 to **3** show waveguides made out of 6061 aluminium alloy (Al-Mg-Cu-Cr alloy). These components were to be gold plated uniformly to a thickness of 5 µm to impart surface conductivity. Gold plating of these components posed the following challenges:

- Obtaining an adherent coating on 6061 aluminium alloy, which belongs to the group of difficult-to-plate materials.
- Obtaining a very uniform coating on such complex shaped components.
- Obtaining first quality gold deposits to meet the space qualification requirements.

Obtaining an adherent coating on 6061 Al alloy is difficult for the following reasons:

- The surface is covered with a tenacious, impervious oxide film. This film, after removal by normal cleaning processes, is rapidly formed again and thereby hinders metal-to-metal bonding, leading to non-adherent or poorly adherent deposition.
- The alloy contains 1 % Mg, 0.25 % Cu and 0.25 % Cr besides aluminium. These alloying elements may appear in several different forms - as a solid solution in the aluminium lattice, as micro particles of the elements themselves or as particles of intermetallic compounds formed by combination with aluminium or other alloying elements. Such microstructural and compositional heterogeneity causes non-uniform electrochemical behaviour.

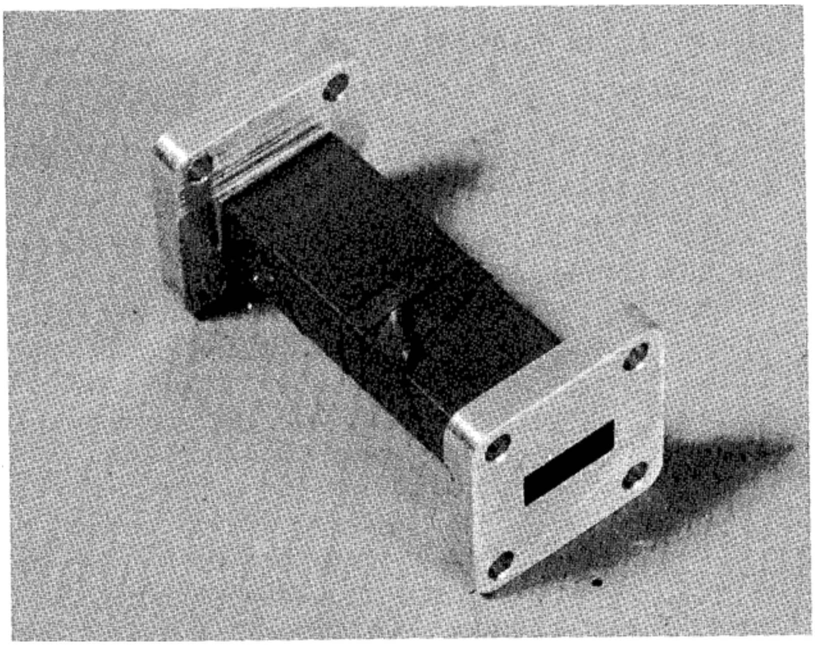


Figure 1:
Waveguide in 6061 aluminium alloy

Hence, to achieve excellent adhesion, the oxide film should be removed and replaced by an adherent and more receptive film. Such a film should be capable of forming on a surface with a non-uniform electrochemical reactivity and converting it to a surface of uniform activity. This is accomplished by proper choice of the preplating schedule.

The following process sequences proved to be the best for achieving excellent adhesion.

1. Degreasing

The components were degreased with trichloroethylene/acetone. To effectively clean the bores and internal surfaces of the components, ultrasonic agitation was employed.

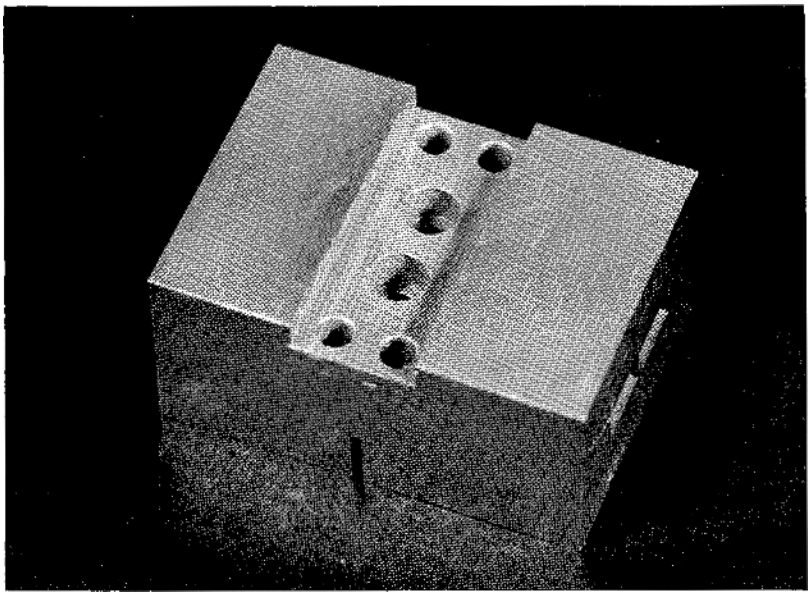


Figure 2:
Waveguide in 6061 aluminium alloy

2. Alkaline Cleaning

The components were cathodically cleaned in a mild alkaline cleaner (**Table 3a**, p. 66). At this stage, after thorough washing, the components were in a perfectly clean condition for further processing.

3. Deoxidising

Generally, after cleaning, the components are subjected to etching treatment. Though the aluminium alloy surface is free from dirt and grease, the surface may be covered with a thin natural film or thick tenacious oxide film formed during the fabrication of the parts or as a result of chemical or thermal processes. This oxide film may result in non-uniform etching. Hence to facilitate uniform etching we found that it is essential to introduce a deoxidising step, wherein the oxide film is uniformly removed. For this purpose the components are treated in a hot solution of phosphoric acid and chromic acid mixture for five minutes:

H_3PO_4 = 30 ml/l
CrO_3 = 25 g/l
Temperature = 95 °C
Time = 5 minutes

The oxide film is completely removed in this step. The main advantage of using this solution is that it removes only the oxide and there is practically no attack on the aluminium alloy substrate.

4. Etching

To achieve best adhesion in the subsequent deposition processes, the surface of the components are subjected to mild etching, which produces uniform 'keying in' points. Etchants should be so chosen that they produce a uniform micro-roughened surface. The composition of some of the acid etchants tried and found to be satisfactory are given in **Table 1**.

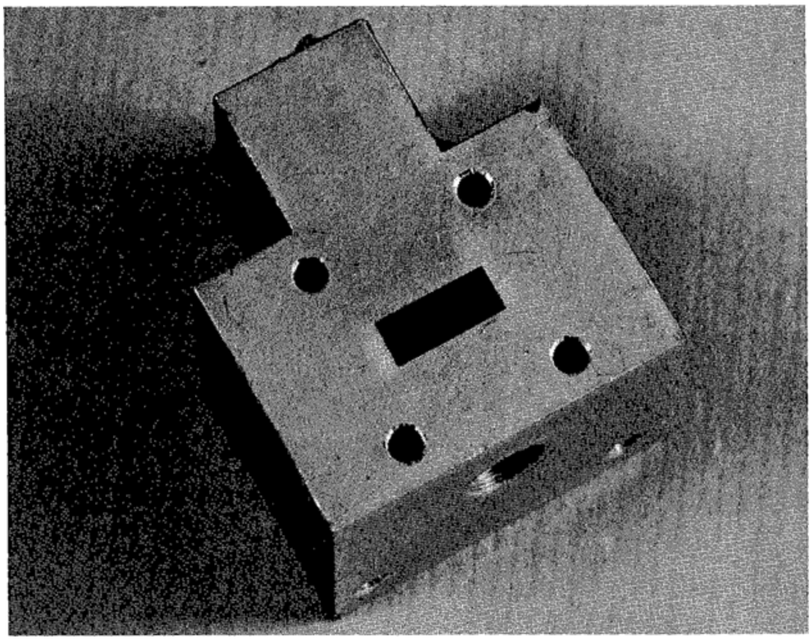


Figure 3:
Waveguide in 6061 aluminium alloyl

5. Smut Removal

After etching, the surface of the components may be contaminated by non-adherent smut. This is removed by immersion in 50 % nitric acid for 15 to 30 seconds.

6. Double Zincating

The components are then zincated in a modified dilute zincating solution of the following composition at room temperature:

ZnO = 20 g/l
$NaOH$ = 120 g/l
Rochelle salt = 50 g/l
$FeCl_3 \cdot 6H_2O$ = 1.5 g/l

Double zincating provided a uniform thin immersion zinc coating, which had better receptivity than single zincated film.

Table 1:
Etchants for 6061 aluminium alloys

1)	CrO_3	=	5 % (by weight)
	H_2SO_4	=	15 % (by volume)
	Temperature	=	65 °C
	Time	=	2 minutes
2)	H_3PO_4	=	10 % (by volume)
	H_2SO_4	=	5 % (by volume)
	Temperature	=	65 °C
	Time	=	2 minutes
3)	HNO_3	=	2.5 % (by volume)
	H_2SO_4	=	1 % (by volume)
	NH_4HF_2	=	3 % (by weight)
	Temperature	=	30 °C

7. Electroless Nickel (EN) Bond Coating

After zincating, the common practice is to give a flash coating of copper from a special bath of Rochelle copper cyanide, which does not attack zinc when the zincated parts are plunged into the bath with the current on. Instead of copper strike we used electroless nickel bond coating from a special purpose EN bath. This is a crucial step which dictates the adhesion of subsequent gold plating. Since the zinc coating thickness is very small, the reaction in the electroless plating bath should not be vigorous. (This will lead to the corrosion of the underlying aluminium alloy resulting in spongy deposition.) Out of the several formulations tried, the bath based on citrate-fluoride was found to be the best. The bath composition and operating conditions are given in **Table 3b** (p. 66).

This bath when used at room temperature produces a uniform and extremely adherent coating of electroless nickel. EN is built up to a thickness of about 2 µm and serves the same purpose as the copper strike. Operation of the bath at room temperature is beneficial since the problems associated with high temperature processes are avoided. Replacement of the copper strike by electroless nickel plating was advantageous because the latter produced a uniform deposit inside bores and on components of complex shape.

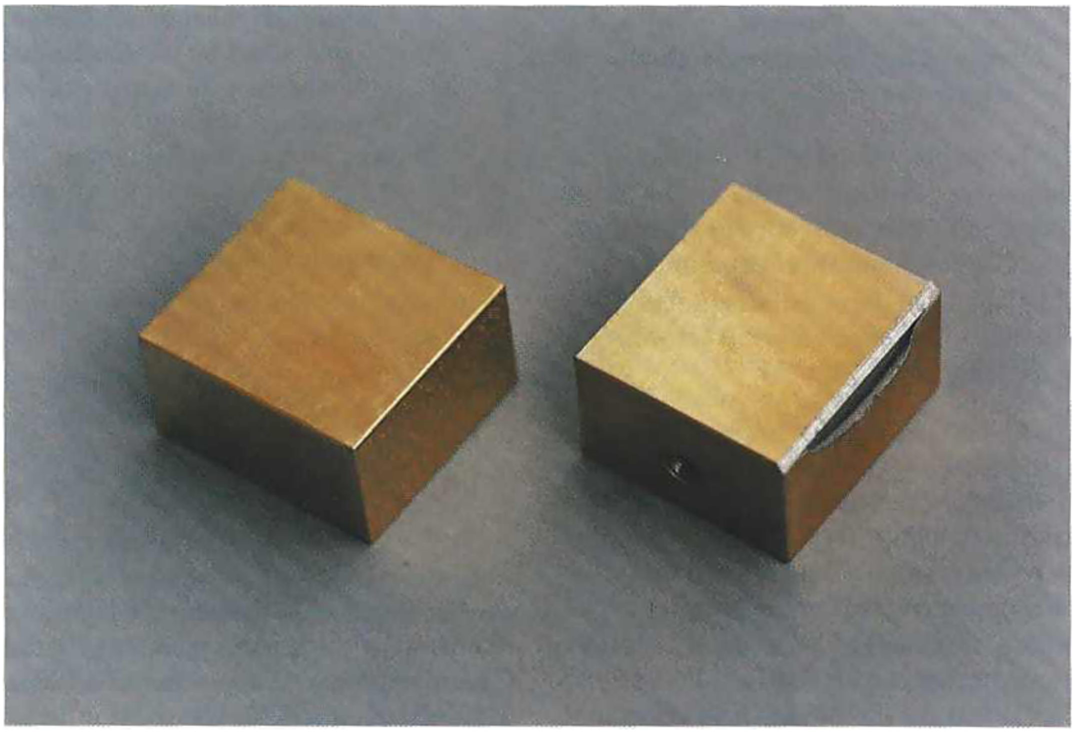
The above preplating schedule has to be carefully followed to achieve excellent adhesion. **Figsures 4** and **5** show clearly the vital role played by the preplating schedule. **Figures 4a** and **5a** (left samples) show samples of 6061 Al alloy gold plated after a thorough precleaning schedule. No delamination or peeling occurs. The gold plated samples were found to pass all the tests - namely bending, drilling, cutting and heat-quenching tests and a test of thermal cycling under high vacuum conditions. In **Figures 4b** and **5b** (right samples), the gold plated samples show respectively blistering and delamination, due to improper pretreatment.

8. Gold Plating

The other two problems, namely achieving uniform coating on complex shapes and gold deposit characteristics to suit space applications, are now considered in detail.

Achieving uniform deposition on complex shapes before the gold plating stage was not a problem since all the processes are of the immersion type. In the gold plating stage, uniformity is the prime consideration. To plate internal surfaces of the components, an internal anode arrangement is needed. A thin stainless steel anode plated with gold (2.5 µm) was insu-

Figures 4 & 5:
6061 aluminium alloy samples after gold plating
left: *gold plating after a thorough pre-cleaning*
right: *gold plating after improper pretreatment*



lated with a loosely braided glass fibre cloth and used to effectively plate the inner side. The flexible braid prevented short circuiting and burning while permitting flow of electrolytic current. Forced circulation of the electrolyte by means of a pump was used to overcome the problems due to depletion of gold in the electrolyte inside the holes. Frequent to and fro motion of the anode was used to further assist the supply of fresh electrolyte and hence uniformity of deposition.

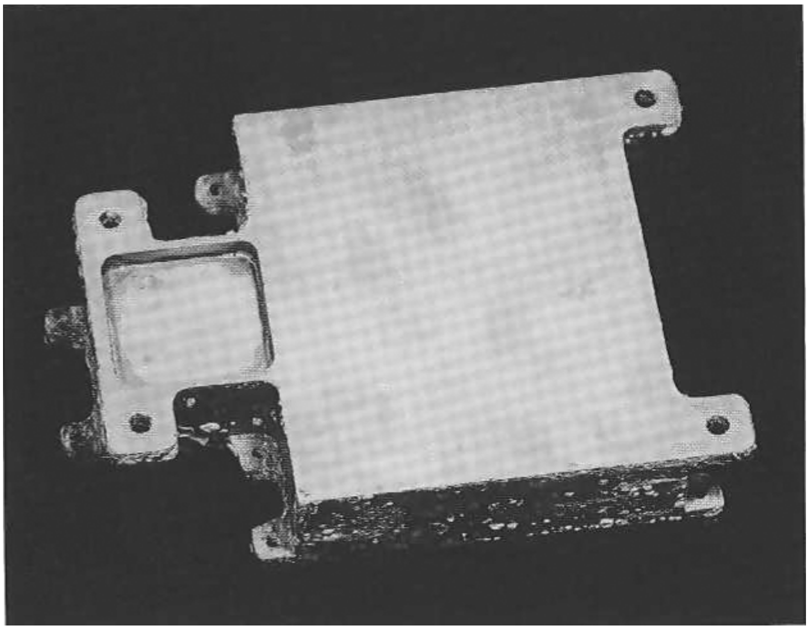


Figure 6:
Exemple of a typical communication package made out of RZ 5 magnesium alloy

The gold plating bath formulation was selected to suit the space qualification requirements according to which the gold deposit

- should be of high purity, i.e. 99.9 %
- should have a hardness of less than 100 KHN
- should have high conductivity, i.e. resistivity should not be more than 3.5 μΩ-cm
- should have a thickness of 5 μm
- should be completely free from porosity.

For this purpose, alkaline gold cyanide solutions cannot be used because they contain measurable quantities of impurities [1] and are also porous at a thickness of 5 μm. Acid cyanide baths are also not suitable because the deposits from these baths are found to contain polymeric derivative of a cyanogen or partially hydrolysed polyhydrocyanic acid [2] Neutral phosphate baths produce stressed deposits. We found that neutral citrate baths are ideal in all respects. The compositions and operating conditions are given in **Table 3e** (p. 66). The deposits are pure, pore free at thicknesses greater than 3 μm, stress free, ductile and fine grained.

Anode selection also requires careful consideration. Although gold anodes are ideal, they were not used in order to keep the capital investment low. Hence the choice was to use insoluble anodes. The insoluble anode that is used for gold plating should not contaminate the bath. Iron or stainless steel anodes that are normally used in cyanide gold plating solutions should not be used due to the risk of bath contamination by iron and nickel at low current densities in citrate medium. Graphite anodes are not recommended in view of the contamination of the deposit with carbon. Platinised titanium anodes or gold plated stainless steel anodes are ideal anode materials.

6061 aluminium alloy components, gold plated by the above procedure, were found to pass all the space qualification tests.

GOLD PLATING ON MAGNESIUM ALLOY BOXES

'APPLE' (Ariane Passenger Payload Experiment) is an Indian experimental geostationary communication satellite launched in the year 1981. The communication between the ground station and satellite was via C-band antennas at communication frequencies of 6 GHz (receive) and 4 GHz (transmit). The electronic circuit cards of this equipment were mounted in magnesium alloy boxes made out of RZ5.

The communication packages, made out of RZ5 alloys, are of complex geometry and some typical boxes are as shown in **Figures 6** and 7. RZ5 is an alloy of Mg-Zn-Zr with Zn=4 %, Zr=0.7 % and rare earth 1.3 %. The zinc addition confers grain refinement and increases the strength. Zirconium improves grain refinement. The presence of rare earth metals helps to improve the long-term creep resistance (at temperatures less than 250 °C). This alloy was chosen because of its ease of fabrication and other space requirements.

Since no published information is available on plating these alloys, development work on this process was undertaken in our laboratory.

For proper communication, there should be low loss at the operating frequencies and minimum pick-up of stray voltage across the passive components of the subsystem. At microwave frequencies, current flows on the surface of the package (skin effect). Hence surface conductivity of the package should be very high to provide noise immunity. Gold coating is the best since it has low resistivity (2.1 µΩ-cm) and also has excellent corrosion resistance. Thus the communication packages require the application of 5 µm of pure pore free gold on RZ5 alloys, which should conform to the following specifications, in addition to those discussed under gold plating on aluminium alloy waveguides.

- The coating properties should not deteriorate within the lifetime of APPLE, which was two years.
- The temperature of the packages will vary from 5 to 45 °C because of the night and day cycle. The coating should withstand this temperature cycling.
- Ambient pressure is of the order of 10 to 12 Torr. The coating should withstand such high vacuum.
- Adhesion of the gold coating should be excellent. The coated components should pass bending, drilling and cutting tests.

Magnesium, like aluminium, also belongs to the category of difficult-to-plate metals due to its chemical reactivity. It is much more reactive than aluminium as indicated by its position in the e.m.f. series (Mg $E^{\ominus}$ = -2.37 V, Al $E^{\ominus}$ = -1.67 V). The metal corrodes even in moist air and in distilled water.

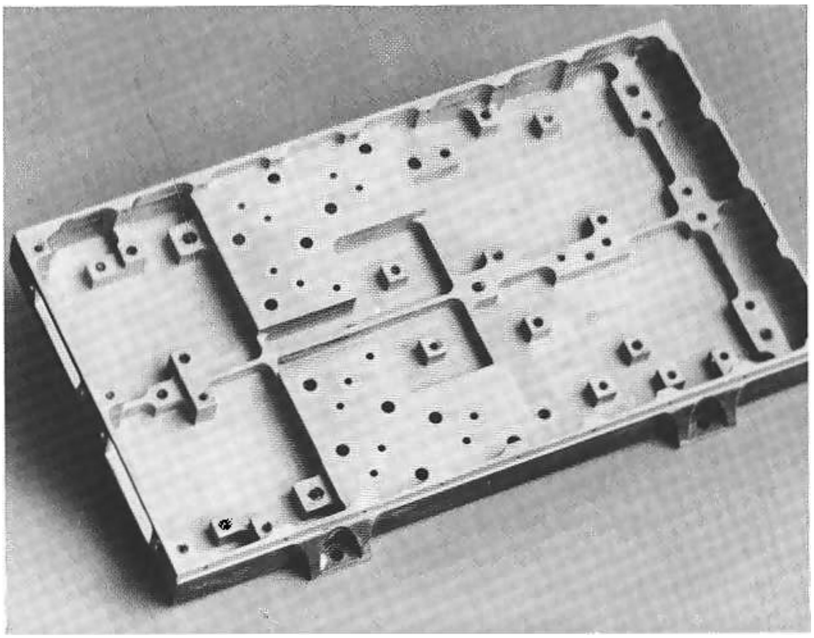


Figure 7:
Typical R25 magnesium alloy component

Because of its high reactivity it reacts with oxygen to form a surface oxide. The oxide film on magnesium (unlike that on Al) is porous and not of the self-healing type and consequently it does not offer protection. However, it prevents the formation of metal-to-metal bonding during plating, resulting in non-adherent deposition.

As in the case of aluminium alloys, magnesium alloys make the plating procedures still more complex. The alloying constituents, together with the magnesium matrix, form local cathodic and anodic sites, introducing electrochemical heterogeneity. If the cathodic site has low hydrogen overvoltage, hydrogen evolution is facilitated in these areas and hence corrosion current is substantially increased. The alloy composition, quality of the castings, design of the castings, mechanical surface preparation and metal finishing processes determine the quality of the coating concerned. The presence of alloy impurity phases and different intermetallic phases differing in their chemical activity to different reagents leads to patchy deposition. If the castings have surface porosity, flaws or oxide and flux inclusions, the quality of the plating is seriously affected. In the design, if there are deep recesses, narrow cavities and sharp corners, uniformity of the coating is very difficult to achieve. Since magnesium is soft, the possibility of inclusion of SiC or Al_2O_3 particles in the matrix during polishing and buffing and particles of heavy metals during shot blasting is another potential problem. Such inclusions, flaws, porosity and presence of different phases cause electrochemical heterogeneity. Plating on such alloy results in non-uniform deposition which results in vastly aggravated corrosion because these defects tremendously accelerate galvanic corrosion.

All the above factors are to be looked into while developing a suitable process sequence for plating on magnesium alloys.

Zincating followed by copper plating is the usual procedure recommended for plating on magnesium and its alloys. The zincating solution used for magnesium differs from that used for aluminium. It is an aqueous solution of a zinc salt, pyrophosphate and a fluoride salt with a small amount of carbonate added to adjust the alkalinity in the proper range. Pyrophosphates assist the formation of an adherent zinc coating by readily reacting with the surface films of magnesium oxide and hydroxide and dissolve them by forming water soluble complexes. The presence of fluoride helps to control the rate of deposition. The bath is operated at 68 to 74 °C and, depending upon the alloy composition, bath temperature, and surface preparation, treatment time varies from 2 to 15 minutes.

However, on RZ5 magnesium alloy, it was very difficult to get uniform zinc coating. The zinc coating was patchy and non-uniform. Double zincating, which is commonly used for most of the aluminium alloys, was found to be ineffective in the case of magnesium alloys. The dissolution of the first layer of zinc in phosphoric acid/ammonium fluoride followed by a second immersion in the zincating bath results in a large amount of gas evolution and consequent non-uniform coverage of the magnesium alloy.

Direct electroless plating was tried after chemical etching and it also resulted in non-uniform deposition. The problems encountered were:

- Excessive corrosion even under cathodic conditions, and
- exfoliation of the deposit.

Detailed investigations showed that these difficulties arose for the following reasons:

- The grains in the substrate were coarse and non-uniform.
- The chemical composition of the alloy castings showed variation from batch to batch and also from location to location in one and the same casting.
- The rare earth addition instead of forming a mushy compound along the grain boundaries (as it is normally supposed to) was seen to be distributed in a non-uniform fashion within the grains.

Due to the variation in chemical composition, cata-

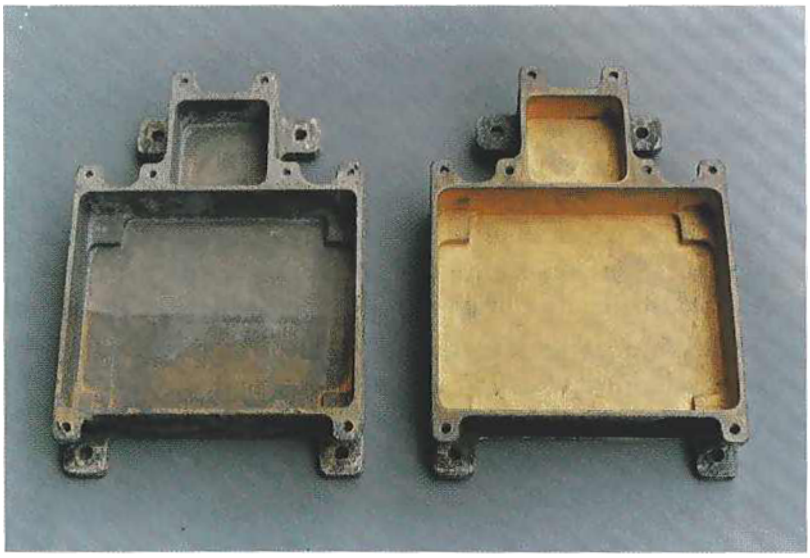


Figure 8:
Gold plated RZ 5 magnesium alloy box
left: *patchy gold plating due to improper pretreatment*
right: *uniform gold plating accomplished by employing EN as a bond coat*

lytic activities of different sites varied drastically leading to non-uniform deposition Hence it was thought that these problems could be overcome by adjusting the conditions of preplating such that the compositional and metallurgical heterogeneities do not significantly influence the electrochemical properties of the substrate during the preplating operations.

The following process sequence was found to be the best:

- Acetone degrease, rinse.
- Cleaning in alkali.
- Mild chromic acid pickling (to remove the surface oxide, loosely adherent cold worked metal and surface contamination).
- Fluoric acid dip:
  48 % HF 7.3 vol.%
  temp. = 25 - 30 °C
  time = 10 min.
- A.c. electrolytic treatment at 5 V for two minutes. This step is very important and ensures the uniformity in subsequent plating sequences. It makes the whole surface uniformly active for further electroless nickel plating, probably by forming an adsorbed film of fluoride after dissolving away the surface oxide and hydroxide. Omitting this step results in patchy deposition (**Fig. 8, left**). On the other hand, it is possible to get very uniform gold deposition on magnesium alloy boxes by means of these fluoride dip and a.c. electrolysis steps (**Fig. 8, right**).
- Electroless nickel plating from a fluoride-containing bath (**Table 3b**, p. 66). The pH of the bath is adjusted to be around 7. Electroless nickel is built up to 5 µm.

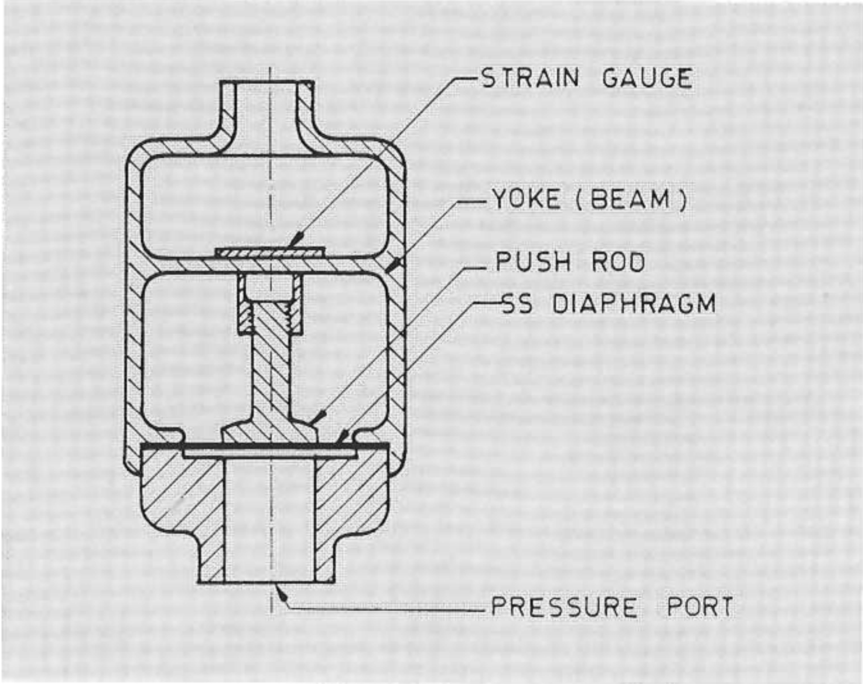


Figure 9a:
Cross-sectional view (schematic) of a pressure transducer employing a stainless steel diaphragm as a pressure sensor

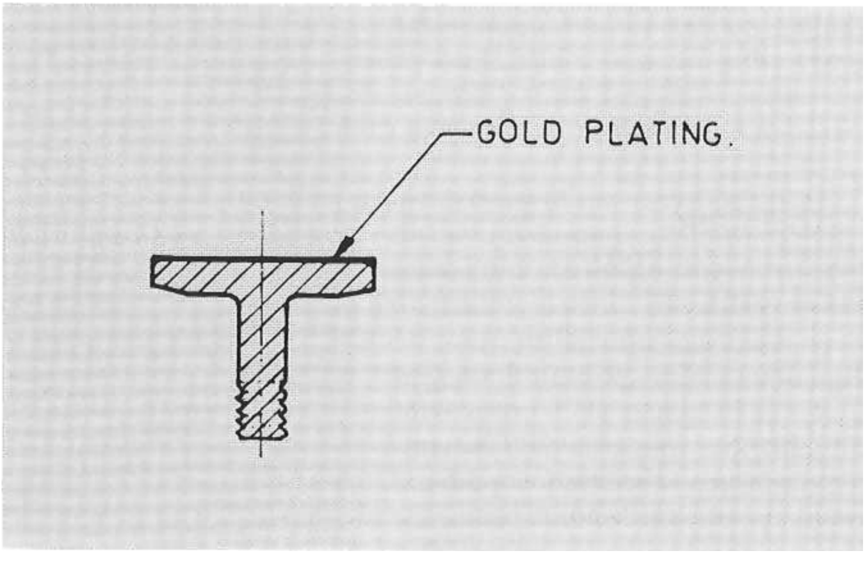


Figure 9b:
Cross-sectional view (schematic) of the push rod showing the area over which gold plating is applied for brazing applications

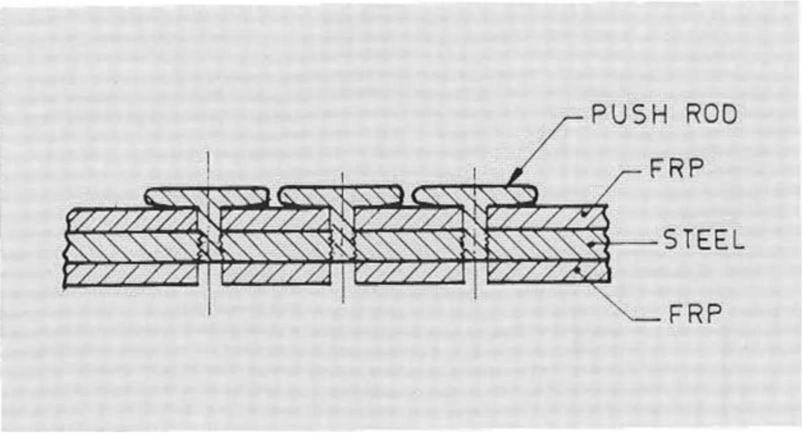


Figure 10:
Cross-sectional view (schematic) of jig used for plating push rods

- Nickel plating from standard nickel sulphamate bath (**Table 3d**, p. 66). The nickel coating is built up to a thickness of 5 µm.
- Gold plating from neutral citrate bath (**Table 3e**, p. 66). A 5 µm gold coating is applied.

Magnesium alloy boxes gold plated by the above procedure were used in APPLE. APPLE successfully performed its mission for a period longer than the expected life period of two years, thereby demonstrating the success of the gold plating.

GOLD PLATING ON STAINLESS STEEL PUSH RODS

Figure 9a shows a schematic drawing of a pressure transducer which makes use of a diaphragm as a pressure sensor. The sensing diaphragm is bonded to a push rod which in turn is joined to a beam. The pressure sensed by the diaphragm is thus transferred as a load to the beam. The resulting strain in the beam, which is proportional to the pressure, is measured by four strain gauges bonded onto it.

The stainless steel (SS) push rod bonded to the SS diaphragm (approx. 0.1 mm thick) is a vital part of the transducer. For the quantitative transmission of the load, the bond between diaphragm and push rod must be perfect. The joining of the push rod and the diaphragm is best carried out by vacuum brazing. For this purpose, a thin coating of filler material has to be applied to the front surface of the SS push rod (**Fig. 9b** is a schematic drawing of the push rod).

Au-Ni alloy Au(82)-Ni(18) has been widely used for brazing stainless steel for space applications [3]. Plating of Au-Ni alloy on SS push rods poses the following problems:

- Stainless steel also belongs to the class of difficult-to-plate materials because of the presence of a thin transparent oxide film of chromium/and or nickel which reforms quickly when destroyed. This film prevents adhesion of the electrodeposit.
- Generally, alloy plating is a complex process and hence electroplating an alloy of specific composition poses practical problems.

Figure 11:
Typical gold plated push rod, with brazed stainless steel diaphragm and assembled transducers

The first problem can be overcome by a suitable activation process prior to plating wherein the oxide film is removed and the surface is covered with an electrodeposit before the oxide reforms.

A possible solution to the second problem was to see whether a Ni+Au composite coating could be used as a filler material in place of the gold-nickel alloy deposit for brazing SS. Such a composite coating would be likely to form a Au-Ni alloy at the brazing temperature and function as a Au-Ni alloy filler material. If this idea worked, then it would be a simpler method of coating the filler material on to SS than the tedious and quite involved alloy plating process.

For removing the oxide layer, and to deposit an adherent coating on SS, acid activation immediately followed by a Wood's nickel strike was employed. No adhesion failure at the interface was experienced. Activation by simple immersion in 50 % HCl alone led to failure at the SS/Ni-Au interface, indicating that the activation treatment is inadequate.

To form the Au-Ni alloy, a two-layer system – a first layer of nickel and a second layer of gold – was used. In principle, the Au-Ni alloy should form at the temperature of brazing and help in the realization of good brazed joints.

Nickel from a nickel sulphamate bath and gold from a citrate bath were found to be suitable for this application. To optimise the nickel undercoat thickness, several push rods were plated with different thicknesses of nickel and gold and tested for the quality of the bond. The thickness of nickel was varied from 1.5 to 12 µm and that of the overlay gold coating from 3 to 20 µm. Some typical results are given in **Table 2**.

Table 2:
Effect of various coatings on brazing of stainless steel diaphragm to SS push rod

Coating			Quality of brazed joint
Gold (2 µm)			poor
Gold (5 µm)			poor
Gold (10 µm)			poor
Gold (15 µm)			good
Gold (20 µm)			good
1.5 µm Ni	+	3 µm Au	poor
5 µm Ni	+	5 µm Au	poor
10 µm Ni	+	10 µm Au	poor
5 µm Ni	+	20 µm Au	good
2 µm Ni	+	8 µm Au	good
2 µm Ni	+	5 µm Au	good
1.5 µm Ni	+	5 µm Au	good
1 µm Ni	+	5 µm Au	poor

From the table it is seen that the minimum thickness required for the realization of a good bond is 1.5 µm Ni + 4 µm Au. Hence the coating of 2 µm Ni + 5 µm Au was chosen as the best.

As seen above, only the front surface of the push rod is to be plated with the filler material. It is important that the shaft and threads of the push rod should not be plated. If plated, this will interfere with the subsequent assembly. If these areas are accidently plated then the coating has to be removed by machining to restore the original dimensions with the required tolerances. Post-plating machining operations should be avoided to save labour as well as gold.

Because of these constraints, the components cannot be plated by barrel plating or by tying them by a wire. Hence the components have to be plated by jigging which means that a suitable jig has to be designed.

A schematic drawing of the special jig designed and fabricated for this purpose is shown in **Figure 10**. It consisted of a steel plate sandwiched between two fibre-reinforced plastic sheets. At regular intervals holes were drilled through and were tapped to match the threading on the push rod (**Fig. 9b**, p. 63).

The thickness of FRP sheet was such that the back face of the push rod would be snugly in contact with the sheet and the threaded portion would be within the steel sheet when the push rod was screwed tight. This ensured that there would be no plating on the back side, stem and threads of the push rod. The through hole ensured that drag-out by entrapment was negligible, which was vital in the case of gold plating in view of its high cost. The final procedure followed for plating the push rods for brazing is given below.

- Degrease the push rods and fix in the jig.
- Degrease again with methyl alcohol to remove any grease introduced while handling.
- Cathodically clean in the standard alkaline solution (**Table 3a**)
- Rinse thoroughly in distilled water.
- Immerse in 50 % HCl for 10 seconds and rinse thoroughly.
- Give nickel strike from Wood's nickel bath (**Table 3c**).
- Plate nickel from the sulphamate bath (**Table 3d**).
- Rinse thoroughly and plate gold from the citrate gold bath (**Table 3e**).
- Drain to minimise drag-out loss, rinse in a rinse tank, wash in running water, rinse in distilled water and dry.

Push rods plated by this procedure bonded very well to the diaphragm. **Figure 11** shows respectively the gold plated push rod after brazing to the SS diaphragm and the assembled transducers.

This process has been used by the pressure transducer fabrication facility for several years. More than 600 transducers have been produced by them and they found that the process gave good bonds and virtually zero rejection rate. In addition this process used only 5 µm of gold as compared to 25 µm of gold recommended by the French process [4]. The jig effectively prevented the deposition of gold on unwanted areas and thereby saved not only gold but also the extra machining needed to machine away the unwanted gold.

Table 3:
Summary of plating procedures for stainless steel

a) Alkaline cleaning solution

$NaOH$ = 10 %
Na_3PO_4 = 10 %.
Current density = 100 mA/cm^2
Time = 2 minutes

b) Electroless nickel bath

Basic nickel carbonate = 10 g/l
HF (70%) = 9 ml/l
Citric acid = 5 g/l
Ammonium bifluoride = 10 g/l
Sodium hypophosphite = 20 g/l
NH_4OH (30 %) = 30 ml/l
ph = 4.5 - 7
Temperature = 30 - 35 °C

c) Wood's nickel strike bath

$NiCl_2 \cdot 6H_2O$ = 100 g/l
HCl = 180 ml/l
Current density = 20 mA/cm^2
Time = 30 seconds

d) Sulphamate nickel bath

Nickel sulphamate = 150 g/l
Nickel chloride = 5 g/l
Boric acid = 10 g/l
Current density = 2.5 mA/cm^2
Time = 5 minutes

e) Gold plating bath

Potassium gold cyanide = 20 g/l
Ammonium citrate = 75 g/l
Temperature = 25 - 30 °C
Current density = 2.5 mA/cm^2
pH = 6
Anodes = Platinised titanium
Time = 38 minutes

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