Investment Casting of Gold Jewellery

THE SURFACE PROPERTIES OF CASTINGS: EFFECTS OF CASTING ATMOSPHERES AND OTHER FACTORS

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Measurements made by a very simple method have shown that many of the factors which affect the quality of castings are sensitive to surface and interfacial energies during the pouring of the melt. The results of a number of measurements of these parameters are presented and discussed.

The surface finish which is obtained in the casting of gold jewellery is very important. In this connection special significance attaches to the surface energy of the melt and the interfacial energy between the melt and the investment. The values of these parameters, however, are greatly affected by the composition of the melt, by its purity, and by reactions which occur between it and both the casting atmosphere to which it is exposed during melting and pouring and the investment material. Further, both the macro- and the micro-geometries of a model affect the surface finish of castings made from it.

Although a number of investigators have studied factors affecting the surface properties of dental gold alloy castings made by the investment process (1-5), no analogous studies of the factors affecting the surface properties of jewellery gold alloy castings appear to have been recorded. Most of the dental alloy studies have been concerned with the effects of the casting machines used. Nevertheless the effects of crystal grain size (6-7) and porosity (8-9) have received attention as well as those of penetration of the mould wall and reaction with the investment material (10). The latter are considered to be the main factors affecting the roughness of dental gold alloy castings, with the degree of penetration of the mould walls being dependent upon their porosity, the casting pressure, any back gas pressure, and the interfacial energy between the molten alloy and the investment.

In their work (1), Fusayama and Yamane recognised the possibility that the interfacial energy might be affected by the degree to which the alloy was oxidized during melting and pouring, but did not demonstrate the effect because of the many other variables with which they had to contend in their experiments. They did, however, observe that in centrifugal castings the extent of the especially rough areas on their castings was greater with gas heating than with electrical heating and greater with horizontal than with hanging moulds.

Our experiments have been focussed specifically upon measurement of the interfacial energies of molten gold jewellery alloys under casting conditions, the effects on the interfacial energies of gold jewellery alloys of additions of small quantities of certain metals and of contamination of the alloys with oxides during the melting and pouring processes. In this latter connection the effects of melting and casting in different atmospheres have been studied. The effects upon the surface finish of castings of reactions between the molten metal and the investment have also been considered and explanations are suggested for the occurrence of roughness caused

by dendritic patterns on the surfaces of castings and of severe sub-surface porosity under some conditions.

Experimental

Useful data on surface and interfacial energies can be derived by using a greatly simplified version of the sessile drop method (11-13). Simplification is achieved by the use of flasks which are so designed that the casting button forms a large drop on a slightly inclined surface. This drop, in its solidified form, is sectioned vertically and the section surfaces ground and polished so that they can be used for determination of the contact angle. The contact angle can be used to calculate the interfacial and surface energies provided that no wetting of the investment material occurs. The contact angle must therefore be greater than 90°.

The results obtained by this simple technique refer only to the state of affairs at the moment at which solidification of the drop occurs. Since, however, this is the most interesting stage in the casting procedure, the data are directly useful in considering the behaviour of the melt. Certain unavoidable inaccuracies in the procedure must be accepted.

The interfacial energy may be calculated as follows (2):

$$\sigma = d \cdot g \cdot \left(\frac{h^2}{2} + 0.3047 \frac{h^3}{D/2} \right) \cdot \left(1 - \left(\frac{4h}{D} \right)^2 \right)$$

Where σ = interfacial energy D = diameter of the drop across its equator

h = height above the equator

g = acceleration due to gravity d = density

For large drops ($D \geq 3$ cm) this formula may be reduced to:
 $\sigma = \frac{1}{2} d \cdot g \cdot h^2$

Examination of the surface finishes of castings was carried out by optical microscopy. Surface roughness was determined mechanically by means of a Perthometer on test specimens cast using the stepped model (see *Gold Bull.*, 1985, 18, (2), 58) which was found suitable for the purpose. The different thicknesses of the three steps made it possible to assess the effects on surface finish of different rates of solidification. In addition to the stepped test specimens, samples cast using a gramophone record model were also examined. For the measurement of other properties, castings of appropriate designs were used (see the above reference).

Table I
Surface Energy and Contact Angle

Alloy	Casting atmosphere	Contact angle (°)	Surface tension (N/mm ²)
14 ct yellow gold	Vacuum (10 ⁻¹ mbar)	144	1210
	Form gas	148	1330
	Argon	161	660
	Air	< 50	—*
18 ct yellow gold with 1% Zn with 1% Ni	Argon	152	1230
	Argon	106	30
	Argon	157	191
18 ct Pd-white gold	Form gas	150	1510
18 ct Ni-white gold	Argon	153	193

*Alloy surface in sprue very flat, wetting not uniform, surface energy not measurable.

Fig. 1 Dendritic texture of a cast 14 carat yellow gold alloy

x 112

Results

Surface and Interfacial Energies

Some results of measurements of these which were made on different alloys in various atmospheres are given in Table I.

The interfacial energies of the 14- and 18-carat yellow gold alloys are very similar. Even small additions of zinc and nickel cause large decreases in their interfacial energies, and, moreover, additions of zinc lead to wetting of the investment material.

The 18-carat palladium white gold alloy has a very high interfacial energy, in contrast with the 18-carat nickel white gold alloy which has a small one. The poor casting behaviour of the former can therefore be improved by introducing into it 10 per cent of nickel in place of the same percentage of palladium. In this way, its interfacial energy can be reduced to levels comparable with those of white gold alloys containing nickel.

In the case of the yellow gold alloys, the atmosphere in which casting was carried out was highly significant. If vacuum or reducing atmospheres of 'forming gas' were used, the melts remained oxide-free, the interfacial energies were relatively high and the investment material was not wetted. If casting was carried out in air, then sufficient oxidation of the melt occurred for the interfacial energy to be greatly reduced so that it wetted the investment material and determination of the actual value thereof by the method used was not possible.

The variations in interfacial energy which result from the use of different atmospheres have important effects upon the behaviour of alloys during casting. Thus mould filling is better when casting is done in air than when it is carried out under reducing conditions. When interfacial energies are low and the investment material is wetted, smooth surface finishes are obtained. This is particularly the case with thicker walled castings. In reducing atmospheres, the investment material is not wetted and with thick-walled castings

dendritic patterns appear on the surfaces of castings which are very rough.

Surface Roughness

18-carat and 14-carat yellow gold castings are characterised by dendritic structure such as that illustrated in Figure 1 which is a photograph of a section of a cast 14-carat yellow gold alloy.

As indicated above, if casting is carried out in a reducing or neutral atmosphere, the melt does not wet the investment material. During the relatively slow solidification of thick castings a dendritic framework then characteristically first forms at the boundary between the melt and the wall of the mould. With progressive solidification, the reduction in volume which accompanies the phase transformation causes the residual unsolidified metal to be sucked away from the surface, with the result that the initially formed dendritic framework tends to stand proud of the surface and increase its roughness.

Figure 2 illustrates the dendritic surface of the thickest step of a stepped test piece cast under vacuum. Typically, the roughness of surfaces cast under these conditions decreases with the thickness of the casting. This is in tune with the decrease in the shrinkage effect with decreasing thickness of the casting, and is illustrated in Figure 3 in which are shown the roughness profiles of the three steps of a stepped casting.

When this same test piece was cast in air or any oxygen-containing atmosphere, then the wetting of the mould, which resulted from the formation of oxides in the melt, hindered the development of a dendritic surface structure on the casting, which was very much smoother. Figure 4 illustrates this, as well as the fact that under these conditions, well developed dendritic structures are not exposed even on the surfaces of the thicker steps of the casting.

Commercially available gold-silver-copper yellow gold alloys

Fig. 2 Dendritic surface structure of the thick step of a stepped test piece x 32

exhibit smooth surfaces when cast in the presence of oxygen. This is true, however, only in the case of thick castings. Thin-walled or filigree castings do not exhibit very great variations, but nevertheless some adverse effects resulting from oxide formation can be observed.

Reactions between Melts and Investment Materials

The extent to which the investment material undergoes decomposition or reaction with the casting alloy is greatly affected by casting or mould temperatures outside the normal range, by the

composition of the alloy and the casting atmosphere. It may also be affected by the presence of organic or carbon residues, if the burning out of the mould has been incomplete.

As demonstrated in an earlier communication, breakdown of or attack on the investment material can lead to the formation in the melt of sulphides. These, it has been suggested (*Gold Bull.*, 1985, 18, (3), 98-108), may diffuse into the melt and react with oxygen dissolved in it to form sulphur dioxide, thus giving rise to the sub-surface gas porosity sometimes encountered in casting gold jewellery. If sufficiently great, this gas porosity can affect the surface of a casting when it is sand-blasted, because of deformation of the metal over the porous area.

Not all sub-surface porosity, however, is gas porosity, for in some instances the pores are irregular in shape and more like 'dendritic' pores. At this stage it is not possible to do more than speculate as to how such sub-surface porosity arises. As described above, shrinkage of the solidifying melt, behind the dendritic, but not fully solidified skin of a casting can lead to a sucking out of remaining liquid metal from close to the surface, leaving dendritic structures projecting from it. Where, however, the dendritic skin of the casting is not intact (gas-tight), it is suggested that melt may be withdrawn and replaced by gas preferentially and to greater depth, thus giving rise to localised sub-surface porosity or surface sponginess of a dendritic type. This type of effect as well as dendritic surface roughness could also be caused or reinforced by any process, such as decomposition of the investment or reaction of it with the metal, which gave rise to gas pressure at the interface.

We have indeed observed that decomposition of the investment is associated with the formation of pronounced dendritic surface

Fig. 3 Typical roughness profile of the three steps of a stepped test piece showing the dendritic-type profile of the thickest step

Fig. 4 Typical roughness profile of the three steps of a stepped test piece cast in air

structures even on thin castings where shrinkage effects would be expected to be very small. Figure 5, for example, shows the very poor and highly dendritic surface of a gramophone record casting made under strongly reducing conditions following decomposition of the investment and development of gas pressure at the interface. The grooves of the record can only just be seen. This figure should be compared with Figure 6 which shows the surface of a good casting.

Where casting is accompanied by more vigorous gas production, the formation of coarse bubbles may accompany the surface defects discussed above. This is observed, for example, when zinc-containing white golds are cast in vacuum, because of the vaporisation of the zinc. It is also observed when there is vigorous production of sulphur dioxide, such as may occur when white golds free from zinc are cast under

Fig. 5 Surface of a reproduction of a portion of a sound record cast under strongly reducing conditions x 32

Fig. 6 Surface of a good casting of a portion of a sound record x 32

Fig. 7 Upwelling of the surface of the melt in the sprue as a result of gas evolution (nickel-white gold) x 1

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unsuitable conditions. Figure 7 illustrates the upwelling which takes place at the head of the sprue as a result of sulphur dioxide formation during the casting of a white gold alloy. Coarse bubbles or blisters may arise from causes (14) other than reaction of the investment with metal, however, so that diagnosis of their causes needs to be made with care.

Summary

A much simplified method is recommended for determining the interfacial energies of gold jewellery alloys during casting. The method yields results which are of sufficient accuracy for the study of casting processes.

Interfacial energies are dependent on alloy composition, and are affected by minor additions of other metals, such as zinc, which greatly reduce them. They are also greatly reduced by exposure of the molten alloy to oxygen which causes it to wet the mould and appears to slow down or inhibit dendritic formation. Mould filling and the surface finish of castings are thereby greatly improved. If cast in an oxygen-free atmosphere, the surface roughness of castings is increased, especially if they are thick-walled, because shrinkage effects are then significant and dendrite formation is not inhibited.

Under reducing conditions, on the other hand, the surfaces of castings may be spoiled through reactions of the melt with the material of the crucible and, more especially, the investment material. This results, *inter alia*, in the formation of sulphides in the melt and the development of bubbles beneath the surfaces of castings (sub-surface gas porosity). It may also result, however, in the formation of sub-surface cavities of irregular shape and it is suggested that these develop as a result of localised and therefore enhanced liquid metal withdrawal from the dendritic skeleton soon after it has formed at the skin of the casting.

This withdrawal is visualised as occurring through the combined effects of shrinkage and the pressure of gases formed at the interface over localized areas where no air-tight solid skin has yet formed on the surface of the solidifying casting.

Whatever the causes may be in any one instance, the outcome is the formation of spongy areas on certain parts of castings, which become deformed during sand-blasting.

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