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As manufacturers and jewellers know from hard experience, cracking in precious metal jewellery can occur at any time in manufacture. It can also occur much later, when the jewellery has been sold to the customer or even during repair. Such cracking is an inconvenience and an undesirable cost and may reflect on the manufacturer's reputation. In many cases, it is preventable and the challenge is to understand which of the many possible causes is responsible for a particular incidence of cracking.

This paper reviews the common causes of defects that lead to cracking and the steps that can be taken to minimise their occurrence. These include:

- *Poor quality start materials that lead to contamination & embrittlement*
- *Poor melting practice leading to casting defects, porosity and blisters*
- *Poor ingot or material working practice*
- *Incorrect annealing practice, including quench cracking and fire cracking*
- *Stress corrosion cracking*

Cracking up? Causes of cracking in manufacture and beyond

Introduction

As many jewellery manufacturers and goldsmiths will know from hard-learnt experience, cracking in jewellery can occur at any time during its manufacture and even much later, after the jewellery has been sold to the consumer. It can also be a problem during subsequent repair of a broken item of jewellery. Indeed, the causes of cracking can be rooted in the processing of the starting materials – the casting grain and mill products from which the jewellery is to be made - but may not be detected until jewellery manufacture has been progressed several stages later. An example of unexpected cracking in a mill product is shown in Figure 1.

Figure 1 Fire cracking in an 18 carat white gold tube [from reference (14)]

Such cracking, whenever it occurs, is an inconvenience and an undesirable cost, to say the least, and will usually lead to scrapping of the item or the complete batch of items, delaying delivery of the order and possibly reflecting adversely on the company's reputation. In many cases, such cracking is preventable if due care is paid to each processing step. A problem for manufacturing jewellers (and repairers) can be to understand which of the many possible causes is responsible for a particular incidence of cracking. Without that understanding, prevention of a reoccurrence is difficult.

A very significant proportion of jewellery is manufactured either by investment casting, using casting grain, or from mill product (sheet, strip, wire, bar and tube) that, in turn, derives from statically-cast ingot or continuously-cast material. A major objective for suppliers and manufacturers is in maximising the yield of good quality material and the jewellery made from it.

Achievement of this objective is addressed by attention to the equipment that is used, both in its selection and its maintenance. Perhaps even more attention has to be focussed on the materials that are used and on the processes that are followed. Nevertheless, in the real world, defects do occur from time to time, scrap is generated and materials and products do crack and fracture.

In this presentation, we will review the common causes of cracking in jewellery, both in manufacture and subsequently in service, and provide some practical advice on how to prevent or minimise its occurrence. The focus is on gold, but much will be applicable to all four precious metals – gold, silver, platinum and palladium.

Causes of cracking

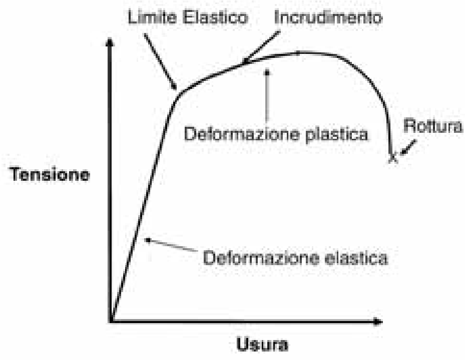
There are many origins of cracking in jewellery alloys.
The basic ones include the following:

1. Mechanical overworking
2. Embrittlement by impurities, including gases
3. Casting and working defects and inclusions
4. Stress corrosion cracking
5. Quench cracking in castings
6. Fire cracking

Failure by fatigue and creep stresses, commonly found in stressed engineering components, are rare in jewellery and are not considered here.

Why do jewellery materials crack? The answer is simply that the imposed stresses exceed the mechanical strength of the material, which may be reduced from the anticipated value for a number of reasons. In this situation, the material cannot deform to relieve the stress and so it simply cracks and fractures. To understand this, let us look at a simple tensile test. If we take a test specimen, such as a rod or strip, of the metal and subject it to a tensile load, it will stretch and become longer. We can measure the extension against applied load and typically obtain a load- extension curve as shown in Figure 2. We normally convert the load to a stress (i.e load per unit cross-section area) and the extension to a strain (i.e. extension per unit length).

Figure 2 A typical tensile test curve



Examination of Figure 2 shows that initially the extension (strain) increases linearly with load up to a fixed stress, that we call the Yield Point (or Stress). If we release the stress at any point on this section, the strain will reduce back to zero, i.e. the specimen returns to its original length. This is elastic deformation. However, if we continue applying the stress beyond the Yield Point, the curve bends over and plastic deformation occurs. This means that the metal has lengthened permanently. If we release the stress, there will be some elastic recovery but there will also be some permanent deformation – the specimen has become longer. During the plastic deformation stage, we note that the stress continues to increase, i.e. it is getting stronger and harder; this is called work hardening and we often use this phenomenon in jewellery manufacture to harden our piece of jewellery to give it more durability and shape stability.

At some stage during plastic deformation, we attain a maximum stress (the Ultimate Tensile Strength or UTS) and then note that the stress starts to fall; this is due to necking, i.e. the cross-section starts to reduce locally, and if we continue, the specimen under test starts to crack up and the specimen eventually fractures. Fracture is when the specimen cracks so far that the remaining metal cannot sustain the load and the cracks propagate to failure of the specimen.

In jewellery manufacture, the applied stresses may be more complex than simple tension, but the net effect is the same. We should also note that some types of cracking are due to internal, or residual, stresses within the material rather than imposed external stresses, as will be discussed later.

It is worth recalling that all metals and alloys (with rare exceptions) are composed of many crystals, where the atoms are arranged in a regular array called the crystal lattice. They are 'polycrystalline' and, during deformation, each crystal must change its shape to accommodate the overall shape change (1, 2). It does this by a process of slip whereby the crystal planes slide over each other in a complex way via lattice defects called dislocations. At the surface, the movement of crystal planes can lead, at the microscopic scale, to intrusions and protrusions and these can also act as nucleation sites for surface crack initiation.

It is also worth noting that hard particles such as inclusions or second phases at the surface, Figure 3, or within the alloy can act as stress raisers, i.e. they amplify the local stresses in the adjacent metal, which means that cracks can initiate and grow more easily around them, even when the imposed stresses are lower than those normally leading to crack formation.

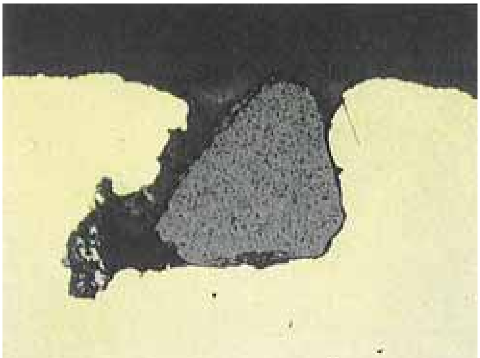


Figure 3
Inclusion at surface of 18 carat yellow gold investment casting [from reference (8)]

The various causes of defects, many of which manifest themselves as cracking during working and manufacturing operations, can be attributed to the following factors:

- Poor quality start materials, including recycled scrap, leading to contamination and possible embrittlement
- Poor melting practice, leading to casting defects such as pipes and/or gas porosity and blisters, incorporation of inclusions, excessive shrinkage porosity and chemical segregation
- Poor ingot or material working practice; this may be related to changing alloy composition without changing the working procedure. It can also lead to surface defects such as laps that later develop into cracks.
- Incorrect annealing practice, often due to incomplete metallurgical knowledge of the precious metals and their alloys
- Residual (internal) stress, possibly linked to a corrosive environment. This can be generated mechanically or thermally and lead to phenomena such as stress corrosion cracking, quench cracking and fire cracking.

It is appropriate to examine these causes as they relate to cracking and the steps that can be taken to minimise their occurrence. As stated earlier, the focus is on carat golds, but much is also applicable to silver, platinum and palladium jewellery.

Start materials

It is essential to have good clean, oxide-free metals for making up the alloys, be they the pure metals or pre-alloys (master alloys). All should be analysed or purchased with certificates of analysis as a matter of good practice. The purity of the precious metal, be it gold, silver, platinum or palladium, should be at least 99.9% with certain impurities such as lead, tin, bismuth, antimony, selenium and tellurium specified as less than 0.01%, all of which can be present and which can lead to alloy embrittlement (3,4). Gas content, especially oxygen in the case of silver and hydrogen in the case of palladium, should also be low. Carbon can also embrittle palladium alloys (5), so they should be melted in ceramic crucibles. Embrittlement of an alloy means a tendency to crack when a moderate load is applied, such as when working the material.

Embrittlement problems can also arise from the use of free-machining brass (containing lead) as a means of adding pre-alloyed zinc (only use lead-free brass for alloying) and the use of silicon-containing master alloys for the carat golds in particular. Both lead and silicon can embrittle all precious metals. However, the major problems often revolve around the use of scrap, which tends to be a continual source of contamination. This is particularly true for bought-in scrap, a common source of start material in some countries, but even internally-generated scrap can be problematical, especially if it is recycled because of prior process failures. The use of scrap to make new product should be strictly controlled and, preferably, should be subject to melting and analysis before use in making up new alloy ingots or recycled in investment casting.

Typical contaminants arising in scrap include refractory materials, such as investment particles on poorly cleaned sprues, oxides from dirty surfaces, silicon from casting alloys and lead-tin solder from repaired jewellery, all leading to inclusions or alloy embrittlement. In fact, any scrap jewellery containing soldered joints is likely to result in some contamination, especially if some of the newer solders containing indium, germanium or tin have been used. The only guaranteed safe way of utilising scrap is to refine it first.

Embrittlement by low melting point metals (as well as sulphur and silicon) tends to result from the formation of low melting point metallic second phases or eutectics, either the contaminating metal itself, which has extremely low solubility in the alloy, or a reaction product of the contaminant with gold, silver or copper in the case of carat golds or with platinum or palladium, often intermetallic phases which in themselves are usually brittle. Table 1 illustrates the low melting point of some eutectic systems that can be formed.

Contaminant	**Phase formed**	**Melting point**	**Comment**
Si - in Ag	Eutectic	835°C	@ 3,1% Si
Si - in Au	Eutectic	363°C	@ 3,2% Si
Si - in Pt	Eutectic	~830°C	@ ~ 5% Si
Si - in Pd	Eutectic	824°C	@ ~5% Si
Pb – in Au	Eutectic	212°C	@ 84,1% Pb
Sb – in Au	Eutectic	360°C	@ ~27% Sb
Sn – in Au	Eutectic	278°C	@ 20% Sn
Ge – in Au	Eutectic	361°C	@ 12% Ge
Au-Ge-Si solder alloy (22 carat)	Eutectic	~370°C	See reference (6)

Table 1 Melting temperatures of some contaminants in precious metals

Most of the low melting point contaminants such as silicon and lead can cause embrittlement of gold, silver, platinum and palladium alloys at very low concentrations. Normandeau has quantified the embrittlement of carat golds by silicon, Figure 4 (7). The effect is magnified if the grain size of the alloy is large as these second phases tend to be dispersed as very thin films around the grain (crystal) boundaries. Fine-grained alloys will tend to have a lower concentration of embrittling phase per grain boundary area. Often, these contaminants manifest themselves as cracking during metal working operations although, as will be discussed, there are other reasons for carat gold and other precious metal alloys failing during fabrication.

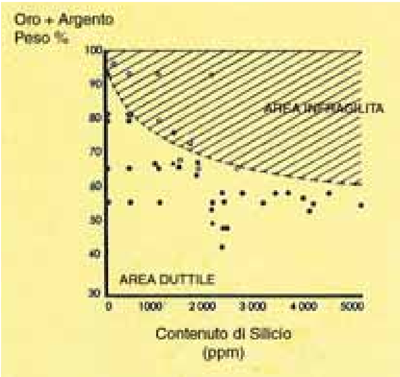


Figure 4 Effect of silicon content on embrittlement of carat golds [from reference (7)]

Melting and casting practice

Continuous casting of carat gold and silver alloys almost always uses high density, fine grain graphite for the die material to ensure good quality product. It is capable of giving much higher quality and higher product yields, because there is no shrinkage pipe, as occurs with statically-cast ingots. However, erosion of the die can lead to graphite inclusions in the melt. Surface defects are also a possibility if die wear or sticking occurs to any extent but, by and large, continuously-cast materials should seldom give rise to mechanical defects. One rare example of cracks on ring surfaces after working, Figure 5, made from continuously-cast 14 carat tube, is attributed to incorrect casting conditions (8).

Figure 5 Cracking on the surface of ring made from continuously cast 14 carat gold [from reference (8)]

Static casting of ingots tends to be a much simpler operation, with melting by gas heating, oil-fired furnaces, electric resistance heating or, preferably, induction heating which ensures maximum stirring of the alloy constituents although physical stirring of the melt with graphite or refractory rods is commonplace. For gold and silver, crucibles are typically clay-graphite or graphite (fireclay for nickel white golds as nickel will react with graphite) and casting will usually be into dressed iron moulds or water-cooled copper moulds. For platinum and palladium, zirconia or zirconia-washed silica crucibles are used. Static casting can be a source of several problems:

Shrinkage and pipes

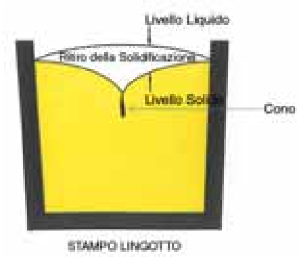


Figure 6 Schematic: pipe formation on statically cast ingot [courtesy E.Bell]

When a cast ingot solidifies, it shrinks and this becomes evident as a central pipe at the top of the ingot, Figure 6. It is necessary to cut off this pipe before working the ingot, otherwise a central defect will be introduced which will elongate on working and is likely to result in subsequent longitudinal cracking. The extent of the pipe into the bulk of the ingot is increased if the casting temperature is too high and it is normal practice to restrict this temperature to no more than 95°C/200°F above the liquidus temperature of the alloy. High casting temperatures also encourage large grain sizes which decrease the ductility of the alloy (2) and, at the same time, magnify the effect of any low melting point impurities which might be present.

Blistering and porosity

Surface blistering or internal gas porosity can show up later in fabrication operations as surface defects or cracks. Gas from the start material (dissolved gas or damp materials) or gas dissolved during the melting operation (aggravated by too high a melting temperature, lack of a protective atmosphere or a flux and use of gas melting) evolves as porosity during solidification. Silver is especially prone to this problem, arising from poor de-oxidation. Initial working may flatten the pores and cause small laminations and cracks or it may close the porosity only for annealing operations to allow the gas to expand and reappear as blisters on the surface. Also, annealing silver containing dissolved oxygen or copper oxide inclusions in hydrogen-containing atmospheres can result in hydrogen absorption and the formation of pores due to the 'steam' reaction between the hydrogen and oxygen (9). It can also occur in carat golds. Figure 7 is an example of porosity in a 3N 18 carat gold, taken from reference (8), due to the steam reaction on annealing. [Another well-known problem with silver due to gas ingress is the formation of firestain due to internal oxidation during annealing].

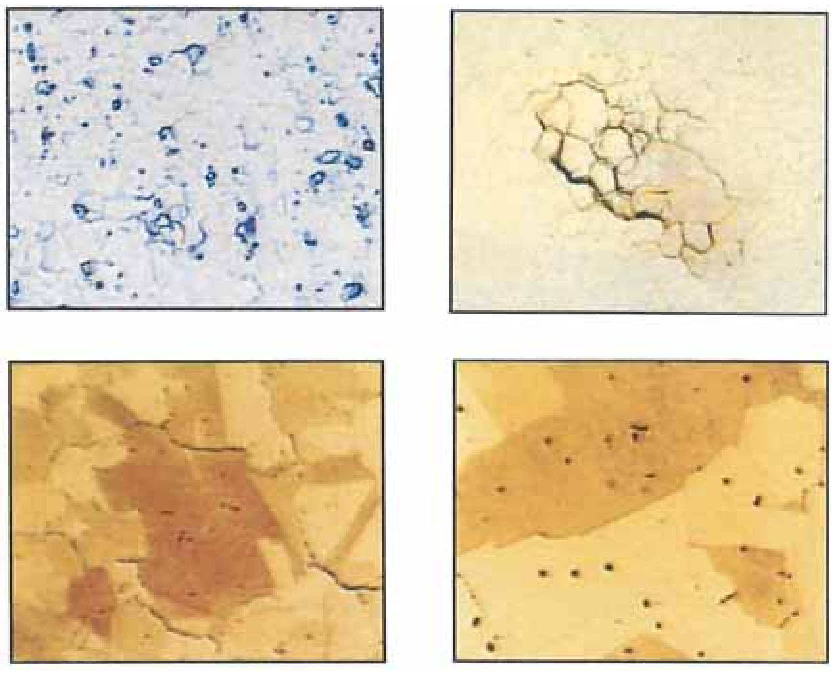


Figure 7 Porosity formation due to the 'steam' reaction in 18 carat gold: top – annealed surface; bottom - cross-sections 200x [from reference (8)]

Inclusions

Inclusions of oxides and other refractory particles, graphite and even metallic particles can be incorporated into the melt from several sources such as erosion of the crucible itself, from furnace insulation or lining, broken stirring rods, the reaction between the atmosphere and alloying element (for example, oxygen and copper form copper oxide) or the use of grain refiners, particularly iridium in carat golds, which have not been dispersed correctly. Such inclusions can act as stress raisers and give rise to cracks or failure during subsequent working.

Surface defects

Surface defects, which can lead to cracks, can arise due to poor melting and casting practice. These arise from solidified splashes during casting sticking to the mould wall, surface inclusions, oxidation and mechanical damage. The golden rule should be to inspect all ingot surfaces and remove (file, grind or machine off) and generally clean away all evidence of defects before any working operations are undertaken. If necessary, the surface might have to be milled to ensure it is clean and flat.

Investment (lost wax) casting

Investment (lost wax) castings are also prone to embrittlement, particularly where silicon-containing alloys and scraps are used (in the casting of gold and silver), to inclusions from crucibles, weak investment moulds and unclean scrap, to quench cracking (see below) and to shrinkage and gas porosity. Large porosity, shrinkage porosity in particular, may act to cause cracking during subsequent processing.

Working practice

Overworking

All forms of metal working - sheet and rod rolling, wire and tube drawing, blanking, stamping, coining, spinning and raising, milling, turning and machining or simply bending by hand - result in the material becoming harder and less ductile. The degree to which it hardens and loses ductility depends on the amount of deformation imparted. If material is overworked, the ductility reduces to zero and it will crack and fracture (1). Materials in the age-hardened condition will have inherently lower ductility and tend to crack on further working.

Therefore, at appropriate stages in the working process, the material has to be annealed to restore its ductility (through the process of recrystallisation). The rate at which alloys work-harden and the extent to which they can be worked varies from alloy to alloy. Typically, most precious metal alloys can be worked up to about 70% reduction in area (strain) before requiring annealing. However, there are considerable variations: nickel white gold hardens rapidly and requires relatively small reductions per working operation with annealing necessary after perhaps only 35 or 40% reduction. On the other hand, fine gold and some of the high carat golds can be worked well in excess of 90% reduction in area before annealing becomes necessary.

Rolling

Rolling of sheet material can result in edge cracking; this is a due to overworking between anneals. It is important to trim the edges at the time, as further rolling after annealing will increase the danger of some cracks running in towards the sheet centre, Figure 8. Fins and laps can arise during rod rolling, which can open up as cracks at later stages. The formation of fins is due to pushing too much material into the rolling groove, so that the rolls are forced apart and excess metal is squeezed out sideways, Figure 9. These fins are then rolled into the rod, becoming laps. Their formation can be prevented by avoiding too large a reduction and by rotating the rod through 90° between successive passes.

Figure 8 Schematic: Edge cracking in rolled strip [from reference (10)]

Figure 9 Schematic: Lap formation in rod rolling [from reference (10)]

Sheet forming

Figure 10 Cracking due to overworking during stamping [from reference (11)]

Sheet metal forming operations such as stamping or deep drawing can also result in cracking due to localised overworking, Figure 10. Fracture will take place at the weakest or thinnest part and is most likely where the sheet is bent round an angle under tension as extra thinning will tend to occur there. It may be necessary to part shape the component in one die-set and then further form in another die-set. This is the basis of stamping in which strip or sheet is processed in a series of dies to achieve the desired final shape. Selection of the correct material and processing conditions is important, if cracking is to be avoided.

Embrittlement by impurities

Certain metallic impurities (including silicon) will embrittle precious metal alloys, as has been discussed in the earlier sections. Battaini gives an example for a 950 palladium alloy (12). Any attempt at working embrittled material will result in cracking. Figure 11 shows cracking in an18 carat yellow gold due to silicon embrittlement.

Manual working, such as raising, and repair operations often involve hand working on a soft former, frequently made of lead, to prevent surface damage. An example of embrittlement has been reported by Grice (13) whereby the forming operation allowed lead contamination of the gold material surface, with diffusion of the lead into the gold on subsequent annealing or soldering and leading to embrittlement and failure of the jewellery item. Use of metallic lead in contact with gold and the platinum metals is always risky but, if considered essential, there must be separation of the piece from the lead by interleaving with a tough grade of paper.

Figure 11 Cracking due to silicon embrittlement in 18 carat gold [from reference (8)]

Non-metallic inclusions

Hard refractory inclusions resist deformation during working and act as stress raisers, i.e. crack initiators, in the precious metal alloy. If present on the surface, they can break out, leaving large surface porosity (8) that is drawn into a longitudinal surface crack on further working.

Residual stresses

Residual or internal stress may be present in a wrought item, often due to non-uniform plastic deformation during processing (12), for example in rod, wire and tube drawing where tensile forces may develop at the surface and compressive stresses in the central region. Such stresses can be circumferential, longitudinal or radial. They are often localised and can lead to spontaneous cracking, for example during heat treatments. Nickel white gold is particularly prone to this problem, where it is known as fire cracking (12, 14); it is discussed specifically later.

Incorrect annealing practice

Selection of the incorrect cooling conditions after annealing can, paradoxically, lead to hardening rather than softening in some carat golds, due to metallurgical instabilities, namely second phase formation. On subsequent working, the material cracks. Yellow-red golds in the 8-18 carat range should be rapidly cooled after annealing by quenching directly into water; this maintains a soft ductile condition, whereas slow cooling results in second phase formation and hardening. Repairers should also anneal and water quench such jewellery items before re-sizing or repair for this reason.

Overannealing - i.e annealing at too high a temperature and/or too long a time - can result in a large, coarse grain size and subsequent deformation can lead to premature cracking and fracture (as well as an 'orange peel' surface). This is particularly a problem with torch annealing, where the capability to control temperature is limited.

Stress corrosion cracking

Stress corrosion cracking can occur in some lower carat gold alloys by the combined effects of applied or residual stress and a corrosive agent, often vapours of chemicals in the local environment. Examples are not uncommon in 8, 9 and 10 carat golds and, less frequently, in 14 karat golds, particularly nickel white golds. Cracking or, as sometimes happens, spontaneous failure, only occurs in the presence of both influences and may happen during manufacture; for example, a spool of wire left exposed to fumes from a pickling shop can completely disintegrate. More worryingly, it can occur much later in jewellery owned by the customer, even after several years of satisfactory service. The mechanism of stress corrosion cracking is complex and has been discussed by Rapson, Normandeau and others (15-18).

The residual stress may be introduced during production by the manufacturer and so all potentially susceptible alloys should be fully annealed or, at least, stress relief annealed. This latter is an annealing treatment at 250-350°C/480-650°F, typically for 30 mins. It has little effect on hardness or grain structure but simply relieves internal stresses. However, stresses can also be introduced in service with the customer (for example, chains stretched by children pulling them) or by the jeweller when rings are re-sized without a subsequent annealing treatment. Initiation of a crack is likely to be at some stress raiser - a scratch or defect or even a Hallmark or manufacturer's mark.

As for the corrosive part of the equation, chlorine or chlorides are a major agent; acids and pickling solutions are the usual source at the manufacturer but for the user the list is almost endless: detergents and household cleaning fluids, inks, swimming pool water, sea water and coastal atmospheres, some foodstuffs, perfumes, deodorants and human sweat can all act as the source of corrodant.

The failure usually manifests itself by a characteristic inter-granular fracture, an example of which is shown in Figure 12. The susceptibility of alloys to stress corrosion is particularly determined by composition and by metallurgical structure but the subject is a complex one with initial attack determined by local differences in composition and initiating at a defect or stress raiser. However, despite the vulnerability of the low carat golds to this phenomenon, it is not widely observed today which tends to suggest that the manufacturers at least are aware of the potential problem and take steps to minimise its occurrence.

Figure 12 Example of stress corrosion cracking in 14 carat gold [from reference (18)

Quench and Fire Cracking

Nickel white golds, as any manufacturer knows, can be extremely difficult to fabricate.

They tend to have a high rate of work hardening, which effectively means more frequent annealing is required and they separate into two immiscible phases on slow cooling after annealing, which normally dictates quenching from the annealing temperature.

However some nickel white golds and other carat gold alloys, particularly those containing silicon additions are prone to quench cracking which is usually attributed to the generation of residual or internal stresses between the more rapidly cooled outer layers and the less rapidly cooled interior of the material on quenching, sufficient to result in cracking in what is an inherently brittle alloy. To avoid the quench cracking effect and also to avoid the hardening effect induced by slow cooling in nickel white golds, a variety of techniques are used to achieve an intermediate cooling rate after annealing. These include forced air cooling, cooling by placing on an iron plate, quenching into hot water, or slow cooling to close to the critical temperature when precipitation of the second phase occurs and then quenching. Individual manufacturers will have their own techniques for particular alloys and sizes of component but still will often face difficulties.

In the case of investment cast silicon-containing carat golds, such quench cracking is attributed to hot shortness, whereby quenching the flask (mould) after casting from too high a temperature leads to hot tearing and cracking, due to low-melting silicon-rich phases on grain boundaries. Figure 13 illustrates an example of a quench crack in a 9 carat gold (19). McCloskey has reported it in 14 carat golds (20).

Figure 13 Quench cracking in investment cast silicon-containing 9 carat gold [from reference (19)]

The second problem that can be faced by the fabricator is fire cracking , particularly in nickel white golds (14), which occurs during the heating associated with annealing or soldering. The cause is usually attributed to the presence of residual stresses from working operations, these being sufficient to fracture the component as the temperature increases (and the strength, therefore, decreases). The remedy is to heat up to 300°C/575°F slowly, possibly holding at this temperature for a time, to relieve the stresses before continuing on to the annealing or soldering temperature. An example of this type of failure is shown in Fig 1.

Figure 1

Concluding Remarks

The issue of cracking arising during the fabrication of precious metal jewellery, or later during service or repair, can be complex because, although there are well-defined causes, the crack's appearance is not uniquely associated with one particular cause. To establish the precise reason for failure may require specialised equipment and knowledge and the situation may be further complicated as, frequently, defects may arise as a result of more than one cause.

However, there are probably two aspects of manufacturing that contribute most towards minimising the production of defective or scrap jewellery products:

- a good understanding of the metallurgy of the precious metals and alloys, and
- the establishment of good manufacturing practice for materials and products and the strict adherence to those practices.

All too frequently, operators on the shop floor will introduce their own "improvements" to procedures or the size or alloy composition will be changed without considering a simultaneous change in procedure. Whilst most precious metal alloys are tolerant and eminently workable, some are very much more difficult to fabricate, but all of them benefit from establishing good maufacturing procedures to be followed at all times.

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