1. Introduction

The reduction of defect rates and improvements of quality are of significant importance in order for the jewellery industry to stay competitive. For investment casting most research into the influence of process parameters and alloy properties has been carried out in relation to carat gold jewellery production. The corresponding outcomes are published in Handbooks and Journals published by the World Gold Council as well as in Conference Proceedings 1-3. Much less work has been carried out or published for sterling silver jewellery investment casting; profound information about basic mechanisms of defect evolution in sterling silver castings is available already from several references 4-10, however. It is commonly agreed, that a large share of defects is related to the huge solubility of oxygen in silver melts, which drops tremendously upon solidification, leading to the release of the oxygen and development of gas pores.

Sterling silver jewellery has become more and more popular in recent years. Production of silver jewellery increased, and so did the defect rates, most probably due to a combination of limited awareness of already available knowledge, but also limited available knowledge about some specific defect types as well as limited resources to study defect sources systematically in production environments. The efforts required to trace back defect sources are a specific problem for the silver jewellery market due to low margins and price competition. Hence, the aim of a European Collaborative Research Project (CRAFT = Co-operative Research Action for Technology) has been to (re-)discover the main sources of defects in silver castings and to consider concrete recommendations for process improvement, defect reduction and overall quality improvement in close cooperation with industrial partners. That project, and so does this paper, focussed on defects (or better: features of defects) that are of specific relevance for silver investment casting, i.e. bad surface quality due to porosity, inclusions and firestain, but also fracturing (hot cracking). Other defects of general importance, especially those caused by process steps related to wax production, the investing, de-waxing and burn-out process, are not covered and corresponding information is available via the references.

Concrete case studies on selected defects are presented, basic defect mechanisms are explained, major and further possible sources are identified and practical measures to reduce the related casting defects are suggested. Examples for successful industrial implementation of some suggested measures are presented.
resistant alloys and their typical alloying additions, but it needs to be stressed that the recommendations for defect reduction mainly have been worked-out and confirmed for standard sterling silver.

2. Collaborative research project approach and experimental procedures

The European project consortium with partners from France, Germany, Italy and UK was composed of 6 casting companies, a casting equipment manufacturer, a refinery, as well as four institutions with complementary competences in research, technology transfer and training.

In the very beginning of the project, all industrial partners were visited by fem, aiming at an inventory of individual standard process parameters, raw and processed material as well as prevailing defects, production problems and difficult-to-cast design. The partners were asked to send in further samples with casting defects regularly. Interestingly, by far the majority of sent-in defects consisted in medium-sized to heavy patterns. Every partner was asked to cast a standardized tree, composed of research pattern as well as some of the difficult-to-cast jewellery pattern, applying their individual standard process parameters. Case studies on casting defects and investigations on the sent-in industrial castings were carried out.

Research lab casting trials, using the standardized tree set-up, were performed and investigated with the aim of backing-up the conclusions from case studies by systematic research into the influence of variations of process parameters. The following set of experimental casting process parameters was used:

- vacuum-assisted bottom pouring equipment (Indutherm VC 500);
- regular pressure-over-vacuum bottom pouring equipment (Neutec J5)
- usually standard sterling silver 925-935, (Ag, Cu, no additives); few castings with variation of alloy composition (grain refiners, Zn, Si, Ge, etc.)
- tree size 330 g to 560 g
- main sprue diameter 10 mm; feed sprue length 15-20 mm; junction angle of feed sprue to main sprue 45°
- gypsum bonded investment (SRS classic)
- flask temperatures 400 °C - 500 °C
- Argon protective gas; different melt treatment procedures (to be discussed)
- maximum melting temperature 1020 °C
- casting temperature 970 °C - 1000°C
- no additional overpressure, pressure difference ~ 1 bar
- after pouring: different cooling and quenching procedures of flasks (to be discussed)

The reproducibility of experimental results was checked by at least 2 nominally identical experimental set-ups. For each experimental casting, thermocouple measurements were conducted to learn more about the solidification process and the heat-up of investment material, as well as to verify complementary findings obtained by computer simulation.

Investigations on different locations of selected pattern were performed to analyze porosity and other aspects of interest. The investigations usually required metallography and optical microscopy, as well as Scanning Electron Microscopy and chemical analysis (a.o. oxygen analysis) if judged as necessary. A total of ~ 350 experimental and industrial castings incl. defect case studies was analyzed. Based on the results obtained, recommendations for process improvement were considered and the industrial partners were asked to re-cast the standardized tree with corresponding variations of process parameters. Eventually, varied procedures were transferred to production. Results were verified on research pattern added to production trees (Figure 1) and, more important, by the industrial partners during and after finishing of produced jewellery.

![Figure 1: As-cast production tree of an industrial partner with research pattern added to top, middle and bottom sections](image)

As a finale deliverable of the project, a defect catalogue was set-up, which presents typical sterling silver casting defects together with short explanations and concrete recommendations for defect reduction.

3. Porosity, inclusions and bad surface quality

This chapter reviews different features of porosity in sterling silver, starting with massive and large pores, over spongy and shrinkage-like porosity to microporosity.

3.1. Case studies

Case #1: Large pores and oxide inclusions

Figure 2a shows a typical example for large pores on an as-cast ring surface obtained from a 935 Ag casting with 50 % recycling material. The metallographic investigation revealed large and small gas pores, with significant porosity also in the interior of the
Another issue is internal contamination with residues from investment material due to investment breakout. Obviously, thorough surface cleaning of scrap by blasting and pickling simply cannot yield sufficiently clean recycling material. In addition, proper measures to decompose oxides and degas the material in order to obtain good to high quality recycling material are required. In addition, severe internal contamination of scrap due to internal oxidation can be reduced effectively by improvement of the cooling procedures of flasks after pouring (see: 4. Firestain).

Case #2: Spongy and shrinkage-like porosity

Figure 4 shows the as-cast surface of a 930 Ag ring after devesting and cleaning.

The massive gas porosity was caused by usage of polluted recycling material. It is assumed that oxide inclusions partly dissociate during melting and increase the oxygen level of the Ag-melt, which then cause gas porosity during solidification. Further case studies demonstrated that scrap can be heavily internally contaminated by residues of slag and especially severe internal oxidation due to cooling flasks on air after pouring (Figure 3; see also Case #6, figure 11 in 4.1 Firestain).

Spongy porosity was observed almost over the whole surface of that ring which had a uniform shape and diameter. The ring was cast using 100% fresh material with flask and casting temperatures of 650 °C and 1015 °C, respectively. A metallographic cross section through the defective areas reveals heavy porosity in direct contact to the surface (Figure 4c). It expands also significantly into the interior, however, which explains why extended finishing can not help to improve the bad surface.

The porosity is located in the spaces between the first crystal branches which grow during solidification, called dendrites. The so-called ‘interdendritic porosity’ resembles shrinkage porosity. However, it is very unlikely that shrinkage pores form in evenly distributed way all over the surface of a uniformly shaped ring. Instead, the defect appearance is characteristic for interdendritic gas porosity caused by decomposition of investment: If gas is generated due to the decomposition reaction at the interface between investment material and the surface of a partially solidified sample (Figure 2b). The casting contains heavily polluted areas all over the complete cross section, with fine traces of oxide inclusions (Figure 2c), which in part were identified as zinc oxide although Zn was not a nominal component of the alloy. In many similar cases, bad surface quality due to oxide inclusions on finished surfaces has been observed.
Figure 6: Case # 3;  
- a) Fine and evenly distributed microporosity on a finished 935 Ag surface as visible by stereo-microscopy;  
- b) Metallographic cross section showing low amounts of residual gas porosity

The microporosity present on the surface is the result of a low, residual amount of gas porosity. The round-shaped small gas pores embedded in the grey-coloured eutectic phase are characteristic for a slightly too high gas level (mainly oxygen) in the silver melt. Upon solidification, the gas solubility in the metal drops tremendously.

The gas that is released from the solidifying metal first accumulates in the rest of the melt and then forms micro pores during the very final stages of solidification, i.e. during the formation of the low-melting eutectic phase.

The specific reason for the increased gas level was not identified unambiguously in the present case, but can be ascribed to a non-optimum combination of raw material quality, (pre-grained) alloy quality and melting/casting process parameters. Further research has shown that a complex combination of these factors needs to be taken into account (see 3.2 and 3.3).

Microporosity is difficult to avoid completely depending on the type of equipment and raw material / alloy source available. It is often observed only by very critical inspection of finished surfaces at higher than usual magnifications.

Case #4: Microporosity; Overlapping defect-sources

As always, life and defect analysis would be much easier if sources for defects would not overlap in many complex ways which can not be covered by this review.

Figure 7 shows a metallographic cross sectional investigation on a flat, plate-shaped pattern (again ~ 3 mm thin) with microporosity on the finished surface which was somewhat more pronounced than for the example shown in figure 6.

The pattern was cast on vacuum-assisted pressure-over-vacuum equipment using purchased 935 Ag alloy casting grains and casting and flask temperatures of 1020 °C and 600 °C, respectively.
Figure 7: Case # 4:  
a) Metallographic cross section on a 1% Ag pattern with microporosity on the finished surface, revealing an evenly distributed amount of gas porosity;  
b) Increased levels of surface-near interdendritic gas porosity along less-finished side-faces

Figure 7a suggests that a substantially increased oxygen level of the silver melt has led to gas porosity and is the main cause for the observed microporosity. However, the pattern had some specific geometrical features resulting in difficult-to-finish side-faces. The cross section through these areas clearly reveals increased surface-near porosity all along these side-faces which have been less exposed to the finishing treatment. Hence, some reaction with investment must have taken place, although less pronounced as for Case #3, which has led to uptake of oxygen by the melt inside the mould and therewith has contributed to gas porosity. Anyway, the overall gas and microporosity level is much more pronounced than for Case #3, although regular alloy casting grains from a refinery were used. Substantial improvements are possible according to the outcomes of further investigations (see. 3.2 and 3.3), especially by effectively vacuum degassing the purchased alloy grains in the investment casting equipment in advance to pouring.

Another example for complex interaction of multiple defect sources is given with Case #6 (see 4.1 Firestain).

3.2. Further research results

Overlap of gas porosity and shrinkage-porosity
A case with typical shrinkage porosity was not shown in the preceding chapter. Of course, shrinkage porosity remains an issue also for sterling silver investment casting, although the majority of cases studied in the present project that were originally categorised as shrinkage porosity eventually were identified as interdendritic gas porosity, or at least as overlapping with the latter in manifold ways.

Similar to shrinkage porosity, interdendritic gas porosity due to investment reaction is often restricted to the heaviest part of a pattern, since near to these areas the heat-up of investment is most pronounced. Porosity caused by this mechanism can also be restricted to areas where dissipation of heat is constrained due to design effects (e.g. abrupt changes in cross section leading to ‘edges’).

Detailed investigations into shrinkage porosity phenomena are presented separately and were backed up by computer simulation. The simulations have proven to be particularly helpful in differentiating between gas and shrinkage porosity phenomena. As a general rule, we should have in mind that lowering flask temperatures to reduce susceptibility for reaction with investment requires correct feed-sprue design and positioning, otherwise increasing the susceptibility to shrinkage porosity in turn.

Further investigations proved that susceptibility to gas porosity due to reaction with investment is triggered by three further aspects:

First and most important, a worsening of the situation is caused especially by poor burnout processes: Carbon-residues in the mould create a reducing atmosphere and lower the decomposition temperature of the investment, therewith increasing the risk for reaction with investment.

Second, some casters evacuate not only the flask chamber but also the melting chamber right before pouring. By doing this, a vacuum is obtained also inside the mould cavity. While this will help to improve form-filling of filigree items, it can not be a good choice for medium-sized to heavy pattern unless flask and casting temperatures are reduced significantly. The vacuum inside the mould causes a drop of the decomposition temperature of gypsum bonded investment material. This enlarges the risk for a reaction with investment for medium-sized to heavy patterns. For filigree items the risk is little, because the solidification time is short and the heat-up of the investment material not pronounced.

Third, zinc has been identified to increase reactivity with investment for sterling silver alloys, either if the amount is too high, and/or if no further alloy additions like Si are present. In many cases, reaction products like zinc sulphides have been identified by SEM/EDX-analysis which is a direct proof for the investment decomposition reaction. Nearly all commercial firestain-resistant alloys contain Zn only in combination with Si and/or Ge. The simultaneous effect of Zn and Si to reduce reaction with investment has recently been discussed for 14ct gold alloys, and it may be reasonable to assume a similar mechanism for most firestain resistant sterling silver alloys.

Impact of oxygen levels in raw and pre-alloyed materials, scrap and recycled material
Fine silver grains and pre-alloyed sterling grains usually contain significant residual levels of oxygen although they are prepared using graphite crucibles, protective atmosphere and additional charcoal cover. The analysis of grains obtained from 6 different suppliers revealed oxygen levels between 100 and 600 ppm. Oxygen levels of 200-300 ppm can be can be considered as most common in purchased grained material. Compared to that, purchased materials prepared by continuous casting usually have substantially lower oxygen levels, ranging from 5 - 50 ppm. The data are in general agreement with data from other sources.

The defect case studies indicated that different levels of microporosity / gas porosity
Investment cast material and therewith scrap can contain tremendous amount of oxygen depending on melting, casting and cooling conditions. We have observed oxygen levels between 30 - 60 ppm for ‘good’ castings, 100 - 300 ppm for less good to poor castings, and 400 - 1500 ppm for very poor castings. (‘Good’ and ‘poor’ refer to the porosity level and the amount of internal oxidation observed.) The defect case studies revealed that some casters still re-cast scrap directly or without adequate recycling measures leading to massive oxide inclusions and gas pores. On the other end of the spectrum, casters prefer to use 100 % fresh material to avoid any trouble due to contaminated recycling material, while most casters mix a certain percentage of scrap with purchased fresh material and prepare in-house pre-alloyed material by graining or continuous casting.

In summary, the reduction of oxygen levels during in-house pre-alloying and recycling, achieved by an effective degassing and deoxidisation process during the melting step in advance to graining or continuous casting is essential und preferably consists in:
- melting at ~ 50-100 °C above usual casting/graining temperature applying a reducing atmosphere (e.g. forming gas, charcoal cover)
- lowering the temperature to usual casting/graining temperature before starting the process

Consistently low oxygen levels of < 20 ppm or better can be obtained by graining, but usually are more easily obtained for continuously cast material.

Uptake of oxygen by the melt after pouring
The need to melt sterling silver in protective gas atmosphere in order to avoid uptake of oxygen by the melt otherwise leading to gas porosity and copper oxide formation is well understood and respected. The danger to take-up oxygen after pouring into the flask has been much less considered, however.

In a lot of samples of industrial castings, significant amounts of gas porosity were still observed even if optimum degassed starting material as well as optimised melting and casting process parameters were used. The possibility of decomposition of investment due to a strong heat-up of the investment layer which is in direct contact with the melt, has already been discussed in detail. Apart from the described characteristic interdendritic gas porosity exposed to the surface, it may also lead to significant take-up of oxygen by the melt which then leads to more evenly distributed interdendritic and spherical gas porosity.

Two further defect sources for gas porosity were identified during joint industrial casting trials:

First, it was observed that casters prefer to move the flask from the burn-out oven into the flask chamber very shortly before start of the pouring process. Evacuation times of flasks of less than 1 min were observed repeatedly. Experimental casting trials revealed that gas porosity decreases continuously with increasing evacuation time of flasks after loading into the flask chamber (Figure 9).
During this time, protective gas is soaked from the melting chamber through the mould material and 'cleans' it from oxygen. The drop in flask temperature during these first minutes is negligible. It is assumed that the melt can take up remaining oxygen after pouring inside the mould if this 'cleaning' step is kept too short. Another explanation could be that the mould interior is 'cleaned' from CO-gas that has been generated during the burn-out process in case of an incomplete de-waxing process. In any case, the effect will depend strongly on flask temperature and permeability of investment.

Second, casters often remove the flask from the flask chamber very early after pouring in order to increase casting frequency. Removal times of flasks of 1 min or less after pouring were observed frequently. However, the solidification time of sterling silver castings is significantly higher even for medium-sized pattern and can take up to several minutes for heavy pattern (see also 5.2). Hence the metal can still be partially liquid if the flask is removed too early from the flask chamber. During backfilling the flask chamber with air and further cooling on air, oxygen penetrates the mould material quickly and can diffuse into the melt, eventually leading to gas porosity and/or copper oxide formation. As a consequence, flask chambers should not be backfilled with air and flasks should not be removed from the flask chamber before solidification is finalised. Removal times of ~ 4 min after pouring have proved to be a good choice, based also on further considerations related to avoidance of firestain and fracturing (see 4. and 5.).

### 3.3. Recommendations

In summary, the following measures to reduce porosity and oxide inclusions are recommended:

- control of oxygen levels in raw materials (fine silver, copper) as well as pre-alloyed and recycled material on a regular basis;
- reduction of oxygen levels during pre-alloying and recycling achieved by an effective degassing/deoxidisation process during a melting step under reducing gas atmosphere in advance to graining or continuous casting;
- adequate melt treatment in the investment casting equipment:
  - for vacuum assisted equipment (evacuation of the melting chamber possible): ensure sufficient evacuation of the melting chamber before melting; keep the vacuum also during melting and superheating to at least 1000 °C in order to (further) degas efficiently the melt; backfill the melting chamber with protective gas before pouring into the flask;
  - for regular pressure-over-vacuum equipment (evacuation of melting chamber not possible): usage of already optimum degassed pre-alloyed material or optimum Ag and Cu raw materials is most important (minimum oxygen levels and oxide impurities); heat-up to 1000 °C for decomposition of remaining oxides but avoid extended melting times significantly above ~ 1000°C; moderate protective gas flow on the melt to avoid gas turbulences;
- avoidance of oxygen uptake by the melt after pouring into the flask:
  - avoidance of reaction with investment (see below);
  - sufficient evacuation time of the flask chamber before pouring, i.e.: load the flask in the flask chamber minimum 2 min in advance to pouring;
  - increase of the time until the flask is removed from the flask chamber after pouring (~ 4 min is recommended; increase for very heavy items);
- avoidance of reaction with investment:
  - lowering of flask and casting temperature, especially for medium-sized to heavy pattern; Note: The feed-sprue may need to be re-positioned on or near to the heaviest section of the pattern in order to avoid shrinkage porosity.
  - control / improvement of the de-waxing and burnout process.

### 4. Firestain

Although firestain is a well-understood phenomenon, it is worth mentioning here and how it can be minimised also for standard silver castings (Ag and Cu only).

#### 4.1. Case studies

**Case #5: Grey discoloured areas on finished surfaces**

Figure 10a shows a typical example for a sample with firestain, i.e. grey discoloured areas on the finished surface of a ring, which can only partially be removed by continued polishing. The casting was left to cool 1-2 min in the flask chamber after
pouring. The vacuum was released by backfilling the flask chamber with air and the flask was air cooled – 25 min before quenching in water.

The metallographic cross section through the defective areas clearly shows a grey layer of internal oxidation below the surface (Figure 10b). Those regions, where the layer is not removed completely by mechanical finishing, display a grey surface colour after polishing. Figure 10c shows an example for a thick firestain layer observed for a casting that was air cooled to room temperature.

In general, castings of sterling silver which are cooled on air before quenching have a layer of internal oxidation below the surface. The layer consists of small copper-oxide particles in the silver matrix and develops due to diffusion of oxygen into the solid but still hot material during the cooling of flasks on air. Depending on layer thickness, which can vary with pattern weight / design and process parameters, these layers are not removed by usual blasting, pickling and further finishing. Firestain can be avoided by using a firestain resistant alloy containing Zn, Si and/or Ge 9,14,15, but it can also be reduced or avoided almost completely by improving the cooling process of flasks after casting (see. 4.2).

Case #6: Firestain, porosity and inclusions

On the finished surface of the 925 Ag bracelet shown in figure 11 large grey discoloured areas were observed, which were not removable at all by continued polishing. Some pores and inclusions are also embedded in the discoloured areas. Similarly to Case #5 the flask was cooled 1-2 min in the flask chamber after pouring, and air cooled ~ 25 min before quenching in water. The metallographic cross section through the defective areas reveals large, grey-coloured areas of severe internal oxidation that expand almost over the complete cross section (Figure 11b). This explains why even extended finishing was not successful in removing firestain in this case. Further analysis at higher magnification reveals fine interdendritic porosity as well as tiny lines of oxides in the centres of the grey-coloured areas (Figure 11c).
Several measures need to be taken into account, including improvement of feed-sprue design / position, improvement of recycling / pre-alloying procedures and improvement of the cooling process of flasks after pouring, to avoid this complex combination of firestain, porosity and inclusions. The case is another typical example for heavy internal contamination of scrap due to air cooling of flasks after pouring (see comments to Case #1, 3.1 Porosity).

4.2. Further research results

During the lifetime of the project, the involved industrial partners preferred standard sterling silver alloys (Ag, Cu, no additives) over firestain-resistant alloys. Hence it was aimed at identifying adequate measures to avoid firestain by processing. Based on the defect source, i.e. the diffusion of oxygen into the metal during cooling flasks on air, the basic idea is to minimise the time, during which the flask with the still hot metal is exposed to air after casting.

Figure 12 indicates how variations of cooling conditions influence the thickness of the layer of internal oxidation below the surface. The data were obtained on experimental castings of 925 Ag with casting and flask temperatures of 970 °C and 500 °C, respectively. For each casting, the average layer thickness was determined on metallographic cross sections of 5 research pattern (ring with sphere Ø10 mm), which were distributed evenly over the tree length (top...bottom).

First trials consisting in simply backfilling the flask chamber with protective gas (Ar, N2) instead of air did not result in a satisfying improvement. The same conclusion holds for earlier quenching of flasks: cooling flasks on air for as short times as 2 min. proved to be enough to build up significant internal oxidation layers of > 10 µm thickness. Substantial reduction of internal oxidation eventually was obtained for trials where flasks were immediately quenched in water after removal from the flask chamber. The short arrows in figure 12 indicate that internal oxidation can be almost completely eliminated if the process is carried out sufficiently quick and if flasks are moved around in the water during quenching. If everything works perfectly, quenched trees display a yellowish colour rather than being dark grey or even black.

For the actual combination of alloy composition, pattern weight and casting process parameters, solidification is completely terminated 2 min. after pouring, so that crack-free castings were obtained even for flasks quenched as early as 2 min. after pouring. Extending the time to 4 min. turned out to be a reasonable schedule for most castings, however, including those with comparably heavy pattern.

As indicated in figure 12, the varied cooling process works best if the flask chamber is backfilled with protective gas upon releasing the vacuum. When transferring the process variation to industrial application, it turned out that backfilling with protective gas may be difficult-to-realise for some casting equipment without major equipment modifications. The examples shown in figure 13 demonstrate, that very satisfying improvements are obtained for castings under production conditions also for quick backfilling with air, or slow backfilling with protective gas via an overpressure in the melting chamber (simply by switching off the vacuum pump), as long as the flasks are quenched immediately after removing them from the flask chamber.

Figure 12: Influence of cooling conditions of flasks after pouring on the thickness of the layer of internal oxidation for a 925 Ag research pattern

Figure 13: Metallographic cross sections on test patterns from industrial castings documenting the influence of improved cooling procedures of flasks on internal oxidation;

a) backfilling flask chamber with air 75 s after pouring/air cooling 25 min./ water quenching
b) slow backfilling with N2, starting 1 min. after pouring, immediate water quenching after removing flask from flask chamber 3 - 4 min. after pouring;
c) backfilling flask chamber with air 4 min: after pouring / immediate water quenching
For sake of completeness it is mentioned, that the quenching step is not feasible for stone-in-place castings. For casting companies with low amounts of stone-in-place castings, a further increase of the time under vacuum in the flask chamber may be a practical solution. Further options are indicated below, but usage of a firestain resistant alloy may be the only viable solution for companies with a high number of flasks per day and a large share of stone-in-place castings.

4.3. Recommendations

In summary, the following measures to minimise firestain for standard sterling silver castings are recommended:

- reduction of the time during which the flask with the hot metal is exposed to air after pouring, achieved by:
  - maximising the time until the flask is removed from the flask chamber after pouring (~ 4 min is recommended; increase for very heavy items);
  - backfilling of the flask chamber with protective gas instead of air upon releasing the vacuum;
  - most important: immediate quenching of the flask after removal from the flask chamber (for castings without stones only).
- For stone-in-place-castings: moving the flasks in a protective gas environment immediately after removal of the flask from the flask chamber:
  - e.g.: moving into a furnace with protective gas circulation;
  - optimum: moving into a dedicated ‘cooling-box’ with possibilities for evacuation and backfilling with protective gas.

5. Fractures in as-cast material

Cracks in cast of parts can be a very complex phenomenon. For sterling silver, however, fracturing in many cases occurs due to unnecessary stress on the solidifying material.

5.1. Case studies

Case #7: Cracks on a ring shank
Figure 14a shows a 935 Ag ring with cracks on a ring shank. A metallographic cross section through the crack surface revealed some minor local porosity, but no evidence for impurities or inclusions. The analysis of the crack surface in the Scanning Electron Microscope revealed that the surfaces of the crystals (dendrites) are roundly shaped (Figure 14b), which proves that the crack opened while the material still was in a partially liquid state: Only liquids will build roundly shaped surfaces due to surface tension. The fracture surface characteristics are typical for hot cracking which occurred due to stress during solidification. The flask was removed from the flask chamber only 50 s after pouring, whereas the solidification time of silver castings of such pattern dimensions will be around 90 s depending on actual casting and flask temperatures. Hence, the ring still was in a partially molten stage when the flask was removed from the flask chamber, which is supposed to be the main reason for local stress increase in the present case. Extension of the time until the flask is removed from the flask chamber has proven to avoid fractures of this kind of hot cracking in many cases.

Case #8: Cracks on a ring shank near to the feed-sprue to pattern junction
Cracks on the inside radius of a ring shank, positioned exactly at the junction of the feed-sprue to the ring shank as shown in figure 15a, are observed frequently. In this case, cracks occurred at identical locations for ~ 10% of the rings on that tree. A metallographic cross section through the cracked region revealed a deep crack which follows a serrated path along a grain boundary (Figure 15b). No oxide inclusions or other contamination and no shrinkage porosity were revealed by the analysis.

Similarly to the case described before, the crack surface suggested that cracking occurred due to stress during solidification, which may have been enlarged due to a very early removal of the flask from the flask chamber after pouring. However, cracking of the same pattern and at exactly the same location still occurred (although less frequently) for castings that were kept for 4 min in the flask chamber before quenching. Hence in this particular case, the stress mainly was build up due to geometric reasons and the different shrinkage behaviour of the investment material.
relative to the metallic pattern. Variation of the feed-sprue ‘design’ and casting process parameters for the same pattern is the only way to overcome this problem.

5.2. Further research results

It is often observed, that casters mark the buttons of their trees by hammering in numbers directly after removal of the flask from the flask chamber. This can certainly exert high stresses on the inside material, especially if flasks are removed too early from the flask chamber and the material then still is in a partially liquid state. Susceptibility to hot cracking is reduced mainly by avoiding any stress on the material inside the flask during solidification. Extension of the time until the flask is removed from the flask chamber has proven to avoid hot cracking in many cases. Susceptibility to hot cracking can be largely increased for some of the modern firestain resistant alloys, i.e. alloys with additions of Zn, Si and/or Ge etc. These elements form low-melting phases on grain boundaries and extend the total solidification time significantly if compared to standard sterling silver. Hence an increased potential risk for generation of hot cracks is given for many firestain resistant alloys, and process parameters need to be adapted accordingly.

However, in a lot of cases cracks of course develop due to porosity, especially interdendritic porosity, or because of geometric or design reasons as demonstrated with Case #8. Large and abrupt differences in cross sections / diameters often are a problematic issue due to the different shrinkage behaviour of the investment material relative to the metal which always results in some stress on the pattern. The geometry of the main sprue as well as the position and geometry of the feed-sprue control the cooling behaviour of the pattern. These parameters interact in a complex way also with casting and flask temperatures. Programmed experiments with a variation of e.g. the feed-sprue ‘design’ and casting parameters for the same pattern are the most practical approach to find a solution that ‘works’ 2. In some cases a change in main sprue diameter may be the only solution 17. All in all, certain cracks in cast parts may develop due to very complex interactions and demand for very detailed analysis of all parameters. In future, computer simulation of stress development during cooling may be helpful to understand and prevent hot cracking.

5.3. Recommendations

In summary, the following measures to reduce / avoid fractures for standard sterling silver castings are recommended:

- avoidance of unnecessary mechanical stress on the casting during solidification, achieved by
  - increasing the time until the flask is removed from the flask chamber after pouring (~ 4min is recommended; increase time for very heavy pattern)
  - avoidance of marking sprue buttons by hammering short time after removing flasks from the flask chamber
  - optimisation of (feed-) sprue design, especially for cracks near to the junction of feed-sprues to pattern; avoid abrupt changes in cross section

6. Summary and conclusions

In agreement with earlier work 4-10, we can state that reduction of most defects (maybe apart from fractures) and improvement of quality for sterling silver jewellery castings invariably comes back to one main problem: oxygen and silver.

The silver melt can absorb huge quantities of oxygen, which is released during solidification, leading to gas porosity. Raw and recycling material can contain significant levels of oxygen or oxide impurities that can lead to porosity if no proper degassing of the material is carried out during recycling or pre-alloying before casting. Inadequate process parameters can lead to uptake of oxygen either during melting or after pouring (i.e. inside the flask before and during solidification).

Probably an underestimated problem with silver casting is the danger of reaction between the melt and the investment, i.e. decomposition of the investment leading to gas porosity. A vast majority of defects studied in the recent years, originally categorised as shrinkage porosity due to its spongy appearance, eventually turned out to be interdendritic gas porosity due to reaction with investment.

Also firestain is related to diffusion of oxygen into the solidified material after casting. Another consequence of the latter issue is, that scrap from castings (sprues etc.) can be heavily contaminated internally, leading to gas porosity and hard surface inclusions if no adequate recycling process is applied. Hence, the ‘oxygen and silver’-problem can follow the casting process all the way through from the start to the finish and can generate multiple sources of defects and quality reduction.

In recent years, many alloys have been developed with a significantly differing spectrum of alloying additions aiming at firestain resistance, deoxidation, grain refinement, improved fluidity and tarnish resistance. These types of alloys are often classified as being more ‘forgiving’ in production environment with regard to the manifold defect sources. Possible disadvantages of some of these alloys a.o. are: increased susceptibility to fractures, increased slag formation during melting and related recycling issues.

Many casters therefore still prefer standard sterling silver alloys (i.e. Ag, Cu, no additives). Concrete recommendations for process improvement and defect reduction have been considered in the present paper which have also been summarised in a more detailed defect catalogue during and after the research project 18. Keeping flasks for ~ 4 min in the flask chamber after pouring, followed by immediate quenching, has proven to be extremely helpful with regard to several issues: minimisation of firestain and internal contamination of scrap, reduced risk for fracturing as well as minimisation of gas porosity and oxide inclusions caused by uptake of oxygen inside the flask after pouring. It should be noted that quenching flasks ~ 4 min after pouring provides also a potential for age-hardening sterling silver directly from the as-cast state without the need for high temperature solution annealing treatment 16.
The following question has been asked many times during the course of this project:

**What is the best or a "standard" quality level that can be obtained in silver jewellery investment casting?**

There is no doubt that a few but effective agreed procedures and measures of daily house-keeping and cleanliness can help to reduce a large number of casting defects, and most casters have experienced this independently from their particular production environment.

The second step requires solutions or measures that are adapted to the specific production conditions of a company: i.e. quality and availability of equipment and personal, levels of quality control and quality management. It is then possible to obtain consistent quality in silver investment cast jewellery. More efforts and attention (and investments in equipment and personnel) are needed to obtain consistently high quality. But it is practically impossible, even from a metallurgical point of view, to obtain consistent "perfection". The higher the quality requirements are, the higher rise the production costs. For this reason it is necessary to find the correct balance between quality and costs for any type of item in order to keep the commercial costs under control. If e.g. also the least residual amount of microporosity on a highly-polished surface, which is detectable only by high magnification with a stereo-microscope, needs to be avoided, then almost all facets of the recommended measures (and probably more) for minimisation of porosity need to be taken into account. Such large efforts may be difficult to justify especially in the silver jewellery market, where margins are comparably low and price pressure extremely high.

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