Platinum Investment Casting, Part I: Simulation and Experimental Study of the Casting Process

Developing a materials database for the casting simulation of platinum alloys

By Tiziana Heiss, Ulrich E. Klotz* and Dario Tiberto
The Research Institute Precious Metals and Metals Chemistry (FEM), Katharinenstrasse 17, D-73525 Schwäbisch Gmünd, Germany

*Email: klotz@fem-online.de

This paper summarises the results of collaborative research on investment casting of widely used platinum alloys (platinum with 5 wt% ruthenium (Pt-5Ru) and platinum with 5 wt% cobalt (Pt-5Co)) for jewellery purposes. To enable the simulation of the casting process, a materials database was developed as a first step. Casting simulation tools based on computational fluid dynamics (CFD) were used to optimise the casting process parameters and develop an improved understanding of their role. Selected casting trials were conducted using industrial tilt and centrifugal casting machines and the casting process was monitored in detail. Dedicated tree setups for the different machines were optimised using the casting simulation tools. The form-filling, surface quality and microstructure and porosity of the cast items were analysed to investigate the role of different casting parameters and geometrical conditions in the different casting setups. The casting simulation results led to a deeper understanding of the experimental casting results.

1. Introduction

The investment casting of platinum alloys has been empirically investigated by various groups. The aim of these investigations was a better understanding of the casting process and its optimisation. The studies vary in terms of the applied casting methods, the alloy compositions and the tree setup used (1–4). However, due to the high material costs and the limited distribution of platinum jewellery fewer studies have been conducted on platinum than on gold or silver alloys. Simulation of the casting process by fluid dynamics (in this paper referred to as ‘casting simulation’) has proven to be a valuable tool in gold and silver investment casting (5, 6), complementary to conventional empirical casting studies. The combination of casting simulation, casting experiments and characterisation of the resulting cast parts results in a better understanding of the casting process and hence better (quality) control.

Casting simulation of platinum alloys is expected to have huge potential for the optimisation of process parameters and hence the reduction of costs. However, no studies have yet been published in the open literature and there have also been no systematic correlations between process parameters and casting quality. Some general knowledge can be inferred from gold and silver casting, but there are many different material parameters to take into account when dealing with platinum.

The aim of this work is to address this deficit. Specifically, it strives to understand and optimise the influences of process parameters on the quality of Pt-5Ru and Pt-5Co casts with the aid of casting simulation. This paper records the results of a collaborative research project, which aimed to develop a materials database enabling the casting simulation (form-filling and solidification) of platinum alloys. Simulations were carried out and the results validated by selected casting trials including detailed process monitoring. The work was focused on controlling the melt temperature during
casting and observations of the metal cooling inside the flask. The simulation was calibrated and used to simulate the casting process in order to understand the role of parameters on casting quality. The casting trials were carried out with different process parameters employing two different alloys and several crucibles and investment materials.

This is the first of two papers on platinum investment casting. The second paper will deal with the optimisation of alloy composition using thermodynamic simulations (7). The results described in these two papers were presented in an oral presentation at the 28th Santa Fe Symposium® on Jewelry Manufacturing Technology in 2014 and will be published in 2015.

2. Experimental

CFD can be applied to simulate the complex flow of the melt during casting and the temperature distribution as a function of time. The methods used in this work are described elsewhere (5, 6). The simulation was conducted in two steps. Form-filling during casting was simulated with the software FLOW-3D (Version 10.0.3, Flow Science, USA), while Poligon software (Version 12.1, PoligonSoft, Russia) was applied to predict solidification shrinkage and investment heating.

FLOW-3D uses the finite difference model, a method which discretises the spatial domain into small cells to form a volume mesh (or grid); the software has its own internal multi-block meshing system, which allows the level of detail on specified areas of geometry to be increased, then adopts a ‘control volume’ approach to solve the Navier-Stokes equations. For the examples presented here a grid with 600,000–1,500,000 cells (depending on the model) was adopted, with a cell size between 0.005 mm and 0.0015 mm. To simulate the tilting and centrifugal processes, the corresponding physical models were activated (‘moving and deforming objects’).

Poligon uses instead the finite element method and requires the grid to be fitted on the geometries (both cast and mould) and then to be processed by the software HyperMesh (Version 11, Altair Engineering, Germany), in order to obtain a tetrahedral solid mesh of the model that can be used for the computational step. The models adopted here have approximately 25,000–27,000 nodes and 90,000–100,000 elements, in sizes between 0.5 mm and 1 mm.

The temperature distribution after complete form-filling in FLOW-3D was transferred to Poligon by measuring the predicted temperatures of four or five points in the cast part and then assigning these values to the corresponding nodes in the tetrahedral solid mesh. The Poligon software then interpolated the values, creating a temperature distribution in the part.

Evaluating the results of the form-filling simulations allowed the optimum placement of parts, inclination of sprues and main sprue diameter to be determined. It should be noted that FLOW-3D was not used to predict incomplete filling of the form: the different tree geometries were compared based on the turbulence shown while metal flowed into the mould, paying attention that the parts were sequentially filled (avoiding the premature splashing of cold droplets in the cavities).

Using the above described criteria, five different proposed tree designs (8) (Figure 1) were tested for suitability with the FLOW-3D software (9). The trees B and D in Figure 1 were chosen and optimised for tilt and centrifugal casting experiments, respectively (Figure 2).

In order to set up the simulation of the casting process, materials data for both metals and investment materials are required. Relevant data are the viscosity, melting range, fraction of solid, thermal conductivity, density and

---

**Fig. 1. Simulated tree designs for tilt and centrifugal casting**
specific heat of the alloys as a function of temperature. The melting ranges of the alloys were taken from their binary phase diagrams. However experimental data are very limited for platinum alloys (10–12). If alloy data were not available, data for pure platinum were used. An example of temperature dependent properties for the alloys can be seen in Figure 3.

Material data for investment materials are even more difficult to determine. The thermal expansion, melting range and gas permeability were determined experimentally for three selected investment materials, while their thermal conductivity could not be determined. Therefore experimental measurements were conducted and the values obtained were used to calibrate the simulation. The output was adjusted by manipulating the internal fit parameters in the Poligon software; the same was done for the heat transfer coefficient between metal and investment.

In order to calibrate the simulation, cooling curves of the metal inside the flask were measured using Type B (Pt-30Rh-Pt-6Rh) thermocouples. Figure 4(a) shows the thermocouples mounted on the wax tree. The thermocouples were inserted in ceramic tubes and connected to a data logger inside the casting machine (Figure 4(b)). The two casting machines required a specific adaptation of the thermocouples that took into account the movement of the flask during casting (tilting, rotation). The exact position of the thermocouples was controlled by X-ray imaging the flasks after casting in order to determine the distance of the thermocouples from the tree. This distance was taken into account when comparing the calculated and measured cooling curves (Figure 4(c)). The experimental cooling curves allowed the casting simulation to be calibrated for the two different casting machines used in the project. More details on the experimental setup are given in a previous report (9).

A number of casting experiments were carried out in order to evaluate the influence of the casting parameters on the cast parts. The selection of casting tree design for tilt and centrifugal casting was made based on the form-filling simulation of different tree design variations (Figure 2). Each tree contains eight typical jewellery pieces and one grid for the determination of form-filling. Two pieces of four different rings were used on the tree, in
particular ‘solitaire ring 1’ for a larger stone, ‘solitaire ring 2’ for a smaller stone, a ‘single-gate’ ring with one sprue at the ring shank and a ‘double-gate’ ring with two sprues at the heavy sections. The two selected trees had a casting weight of ~100 g and ~125 g for tilt and centrifugal casting, respectively. The casting trials were carried out in purified synthetic air. The tilt casting machine model was a VTC100VTi (Indutherm, Germany). The centrifugal casting machine models were a TCE10 (TopCast, Italy) and a Platincast600 (Linn, Germany). The metal temperature during heating and melting was monitored using a pyrometer and a thermal imaging camera. The experimental setup was slightly different during centrifugal and tilt casting depending on the setup of the machines. The detailed experimental setup is described elsewhere (9).

The temperature/time profile in selected areas was recorded for every single casting trial. The ‘casting temperature’ was the temperature of the melt at the moment when it left the crucible. The casting temperatures were 1850ºC–2040ºC depending on alloy and casting machine (Table I and Table II). The flask temperature was varied between 550ºC and 950ºC. The alloys used were Pt-5Co and Pt-5Ru. In the second part of the work modified alloy compositions were tested (7).

Eight different investment materials were tested and three were chosen for the casting trials. Pro-HT Platinum (Gold Star Powders, UK), referred to as ‘EBM7’ is a one-part jewellery investment material for platinum alloys. Ransom & Randolph (R&R®) Platinum Binder & Investment (Dentsply, USA), referred to as ‘EBM8’ is a two-part jewellery investment material
for platinum alloys. SHERAFINA® 2000 (SHERA Werkstoff-Technologie GmbH & Co KG, Germany), referred to as ‘EBM5’, is a dental investment.

After casting the tree was water-blasted. In order to evaluate the surface quality its surface was inspected by optical microscopy and scanning electron microscopy (SEM). The form-filling was assessed by the filling of a grid. In order to identify shrinkage porosity and other casting defects X-ray computed tomography (CT) and metallographic investigation were carried out.

3. Casting Results

3.1 Form-filling

The form-filling ability was judged by assessing the percentage of fully intact grid parts (Figure 2) and strongly depends on the alloy composition. In previous studies with a ‘diabolo-type’ tree, Pt-5Co showed superior form-filling in comparison to Pt-5Ru (1). This was confirmed for the more conventional trees employed during the present study (Figure 5). Centrifugal casting of Pt-5Co allowed complete form-filling at melt and flask temperatures exceeding 1850°C and 550°C, respectively. Pt-5Ru required a casting temperature approximately 100°C higher. Tilt casting generally required higher casting temperatures for complete form-filling compared to centrifugal casting. For Pt-5Co, it was sufficient to increase the casting temperature by approximately 100°C. For Pt-5Ru both the casting temperature and the flask temperature had to be increased by 100°C each. The reasons for the poorer form-filling ability of Pt-5Ru are explained in detail in Part II (7).

3.2 Surface Quality

The surface quality depends primarily on the alloy but is also affected by the investment material. For Pt-5Ru significant differences were also observed between the thin and thick sections of the same cast part. Figures 6–8 show the casting results obtained by two investment materials (EBM7 and EBM8). For the Pt-5Ru alloy EBM7 produced a very poor surface quality with a glassy layer visible at higher magnification in the thick sections of the ring (Figure 6(a)). In the thin sections of the ring the surface quality was acceptable. Surface quality deteriorated with increasing casting and flask temperatures for every investment material tested; however the extent to which this effect occurred was different for each. EBM8 showed only a slight deterioration of the surface even at high casting and flask temperatures (Figure 6(b)).

The SEM investigation of the ring cast with EBM7 (Figure 7(a)) revealed dimples on the surface formed by gas bubbles at the interface of metal and investment (Figure 7(c)). The investment material was molten in contact with the metal during casting and the gas bubbles were presumed to form due to the coagulation of the investment porosity. The molten area appeared to be covered by a transparent and shiny surface layer similar to the appearance of silica glass, about 500 μm thick. X-ray diffraction (XRD) measurement of the molten investment at the interface (Figure 7(d)) revealed an amorphous structure, confirming its glassy nature. Prior to the casting experiment, the investment material consisted of hexagonal α-quartz, tetragonal β-cristobalite, orthogonal tridymite and trigemagnesium diphosphate (Mg3(PO4)2). It may be concluded that the melting point of EBM7 is too low to withstand the high temperatures of the Pt-5Ru melt.

By contrast the interface produced by EBM8 for the complete double-gate ring was smooth (Figures 6(b) and 7(b)). No gas pores were observed at the interface and the investment was not molten during casting (Figure 7(b)). A molten surface layer was not observed, only a ~30 μm sintered layer. The initial crystalline structure of pure hexagonal α-quartz was found to be intact (Figure 8(b)).

The dental investment EBM5 showed similar characteristics to EBM7, but produced a slightly better surface quality of the as-cast platinum rings. In an
isothermal melting test (10 min) none of the investments melted at 1675°C (the solidification temperature of Pt-5Co). At 1725°C EBM5 and EBM7 partially melted, while EBM8 did not melt. At 1775°C (the solidification temperature of Pt-5Ru) all investments melted. It appears that EBM8 has the highest temperature stability enabling it to withstand melting when subjected to short term heating during casting. For Pt-5Co, the casting and flask temperatures had very little influence on the surface quality. With all three investment materials a blue layer of cobalt silicate formed, but the surface was generally smooth.

3.3 Porosity

The casting simulation predicted decreasing shrinkage porosity with increasing casting and flask temperatures (Figures 9 and 10). Metallographic investigations confirmed this prediction for both casting machines used, in agreement with earlier studies (1). In general, high shrinkage porosity could be avoided by the correct sprue design, as in the case of the double-gate ring, allowing defect-free castings to be achieved with Pt-5Co. Only very small (<1 μm) and scattered gas pores and oxide inclusions were found, which do not deteriorate casting quality. Pt-5Ru on the other hand, showed a pronounced tendency to form micro-shrinkage porosity, even with properly designed sprues. An explanation of this effect is given in Part II (7). One way to close micro-shrinkage pores would be hot isostatic pressing as described elsewhere (13).

In tilt casting the tendency for micro-shrinkage porosity was less pronounced. However, very high casting (2040°C) and flask temperatures (950°C) were required for complete form-filling of the filigree item. As described above, very temperature resistant investment materials are required for good surface quality. Generally, the investment material has a rather small influence on the porosity formation, although EBM8 showed slightly better results compared to EBM5 and EBM7.
Fig. 7. Influence of investment material on surface quality of Pt-5Ru, T_{melt} = 1850°C/T_{fus} = 850°C. SEM image of the metal-investment interface in the thick section: (a) EBM7; (b) EBM8; and SEM surface image of the thick section: (c) EBM7; (d) EBM8

Fig 8. XRD measurement of the investment at the interface: (a) EBM7; (b) EBM8
Porosity

4.9%  4.4%  3.9%  3.4%  3.0%  2.5%  2.0%  1.5%  1.0%

Fig. 9. Simulation of calculated porosity for tilt casting of Pt-5Co. Flask temperature of 850°C and casting temperature of: (a) 1850°C; (b) 1950°C

Fig. 10. Metallographic investigation showing porosity for tilt casting of Pt-5Co. Flask temperature of 850°C and casting temperature of: (a) 1850°C; (b) 1950°C

In centrifugal casting, the tree design plays a much more important role for form-filling and solidification than in tilt casting. The tree orientation with respect to the centrifugal direction (leading and trailing side) and ring inclination with respect to the main sprue (for example 45° or 90°) have to be considered. The trees used in this study are shown in Figure 1. The tree for centrifugal casting consisted of a thin main sprue with two rows of four parts. Most of the parts were mounted at an angle of 90°±5° and some were mounted at 45°±5° to investigate the influence of the mounting angle (Figure 11). In centrifugal casting, the rings are usually mounted at 90° to the main sprue, because this causes less turbulence during form-filling as shown in Figure 12. The centrifugal machine rotated clockwise, i.e. the parts shown on the tree in Figure 11 were
mounted on the leading side. Other parts were mounted on the trailing side. Different variations were simulated and then experimentally tested.

An example of improper sprueing is the single-gate ring (Figure 1). This way of mounting resulted in dimples on the thick section of the ring, which faced towards the crucible (Figure 13(a)). Although the ring showed no major porosity (Figures 14(a) and 15(a)) it had to be discarded, because the dimples could not be removed or repaired. It is assumed that the thick section was isolated during solidification and the one-sided dimple formed because the melt was forced by centrifugal acceleration to the outer side of the flask. If instead the ring was mounted at 45º no surface dimples were observed (Figure 13(b)). However, the X-ray CT investigation (Figure 14(b)) showed large shrinkage pores in the ring shank. Metallography revealed centreline porosity along the ring shank (Figure 15(b)), while the thick section showed only micro-shrinkage (Figure 13(b)). The ring shank acted as a feeder for the thick section and formed the centreline pores. The centreline pores did not appear during polishing and the ring would pass quality control. However, the position of the pores is random. In this case the pores were not visible, while in other cases they will be closer to the surface and would appear during polishing. Some manufacturers use hot isostatic pressing to close internal porosity. That works well with gas pores or microshrinkage. However larger pores, such as centreline pores, would leave dimples at the surface and the part would be rejected. In order to be safe proper sprueing should be used.

The metallographic investigation of the double-gate rings mounted at 45º and 90º showed no such inhomogeneities in porosity distribution nor any surface dimples. Therefore this sprue design would be preferred for reliable production. Leading and trailing sides showed no significant difference in terms of form-filling and porosity.

4. Discussion

Casting simulation enables a deeper understanding of possible defects, for example, the formation of shrinkage porosity (Figures 9 and 10) or the deterioration of surface quality by investment breakdown (Figures 6–8 and 16). Casting can be understood as a two-step process. The first step is form-filling. During this step the forces acting on the melt control its flow into the flask. In tilt casting the major acting force is gravity. Therefore the flow speed of the melt is relatively low,
Fig. 13. Centrifugal casting of the single-gate ring in Pt-5Ru. Metallographic cross-section at the thick section, the angle of the ring mounted to the main sprue at: (a) 90°; (b) 45°

Fig. 14. CT images of the ring mounted to the main sprue: (a) 90°; (b) 45°

Fig. 15. Metallographic cross-section at the ring shank. The angle of the ring mounted to the main sprue: (a) 90°; (b) 45°
resulting in a comparatively long form-filling time and promoting significant cooling during form-filling. For the chosen tree design the temperature of the melt significantly deviated along the tree axis resulting in a temperature gradient from the main sprue to the tree tip. The temperature difference between the melt entering the first layer of parts in the sprue and that entering the second layer was about 40ºC (Figure 12(a)). The complete filling of the tree took about 0.6 s. The tree geometry was optimised based on the filling simulation. The main sprue diameter was reduced from 10 mm to 5 mm, because the filling speed increased with a smaller main sprue. In addition, this saved about 50% of the tree weight – an important amount of otherwise ineffectively used precious metal.

In centrifugal casting, the main acting force is ‘centrifugal’ force. The way the tree filled was found to depend strongly on the way in which the pieces were mounted on the main sprue. If the parts were mounted on the leading side of rotation, inertia caused an acceleration of the melt to the trailing side of the main sprue. Parts mounted at an angle of 90º to the main sprue were then successively filled from the tip of the main sprue towards the in-gate. This situation is illustrated in Figure 12(b) for the upper row of parts. If the parts were mounted on the trailing side of the tree, the momentum of inertia of the melt caused all parts to be filled simultaneously. The simulation indicated that such simultaneous filling might cause cold shuts. This effect was, however, in practice substantially smaller because the acting forces were small. The filling time was approximately 50% shorter for centrifugal casting compared to tilt casting although the tree was ~25% heavier. The shorter filling time resulted in a higher residual melt temperature, which explains the better filling ability of centrifugal casting at low casting and flask temperatures.

The lower row of parts in Figure 12(b) were mounted at an angle of 45º to the main sprue. This resulted in a gradient in centrifugal force \( F_c \) (as in \( F_c = m\omega^2 r \) with the mass \( m \), the angular velocity \( \omega \) and the radius of curvature \( r \)) and in hydrostatic pressure, which resulted in an inhomogeneous filling of the parts. Figure 11 shows the pressure distribution after complete filling. There is a significant gradient in the centrifugal force along the tree. This suggests that filigree items should be mounted on the tip of the tree, where the pressure is high and which fills first during casting. The parts mounted at 90º to the main sprue showed a small internal pressure gradient. However, even this small gradient could cause casting defects, as shown for the single-gate ring (Figures 13–15 and 17). The pressure gradient in the parts mounted at 45º was quite high. As described above, this caused inhomogeneous filling that might be detrimental. However, the pressure gradient also allowed feeding in the semi-solid state and helped avoid shrinkage porosity at critical positions.

Fig. 16. Temperature distribution in the investment after centrifugal casting of Pt-5Co obtained by Poligon at a flask temperature of: (a) 550ºC; (b) 850ºC
in some parts. This was also demonstrated for the single-gate ring in Figures 13–15.

The second casting step, solidification, was simulated using the Poligon software that allowed the solidification shrinkage and therefore local shrinkage porosity in the parts to be simulated (Figure 17). The red areas indicate high shrinkage porosity. At the tip of the tree almost no porosity would be expected in the cast parts according to the simulation. The single-gate appeared to be most prone to shrinkage porosity, especially at its thick section which was probably isolated from the melt in the main sprue due to premature solidification in the narrower parts of the sprue. In this case, feeding with fresh melt was interrupted. The pressure gradient inside the part forced the remaining melt towards the tip of the tree. Finally, a dimple formed on the ring side facing towards the in-gate. This explains the experimental findings in Figures 13–15.

The heating of the investment was also simulated using Poligon. Figure 16 shows the temperature distribution in the investment for the double-gate. Along the thin ring shank the temperatures were relatively low. Critical positions were the thick sections of the ring. A hot spot was found where the heavy sprues were connected to the ring. With increasing casting and flask temperatures local overheating increased significantly. Figures 6(b) and 7(b) show the investment reactions at the thick sections. The locally very high temperature caused the breakdown of some less stable investment materials, which resulted in poor surface quality. The breakdown of the investment materials was promoted by high amounts of magnesium phosphate used as a sintering additive, which reduces the melting range of the investment (14). Such additives can be a significant restriction for the investment material. In order to avoid investment breakdown more stable investment materials must be used or the solidification temperature of the alloy might be modified as described in Part II (7).

5. Summary

Pt-5Co has good form-filling characteristics compared to Pt-5Ru independently of flask and casting temperatures. For the machines used during this study, form-filling was better in centrifugal casting compared to tilt casting, because the acting forces are four times higher. Hence, centrifugal casting had faster filling and higher melt temperatures during filling. In tilt casting higher overheating was needed to obtain the same results.

An improvement of the form-filling with Pt-5Ru could be achieved with increased casting and flask temperatures. However, very stable investment materials had to be used in order to avoid investment breakdown. Locally, very high investment temperatures could occur and this was demonstrated by simulation. Local melting or sintering of less stable investment materials resulted in poor surface quality of the product. The most stable investment material in this study contained high amounts of hexagonal α-quartz and low amounts of sintering additives.

As predicted by casting simulation, the shrinkage porosity decreases with increasing casting and flask temperatures. This was particularly true for Pt-5Co, which only showed very small gas pores and oxide inclusions under optimum conditions. Pt-5Ru showed a
pronounced tendency to form micro-shrinkage that was
difficult to avoid in centrifugal casting. In tilt casting, the
micro-shrinkage was less pronounced due to slower
cooling in the specific machine employed in this work.

Important and helpful indications about tree design,
positioning or inclination of the parts on the tree and
the temperature distribution of the investment could be
concluded from the casting simulation. Particularly in
the case of centrifugal casting (where the acting forces
are more complex), casting simulation helped to gain
an understanding of observed casting defects and find
suitable solutions.

Lastly, the project showed the limits of conventional
jewellery alloys (Pt-5Ru and Pt-5Co). Further alloy
optimisation appears necessary (7).

Acknowledgements

This work was financially supported by the German
Federal Ministry for Economic Affairs and Energy
(BMWi) under the IGF programme (Project No.
AiF-IGF 16413N). The industrial partners (Indutherm
Erwärmungsanlagen, C. Hafner, Linn HighTherm,
Wieland Edelmetalle, Kalman Hafner Schmuckguss,
Porzellanfabrik Hermsdorf and SHERA Werkstoff-
Technologie GmbH & Co KG) are acknowledged for
supporting the project. The authors are grateful to
coworkers from the department of metallurgy at FEM
for the realisation of the research work.

References

1 U. E. Klotz and T. Drago, *Platinum Metals Rev.*, 2011,
55, (1), 20
2 D. Miller, T. Keraan, P. Park-Ross, V. Husemeyer and
3 D. Miller, T. Keraan, P. Park-Ross, V. Husemeyer,
A. Brey, I. Khan and C. Lang, *Platinum Metals Rev.*,
2005, 49, (4), 174
4 T. Fryé and J. Fischer-Buehner, ‘Platinum Alloys in the
21st Century: A Comparative Study’, in “The Santa
Fe Symposium on Jewelry Manufacturing Technology
2011”, ed. E. Bell, Proceedings of the 25th Symposium
in Albuquerque, New Mexico, 15th–18th May, 2011,
Met-Chem Research Inc, Albuquerque, New Mexico,
USA, 2011, pp. 201–230
6 U. E. Klotz and D. Tiberto, ‘Computer Simulation in
Jewelry Technology – Meaningful Use and Limitations’,
in “The 26th Santa Fe Symposium of Jewelry
Manufacturing Technology 2012”, Proceedings of
the 26th Symposium in Albuquerque, New Mexico,
USA, 20th–23rd May, 2012, Met-Chem Research Inc,
Albuquerque, New Mexico, USA, pp. 297–320
7 U. E. Klotz, T. Heiss and D. Tiberto, *Johnson Matthey
Technol. Rev.*, 2015, 59, (2), 132
8 J. Maerz, ‘Platinum Casting Tree Design’, in “The
Santa Fe Symposium on Jewelry Manufacturing
Technology 2007”, ed. E. Bell, Proceedings of the
21st Symposium in Albuquerque, New Mexico, USA,
20th–23rd May, 2007, Met-Chem Research Inc,
Albuquerque, New Mexico, USA, 2007, pp. 305–322
9 U. E. Klotz, T. Heiss and D. Tiberto, ‘Entwicklung
der Gießsimulation und experimentelle
Untersuchungen von Platinlegierungen zur
Optimierung des Feingussprozesses für Uhren- und
Schmuckanwendungen’ (in German), Final report of
the research project AiF-IGF 16413N, 2014, available
on request at www.fem-online.de
10 G. Beck, ‘Edelmetall-Taschenbuch’, Degussa
AG, Frankfurt und Hüthig GmbH, Heidelberg,
Germany, 1995
Mater. Trans. A*, 2012, 43, (13), 5029
12 S. Mehmood, U. E. Klotz and G. Pottlacher,
‘Thermophysical Properties of the Platinum-Copper
System’, in “EPD Congress 2011”, eds. S. N. Monterio,
D. E. Verhulst, P. N. Anyalebechi and J. A. Pomykala,
John Wiley & Sons, Inc, Hoboken, New Jersey,
USA, 2011
13 T. Fryé, J. T. Strauss, J. Fischer-Buehner and U.
E. Klotz, ‘The Effects of Hot Isostatic Pressing of
Platinum Alloy Castings on Mechanical Properties
and Microstructures’, in “The Santa Fe Symposium on
Jewelry Manufacturing Technology 2014”, ed. E. Bell
and J. Haldeman, Proceedings of the 28th Symposium
in Albuquerque, New Mexico, USA, 18th–21st May,
2014, Met-Chem Research Inc, Albuquerque, New
Mexico, USA, 2014, pp. 189–210
14 H. Gamsjäger, ‘Equilibrium’, in “Geochemistry”,
Encyclopedia of Earth Science, Springer, Netherlands,
The Authors

Tiziana Heiss has a Bachelor's degree in Materials Engineering with specialisation in surfaces treatments (Politecnico di Milano, Italy) and a Master's degree in Materials and diagnostic techniques in heritage manufacturing (University of Pisa, Italy). She works in the Department of Physical Metallurgy at the Research Institute for Precious Metals and Metals Chemistry (FEM) in Schwäbisch Gmünd, Germany.

Ulrich E. Klotz graduated from the University of Stuttgart, Germany, as a Diploma Engineer in Physical Metallurgy and has a PhD in Materials Science from ETH Zürich, Switzerland. He is Head of the Department of Physical Metallurgy at the FEM.

Dario Tiberto has a Bachelor of Science in Mechanical Engineering (Politecnico di Torino, Italy). He works in the Department of Physical Metallurgy at the FEM.