Introduction

Palladium, one of the rare and coveted platinum group metals, has all the indications of becoming the latest metal trend in fine jewelry. Starting with China in 2003, and later emerging in North America in 2005, the global demand for palladium jewelry has risen exponentially. In 2005, purchases of palladium for jewelry product climbed by an impressive 54 percent and 2006 looks postured to continue this trend.

As is the case with the introduction of any new metal, the development and optimization of manufacturing methods must be undertaken to produce consistent high-quality product. At the time of this writing, jewelry-making fundamentals such as alloy formulas, design guidelines, casting techniques and finishing methods are rapidly unfolding nationwide. From small custom shops to large-scale manufacturers, the trade is truly embracing this appealing sister metal to platinum. And, as was the case in the early days of platinum’s rebirth, the learning curve is upon us and demanding much in the way of research and development. In fact, publicly available documentation of existing research would appear quite sparse. A review of jewelry and dental industry publications, as well as extensive internet searches on 950 palladium casting methods, turned up very little and when literature was found, it was not well supported by scientific data. In light of the fact that investment casting would appear to be the most challenging aspect of working with 950 palladium, we therefore had great impetus for our research and the publication of this paper.

Purpose

The core purpose of this paper is to gain a better understanding of the casting characteristics of 950 palladium alloys used in the jewelry industry. Through the use of controlled experiments and analysis of the resulting cast metal, it is our hope that jewelry manufacturers will have a greater understanding of how to successfully manage this most challenging aspect of working with palladium.

For purposes of expediency, much of the information presented here will be in the form of comparison with platinum alloys. Given that platinum’s casting characteristics are relatively well understood by the trade, the contrast-and-compare approach enabled more information to be conveyed in fewer words.
**About Palladium**

Palladium has very attractive and unique properties. Palladium is noble, naturally white, malleable and strong at 95% purity levels. It polishes to a platinum-like high luster and, like platinum, it is also tarnish resistant. Rhodium plating is not required as the natural color of palladium is bright white. In addition, allergies to palladium are extremely rare, making it a safe choice for individuals prone to allergic skin reactions.

Furthermore, at the time of this writing palladium has a significant economic advantage when compared to platinum. The market price is approximately one-fourth that of platinum and this, combined with the fact that palladium’s density is about half that of platinum, places it at a much lower price point. At present, there is a sizeable force in the market that is investing in the belief that those individuals that cannot afford platinum, or are deterred by the problems associated with white gold, will find palladium to be an attractive, high purity alternative (the yellowing of white gold and the low wear resistance of rhodium plating used to brighten the surface of white gold are well-known concerns for many jewelers and consumers).

**Investment Casting**

The next section will address basic process methods that have proven successful in casting 950 palladium alloys at TechForm. These methods, while generally quite successful, are still very new and will undoubtedly undergo change and refinement with increased experience. After this initial overview of basic process
methods, the following sections will focus on original research designed to understand the key melting and casting characteristics of 950 palladium alloys.

**Wax Spruing Techniques**
The most successful sprue techniques used at TechForm in casting 950 palladium have been large platinum-style sprues. Like platinum, palladium solidifies quickly and therefore requires an abundant reservoir of metal to avoid shrinkage porosity in the finished piece. However, compared with platinum, palladium requires the use of more auxiliary sprues on thin sections to facilitate fill.

It is worth noting that these sprue recommendations are based purely upon our experience with positive visual and polishing results over a number of months and did not include controlled metallurgical studies. More in-depth experiments need to be performed utilizing x-ray and metallographic sectioning to better understand solidification and flow principles of 950 palladium alloys.

**Investing**
950 palladium alloys melt in the range of 1400°C (2552°F) to 1500°C (2732°F) and therefore a high temperature phosphate-bonded investment, as commonly used in platinum casting, is required. In the experiments performed for this paper, a high-refractory ceramic shell system was used (TechForm's investment casting process utilizes ceramic face coats consisting of a proprietary slurry system). However, we do not believe such a system is mandatory to produce high-quality palladium castings. Any phosphate-bonded investment that performs well in platinum casting should also perform well when casting palladium.

Compared to platinum, palladium is much gentler on the investment for two reasons. First, palladium has a much lower density. Palladium’s specific gravity is 12.02 versus platinum’s at 21.50g/cc. When using centrifugal or spin casting, this difference is important as it translates into roughly half the weight for a comparable volume that is thrust into molds at very high speed. Second, the pour temperature is approximately 200°C (360°F) lower, resulting in an overall smoother surface finish. The result is a lower incidence of mold infiltration and other metal-mold reactions typically brought on by the combination of high temperatures and high-velocity centrifuge.

**Casting**
In our experience, it is the melting component of 950 palladium alloys that presents the biggest challenge in the manufacture of jewelry pieces. This is true for several reasons, most dealing with the risk of oxidation. Unlike typical platinum alloys, palladium oxidizes at temperatures between 600°C (1112°F) and 800°C (1472°F). Melting must therefore be done in a protected environment to avoid
absorption of oxygen (oxygen is soluble in molten palladium) and potential embrittlement of the metal. In addition, overheating of palladium alloys may be risky since this will typically increase the chances for oxygen absorption. Lastly, in some alloys, constituent elements that are volatile or have volatile oxides may vaporize, also lending to the formation of gas porosity. In the case of oxidation, once the oxygen is absorbed and has become soluble in the molten palladium, defects in the cast product may emerge as the oxygen attempts to escape in the form of gas during solidification.

Given the above challenges, palladium requires a highly controlled casting process in order to produce jewelry pieces with good metallurgical and dimensional integrity. For the experiments presented in this paper, we used a high-frequency induction melter with horizontal arm-spin cast and optical temperature reading capability. This equipment is suitable for palladium because of its excellent control over the melting and casting process. In addition, both vacuum and/or argon cover gas was used to prevent oxidation. Crucibles were high-temperature (platinum-type) and were coated with zirconium oxide.

Note: Torch melting of existing jewelry alloys, while perhaps feasible under ideal conditions, is not recommended due to the risk of oxidation and the difficulty of judging actual temperatures with this method. Given the challenges outlined above, it is unlikely that high-quality 950 palladium product can be cast consistently using the torch melting system.

Devesting
Devesting is a relatively simple operation when casting 950 palladium. The lower pour temperatures in comparison with platinum make investment removal possible with use of a simple solution composed of approximately one part sodium hydroxide beads and three parts water. The solution should be brought to boiling and the trees submerged for approximately five minutes, followed by water blasting. Hydrofluoric acid, a necessary but dangerous staple in platinum casting, is therefore not needed when devesting palladium castings. However, if one chooses to speed up the devesting process by using hydrofluoric, this will not harm the palladium.

Phase One Research: Alloy Testing
The first hurdle in developing a robust casting process for any metal is the alloy choice. When palladium first emerged as a significant jewelry metal in North America, the designs were primarily simple machined bands made from 95% Pd-5% Ru alloy. This alloy, while superb for machining and fabrication, will generally become brittle when casting. Luckily, alloy makers have recognized this
problem and several new formulas are now on the market. Purity is an important factor in jewelry appeal and thus the new alloys have remained at the 95% Pd level, but have combined new elements that increase ductility while still maintaining reasonable hardness.

**Alloy Criteria**

In seeking a suitable alloy for our casting experiments, we selected criteria for hardness, ductility, recycle ability, melting cleanliness and fluidity. Detailed descriptions of these criteria are as follows:

**Minimum hardness of 110HV**

Hardness is an essential characteristic to be evaluated whether you are designing, selling or casting jewelry metals. Consumer satisfaction is the yardstick by which we as a trade measure our products, and from this standpoint hardness as an indicator of wear resistance is critically important. American consumers in particular want jewelry that will hold up well with daily wear and this, of course, must start with the alloy. Just as engineers define mechanical properties requirements for alloys used in aircraft engine components, it is in the jewelry trade's interest to define minimum hardness requirements for rings and other designs in all alloys. While the difference may not be life and death to the consumer, as in the former example, it may well mean life and death to the product in the latter example. In our experience at TechForm, most designers require hardness in the range of 110 to 135HV to assure good wear resistance.

**Ductility**

Ductility is normally measured in mechanical testing as elongation percentage and has an essential range for stone setting and sizing. This range is generally 15 to 20% for most alloys and is preferably achieved without giving up too much on the alloy's hardness. This critical balance between hardness and ductility values (which normally involves a trade-off in the extremes) is a familiar issue for alloy developers and one that has been particularly challenging in the early stages of 950 palladium development. For example, many of the first alloys tested at TechForm reported good hardness in the range of 140 to 150HV. However, they were crack-prone after casting, an indicator of low ductility. Although formal testing for elongation values was not carried out, for purposes of this study, we defined “good” ductility in terms of crack-free bend tests and positive feedback from multiple jewelers that had set stones and sized ring shanks.

**Recyclability**

One of the beauties of high-purity alloys such as those commonly used in platinum jewelry is their recyclability. As a caster, the importance of this point cannot be understated. First, there are obvious economic advantages to favorable...
recyclability as refining costs are kept in check through continued re-use of the metal supply. Second, the integrity of the metal supply and the quality of cast product is more likely to be maintained when elements that naturally degrade under repeated melting conditions are not present. This translates into fewer surprises at the bench, where embrittled metal might only be discovered during final polish, stone setting or sizing operations.

**Clean melting**

In our initial melting trials of 950 palladium alloys, we encountered a high degree of dross (impurities on the surface of the melt) and smoke. Dross and smoke are clear troublemakers in the casting process as they obscure the surface of the melt, impairing optical pyrometer function and making the actual pour temperature a hazardous guess at best. Moreover, any elements that are floating on the top of the melt will become integrated with the pour and may lead to gas porosity or inclusions. A controlled palladium casting process should utilize alloys that exhibit clean melting to assure temperature control while simultaneously validating the cleanliness and stability of the alloy.

**Fluidity**

Another feature of palladium alloys that emerged very early in our trials was low fluidity. Using 950 platinum alloyed with ruthenium as our benchmark, we observed that 950 palladium seemed to have lower fluidity as we experienced a greater tendency towards no-fill when casting thin-walled or filigree type designs. Consequently, experiments aimed at finding maximum flow parameters were high on our list of priorities.

**Experimental Parameters**

Our preliminary alloy testing was performed on six different metals from five different alloy suppliers. (Note: Given that most U.S. companies are still in the early phases of 950 palladium alloy development for casting grain and have not yet optimized their products, the names of suppliers have been omitted to avoid any negative interpretations regarding a specific company’s products). All alloys possessed a 95% minimum palladium content with additional elements that are, for the most part, proprietary in nature. Ruthenium and gallium were the dominant additions and the most likely to be disclosed, however, a number of other elements were reported in the collective group.

During this initial phase, the above criteria (hardness, ductility, recyclability, melt cleanliness and fluidity) were judged by casting test flasks of each metal using identical parameters. The parameters were chosen based upon alloy makers’ recommendations, our research of existing literature and the degree of suc-
cess in a number of TechForm casting experiments preceding this formal study. The flask temperature used, which is high for most metals, was selected due to frequent incidences of no-fill on previous experiments.

As mentioned earlier, from a casting perspective, a big concern with palladium is the fact that it readily oxidizes when exposed to oxygen at temperatures between 600°C (1112°F) and 800°C (1472°F). Oxygen absorption can contribute to embrittlement of metals in several ways. First, brittle oxides entrapped in the metal can become nucleation points for cracks. Second, dissolved oxygen can expel in the form of tiny microscopic gas bubbles that may also act as nucleation points for crack formation. Lastly, oxygen atoms that stay dissolved in the metal can disrupt the crystal lattice of the metal, not allowing dislocations to move freely as is desirable. These dislocations may then concentrate, building up stress areas to the point where fracture is initiated.

Given these risks associated with oxidation, specific measures should be taken to protect both the finished product and the metal supply itself from degradation. At the outset of our experimentation, we chose vacuum casting as the best logical method to protect the melt from oxidation and further included argon cover gas to provide an inert environment. Table 1 details the parameters used in these experiments and the resulting condition of the different metals. Visual examination of the casting trees to detect the presence of cracks and subsequent bend testing of the trees was used to determine the level of ductility.

**Table 1  Alloy testing results with vacuum and argon**

<table>
<thead>
<tr>
<th>Metal ID</th>
<th>Flask temperature</th>
<th>Pour temperature</th>
<th>Atmosphere</th>
<th>Result</th>
</tr>
</thead>
<tbody>
<tr>
<td>Pd 950 A</td>
<td>950°C (1742°F)</td>
<td>1600°C (2912°F)</td>
<td>Vacuum/Argon</td>
<td>Brittle</td>
</tr>
<tr>
<td>Pd 950 B</td>
<td>950°C (1742°F)</td>
<td>1600°C (2912°F)</td>
<td>Vacuum/Argon</td>
<td>Brittle</td>
</tr>
<tr>
<td>Pd 950 C</td>
<td>950°C (1742°F)</td>
<td>1600°C (2912°F)</td>
<td>Vacuum/Argon</td>
<td>Brittle</td>
</tr>
<tr>
<td>Pd 950 D</td>
<td>950°C (1742°F)</td>
<td>1600°C (2912°F)</td>
<td>Vacuum/Argon</td>
<td>Ductile</td>
</tr>
<tr>
<td>Pd 950 E</td>
<td>950°C (1742°F)</td>
<td>1600°C (2912°F)</td>
<td>Vacuum/Argon</td>
<td>Ductile</td>
</tr>
<tr>
<td>Pd 950 F</td>
<td>950°C (1742°F)</td>
<td>1600°C (2912°F)</td>
<td>Vacuum/Argon</td>
<td>Ductile</td>
</tr>
</tbody>
</table>

As the above table demonstrates, metals A through C were brittle, exhibiting cracks and tears in the casting tree. Metals D through F, on the other hand, were ductile and crack free. Since some alloys remained ductile while others became embrittled, we decided to investigate whether vacuum played a role in this difference. Our next set of experiments was cast without vacuum, using an argon cover gas only. Table 2 outlines parameters and results.
Table 2: Alloy testing results with argon cover gas only

<table>
<thead>
<tr>
<th>Metal ID</th>
<th>Flask temperature</th>
<th>Pour temperature</th>
<th>Atmosphere</th>
<th>Result</th>
</tr>
</thead>
<tbody>
<tr>
<td>Pd 950 A</td>
<td>950°C (1742°F)</td>
<td>1600°C (2912°F)</td>
<td>Argon only</td>
<td>Ductile</td>
</tr>
<tr>
<td>Pd 950 B</td>
<td>950°C (1742°F)</td>
<td>1600°C (2912°F)</td>
<td>Argon only</td>
<td>Ductile</td>
</tr>
<tr>
<td>Pd 950 C</td>
<td>950°C (1742°F)</td>
<td>1600°C (2912°F)</td>
<td>Argon only</td>
<td>Brittle</td>
</tr>
<tr>
<td>Pd 950 D</td>
<td>950°C (1742°F)</td>
<td>1600°C (2912°F)</td>
<td>Argon only</td>
<td>Ductile</td>
</tr>
<tr>
<td>Pd 950 E</td>
<td>950°C (1742°F)</td>
<td>1600°C (2912°F)</td>
<td>Argon only</td>
<td>Ductile</td>
</tr>
<tr>
<td>Pd 950 F</td>
<td>950°C (1742°F)</td>
<td>1600°C (2912°F)</td>
<td>Argon only</td>
<td>Ductile</td>
</tr>
</tbody>
</table>

These results provide evidence that when eliminating vacuum and casting only with argon cover gas, only one alloy formula remained brittle, while all others were ductile. Based on this, it may seem that the logical answer for ductile castings would be to cast using the argon cover gas only. However, before we can reach this conclusion additional testing for recyclability needs to be performed. The appeal of casting under vacuum is to safeguard against oxidation. When casting with argon cover only, it is possible for pockets of air to become entrapped within the casting grain, thus oxidizing the metal supply and lending to a degradation of mechanical properties.

In seeking to understand the underlying cause of vacuum embrittlement we analyzed fracture surfaces of the embrittled metal using scanning electron microscopy (SEM) and energy dispersive X-ray analysis. The brittle fracture surface of sample Pd 950 C cast under vacuum appears in Figure 1. The distinct facets and grain boundaries indicate brittle intergranular fracture. Intergranular fracture is normally indicative of low strength and ductility and, in general, is undesirable.
Figure 1 SEM analysis of brittle fracture surface on Pd 950 C
In contrast to the brittle fracture of the Pd 950 C sample, the Pd 950 E sample shown below in Figure 2 exhibited distinctly ductile fracture. This alloy was not embrittled and SEM examination of the fracture surface reveals the presence of microvoid coalescence, an indicator of ductile fracture.

**Figure 2** SEM and X-ray dispersive analysis of ductile fracture Pd 950 E

**Figure 3** Magnification of upper right quadrant of Figure 2

Next, (in Figure 3), we have a magnification of the highlighted area where we can observe small, spherical particles distributed throughout the sample. These particles were analyzed using energy dispersive X-ray analysis (Figure 4) and found to be gallium rich. This result would indicate that the gallium does not fully homogenize throughout the chemistry, but rather segregates into concentrated particles.

**Figure 4**

**figure 5**

*Palladium Casting: An Overview of Essential Considerations*
Finally, Figure 5 shows the analysis that was taken from an area free of the gallium-rich particles. As one can see by the peaks, palladium is dominant, followed by gallium. Zirconium was also identified, likely a result of the zirconium oxide crucible coating.

Although we only analyzed one of the brittle samples in Figure 1 (Pd 950 C), we can infer through this result and the presence of brittleness in the remaining samples A and B, that alloys A, B and C all have a negative response to vacuum. Likewise, while only one of the ductile samples in Figure 2 (Pd 950 E) was analyzed, we can infer that alloys D, E and F are not negatively affected by vacuum. With regard to the brittle alloys, the intergranular fracture shown in Figure 1 is indicative of some form of problem at the grain boundaries. Additional testing to determine the precise nature of the problem unfortunately exceeded our time frame for this publication. Further SEM studies should be performed to detect any concentration of elements at the grain boundaries, most notably gallium. Gallium, which has a melting point of 30°C (86°F), is suspect, as palladium is sensitive to contamination and embrittlement by low-melting-point metals.

**Alloy Selection**

Although several alloys showed promise at the time we launched our next phase of experiments, we had to select only one of these in the interest of time and costs. All data presented in the following sections of this paper is consequently based upon using Hoover and Strong’s TruPdä, an alloy composed of 95% palladium with proprietary elements composing the remaining 5%. At the end of our initial alloy testing, Hoover and Strong’s TruPdä had demonstrated the following characteristics:

**Hardness.** As-cast Vickers hardness of 110HV was obtained from a test coupon cast and air-cooled to room temperature. The coupon was tested using a micro-indentation hardness tester with a 100gf load at a certified NADCAP (aerospace) lab.

**Recyclability and ductility.** The metal supply was tested over a period of six months using a maximum of 20% new metal for each pour. Approximately 140 total flasks were poured during this time frame. The metal supply remained ductile and product quality was not diminished over time.

**Clean melting.** Although adjustments had to be made to vacuum levels and argon backfill, reasonably clean melting was obtained. Some degree of smoke is still present to a greater or lesser extent, depending upon the individual melt. It is not known why these minor fluctuations in clean melting exist, but they are not believed to have affected casting quality.

*September 2006*
**Fluidity.** Fluidity was satisfactory on medium- to heavy-weight rings but unsatisfactory on small prongs, thin walls and thin junctions between settings.

**Phase Two Research: Grid Tests**

Once we had completed selection of an alloy that came close to meeting our criteria, we then proceeded to analyze fluidity. As mentioned in an earlier section of this paper, this characteristic of 950 palladium alloys had raised significant concern in our early casting trials as we experienced an unacceptable level of no-fill on lighter weight pieces. Using five wax grids per tree that measured 25.4 x 25.4 x 0.8mm (1” x 1” x .035”), we cast according to the parameters shown in Table 3 below. As indicated, the only variable in these experiments was pour temperature.

*Table 3* Experimental parameters for fluidity test

<table>
<thead>
<tr>
<th>Flask ID</th>
<th>Flask temperature</th>
<th>Pour temperature</th>
<th>RPM</th>
</tr>
</thead>
<tbody>
<tr>
<td>071</td>
<td>950°C (1742°F)</td>
<td>1590°C (2894°F)</td>
<td>400/1</td>
</tr>
<tr>
<td>078</td>
<td>950°C (1742°F)</td>
<td>1620°C (2948°F)</td>
<td>400/1</td>
</tr>
<tr>
<td>032</td>
<td>950°C (1742°F)</td>
<td>1760°C (3200°F)</td>
<td>400/1</td>
</tr>
</tbody>
</table>

*Figure 6* Grid fill experiment of flask ID 071—1590°C (2894°F)

*Figure 7* Grid fill experiment of flask ID 078—1620°C (2948°F)
The 1760°C (3200°F) grids exhibit the best fill and, therefore, this temperature was targeted for further testing to determine the metallurgical impact of casting at higher temperatures.

**Platinum Cross Study**

In order to generate a more familiar baseline for comparison of palladium fill characteristics, we conducted additional flow tests using the same grid design only with a 95% platinum, 5% ruthenium alloy as the benchmark test metal. Two, rather than three, different temperatures were used for this comparison. The table below details parameters and results.

**Table 4** 950 platinum grid fill parameters

<table>
<thead>
<tr>
<th>Flask ID</th>
<th>Flask temperature</th>
<th>Pour temperature</th>
<th>RPM</th>
</tr>
</thead>
<tbody>
<tr>
<td>115</td>
<td>950°C (1740°F)</td>
<td>1880°C (3416°F)</td>
<td>400/1</td>
</tr>
<tr>
<td>116</td>
<td>950°C (1740°F)</td>
<td>1980°C (3596°F)</td>
<td>400/1</td>
</tr>
</tbody>
</table>

Figures 9 and 10 below show grid fill results using 950 platinum and the parameters in Table 4.
This exercise demonstrates that fill of the grid geometry tested is equally achievable in both 950 platinum and 950 palladium. However, the question remains as to whether metallurgical quality is maintained once fill is achieved at a level of 200°C (360°F) superheat. For platinum, there exists a wealth of information that the experimental temperatures are not harmful to the metal. For palladium, we must now generate such data.

**Metallurgical Quality of 950 Palladium Cast at High Temperatures**

Clearly, pour temperature had a significant effect on Pd 950 fill, with the highest temperature of 1760°C (3200°F) resulting in the best fill. As mentioned in an earlier section of this paper, there is substantial, albeit anecdotal evidence that the overheating of palladium alloys can result in gas porosity. Therefore, additional experiments were needed to ascertain whether the ideal fill parameters would also generate good metallurgical quality. Our next set of experiments was designed to determine whether a 1760°C (3200°F) pour temperature resulted in a higher incidence of gas porosity than our standard pour temperature of 1620°C (2948°F).

For this set of experiments we used a simple shank design that was cast using the identical parameters from the flow tests. Parameters were again as follows (Table 5):

<table>
<thead>
<tr>
<th>Flask ID</th>
<th>Flask temperature</th>
<th>Pour temperature</th>
<th>RPM</th>
</tr>
</thead>
<tbody>
<tr>
<td>112</td>
<td>950°C (1740°F)</td>
<td>1590°C (2894°F)</td>
<td>400/1</td>
</tr>
<tr>
<td>113</td>
<td>950°C (1740°F)</td>
<td>1620°C (2948°F)</td>
<td>400/1</td>
</tr>
<tr>
<td>114</td>
<td>950°C (1740°F)</td>
<td>1760°C (3200°F)</td>
<td>400/1</td>
</tr>
</tbody>
</table>
The resulting samples were then X-rayed to look for the presence of gas porosity. Figure 11 below shows the results of the experiments:

![Figure 11 X-ray results of Pd 950 superheat experiments](image)

These X-rays reveal dense metal with no evidence of shrinkage or gas porosity, indicating that all three pour temperatures did not generate porosity in the cast product. One of the rings cast at 1760°C (3200°F) was also polished to a high luster to look for signs of micro-porosity that may not have shown up in an X-ray. No porosity was revealed, demonstrating that superheat in these ranges was successful for the shank design and spruing used in this experiment.

**Conclusion**

Palladium is well on its way to becoming a widely used metal in jewelry manufacture. However, there is still much work to be done to fully comprehend the metallurgical characteristics of working with this exceptional metal. From alloy development through finishing and setting techniques, the trade is fully engaged in a learning process.

In particular, the casting of 950 palladium alloys presents unique challenges compared to other precious metals. Palladium's high melting temperature combined with its ability to absorb oxygen requires a tightly controlled process in order to consistently produce quality castings. Recyclability, normally taken for granted in casting most platinum alloys, is a much bigger concern for palladium alloys and one yet to be fully understood. It is our hope that this paper will both
serve as a solid resource for companies learning to work with palladium, as well as a springboard for further studies.

Acknowledgements

The author sincerely thanks Kevin Mueller and Janice Johnson for their careful execution of the experiments performed for this paper. Special thanks to the many metallurgists that offered their consultation including Stewart Grice of Hoover and Strong, Ed Crombie of Johnson Matthey, Tino Volpe of Tiffany & Co., D.P. Agarwal of Leach and Garner and Mark Lisin of Lisin Metallurgical. Thanks also to the following individuals for their support: Sarah Loveland for photography, Daniel Ballard of PM West, Larry Fell of David Fell Co. and Steven Adler of Automated 3D Modeling.

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