

Platinum Alloy Design for the Investment Casting Process

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The investment casting process is perhaps the most widely practiced mass production technique in the jewelry industry. Requirements for alloy performance are demanding, especially when recycling of expensive materials becomes a significant issue. Casters want and need a material that will provide latitude in handling and overcome the extreme form filling demands of numerous designs. Processing conditions range from polished daily rituals orchestrated with the assistance of optical pyrometers and atmosphere controlled induction melting on tested designs through first time trials with torch melting on new concepts. A material must be versatile to perform in these conditions. Based on international hallmarking standards requiring a minimum of 95% content for unqualified designation as platinum jewelry, the physical characteristics manipulation available through alloying additions is somewhat limited. Previous documented research work in this area is scarce. Phase diagrams of binary and ternary relationships with platinum also unavailable. Platinum is metallurgically incompatible with many of

the elements that act as investment casting performance enhancers in gold materials.

The desirable attributes of a superior investment casting material are outlined and experimental methods to evaluate these noted. Properties of alloys common to the trade are compared to the new hard casting alloy. Color, melting range, density, strength, hardness, ductility and fluidity performance are all reviewed. Material properties during recycling were objectively quantified. Cast surface finish was compared with color photography and the internal quality of various cast items was verified with metallographic sectioning methods. Manufacturing methods and issues such as melting technique, investment temperature and feeding methods are discussed. Results of systematic evaluations indicate that a material with improved hardness has superior long term wear resistance as a jewelry article and finishes significantly easier with conventional processing techniques.

HISTORICAL AND THEORETICAL CONSIDERATIONS:

A systematic study of platinum alloys for the investment casting process was done at the Johnson Matthey Research Center in the late 1970's. Results of that study were published in *Platinum Metals Review*, July 1978. A large number of alloys were explored to overcome form filling deficiencies, poor color from surface oxidation and metal mold reactions in thick sections inherent to the common commercial alloy of the day, 95% Platinum-5% Copper. They divided their study into high and low temperature alloys. The high

temperature group included alloy combinations of Pt with Ruthenium, Iridium, Palladium, Cobalt and Nickel. PGM combinations with Pt produced alloys that were too soft for most jewelry applications. Pd alloys reacted to produce gas porosity while Ru alloys produced rough cast surfaces. Several base metal combinations deploying Nickel produced oxidized surfaces. Only Cobalt showed promise from improved form filling, minimal oxidation and desirable physical properties.

Low melting point alloys based on the binary eutectics of Pt with boron or silicon produced predictable brittle behavior from extreme hardness. Gallium use was also explored in combination with gold. Final recommendations of the research were to replace the standard Pt-Copper alloy with the Pt-Cobalt material for all investment casting applications and consider the benefits of a lower melting point alloy based on Gallium additions.

The issue of platinum casting alloy design was also considered by Volpe and Lanam at the 1997 Platinum Day presentation. They considered the blending of copper and cobalt additions to reduce the issue of magnetism from cobalt while not sacrificing the other desirable cast properties. The ternary alloy had properties midway between the two binary parents. Comparison of grain size and microstructure to the standard 950%Pt-50%Ru material suggested superior cast quality. As expected, the cobalt copper alloy showed superior form filling characteristics, but slightly poorer surface finish compared to the ruthenium material. Some difficulties with hand welding were attributed to copper oxidation.

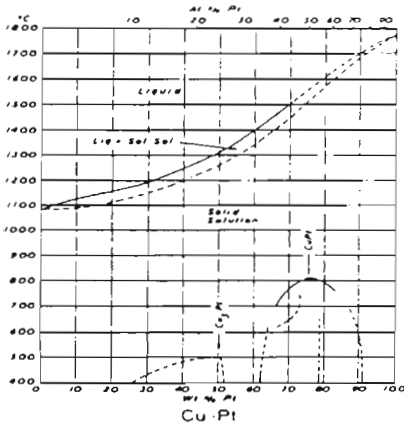


Figure 1: The copper-platinum phase diagram

To date this alloy is not widely used throughout the trade.

Information in the form of phase diagrams of platinum and the various alloying additions that provide a heat treatment response is scarce and usually restricted to binary relationships. A few examples are included. The hardening response mechanisms vary from solid state ordering in the case of copper (figure 1) to limited solubility resulting in two distinctly different solid solutions, in the case of gold additions

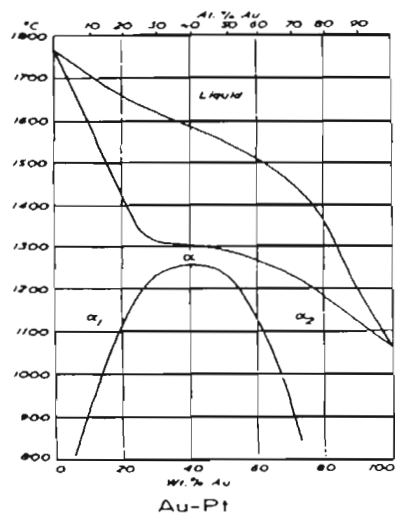


Figure 2: The gold-platinum phase diagram showing strong phase separation

(figure 2). The binary relationship between gallium and platinum, shown in figure 3, indicates solid solubility in the platinum rich region with the formation of brittle intermetallics possible. Solid state solubility is temperature dependent, indicating the possibility for precipitation hardening. The platinum-indium phase relationship is very similar. The ternary relationships between combinations of platinum, gold, gallium, copper and indium are not fully documented.

The relationship with various elements used to enhance the performance of gold and silver investment casting alloys is very different when considering platinum. Reducing conditions encountered during melting operations above 1400°C cause a number of reactions that do not occur in other precious metal systems.

Silicon:

Used extensively in both yellow and white gold to enhance fluidity and provide an oxide free cast surface. Silicon is not compatible with platinum. The common oxide can convert to elemental silicon which may form a brittle intermetallic compound PtSi or Pt₂Si. The platinum-silicon eutectic melts at 830°C. These compounds concentrate at the grain boundaries greatly diminishing physical properties.

Boron:

The same issues noted above occur. The hard and brittle eutectic melts at 789°C promoting hot shortness and reduced ductility.

Phosphorous:

Ceramics used for investment casting contain phosphates as bonding agents. Reduction of the PO₄ radical may allow brittle PtP₂ to form. Such compounds can ac-

cumulate at the grain boundaries severely impairing formability.

Silver:

It dissolves into platinum alloys when molten. Low melting temperature PtAg₃ or Pt₃Ag phases accumulate at the grain boundaries causing hot shortness during assembly or welding operations.

Zinc & Cadmium:

These elements, used in gold alloys to reduce surface tension and enhance form filling, cannot be employed with platinum because of embrittlement and vaporization issues. Both metals have high vapor pressures at 700-900°C that preclude application at 2000°C.

Many of the additives and principles that apply to other precious metal alloys do not produce positive results with platinum because of various metallurgical limitations.

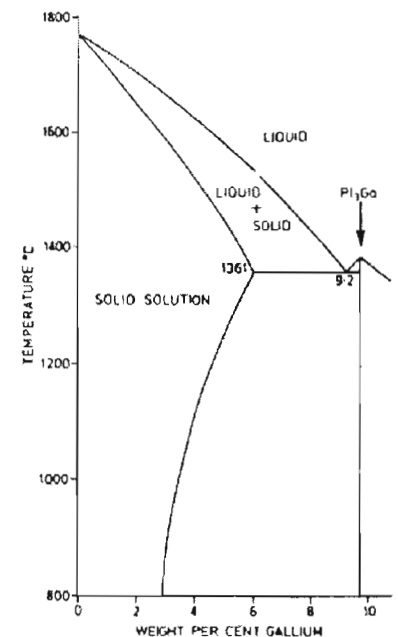


Fig. 3: The gallium-platinum phase diagram showing changing solubility with temperature

PRACTICAL CONSIDERATIONS AND EXPERIMENTAL METHODS:

Desirable attributes of a platinum investment casting alloy are summarized as follows:

1. Good form filling capabilities or fluidity to fill thin sections
2. Low tendency to form an oxide during melting operations in neutral or oxidizing conditions required for platinum
3. No tendency towards forming brittle compounds with ceramic materials encountered in conventional melting operations.
4. A bright white color that does not require rhodium plating for enhancement or wear resistance
5. No excessive loss that hinders scrap recycling through remelting, even at 1700-1950°C
6. Enhanced wear performance during service to provide a high quality finish throughout a conventional lifespan as a jewelry article.

Attributes 1 through 3 are critical for any investment casting alloy. The demands are more stringent when considering the poor wetting action between silica based investments and platinum alloys. Likewise, casting alloy constituents cannot be protected with the application of strong reducing conditions because of issues related to embrittlement that have been noted. The formation of coarse oxide layers that penetrate the cast surface and require extensive grinding for removal is undesirable. The need for special chemical for stripping must also be avoided. Color is an aesthetic issue that can be addressed with rhodium plating. This is how the grayish

color of the 850%Pt- 150%Pd alloy commonly used in Japan is handled. If a material is going to contain 95% Pt, the need for plating should be eliminated. Reality dictates that scrap recasting and recycling must occur in any casting operation. Extensive loss of alloying constituents would be detrimental to platinum control.

Lastly, the issue of platinum durability is becoming a major concern. The buying public expects long lasting shine from a quality jewelry article. This is not always delivered when certain designs utilize soft casting alloys.

We evaluated the first attribute through the investment casting of form fill models and phonograph wedges depicted in figure 4. The total length of metal travel along the diminishing section with 180 degree turns was quantified. The phonograph models were visually examined for the presence of all lines only 0.002" deep. Surface oxide formation was simply a visual check for the presence or absence of a superficial layer. Comparison to conventional materials was done. Physical properties were determined on a Monsanto type 'W' tensile tester with investment cast No. 12 size dumb-bell shaped specimens. Figure 5 shows the large section cast to provide a good measurement of ductility through three dimensional strain. The absence of brittle phases and suitability of physical properties from first use

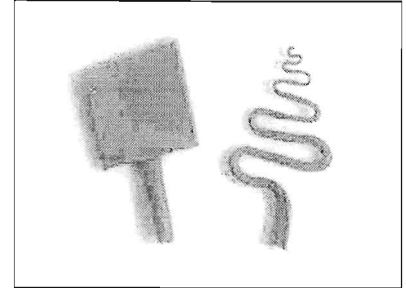


Figure 4: Overview of phonograph and fluidity models

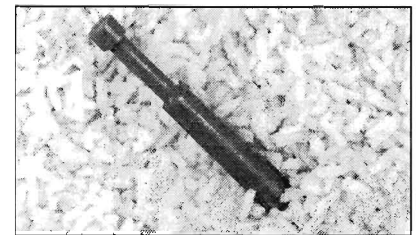


Figure 5: Overview of cast tensile model

through multiple recycling were confirmed. Color was quantified through the CIELAB color coordinate system using a color spectrophotometer. Wear performance was tested through an adaptation to ASTM specification G105-89 (1997 Standard Test Method for conducting wet sand/rubber wheel abrasion tests).

PROPERTIES COMPARISON TO THE PLATINUM HARD CASTING ALLOY:

A variety of physical properties are summarized with comparison to various alloys in use throughout the industry. Alloying additions required to produce significant hardening also reduce the

Alloy Composition	Hardness (HV)	Density (g/cm ³)	Tensile Strength	Yield Strength	Percentage Elongation
950Pt-50 HCA002	160-170	19.9	75,000	54,000	29
950Pt-50 HTA	240-250	19.3	112,000	92,000	15
950Pt-50 Ir	80-90	21.45	40,000	28,000	30
950Pt-50 Co	125-135	20.8	64,000	35,000 ⁵	26
950Pt-50 Ru	125-135	20.6	66,000	35,000 ⁵	25
950Pt-50 Co-Cu	105-115	20.4	54,000	26,000 ⁵	23
900Pt-100 Ir	120-130	21.55	48,000	35,000 ³	10

the melting range of 95% Pt materials substantially (125°C). The melting range is broad at 1000°C compared to the narrow 10-20°C typical of conventional platinum alloys. Color coordinates from the CHELAB system indicate a quality platinum shade. The lightness value (L*) matches well. The overall color difference vector value (DE) is 0.62 versus the 95%PtIr alloy indicating a very close match in color between the standard and hardened materials. The human eye can barely discern color differences that approximate 1 DE value.

COMPARISON OF AS-CAST PHYSICAL PROPERTIES:

The hard casting alloy has superior hardness, tensile strength and yield strength compared to conventional alloys. The hardness range has been specifically selected to match typical white gold materials in the as cast state. This means 30-40 Vickers hardness points higher properties compared to the popular ruthenium and cobalt materials. The additional 80 Vickers hardness points over the 5% iridium material represent a significant advantage in scratch resistance and strength as a jewelry article. The heat treatable alloy is too hard for conventional shop handling, but too soft for tension setting applications. The hard casting alloy represents a compromise in hardness selected to provide better wear resistance and faster finishing while not being too difficult to handle in the shop environment. The increased strength and lower den-

Alloy Composition	Liquidus (C)	Solidus (C)	L* W	a* r/g	b* b/y
950Pt-50 HCA 002	1670	1570	84.2	0.0	3.9
950Pt-50 HTA	1650	1550	83.1	0.1	4.6
950Pt-50 Ir	1790	1780	84.7	-0.2	4.2
950Pt-50 Co	1765	1750	86.6	0.5	4.5
950Pt-50 Ru	1795	1780	84.2	0	4.1
950Pt-50 Co-Cu	1765	1750	87.3	0.5	4.2
900Pt-10 Ir	1790	1770	85.5	-0.1	4.7

sity combine to provide design options for weight reduction that cannot be accomplished with the soft, low strength 95% platinum alloys. All of the alloys tested exhibited ductility. The hard casting alloys exhibits ductility comparable to conventional alloys such as 90%Pt- 10% Ir or 95%Pt-5%Co. These values indicate the alloy is suitable for stretching, hammer sizing, setting and other jewelry applications.

RECYCLING PERFORMANCE:

We tested the consistency and stability of physical properties under conditions of recycling. A 150g lot of metal was subjected to 100% reuse to investment tensile specimens 3 times. Most casting shops supply fresh metal equivalent to their product delivered to finishing operations. This ranges from 30 to 60% new metal input, depending on the wax model and feeding system design. The remainder (40-70%) is recycled. Complete reuse of a batch of metal 3 times represents an extreme abuse to indicate long term performance.

Results demonstrate that critical physical properties such hard-

ness and ductility as indicated by percentage elongation during tensile testing do not deteriorate during abusive recycling. The material does not form brittle compounds with the ceramics used in conventional platinum processing. The retention of hardness and assay results indicate that the alloying additions are not adversely affected by extensive remelting without the benefit of fresh material additions. Tests done on similar developmental alloys indicated the same performance through 5 cycles of 100% reuse in 2 independent tests.

FLUIDITY TESTING:

Tests to determine fluidity were executed with 130g melt lots of new material using two test specimens per flask for each alloy. Total millimeters traveled in each were measured. The time the charge was molten was measured and maintained constant for each of the various alloys in an attempt to fix the absolute quantity of superheat utilized. The results are also expressed as a percentage compared to 95%Pt-5%Co. This was done to provide a basis for comparison to the most fluid and castable material.

Results indicate that the 95% platinum hard casting alloy has fluidity and form filling ability comparable to the standard 90%Pt- 10%Ir material. Both are inferior to platinum cobalt. All lines on the phonograph models

Alloy Composition	Test #1 (mm)	Test #2 (mm)	Total (mm)	%
950Pt-50 Co	104	113	217	100
950Pt-50 HCA 002	78, 94, 78	84, 94, 78	162, 186, 163	78.5
950Pt-50 HTA	93	71	164	76
900Pt-100 Ir	96	92	188	86

95% Platinum Hard Casting	Hardness (HV)	Tensile Strength	Yield Strength	Percentage Elongation
100% new material	160	75,000	54,000	29
100% reused scrap	159	76,200	53,800	27.5
100% reused scrap	161	75,200	53,800	26
100% reused scrap	154	73,600	52,900	27.5

of each alloy filled completely. This means details as small as 0.002" were reproduced. The sharpness of grooves failed to match the results found when zinc containing gold alloys wet gypsum investment.

Casting experiments were successful achieving complete fills of a wide variety of jewelry articles without the use of excessive superheat. The hard casting alloy has form filling characteristics suitable for jewelry manufacturing.

SURFACE OXIDATION:

Figure 6 depicts the as cast surface finish of the 95% platinum hard casting material beside platinum-cobalt and platinum-iridium. All three were melted without the benefit of any protective atmosphere. The additives utilized to achieve enhanced hardness and strength are more prone to oxida-

tion than PGM group metals that do not enhance hardness. A gross, thick oxide layer does not form. The 0.002" deep grooves of the phonograph model reproduced through all testing. Routine surface grinding during finishing operations easily removes the frosted surface. No network of silicates or other detrimental compounds were observed. Intentional oxidation of a finished surface at 700°C for 1 hour with protective atmosphere of flux produced no change in the surface color or finish. 15 minutes exposure to 1100°C without protection produced the surface depicted in figure 7. A thin gray adherent layer forms on the surface.

WEAR RESISTANCE TEST RESULTS:

Hardness is defined as resistance to indentation. This is a

good expression for wear performance in a jewelry article. We studied how alterations to alloy chemistry alter hardness. Manipulation of the gallium to iridium ratio revealed the relationship illustrated in figure 8. Vickers hardness varies in a roughly linear relationship that provides a basis for selecting a hardness range that will provide resistance to indentation and scratching, while not being too high to affect other properties such as ductility. Values from the work of Rushforth et. al are displayed for comparison.

Our abrasion and indentation tests attempted to simulate consumer wear exposure. We used equipment common to the industry to allow for repetition of the method by other individuals. Experimental parameters were as follows:

1. A common vibratory finisher deployed aggressive black plastic cutting media
2. Investment cast washers were machined clean and square. Height was cut after width to ensure the cutting burr could

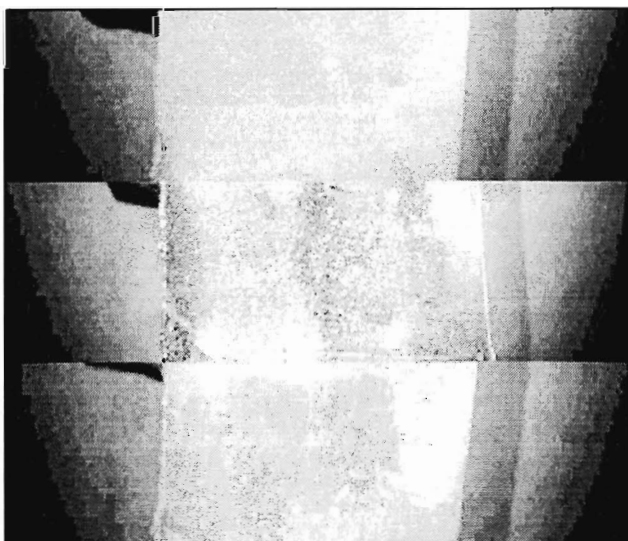


Figure 6: As cast surfaces. Top 95Pt HCA, middle 95Pt 5Ir, Bottom 95Pt 5Co

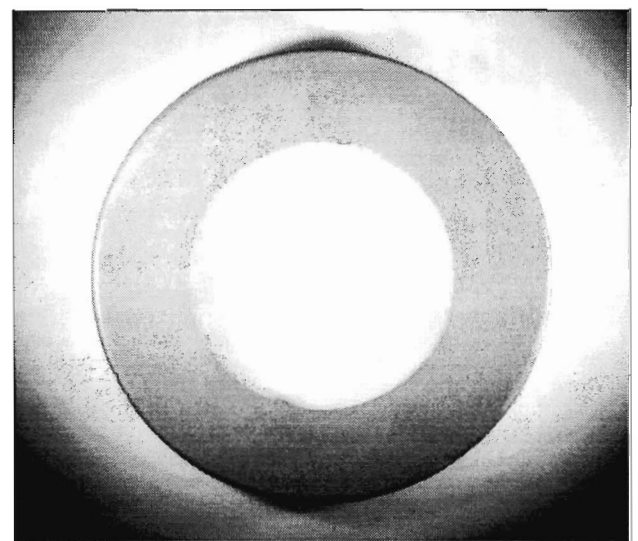


Figure 7: Overview of PtCo surface after 1100°C for 1 hour

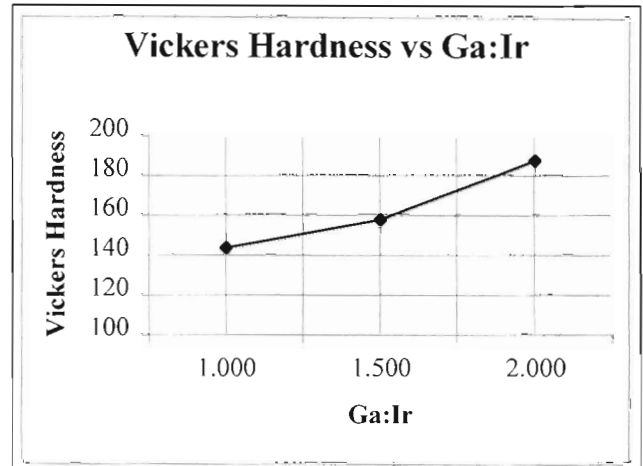
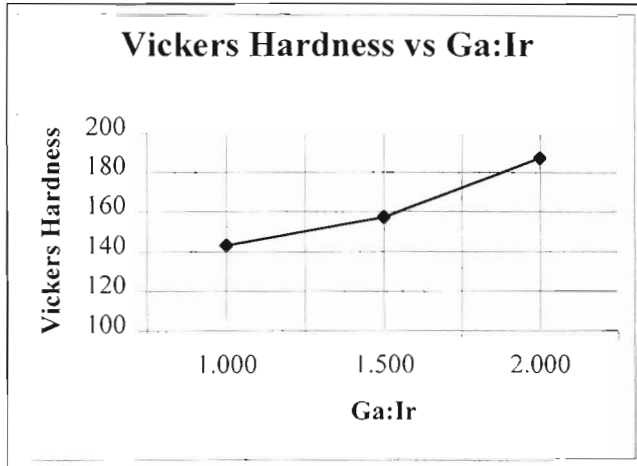


Figure 8: IRSCO data left chart, Rushford data right chart.

- be removed cleanly. 1 surface was lapped to a 1 micron finish
- Pieces were 5.5mm high, 3.5mm wide and weighed 25g for tests 1&2. They were machined to 4.0mm high and 2.5mm wide for tests 3&4.
- 1 washer of each alloy was used simultaneously in each test.
- The washers were subjected to vibratory abrasion and examined at 10 minute intervals.
- Polish loss time was defined as the inability to read the date reflected from a 5 cent piece onto the surface of the test specimen. When the date could not be read, the elapsed time was recorded.
- Weight loss was recorded and volume loss computed after 18 hours exposure.
- The loss of volume was computed from starting mass, density and weight loss values.

9. Tests 1&2 were done in February 2000 by G. Normandeau while 3&4 were done in May by D. Ueno.

Results are summarized by a table and figure 9.

Results indicate that hardness and wear resistance correlate closely. We found variation in the time of polish loss time depending on the illumination and technique deployed. Test 1 was done by visual examination under regular plant lighting. We deployed a bright fiber optic light source with fixed orientation between the illumination, abraded surface and 5 cent piece for tests 2, 3, & 4. This roughly doubled the time to polish loss. Results were unitized to compare time to the 950Pt50Ir material in each test. This minimized the effect of illumination and operator judgment

In all 4 tests the 950Pt 50Ir lost it's surface reflectivity first.

The platinum hard casting alloy lasted from 2.6 to 3.6 times longer, 3.1 times longer on average, before losing it's surface reflectivity. Both the 900Pt100Ir material and 950Pt50Co lasted 2.1 times longer before polish loss. The 950Pt50Ru lasted 2.36 times longer on average than the soft 950Pt50Ir. Weight loss in milligrams was very small, even after 18 hours of testing. This caused the volume loss numbers to be small. Careful attention to surface preparation was required to yield accurate loss values. Specimens used in tests 1&2 had their edges softened by hand buffing. The smaller specimens used in tests 3&4 received careful machining and lapping to ensure their edges were sharp and close to 90 degrees. This explains the 40% or more increase in volume loss between the two test series. The effect is especially significant on the 950Pt50Ir. The weight loss num-

Alloy Composition	(HV)	Polish Loss Time (mm)				Weight Loss (mg in 18 hr) vol Loss rmg/cm ³					
		1	2	3	4	1	2	3	4	1&2	3&4
950Pt-5HCA	165	65	125	180	200	65.8	49.2	44.1	42.6	51.8	76.5
950Pt-50Ir	85	25	45	50	60	73.6	59.3	67.5	59.3	55.6	123
950Pt-50Co	130	55	105	100	110	60.9	49.0	40.2	38.4	49.3	76.7
950Pt-50Ru	130	45	115	130	150	78.3	51.5	42.7	41.1	56.3	82.9
900Pt-100Ir	125	45	75	130	150	73.6	79.8	55.2	50.4	75.2	105

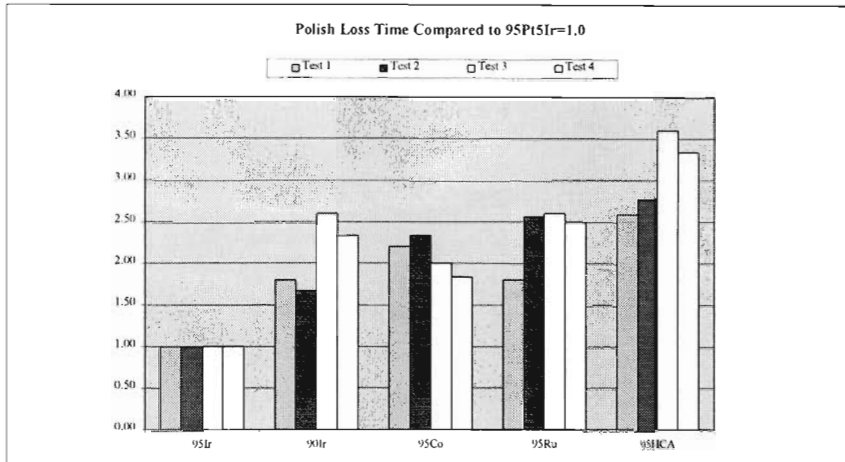


Figure 9: Graph showing summary of test results

bers do not reflect the 50% change in mass between test 1&2 samples versus 3&4. Volume loss in mg/cm^3 more accurately reflects wear and compensates for density differences. The hard casting alloy lasts 30% longer in wear tests than the best conventional alloy. It lasts 210% longer than the worst conventional material.

Wear test accuracy is affected by machining methods, surface preparation techniques, abrasive media performance plus interpretation of reflectivity loss. Weighing for determination of density and calculation of volume loss can be done extremely accurately with a Mettler A6245 precision density balance. More objective

Figure 10: Overview of HCA casting showing surface frost as cast



results could be obtained by using a surface roughness meter to correlate visual estimation. Results indicate that wear and hardness can be closely related. Careful selection of alloy additions can greatly improve wear resistance while maintaining the 95% platinum content required for unqualified hallmarking around the world.

MANUFACTURING ISSUES:

Melting:

Previously alloyed stock can be readily melted using all of the materials and equipment inherent to platinum investment casting. This ensures that high temperature fused quartz crucibles and induction or oxy-hydrogen heat sources are required for small melts. Oxidation of the alloying additives can be reduced by providing a protective cover gas of neutral argon. Avoid reducing conditions that promote the formation of brittle platinum phosphides and silicides.

Careful visual observation of the melt provides a basis for detecting the solidus and noting the broad melting range compared to conventional platinum alloys. It is important to allow the melt temperature to exceed the liquidus before beginning any timing of molten metal superheat. The tendency is to underheat the metal based on observing the solidus and not compensating for the 1000°C melting range. This occurs even with experienced melting staff. Numerous casting tests on a broad range of jewelry articles summarized in figure 10. Articles from experimental trials have been subjected to field finishing with positive approval of quality. Several items of various sizes and sections were subjected to metallographic examination. Longitudinal sec-

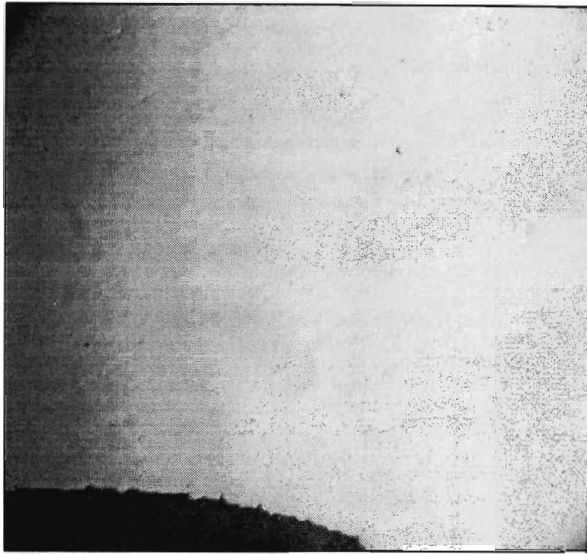


Figure 11: 50X Metallographic section of large mens ring in the shoulder region. Note the absence of shrinkage porosity.

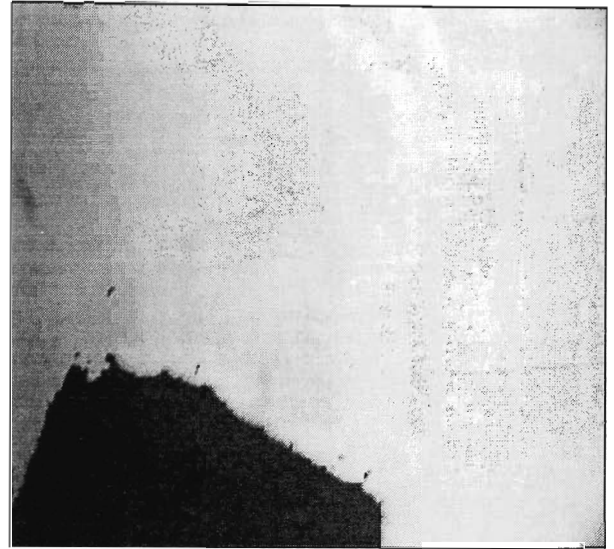


Figure 12: 50X Metallographic section of ladies ring in the shoulder area. Note the absence of any gas porosity.

tions of rings are particularly adept at finding subsurface defects or classifying the presence of shrinkage versus gas porosity. Results are summarized in figures 11, 12, & 13. All show a low incidence of very small shrinkage porosity that is restricted to the interior of the casting.

Flask Temperature:

Because of the broad melting range inherent to the platinum hard casting alloy it is important to form a solidified cast skin quickly upon entering the mold. This minimizes surface feeding where interdendritic regions of the metal adjacent to the mold actually supply metal to volumetric contraction in the core of the casting. The result, depicted in figure 14, shows narrow worm like voids that penetrate inwards from the surface towards the center of the casting. This causes excessive grinding during finishing operations to restore sound metal. The problem can be controlled by reducing the ceramic flask temperature to promote solidification sound outer skin on the casting.

Thick sections typical of mens rings can be fed into a flask at 1300 to 1400°F. Thin sections or 4 prong settings can be fed into a flask at 1600-1700°F. It is important to avoid excessive heat in the ceramic flask. Conventional platinum alloys with their inherent narrow melting range are less sensitive to this issue.

Feeding Gates and Sprues:

The method of feeding molten metal to a platinum casting should be a special consideration compared with items cast in gold. This applies to any platinum alloy. Feeding a material with a broad melting range is best accomplished through thicker than average feeding gates. As always, it is important to place these as close as possible to the thickest section of the cast item. Avoid the use of thin, flat or restrictive feeding gates. Widely tapered gates reduce the impact of molten platinum on the investment surface to prevent breakdown. Tangential feeding on extra thick items can also assist in preventing investment fracture. The length of feeding gates should

be minimized to avoid the need for extra superheat to assist filling. The basic principles that apply to platinum casting, will promote quality product with the hard casting alloy as well. These have been documented at previous Platinum Day Symposiums.

Assembly Issues:

The hard casting alloy can be brazed with conventional platinum solders in the 1100 to 1400°C range. It can self welded with the clean heat of an oxy-hydrogen torch. Care must be taken to accommodate it's lower melting range. Pure platinum foil cannot be used for welding operations because of the melting temperature difference.

Field Trial Results:

Small scale field trials with torch melting and casting have been successful. Virtually everyone who handles the materials notes that finishing times are 50% less compared to other platinum alloys. A high polish is easier to achieve with fewer steps. Smearing is reduced compared to softer



Figure 13: 50X Metallographic section of cast top

alloys like 950Pt 50Ir. Operations that require reasonable softness such as bead setting can be done as well. Drilling for setting small stones produced less tool wear. In general setting operations required less time and effort. Efforts focussing on casting diamonds in place with the platinum hard casting alloy have been successful. In general, the material is well received in both the casting room and bench areas.

CONCLUSIONS & AREAS FOR FURTHER STUDY

1. Previous studies indicate limited alloying alternatives to achieve the multitude of properties desired from an investment casting material.
2. Many of the additives commonly used to enhance the properties of gold materials, cannot be used with platinum alloys because of metallurgical incompatibility.
3. The newly designed hard casting alloy has a platinum white shade that matches any conventional alloy based on the CIELAB color system.

4. The platinum hard casting alloy is 27% harder than the harder conventional materials and 95% harder than the 95Pt5Ir formulation.
5. Ductility of the hard casting alloy is equivalent to other materials with 20% higher strength combined with 8% lower density.
6. Recycling performance, defined as retention of hardness, strength and ductility, with suitable form filling is good.
7. Fluidity test results rank the new hard casting alloy close to 900Pt 100Ir. Both are inferior to the 950Pt50Co material.
8. Surface oxidation is not a significant problem based on furnace exposure tests at 700 and 1100°C for 1 hour. No gross dark oxide forms. Oxidation is equivalent to the common 950Pt50Co material. The thin layer present after casting or heating for soldering can be easily removed by conventional abrasive methods.
9. Wear tests applied to 5 common platinum alloys in a series of 4 distinct trials over 3 months, indicate that the hard casting alloy lasts 30% longer than the best conventional alloy before losing a reflective finish. Superior results, lasting 210% longer than the soft 950Pt50Ir alloy, were repeated in all trials.
10. Platinum wear trials require careful attention to detail in surface preparation and weighing. Surface roughness measurement through an objective meter would be a good supplement to visually rating reflectivity loss.
11. Manufacturing trials supplemented by metallographic examination of a range of articles confirmed internal cast integrity. No incidence of

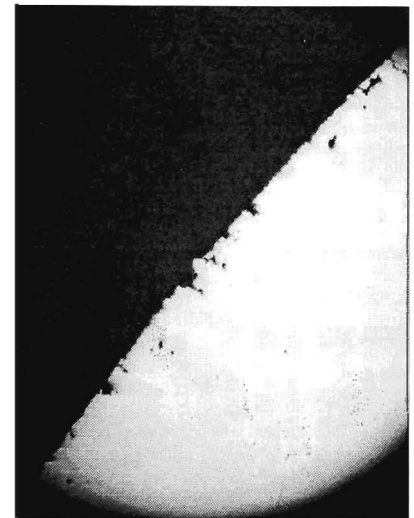


Figure 14: 50X overview of rough surface from excessive ceramic flask temperature.

- non-metallic inclusions, gross shrinkage porosity or gas porosity was found.
12. Ceramic flask temperatures and casting feeding gates can be adjusted to obtain quality results over a broad range of common jewelry items
13. Field trials have produced positive feedback from casting operations, to assembly benches to finishing areas. Finishing times are generally reduced 50% compared to softer conventional alloys.

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