Mechanical Properties and Wear Resistance of Platinum Jewelry Casting Alloys: A Comparative Study

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Introduction

There is scant data available in the literature evaluating fitness for purpose of platinum alloys used in the creation of jewelry designs. In an industry steeped in tradition and ruled by millennia of hands-on experience, this fact is not so surprising. Rather, a substantial body of tribal knowledge exists concerning what does and does not work, and for many years this was largely sufficient. Enter the digital revolution where cast versus hand-fabricated product now dominates, and tribal knowledge alone is no longer enough. This is true because the two methods of production result in very different material properties, and this difference can affect the end consumer’s experience when it comes to wear resistance. Take, for example, the common alloy 90Pt10Ir. This alloy was used to create much of the early 20th century platinum jewelry, and a good amount of this jewelry is still in circulation today. And though purely anecdotal, there is substantial evidence that such platinum estate jewelry has stood up quite well to the test of time, remaining strong and resilient despite decades of daily wear. But is this still the case when legacy alloys used in hand-fabrication are used to make jewelry in a purely cast form? This is the question that we seek to answer in the present research.

In past eras when the vast majority of platinum jewelry was hand fabricated, the metal was bent, formed, twisted, compacted and hammered into the desired shape. All of these hand-working methods introduce work hardening, a mechanism by which the hardness and strength of the metal is increased through deformation of the crystal lattice. Consequently, most hand-fabricated platinum jewelry tends to be inherently strong. Contemporary jewelry designs, on the other hand, are almost entirely produced through casting and not likely to experience the benefits of work hardening. Therefore, platinum alloys that were once viewed as robust are now found to be lacking in their cast forms. Given that today the labor savings achieved through casting near-net-shape jewelry is nothing less than an economic imperative, it is necessary to take a closer look at platinum alloy choices to determine suitable strength levels for cast product.
In order to reach an understanding of alloys that meet fitness for purpose, we must first create data that will help to demonstrate failure modes. In the present work we explore strength, ductility, microstructure, porosity levels, and wear performance for a broad number of platinum casting alloys used globally.

**Previous Research**

Earlier works by Fryé & Fischer-Buehner\(^1\) and Fryé, Klotz, Strauss, and Fischer-Buehner\(^2\) reported the effects of hot isostatic pressing of platinum alloy castings on mechanical properties and microstructures. The present work both increases the number of alloys covered and expands the types of testing performed to include wear testing. The present data also includes castings both with and without hot isostatic pressing in order to augment the comparison of metallurgical quality between the two conditions.

**Experimental Work**

**Alloys Tested**

The following alloys in Table 1 were selected for testing based upon their prevalent use in the United States, Europe, China and Japan. Pure platinum has a hardness of only about 50 HV 1 and can be hardened by solid-solution hardening when alloyed. The effectiveness of different alloying elements in their annealed condition is published in Reference 3.

In this work we categorized the alloys into three groups according to the effectiveness of the alloying elements for a given platinum content of either 90 or 95 mass%. Soft alloys (< 120 HV 1 at 5–10 mass%) are obtained by alloying with Ag, Au, Cu, Pd, Co, Rh, Fe, Cr, Mn and Ir. Medium-hard alloys (120–150 HV 1 at 5 mass%) are possible with the addition of Ru, Ni, Co, Ta and Sb. Finally, hard alloys with a hardness above 150 HV 1 at 5 mass% are achieved by Ga, In, Sn, Ge, Be, Mo, W, Os, Nb, Ti, V and Zr.

Many of these elements have to be excluded for jewelry purposes for various reasons: poisonous or allergenic elements (Be, Ni, Os), highly reactive elements (Ti, Zr, V, Nb, Ta, Cr) and elements that cause production problems such as hot cracking (Ge, Si). The commercial soft alloys are therefore based on additions of Ir, Cu, Rh or Co, the medium-hard alloys contain Ru and Co, while hard alloys require the addition of Ga or In.

Actual hardness depends on the casting condition. Alloys that contain Co are just at the threshold from soft to medium-hard. In the annealed condition they would be categorized as soft alloys, while in the as-cast condition they appear medium-hard. Because this work relates to casting alloys, 95Pt5Co was defined as medium-hard.
Table 1 Experimental alloys: The categories of soft, medium-hard and hard are defined based on the solid-solution hardening in annealed samples according to data published in Reference 3.

<table>
<thead>
<tr>
<th>Soft Alloys</th>
<th>Medium-hard Alloys</th>
<th>Hard Alloys</th>
</tr>
</thead>
<tbody>
<tr>
<td>(&lt; 120 HV 1)</td>
<td>(120–150 HV 1)</td>
<td>(&gt; 150 HV 1)</td>
</tr>
<tr>
<td>95Pt5Ir</td>
<td>95Pt5Ru</td>
<td>95PtAuIn</td>
</tr>
<tr>
<td>90Pt10Rh</td>
<td>95Pt5Co</td>
<td>95PtRuGa</td>
</tr>
<tr>
<td>95PtCuCo</td>
<td></td>
<td>95PtCuGa</td>
</tr>
<tr>
<td>95Pt5Cu</td>
<td></td>
<td>95PtCoIn</td>
</tr>
<tr>
<td>90Pt10Ir</td>
<td></td>
<td>95PtRuGa+</td>
</tr>
</tbody>
</table>

Casting

The casting parameters and conditions for our trials are shown in Table 2. Standard pour temperatures, flask temperatures, and firing curves for platinum alloys were used. All test geometries were 3D printed for dimensional precision and all casting trees were sprued identically among the alloys. The casting was performed using a centrifugal casting machine with induction heating and argon cover gas (no vacuum). All flasks were air cooled for 15 minutes, and de-vesting was done using a water blaster followed by an acid soak. None of the flasks was quenched using full water immersion.

Table 2 Casting parameters

<table>
<thead>
<tr>
<th>Alloy</th>
<th>Pour Temp °C/°F</th>
<th>Flask Temp °C/°F</th>
<th>RPM</th>
<th>Atmosphere</th>
</tr>
</thead>
<tbody>
<tr>
<td>95Pt5Ir</td>
<td>1870 / 3398</td>
<td>850 / 1562</td>
<td>400 / 1</td>
<td>Argon Only</td>
</tr>
<tr>
<td>90Pt10Rh</td>
<td>1960 / 3560</td>
<td>850 / 1562</td>
<td>400 / 1</td>
<td>Argon Only</td>
</tr>
<tr>
<td>95PtCuCo</td>
<td>1900 / 3452</td>
<td>850 / 1562</td>
<td>400 / 1</td>
<td>Argon Only</td>
</tr>
<tr>
<td>95Pt5Cu</td>
<td>1900 / 3452</td>
<td>850 / 1562</td>
<td>400 / 1</td>
<td>Argon Only</td>
</tr>
<tr>
<td>90Pt10Ir</td>
<td>1870 / 3398</td>
<td>850 / 1562</td>
<td>400 / 1</td>
<td>Argon Only</td>
</tr>
<tr>
<td>95Pt5Co</td>
<td>1850 / 3362</td>
<td>850 / 1562</td>
<td>400 / 1</td>
<td>Argon Only</td>
</tr>
<tr>
<td>95Pt5Ru</td>
<td>1870 / 3398</td>
<td>850 / 1562</td>
<td>400 / 1</td>
<td>Argon Only</td>
</tr>
<tr>
<td>95PtAuIn</td>
<td>1920 / 3488</td>
<td>850 / 1562</td>
<td>400 / 1</td>
<td>Argon Only</td>
</tr>
<tr>
<td>95PtRuGa</td>
<td>1900 / 3452</td>
<td>850 / 1562</td>
<td>400 / 1</td>
<td>Argon Only</td>
</tr>
<tr>
<td>95PtCuGa</td>
<td>1920 / 3488</td>
<td>850 / 1562</td>
<td>400 / 1</td>
<td>Argon Only</td>
</tr>
<tr>
<td>95PtCoIn</td>
<td>1850 / 3362</td>
<td>850 / 1562</td>
<td>400 / 1</td>
<td>Argon Only</td>
</tr>
<tr>
<td>95PtRuGa+</td>
<td>1900 / 3452</td>
<td>850 / 1562</td>
<td>400 / 1</td>
<td>Argon Only</td>
</tr>
</tbody>
</table>
Hot Isostatic Pressing

A portion of the castings was subjected to hot isostatic pressing (HIP) in order to compare metallurgical quality with as-cast samples. HIP, a proven densification process for castings in numerous alloys (precious and otherwise) involves placing the castings in a high-pressure vessel for a specified period of time, during which heat and pressure are applied in an inert environment and in accordance with an alloy’s particular melt temperature. Our previous work on HIP of platinum alloys\(^1,2\) demonstrated a substantial reduction in sub-surface porosity for castings that had been HIPed. The reduced levels of porosity demonstrated several benefits for the mechanical properties including a marked increase in ductility for the majority of alloys tested. The present research contains expanded data on comparative properties among the as-cast and HIPed conditions for the new alloys tested.

Test Geometries

The test geometries in Figures 1, 2 and 3 were used for our measurement of mechanical properties.

Figure 1 Tensile bar

Figure 2 Plate for scratch and hardness test

Figure 3 Half shank for hardness test
Results

Micro-Hardness Testing

Vickers hardness (diamond pyramid hardness), hereafter referred to as HV 1, was measured on metallographically polished plates and half shanks using a load of 1 kg. Results are given in Table 3. Data from earlier work\(^2\) are also included in Table 3 for comparison purposes.

The binary alloys containing Rh, Ir, Ru or Co as the sole alloying element show only solid-solution hardening and are therefore relatively soft. The softest and most ductile alloys are those containing Ir and Rh as alloying elements (95Pt5Ir, 90Pt10Ir, and 90Pt10Rh). Alloys containing Co and Ru are slightly harder because these elements are more effective hardeners.\(^3\) The addition of elements such as In and Ga results in even more effective solid-solution strengthening and can furthermore result in precipitation hardening due to the formation of Pt\(_3\)In and Pt\(_3\)Ga precipitates, respectively, if a certain amount of In/Ga is exceeded. Precipitation hardening is very sensitive to temperature history and requires a two-step heat treatment for optimum properties, but this type of heat treatment was not done in the present study. It may also take place to some extent during the slow cooling phase (~800°C/1472°F down to 300°C/572°F), which is distinguished from and follows the rapid solidification after casting. In any event, cooling conditions can play a strong role here.

Hardness is generally proportional to UTS values, but it does not provide information about the ductility of alloys. Such information is generally obtained through tensile testing, which comprises the section that follows.

For two of the alloys (95Pt5Ru and 95Pt5Co), larger data sets from a previous study existed.\(^4\) This allowed a statistical analysis of many as-cast samples. For 95Pt5Ru, 88 hardness tests on 24 as-cast samples were evaluated that provided an average value of 129 HV 1 with a standard deviation \(\sigma\) of 4 HV 1. The table provides the average and a confidence interval of \(\pm 2\sigma\) for these two alloys. Over 95% of all measurements lie in this range.

Tensile Testing

Tensile testing was performed according to DIN EN ISO 10002-1 in a universal testing machine (Zwick Z100HT) at a temperature of 23+/-5°C using the test bar geometry shown in Figure 1. The strain was measured until fracture using a strain gauge on a starting length of 15 mm. The testing speed was 1.5 mm/minute until the yield strength was surpassed and then increased to a strain-controlled strain rate of 0.0025 s\(^{-1}\). The values for 0.2% yield strength (YS\(_{0.2}\)), ultimate tensile strength (UTS), elongation (\(\varepsilon_f\)) and reduction of area (ROA) were determined on (4) four samples, each in the as-cast and HIPed conditions.

Table 3 provides average values for the four tests. The fracture surface for each test bar was inspected using a stereomicroscope to identify casting defects (shrinkage pores). A limited number of samples were found to have casting defects and these test results were excluded from the averaging. It is worth noting that although
material properties of as-cast platinum alloys are scarcely available in literature, the little data that are available for 95Pt5Ru and 95Pt5Co showed very good correlation with our data.\(^5\)

**Table 3** Tensile properties and hardness (AC=as-cast, HIP=hot isostatic pressed). Data marked with a * were taken from References 2 and 4. UTS-YS/YS is defined as the work hardening of alloys.

<table>
<thead>
<tr>
<th>Alloy</th>
<th>YS(_{0.2}) [MPa]</th>
<th>UTS [MPa]</th>
<th>Elongation [%]</th>
<th>ROA [%]</th>
<th>(UTS-YS)/YS [%]</th>
<th>Hardness [HV 1]</th>
</tr>
</thead>
<tbody>
<tr>
<td>95Pt5Ir AC</td>
<td>142</td>
<td>241</td>
<td>45</td>
<td>90</td>
<td>70</td>
<td>79</td>
</tr>
<tr>
<td>95Pt5Ir HIP</td>
<td>121</td>
<td>242</td>
<td>47</td>
<td>94</td>
<td>101</td>
<td>81</td>
</tr>
<tr>
<td>90Pt10Rh AC</td>
<td>140</td>
<td>330</td>
<td>37</td>
<td>64</td>
<td>135</td>
<td>89</td>
</tr>
<tr>
<td>90Pt10Rh HIP</td>
<td>144</td>
<td>333</td>
<td>43</td>
<td>89</td>
<td>131</td>
<td>89</td>
</tr>
<tr>
<td>95PtCuCo AC</td>
<td>172</td>
<td>378</td>
<td>33</td>
<td>69</td>
<td>119</td>
<td>111</td>
</tr>
<tr>
<td>95PtCuCo HIP</td>
<td>142</td>
<td>386</td>
<td>35</td>
<td>80</td>
<td>171</td>
<td>110</td>
</tr>
<tr>
<td>95Pt5Cu AC</td>
<td>171</td>
<td>346</td>
<td>15</td>
<td>46</td>
<td>102</td>
<td>112</td>
</tr>
<tr>
<td>95Pt5Cu HIP</td>
<td>143</td>
<td>387</td>
<td>31</td>
<td>69</td>
<td>171</td>
<td>114</td>
</tr>
<tr>
<td>90Pt10Ir AC</td>
<td>219</td>
<td>353</td>
<td>33</td>
<td>90</td>
<td>62</td>
<td>113</td>
</tr>
<tr>
<td>90Pt10Ir HIP</td>
<td>226</td>
<td>358</td>
<td>36</td>
<td>87</td>
<td>58</td>
<td>112</td>
</tr>
<tr>
<td>95Pt5Co AC *</td>
<td>189</td>
<td>449</td>
<td>38</td>
<td>82</td>
<td>138</td>
<td>129 ± 12</td>
</tr>
<tr>
<td>95Pt5Co HIP *</td>
<td>220</td>
<td>452</td>
<td>36</td>
<td>76</td>
<td>105</td>
<td>122</td>
</tr>
<tr>
<td>95Pt5Ru AC *</td>
<td>229</td>
<td>411</td>
<td>30</td>
<td>61</td>
<td>79</td>
<td>129 ± 8</td>
</tr>
<tr>
<td>95Pt5Ru HIP *</td>
<td>235</td>
<td>419</td>
<td>38</td>
<td>89</td>
<td>78</td>
<td>125</td>
</tr>
<tr>
<td>95PtAuIn AC</td>
<td>297</td>
<td>536</td>
<td>19</td>
<td>25</td>
<td>80</td>
<td>165</td>
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<tr>
<td>95PtAuIn HIP</td>
<td>291</td>
<td>551</td>
<td>35</td>
<td>64</td>
<td>89</td>
<td>163</td>
</tr>
<tr>
<td>95PtRuGa AC</td>
<td>299</td>
<td>501</td>
<td>22</td>
<td>49</td>
<td>68</td>
<td>166</td>
</tr>
<tr>
<td>95PtRuGa HIP</td>
<td>299</td>
<td>523</td>
<td>38</td>
<td>86</td>
<td>75</td>
<td>156</td>
</tr>
<tr>
<td>95PtCuGa AC</td>
<td>308</td>
<td>557</td>
<td>27</td>
<td>50</td>
<td>81</td>
<td>166</td>
</tr>
<tr>
<td>95PtCuGa HIP</td>
<td>247</td>
<td>496</td>
<td>29</td>
<td>40</td>
<td>101</td>
<td>156</td>
</tr>
<tr>
<td>95PtCoIn AC</td>
<td>290</td>
<td>575</td>
<td>27</td>
<td>49</td>
<td>98</td>
<td>167</td>
</tr>
<tr>
<td>95PtCoIn HIP</td>
<td>288</td>
<td>590</td>
<td>34</td>
<td>74</td>
<td>105</td>
<td>164</td>
</tr>
<tr>
<td>95PtRuGa+ AC</td>
<td>421</td>
<td>680</td>
<td>14</td>
<td>32</td>
<td>61</td>
<td>207</td>
</tr>
<tr>
<td>95PtRuGa+ HIP</td>
<td>430</td>
<td>676</td>
<td>22</td>
<td>76</td>
<td>57</td>
<td>190</td>
</tr>
</tbody>
</table>

Work hardening describes the increasing strength of a material with increasing plastic deformation. Plastic deformation happens through dislocations, which are lattice imperfections that allow the movement of atoms under a plastic strain. With increasing strain the number of dislocations increases and adjacent dislocations hinder one another’s movement, making the material stronger. As a consequence, higher stress is required for further straining. This is reflected by
the higher level of UTS (the endpoint of uniform deformation) compared to yield strength (the beginning of deformation).

Elongation $\varepsilon_f$ is the maximum deformation that a sample can take until it fractures, and the ROA value provides information about the necking or contraction of the sample once stresses above UTS have been applied. A detailed description of these four values determined from tensile testing is provided in our earlier work.\(^2\)

Alloys containing Co, Ga and In show higher strength and lower ductility. In particular, work hardening increases compared to the simple binary alloys containing Ru, Ir or Rh. The alloys containing Cu and Ir are the softest and most ductile of the group and show a lesser amount of work hardening, making them easier to deform during bench operations. One curiosity occurs with the Cu-containing alloys that is worth noting: After HIPing, the work hardening increases significantly compared to the as-cast condition. This effect is due to a reduction in the yield strength as hardness and UTS are unchanged by HIPing.

HIP significantly reduces the scatter of results among the four samples of each series, as discussed in detail in our earlier paper.\(^2\) The strength values $Y_{S0.2}$ and UTS are only slightly affected by HIP, with a small but negligible increase observed for most alloys. The effect of HIP is much stronger on the ductility values $\varepsilon_f$ and ROA and is most pronounced in the ROA value. This effect of HIP on ROA is attributed to a reduction in porosity that results from the process. Some alloys such as 95Pt5Ir, 90Pt10Ir and 95Pt5Co show a lesser effect on ROA after HIP because they already exhibit lower levels of porosity in the as-cast condition. The increase of the ROA was most pronounced for the hard alloys 95PtRu+ and 95PtAuIn. Only one alloy, 95PtCuGa, shows a reduction in the strength and ductility levels after HIP, although this result is based upon limited data because of the omission of two of the four samples due to casting defects.

Microstructures

The objective of our microstructural investigation was to identify porosity and determine grain size. The test geometry used for this purpose is shown in Figure 4.

![Figure 4 Half-shank test geometry](image)
The half-shanks were split longitudinally along the centerline and embedded in epoxy resin. The interior surface was then ground with silica sandpaper in successively decreasing grit sizes, followed by polishing with diamond paste at 15 µm, 6 µm and 1 µm. This process requires considerable operator diligence due to the softness of some alloys. With soft alloys pores can be easily smeared, which can result in artificially low porosity values. An example showing the effect of polishing quality can be seen in Reference 5. In order to further avoid artifacts from polishing, an additional ion-polishing step was done that removed the deformed surface layer to obtain optimum image quality. For each alloy the microstructure in the thicker end of the half-ring shanks is shown, both in the as-cast and HIP conditions, in Figures 5–15.

During investment casting the metal solidifies by forming dendrites. Dendrites are irregular-shaped three-dimensional crystals that grow during the solidification process from the surface of the part, where the alloy is in contact with the colder investment material. This forms typical columnar grains from the surface that meet in the center of the part. This appearance is most obvious for the PtIr alloys (Figure 8 and Figure 9). Other alloys show more globular grains. Whether globular or columnar grains form depends on alloy composition but also on casting parameters such as melt and flask temperatures. In particular, the melt temperature is more challenging to control and may vary from one pour to another. Therefore, the resulting microstructure (globular or columnar) may differ from one casting to another for the same alloy. This effect is shown in Figure 7 and Figure 9.

The shape of the dendrites depends on the alloy chemistry. As dendrites grow they come into contact with each other and isolated volumes of liquid metal remain between them. As soon as the solid fraction reaches 50–60 vol.%, further molten feed is no longer possible. The isolated volumes of liquid metal shrink by 4–5 vol.% during solidification, and as a result small, scattered pores remain (seen as micro shrinkage pores). Such micro shrinkage porosity is observed in all alloys that contain Ru, Ga or In (e.g., in Figure 5 or Figure 7). The porosity is most pronounced in thicker sections such as the wide end of the ring shank.

The effect of alloy composition on micro shrinkage porosity in 95Pt5Ru-based alloys is described in detail in References 7 and 8. In the case of shrinkage porosity, most pores are isolated from the surface and do not contain any appreciable amount of gas; therefore, HIP is a useful mechanism for healing them. The external gas pressure applied during HIP acts on material that is soft at high temperature. The internal pores are collapsed and bonded during HIP, leaving a fully dense microstructure under ideal conditions. The effectiveness of HIP is demonstrated by images of the microstructure (Figure 5 and Figure 13) taken following HIP that are essentially free of pores.

A third feature of interest is segregation. Segregation means a change in the chemical composition of the melt during solidification. Under ideal conditions the cast object should have a homogeneous composition after solidification. However, this involves diffusion processes that require a certain amount of time that is not provided for in platinum alloys, which by nature solidify very quickly under typical casting conditions. As a consequence, the high-melting elements
of the alloy concentrate in the dendrite cores while the lower-melting elements concentrate in the remaining melt. The actual segregation can be obtained from phase diagrams and depends on the cooling rate and alloy composition. Low-melting elements such as Ga or In that were added to some alloys in this study showed strong segregation. The inhomogeneous composition of the cast part is shown most clearly in Figure 7 and Figure 10 by the different shades of gray inside the grains. The segregation appears to be unaffected by HIP. It was demonstrated by thermodynamic simulations that the segregation depends strongly on the curvature of the liquidus and solidus surface.

The grain size of the alloys was estimated from the SEM images. Grain size depends on the actual cooling conditions, which might be slightly different from one casting to another as described above. Grain size further depends on the exact position of the metallographic section, especially on the distance of the section from the surface of the part. This might differ by ±0.2 mm from sample to sample. With this caveat in mind, general trends in grain size were observed with most alloys showing a relatively coarse grain size in the range of 0.5–1 mm. The PtIr alloys tend to be at the upper end of this range. Smaller grain size in the range of 100–300 µm is observed for some alloys including 95PtRu, 95PtRuGa and 95PtCoIn. A general trend that the addition of Ga or In results in smaller grain size was not observed. Lastly, it is unknown whether micro-alloying was used by the manufacturers to reduce the grain size in some of these alloys.

Figure 5 95PtAuIn in the as-cast (left) and HIP condition (right)
Figure 6 95PtCuGa in the as-cast (left) and HIP condition (right)

Figure 7 95PtRuGa+ in the as-cast (left) and HIP condition (right)
Figure 8 95Pt5Ir in the as-cast (left) and HIP condition (right)

Figure 9 90Pt10Ir in the as-cast (left) and HIP condition (right)
Figure 10 95PtRuGa in the as-cast (left) and HIP condition (right)

Figure 11 95PtCoIn in the as-cast (left) and HIP condition (right)
**Figure 12** 95Pt5Cu in the as-cast (left) and HIP condition (right)

**Figure 13** 95PtCuCo in the as-cast (left) and HIP condition (right)
Figure 14 95Pt5Co in the as-cast (left) and HIP condition (right)

Figure 15 95Pt5Ru in the as-cast (left) and HIP condition (right)
Wear Testing

Three different types of wear tests were performed in this study in order to simulate abrasive wear, scratching and real-life wear. The abrasion test is a harsh testing method that results in random impacts to the surfaces of the metal piece; the scratch test provides a very defined loading of the sample; and human wear is real-life testing under subjective testing conditions.

Abrasion Test

A rotating barrel was filled with an abrasive mixture designed to be suitable towards simulating abrasive wear of jewelry in short-duration testing (Figure 16). The mixture consisted of irregular-shaped granite stones (ca. 40–60 mm long and 30 mm thick, mass ca. 20–30 g) with sharp edges that were mixed with three types of granite sand with particles of different sizes. The total mass of sand and stones was ca. 2400 g.

As-cast plate samples for each alloy (Figure 2) were used for the abrasion test, and a portion of each sample was protected by adhesive tape during testing. The barrel was rotated at 30 rpm for 15 minutes in one direction and then for 15 minutes in the reverse direction. The samples were documented by light optical microscopy (LOM) and scanning electron microscopy (SEM) before and after interrupted testing for 60 s + 240 s + 600 s in each direction. The total testing time was 15 minutes in each direction. After testing the samples were cleaned ultrasonically to remove sand and debris.

The mass of the samples was recorded before and after testing to determine mass loss due to abrasion. These data are given in Table 4. In order to compare the samples, the mass loss was normalized with the sample surface. The test showed a clear correlation between hardness and mass loss (Figure 17). Samples with higher hardness show a lower mass loss. The results follow a linear trend. If hardness is increased by a factor of two, the mass loss is reduced by 20-25%. It is worth
noting that the mass loss per surface area is very low and in the range of a few µg per mm² sample surface.

**Table 4** Mass loss of as-cast plate samples during the abrasion test for selected samples of different hardness

<table>
<thead>
<tr>
<th>Alloy</th>
<th>Hardness [HV 1]</th>
<th>Mass Loss [µg/mm²]</th>
</tr>
</thead>
<tbody>
<tr>
<td>95Pt5Ir</td>
<td>79</td>
<td>1.89</td>
</tr>
<tr>
<td>95PtCuCo</td>
<td>111</td>
<td>1.85</td>
</tr>
<tr>
<td>95Pt5Cu</td>
<td>112</td>
<td>1.90</td>
</tr>
<tr>
<td>95PtAuIn</td>
<td>165</td>
<td>1.57</td>
</tr>
<tr>
<td>95PtCoIn</td>
<td>167</td>
<td>1.29</td>
</tr>
<tr>
<td>95PtRuGa+</td>
<td>207</td>
<td>1.40</td>
</tr>
</tbody>
</table>

**Figure 17** Correlation of hardness and mass loss during the wear test

The LOM images (Figure 18) show characteristics of abrasion depending on the sample hardness. Each sample contains deep (dark appearing) scratches and dimples. With decreasing hardness the number of dimples increases. The dimples are presumed to have been formed by the impact of the granite stones, and the area between the dimples is presumed to have been scratched by the sand. Clearly, the softer sample is more severely scratched. In order to understand the mechanism of abrasion, the samples were characterized by scanning electron microscopy (see images in the right column of Figure 18). The softest sample (95Pt5Ir) shows heavy scratching of the complete surface with single deeper scratches where the material is pushed to the side (red arrows). As hardness increases it occurs that material is not only pushed aside, but it seems that chips from the material surface
were breaking during loading, because of the reduced ductility of the samples with higher hardness, e.g., alloy 95PtRuGa+ shown with blue arrows in Figure 18.

Figure 18 Surface of plates after 2x 15 minutes tumbling (LOM, left and SEM, right). From top to bottom: hardest sample (95PtRuGa+), medium-hardness (95PtCoIn) and softest (95Pt5Ir). The far left portion of each LOM sample was protected during testing.

**Scratch Test**

The scratch tests were done with a conical Rockwell type C diamond tip under a constant loading speed of 100 N/mm while the sample was moved with a constant speed of 10 mm/minute (Tribotechnic Scratch tester Millennium 200). This results in a scratch exhibiting linearly increasing depth. The 3D scratch profile was documented with a confocal microscope (Nanofocus µsurf) and plotted as 3D image of the scratch (Figure 19) that is compared to a SEM image of the scratch end. Please note that the color code is different for the different 3D images.
Not surprisingly, different hardness values result in different scratch depths. The penetration rate [units µm/N], which is defined as the slope of the depth versus load curve, decreases with increasing hardness. The scratches on the harder samples are therefore not as deep compared to the softer samples.

The abrasion test hinted that the lower ductility of the harder samples might result in metal chipping. To check this hypothesis, SEM images of the scratches were made (Figure 19). The hard alloys did indeed show chipping at the edges of the scratch. The effect was most pronounced for the alloys 95PtRu+ and 95PtCoIn. Soft samples such as 95PtCuGa did not show chipping, but the scratch was deeper. Finally, the softest sample 95Pt5Ir did not show any chipping, but a very deep and broad scratch with heavy deformation along the edges was present.
Human Wear Test

For the human wear tests, a fairly lightweight ring design with respect to cross-section thickness was used (Figure 20). It was important to select a cross-section that would result in visibly different distortion levels among alloys in order that we might define failure modes. The 1.0 x 2.0 mm dimensions were chosen because they are commonly seen in platinum jewelry designs.

![Figure 20 Human wear test band](image)

All twelve alloys were included in the human wear test; however, only some are presented here due to space considerations. The reported alloys are a representative group including soft, medium-hard, and hard alloys.

The rings were polished using conventional bench techniques. Different subjects were selected to wear one ring on the index finger of their dominant hand. The ring surface was documented in the SEM prior to testing, and again at the same position after 12 weeks of daily wear. The rings were of excellent polish quality in their original condition except for a few slight water spots as shown in Figure 21.
After 12 weeks of daily wear (right-hand column of Figure 21) all four alloys exhibit varying degrees of scratching and denting. As expected, the soft and medium-hard alloys display significantly more surface distortion than the two hard alloys.

Figure 21 SEM image of the ring surface of selected alloys before (left) and after 12 weeks of human wear testing (right)
An additional measurement of human wear that is critical in the jewelry industry is roundness. All rings were assessed for roundness following six weeks of daily wear, with results shown in Figure 22. Most of the rings performed reasonably well, with the very notable exception of 95Pt5Ir. As reported in Table 3, this alloy has the overall lowest mechanical properties of the group. Based upon these properties and the results of the human wear tests, this alloy is not recommended for use in platinum jewelry.
Figure 22 Human wear test bands after six weeks of wear

Color
Reflectivity was measured as a function of wavelength on the metallographically polished plates using a spectral photometer (KonicaMinolta CM-5) in a wavelength range of 350–740 nm. The color parameters L*, a*, b* and the yellowness index YI(D1925) were determined according to the CIE Lab system. The measurement was repeated on the samples after the abrasion test. The color change was calculated according to equation (1) while the change of the YI is the difference before and after testing. Results are given in Table 5.

\[ \Delta E = \sqrt{\Delta L^2 + \Delta a^2 + \Delta b^2} \]  \hspace{1cm} (1)

<table>
<thead>
<tr>
<th>Alloy</th>
<th>L*</th>
<th>a*</th>
<th>b*</th>
<th>YI(D1925)</th>
<th>ΔYI</th>
<th>ΔE</th>
</tr>
</thead>
<tbody>
<tr>
<td>95Pt5Ir</td>
<td>86.71</td>
<td>-0.25</td>
<td>3.72</td>
<td>8.74</td>
<td>3.18</td>
<td>6.22</td>
</tr>
<tr>
<td>95CuCo</td>
<td>85.44</td>
<td>-0.25</td>
<td>4.08</td>
<td>9.54</td>
<td>2.62</td>
<td>6.02</td>
</tr>
<tr>
<td>95Pt5Cu</td>
<td>85.88</td>
<td>-0.28</td>
<td>3.65</td>
<td>8.63</td>
<td>3.72</td>
<td>7.02</td>
</tr>
<tr>
<td>90Pt10Ir</td>
<td>87.19</td>
<td>-0.34</td>
<td>3.29</td>
<td>7.77</td>
<td>3.80</td>
<td>6.19</td>
</tr>
<tr>
<td>95Pt5Co</td>
<td>86.17</td>
<td>-0.37</td>
<td>3.22</td>
<td>7.68</td>
<td>3.76</td>
<td>5.95</td>
</tr>
<tr>
<td>95Pt5Ru</td>
<td>87.20</td>
<td>-0.34</td>
<td>2.98</td>
<td>7.17</td>
<td>3.60</td>
<td>5.75</td>
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<tr>
<td>95PtAuIn</td>
<td>85.57</td>
<td>-0.24</td>
<td>3.81</td>
<td>9.02</td>
<td>3.92</td>
<td>6.25</td>
</tr>
<tr>
<td>95PtCuGa</td>
<td>84.50</td>
<td>-0.22</td>
<td>4.03</td>
<td>9.54</td>
<td>4.39</td>
<td>6.85</td>
</tr>
<tr>
<td>95PtRuGa</td>
<td>86.27</td>
<td>-0.32</td>
<td>3.38</td>
<td>8.04</td>
<td>3.83</td>
<td>6.27</td>
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<tr>
<td>95PtCoIn</td>
<td>85.90</td>
<td>-0.34</td>
<td>3.39</td>
<td>8.07</td>
<td>3.37</td>
<td>5.43</td>
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<tr>
<td>95PtRuGa+</td>
<td>85.27</td>
<td>-0.28</td>
<td>3.60</td>
<td>8.57</td>
<td>3.34</td>
<td>5.54</td>
</tr>
</tbody>
</table>
All alloys show excellent white colors that are far below the requirement of “premium white” (YI < 19) for white gold alloys. The YI value correlates with the L* value that reflects the brightness or lightness of a specific color. The a* (red-green variable) is nearly constant. Alloys of lower YI value show a slightly more negative a* value. The b* value (yellow-blue) shows the opposite tendency. Alloys containing gold or copper are less white, while the binary alloys have the brightest and whitest appearance. Additions of Ga and In seem to slightly increase YI and decrease L*.

After abrasion testing, all samples showed an increase of the YI and also a color change ∆E. The color change is defined as the distance between two color coordinates in the three-dimensional color space. If the color change is attributed to the changes in the sample surface during abrasion, it might be linked to the mechanical properties of the alloys. No such correlation was found for the color change value ∆E. A weak correlation between ∆YI and the reduction of area (ROA) was found. Samples with higher ROA show a tendency for a smaller change of the YI during abrasion.

**Discussion**

**Correlation of Hardness and Microstructure**

The alloys containing Ga or In showed significantly higher hardness and strength compared to the binary alloys. This is a result of effective solid-solution strengthening, and eventually also of age hardening by the precipitation of the intermetallic phase Pt₃Ga or Pt₃In, if a certain level of Ga/In is exceeded. Readers unfamiliar with metallurgy are referred to Reference 9 for an introduction to the terms used here. Figure 23 shows the temperature-concentration (isopleth) section of the Pt-Ru-Ga system at 95 mass% platinum. On the left and right side of the diagram the compositions 95Pt5Ru and 95Pt5Ga are shown, respectively. The exchange of Ru by Ga reduces the liquidus and the solidus temperature. At Ga content above 4.5 %, the binary eutectic reaction L => (Pt) + Pt₃Ga is reached at a temperature of 1356°C/2473°F. This is slightly below the binary eutectic temperature of 1361°C/2482°F given in Reference 5. Alloys with Ga content above 2.2% should show the precipitation of Pt₃Ga upon slow cooling from high temperatures or aging above 600°C/1112°F. The In-containing alloys show a similar behavior, but the eutectic reaction is observed at higher In contents.

For the alloys investigated in this study the Ga content is far below 4.5%. In any case, the eutectic reaction can be observed in alloys with lower Ga content due to segregation of Ga in the liquid phase. The segregation was calculated for two alloys with typical Ga content (Figure 23 right). The solid lines provide the maximum segregation, while the dashed lines show the equilibrium solidification. As can be seen from the diagram the eutectic reaction is likely to occur at Ga contents of 2.5%. This would result in significant hardening, especially after slow cooling of the flask following casting.
Figure 23 Left: Isopleth section of the Pt-Ru-Ga system at a constant content of 95% platinum. Right: Scheil calculation for two alloy compositions

The metallographic images (Figure 7 or Figure 10) show the segregation at higher magnification. Based on the thermodynamic considerations for segregation, it can be expected that the hardness of the interdendritic regions, where Ga is concentrated, will be higher compared to the dendrite cores where Ga content is low. Due to the size of the interdendritic regions it is very difficult to make hardness measurements in different areas. Therefore, a matrix of 10 x 10 hardness indents with a distance of 50 µm between indents was measured at a load of 10 g (HV 0.01) and statistically evaluated. Due to the lower load the absolute hardness numbers are higher compared to a load of 1000 g. The histogram (Figure 24) shows different hardness ranges for soft (95Pt5Ir) and hard (95PtAuIn and 95PtRuGa+) alloys. 95Pt5Ir and 95PtAuIn, which do not show precipitation hardening, show relatively narrow hardness distributions. Alloy 95PtRuGa+ shows a very wide hardness distribution from 194–309 HV 0.01 due to the segregation of Ga in the interdendritic regions. The upper value is within the hardness range of 280–318 HV that is achieved for a precipitation hardened 952Pt48Ga alloy.5
Correlation of Mechanical Properties and Microstructure

As described above, the additions of Ga or In increase hardness. The mechanical properties were found to be dependent on the chemical composition of the alloys as shown in Table 3. The effect of Ga addition is shown for selected alloys in Figure 25. Ga shows higher solid-solution strengthening compared to Ru. Therefore, if Ru is partially replaced by Ga, it results in a moderate increase of the strength values (YS and UTS), both in the as-cast and HIP condition. If the Ga content exceeds 1.5%, the effect of precipitation hardening causes a non-linear increase of strength over Ga content. As shown above, only the interdendritic regions display sufficiently high Ga content to allow precipitation hardening, and HIP does not affect the strength levels.

The ductility values (elongation and ROA) are much more sensitive to HIP. As strength levels increase with increasing Ga content, a reduction of the ductility values can be observed at the same time in the as-cast condition. For Ga contents up to 1.5%, this reduction can be compensated by HIP. This means that the reduction in ductility is a result of increasing micro shrinkage porosity with increasing Ga content. This is not surprising as the segregation tendency significantly increases when Ga is added to the alloy (Figure 25, right). HIP closes micro shrinkage pores and restores the ductility values of the alloys with 1.5% Ga to the values for the binary alloy 95Pt5Ru. If more than 1.5% Ga is added, the ductility in the as-cast condition decreases further due to increasing micro shrinkage porosity. HIP can restore ductility caused by micro shrinkage; however, after HIP the ductility of alloys with 2.1% Ga does not achieve the ductility of the binary 95Pt5Ru alloy.
This indicates that precipitation hardening caused an effective reduction in ductility for the alloys with Ga content over 1.5%. Due to the similar chemistry of Pt-In alloys, it is expected that these alloys show a similar behavior. The actual In concentrations above which precipitation hardening occurs requires further experimental evidence.

![Figure 25](image)

**Figure 25** Effect of Ga content on mechanical properties of 95Pt5Ru alloys where part of the Ru is replaced by Ga. Closed and open symbols show the as-cast and HIP conditions, respectively.

**Effect of Hardness on Loss of Mass during Abrasion**

Loss of mass due to abrasion was found to be quite small and was in the range of $\mu$g/mm² for the chosen test conditions. The conditions were quite harsh compared to conventional wearing conditions. Therefore, mass losses in real-life wear are expected to be much smaller. For typical dimensions of a wedding band (4 mm width, 20 mm diameter), a mass loss of maximum 0.5 mg would be expected in the chosen test. Due to the smaller size of the rings tested in this study, the mass loss should be about one quarter of this value.

With increasing hardness, the mass loss that was recorded in the abrasion test decreased; however, this effect was quite small. For instance, the increase of hardness by a factor of two resulted in a reduction of mass loss of only 20–25%. Therefore, the effect of hardness should not be overestimated.

For comparison, a previous study of mass loss for an 18-karat wedding band during one year of daily wear is described in Reference 10. The hardness of the ring tested was 135 HV. (The load for hardness measurement was not specified in the paper.) The author reports an average weekly mass loss of 0.5 $\mu$g/mm².
During a vacation at the beach, which is the closest comparison to our chosen testing conditions, this value increased to 1 µg/(mm² week). This value represents 50% of the mass loss that occurred during the 30 minutes of abrasive wear testing in our study. Therefore, the chosen testing conditions can be assumed to simulate about two weeks of wear under harsh conditions.

Color Change during Abrasion
During abrasion testing a certain color change occurs that is reflected by a change of the color parameters L*, a*, b* and Yellowness Index (YI). The main effect is on the YI and the L* value that change by +3.4–4.4 and -5–6, respectively (Table 5). It is presumed that this color change is related to the change of surface roughness during abrasion.

We tested whether this change could be correlated with the color change. It appears that a weak correlation between the ductility values (especially ROA) exists. Alloys with higher ductility show a tendency for smaller changes of the YI value, meaning they keep their white color better compared to less ductile alloys. However, we do note that this effect is relatively weak and shows significant scatter.

Field Samples
In order to show a correlation of our controlled testing results with real-world jewelry, samples of platinum jewelry that had been worn for at least one year were solicited from a group of jewelers across the United States. Although our results cannot be considered scientific due to the varying wear behaviors and durations of different consumers, they nonetheless provide a compelling comparison with our data. Figures 26 through 33 demonstrate wear behavior for a number of platinum alloys with varying levels of hardness.

Although some of the observed differences in wear are quite subtle, overall we see a good correlation with our hardness results. The soft alloy 90Pt10Ir in cast form shows high levels of distortion, scratching and denting, while the work-hardened 90Pt10Ir in the antique hand-fabricated ring is crisp and resilient with far less scratching and denting. The hard alloy 95PtRuGa+ exhibits considerably less scratching, denting and distortion than a 90Pt10Ir ring worn side-by-side on the consumer’s same finger. And finally, the side-by-side wear results with karat gold alloys, which typically have higher hardness ranges than platinum alloys, show notable differences in wear.
The cast 90Pt10Ir wedding band in Figure 26 was worn by an active consumer with a very hands-on profession that included assembling skate boards and applying abrasive grip tape. It exhibits heavy scratching throughout the surface. The inset indicates that tiny shards of metal in several areas are at risk of shedding. The wear is very apparent under low 10X magnification. The ring was not polished or maintained during the 10 years it was worn.

**Figure 26 90Pt10Ir cast band worn for 10 years**
The cast 90Pt10Ir wedding band in Figure 27 shows heavy scratching after 13 years of wear. The consumer was very active in a variety of sports and farming activities. The wear is very apparent under low 10X magnification. The ring had never been polished or maintained after purchase.

**Figure 27** 90Pt10Ir cast wedding band worn for 13 years
Figure 28 is the engagement ring worn next to the wedding band in Figure 27. The dotted line shows the area flattened by the adjacent band. These prongs, each with a generous radius in the original design, are now very flat on the side. Significant denting and gouging is present over the entire surface. Notably, the prongs still appear to have good bulk and are not in need of build-up for stone safety.

**Figure 28** 90Pt10Ir cast engagement ring worn for 15 years
The hand-fabricated antique ring in Figure 29 has a comparatively low amount of marring compared to all of the field samples, regardless of alloy. As an antique piece with multiple owners, we presume that it has likely been worn a great deal longer than any of the group. The current owner confirmed that she has never had it polished in the 30 years she has owned it. Features such as mill grain are still very crisp and much of the original detail is fully intact. Although we did not test hardness on this ring’s unconventional alloy, it is probable that work hardening is responsible for the apparent high resistance to wear.

Figure 29 Circa 1910 hand-fabricated ring in 87Pt8Ir5Pd
The wedding band in Figure 30 is a two-tone band (red is Pt and green is Au) worn by a consumer who works in an office profession. He is conscientious about the care of his ring and generally removes it for heavy work. Although we did not test hardness on the ring itself, this 585 alloy containing Au-Cu-Ag-Zn is typically in the range of 140 HV, or approximately 30 HV higher than the neighboring 90Pt10Ir ring. The images display somewhat less marring on the gold than the platinum in this side-by-side wear example.

**Figure 30** 585Au and 90Pt10Ir cast wedding band worn for 12 years
The wedding ring (90Pt10Ir) in Figure 31 was worn for six years on its own and then later surrounded by two anniversary bands cast in the hard alloy 95PtRuGa+ (Figure 32). The anniversary bands together with the engagement ring have now been worn for 20 months total without any polishing or refurbishing.

Figure 31 90Pt10Ir cast engagement ring worn for 8 years
Dual anniversary bands (Figure 32) were created for the owner of the ring in Figure 31 because she had observed significant wear and wanted a means to better protect her ring. The hard alloy Pt95RuGa+ was chosen for the bands when the jeweler learned that the consumer is a frequent attendee at sporting events and habitually claps against several rings on her other fingers. The hard alloy Pt95RuGa+ used in the anniversary bands shows considerably less wear marks than the softer 90Pt10Ir alloy in Figure 30, although it is still susceptible to scratching and surface distortion.

*Figure 32 Pt95RuGa+ anniversary band worn for 20 months*
The band in Figure 33 is composed of a cast 95Pt5Ru center section with an 18K AuCuAgZn sleeve that appears to be machined. As with other field samples, hardness was not tested. The Au alloy is presumed to have a higher hardness by composition alone (likely in the 155 HV range) and it displays a lesser degree of scratching and surface distortion than the adjacent 95Pt5Ru domed center section. The mill grain in the Au appears very crisp, while the platinum appears ductile enough to be pushed over the top of the Au detail as a result of wear.
Conclusion and Summary

Extensive testing of twelve different platinum alloys was undertaken to determine mechanical properties, microstructure, abrasion behavior and color in the as-cast and hot isostatic pressed (HIP) conditions. To the authors’ knowledge, this is the most comprehensive and publically available study on platinum casting alloys to date. In summary, there are very significant differences among the mainstream platinum jewelry alloys in terms of wear resistance and general performance for the consumer. The quality of platinum products can strongly benefit when designers and manufacturers deepen their understanding of potential impacts on quality related to their alloy choices. The main conclusions from this study are as follows:

- Based on the solid-solution hardening provided by different alloying elements, the alloys were categorized into the three groups of soft (< 120 HV 1), medium-hard (120–150 HV 1) and hard alloys (> 150 HV 1). Soft alloys typically contain Ir, Cu or Rh as alloying additions. Medium-
hard alloys are obtained by alloying with Ru, and 95PtCo is just at the threshold from soft to medium-hard. Hard alloys require the addition of Ga or In, which are among the most effective hardeners of platinum.

- The soft alloys in cast form (<120 HV 1) should be used with caution and a deeper understanding of the limitations of their strength and hardness. Particular attention should be given to cross-section thickness, bearing in mind that they are more vulnerable to distortion and potential failure in the absence of any appreciable work hardening. The softest alloy (95Pt5Ir) is particularly unsafe for use with gem-set rings or any design that is anticipated to see even moderate amounts of wear. One exception might be when the consumer desires ongoing distortion as part of the ring’s design and style.

- Hardness is directly correlated with ultimate tensile strength. UTS can be estimated by multiplying the hardness value by the factor of 3.3. This is valid in the as-cast and HIPed condition and is a typical value for face-centered cubic materials.

- HIP largely eliminates internal micro shrinkage pores and thereby restores the ductility of platinum alloys to their full potential. This is reflected by a significant increase in ductility and especially reduction of area. The effectiveness of HIPing on ductility depends on the level of micro porosity. The few alloys with low micro porosity in the as-cast condition (e.g., 90Pt10Ir) show no increase while those with a higher level of micro porosity strongly benefit from HIPing.

- The effect of HIPing on the strength values (YS<sub>0.2</sub> and UTS) is less pronounced. For most of the alloys UTS is only slightly affected by HIPing. Yield strength remains constant for most alloys. For some alloys it decreases by 15–20% without clear trends. This might be an effect of casting defects such as larger pores.

- Increasing strength levels are usually offset by decreasing ductility; as UTS increases, ductility and ROA decrease with a roughly linear correlation between UTS and ROA. Such decreases are much more pronounced in the as-cast condition compared to the HIPed condition.

- Alloys containing Ga or In show pronounced segregation of these low-melting elements to the interdendritic areas. This increases the amount of micro shrinkage porosity and results in a greater inhomogeneity of the alloy’s composition and mechanical properties. HIP is effective towards healing this porosity as demonstrated by a pronounced effect on ductility in alloys containing Ga or In. However, neither heat treatment nor HIP was sufficient to remove chemical inhomogeneities by diffusion.

- The addition of Ga or In results in precipitation hardening by Pt<sub>3</sub>Ga/In if a critical level is exceeded. According to phase diagram information, this level is about 2 mass%. However, due to the strong segregation of Ga and In, this critical level might be locally exceeded in the interdendritic regions. It is therefore supposed that even alloys with Ga or In contents of 1.5–2 mass% might show local precipitation hardening of the interdendritic regions. The actual In concentrations above which
precipitation hardening occurs requires further experimental evidence.

- During abrasion and scratch testing, the hard alloys showed indications of chipping at the edges of the scratch while the soft ones showed deep scratches. Abrasion testing showed a certain mass loss that decreased with increasing hardness. A roughly linear correlation between hardness and mass loss was found.

- The surface appearance of the samples from the short-term ring wearing test showed mild scratches compared to samples from the abrasion test. A comparison of jewelry worn for many years with samples from the abrasion test showed that the observed wear in the abrasion test is quite realistic.

- The field samples, although subjective in nature, demonstrate a compelling correlation with our data. The hard platinum alloys significantly outperform the soft ones. The harder karat-gold alloys that benefit from much higher percentages of base metal additions show superior wear when worn side-by-side with soft platinum alloys.

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Mechanical Properties and Wear Resistance of Platinum Jewelry Casting Alloys: A Comparative Study

Fryé