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Dependence of Mechanical Properties of Platinum-Rhodium Binary Alloys on Valence Electron Parameters

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ABSTRACT

Dependence of mechanical properties of binary Pt-Rh alloys on valence electron ratio (VER), number valence electrons (\(e_v\)), and average atomic number of the alloys (\(Z\)) are investigated. The alloys have high number of valence electrons (9 ≤ \(e_v\) ≤ 10) and a wide range of the average atomic number (\(Z = 45–78\)). Clear correlations between VER of the alloys and their mechanical properties are found. By increasing the VER of the alloy from 0.13 to 0.20 following the increase of Rh content in the composition, the hardness, elastic modulus, and ultimate tensile strength of the alloy increases. Creep rates of the selected alloys clearly decrease with increasing VER at high temperatures (1500-1700 °C), whilst stress rupture time at different temperatures consistently increases because of higher Rh content in the alloy solid solution chemistry. Dependence of mechanical properties on valence electron parameters is discussed with reference to the atomic bonding.

1. Introduction

Platinum alloys attract considerable attentions as new areas of their applications are found and continuously explored. Platinum alloys are used for production of jewellery (1, 2), thermocouples (3), resistance thermometer (4) or resistance temperature detector known as RTD sensor (5), catalysts (6), glass (7-9), due to their high strength, good workability, and corrosion resistance at high temperatures (10, 11). The analysis of Gavin clearly indicates increased attention to Pt alloys (12). Hu et. al, have recently presented the research progress of platinum-based superalloys for high
temperature applications (13). Solid solution strengthened platinum-based alloys have been the subject of research and development for some time. All transition group elements have considerable solid solubility in platinum. The elements near platinum in the periodic table form a continuous solid solution with platinum and have different degrees of solid solution strengthening effect on the platinum matrix. Platinum-based alloys are also being developed for high-temperature structural applications with the aim of replacing some of the currently used nickel-based superalloys (NBSAs) (13). The platinum-based superalloys have a similar structure to the NBSAs and can potentially be used at higher temperatures and in more aggressive environmental conditions. Platinum based superalloys show strong chemical stability and excellent mechanical properties such as high creep strength and ductility and can be the next generation gas turbines materials, or be used in the chemical, glass and space technologies (14-21). Of all platinum alloys currently most widely used are alloys of platinum with rhodium with their application range of temperature extended up to 1600 °C (10). Luyten et al. have examined the Pt-Rh, Pt-Pd, Pd-Rh and Pt-Pd-Rh phase diagrams using Monte Carlo simulation method in combination with modified embedded atomic method (MEAM) and optimised parameters (22). Thermodynamics and phase equilibrium of binary Pt-Rh system have been studied by Jacob et al. (23) and Okamoto (24). To adjust the properties of these intermetallics, Rh as the alloying element is added to Pt. Pt and Rh are completely miscible and form a single-phase solid solution at all concentrations of Rh as shown by Okamoto (24). New materials based on dispersion strengthening of Pt-Rh alloys were developed for high temperature applications (25-27). Microstructural analysis of selected platinum alloys used in industry and making jewelry (including PtRh10 and PtRh30) has been performed by
Battaini (28). Fischer et al. (29) have studied the stress-rupture strength and creep behaviour of platinum, Pt-Rh and Pt-Ir alloys, dispersion hardened platinum materials, rhodium and iridium. Investigations of elastic properties (Young’s modulus, modulus of rigidity and Poisson’s ratio) for platinum, platinum alloys, rhodium and iridium at high temperatures using a resonance technique have been carried out by Merker et al. (30). They observed that Young’s modulus and the modulus of rigidity of platinum, rhodium and iridium, and various platinum alloys in the as-cast condition decrease linearly with increasing test temperature. Pt-Rh alloys have more stable properties: an increase in rhodium content leads to higher temperature durability, extended creep life and decreased creep rate (13, 29). At higher Rh content, however, the machinability of the alloys may be negatively affected (13). Darling presented the high and room temperature properties of Pt-Rh alloys as a function of Rh content and service temperature in one of the earlier works (31), whereas the work of Ackmen on the mechanical properties of Pt-Rh is the first published report available in the literature (32). Rdzawski and Stobrawa studied the microstructural evolution and mechanical properties of yttrium- and boron-alloyed Pt-Rh (33). Garbacz et. al. studied the microstructure and mechanical properties of a Pt–Rh alloy produced by powder metallurgy and subjected the alloy to plastic working (34).

One of the research goals in this area is to develop materials with better high-temperature mechanical properties (e.g. tensile, fracture, creep and thermomechanical fatigue properties) and environmental stability (e.g. resistance to high-temperature oxidation and hot corrosion) than nickel-based superalloys (13, 35). Platinum and its alloys represent a major challenge because of the high cost of materials and need for special experimental conditions (10), though, still are worth
further investigation. Finding fundamental correlations between structural factors of these alloys and their mechanical properties can help reduce the cost with less trial-and-error and difficulty.

To understand the factors that control the elastic and mechanical properties and/or transformation temperatures in alloy systems, Zarinejad suggested the need to acquire in-depth knowledge of how the atomic bonding strength of the solid solutions can be influenced by the chemical composition of the alloys (36). Apart from microstructural features such as precipitates, grain boundaries etc., the mechanical properties of the matrix crystals of solid solution alloys in several alloy systems such as NiTi (37-41), TiPd and TiPt (42), TiAu, and TiIr (43), and many other alloy systems (44), were shown to be influenced by the chemistry of the alloys and how the metallic bonding in them changes because of the chemical composition change. Hence, the dependence of mechanical properties of solid solutions on electron variables in alloys was introduced (36-44). It was shown that the mechanical properties (elastic moduli and plastic deformation characteristics) of the solid solution crystals are influenced by the chemical composition change. Knowing that in metallic materials, the delocalised valence electrons dominate the strengths of bonds and elastic properties (45, 46), it is of particular importance to study the electronic parameters of alloys. In this study, the investigation is extended to the Platinum-Rhodium (Pt-Rh) binary alloys to help understand the dependence of the mechanical properties on alloy chemistry. The aim of this study is to show the dependence of mechanical properties of binary Pt-Rh alloys on the valence electron ratio (VER) of the alloys, which is related to the chemical composition, or the atomic fraction of Pt and Rh in the alloys. The study focuses on
existing data of hardness, tensile strength, selected creep rate and rupture time of the Pt-Rh binary alloys.

We reveal and explain the dependence of the mechanical properties of Pt-Rh binary alloys on these parameters with a focus on the correlation of the mechanical properties to VER of the alloys. The correlations found in this study will provide an important understanding towards the effective alloy design.

2. Materials and Methods

Mechanical properties data including creep rate, rupture time and tensile strength, and hardness of majority all the single-phase Pt-Rh binary alloys (without precipitate or mechanical work) made and to date were investigated. The data were extracted from the relevant literatures especially the important works of Trumic et. al (10, 11), Fischer et. al. (29), Darling (31), Acken (32), Hu et. al (47), and other sources (48, 49) as listed in tables or presented in graphs. For the analyses in this study, three simple parameters were considered: 1) the average atomic number of the alloys; 2) the number of valence electrons; and 3) Valence Electron Ratio (VER) of the alloys. The average atomic numbers of the alloys were calculated based on the atomic fractions and atomic numbers of the elements comprising the alloys as follows by Equation (i):

\[ Z = f_{Pt}Z_{Pt} + f_{Rh}Z_{Rh} \]  

where \( Z \) is the fraction-averaged atomic number of the alloy. \( Z_{Pt} \) and \( Z_{Rh} \) are the atomic numbers of Pt and Rh, respectively. The \( f_{Pt} \) and \( f_{Rh} \) are the corresponding atomic fraction of Pt and Rh in the alloy. To study the dependence of the transformation
temperatures on the chemistry of alloys, the basic electron configurations of the alloys were analysed in the following section.

The number of valence electrons is usually considered as the number of $d$ and $s$ electrons for an atom of transition metals. The valence electrons per atom of Pt-Rh binary alloys can be calculated based on the atomic fractions of the elements in the alloy by Equation (ii):

$$\frac{e_v}{a} = f_{Pt} e_{v}^{Pt} + f_{Rh} e_{v}^{Rh}$$

where $f_{Pt}$ and $f_{Rh}$ represent the atomic fractions of Pt and Rh in the alloy, respectively, and $e_{v}^{Pt}$ and $e_{v}^{Rh}$ are the corresponding numbers of valence electrons of elements Pt and Rh. The valence electron ratios (VERs) of the alloys were calculated. VER is defined as the ratio of the number of valence electrons to the total number of electrons of the alloy, $\text{VER} = (e_v/e_t)\), which can be simply calculated by Equation (iii):

$$\text{VER} = \frac{e_v}{e_t} = \frac{f_{Pt}e_{v}^{Pt} + f_{Rh}e_{v}^{Rh}}{f_{Pt}Z_{Pt} + f_{Rh}Z_{Rh}}$$

where, following the earlier Equations (i) and (ii), $Z_{Pt}$ and $Z_{Rh}$ represent the atomic numbers of Pt and Rh, respectively, whilst $f_{Pt}$ and $f_{Rh}$ represent their corresponding atomic fractions in the alloy.

3. Results and Discussion (chemical factors influencing the mechanical properties of the alloys)

3.1. Average Atomic Number
Table I presents the eighteen binary platinum-rhodium (Pt-Rh) alloy compositions (31, 32, 48, 49) that include majority of these alloy compositions studied so far, together with their available mechanical properties including Hardness, Modulus of elasticity (E) and Ultimate Tensile Strength (UTS) in ascending order as reported in the literature and from the present study. The maximum Hardness in the fully annealed conditioned alloys (130 Hv) corresponds to pure Rhodium (maximum Rh content percentage in the alloy). The lowest Hardness corresponds to pure Pt (45 Hv). Pt (Z = 78) has higher atomic number than Rh (Z = 45). This means that by increasing the Rh content percentage of the alloy, the average atomic number of the binary alloy decreases whereas the Hardness increases (Table I, Figure 1). Similarly, for the available data on E and UTS of these binary alloys, the decrease in average atomic number of the alloy with increasing Rh content percentage results in higher values of the properties (Table I). The values of E and UTS of Pt with no Rh content and atomic number of Z = 78 increase from E = 151.7 GPa and UTS = 144.7 MPa to E = 221 GPa and UTS = 413.7 MPa respectively, in a binary alloy with 44.9 at.% Rh an average Z = 63.183. Furthermore, the Hardness increases from 45 (Hv) to 102 (Hv) by the reduction of average Z due to increasing Rh content of the alloy and higher harness is achieved by increasing Rh content.
The average atomic numbers of the alloys in this study are tabulated in Table I. The mechanical properties (Hardness, E and UTS) of these alloys clearly increase with the decrease of average Z of the alloys as shown in Figure 1. In transition metals and intermetallics, it is known that when the average atomic number is halfway through in the transition metals rows of the periodic table of elements, i.e., either Z = 25-26, or Z = 43-44, Z=75-76 and so on, the elastic properties and hardness of the solid solution crystal can be improved to some extent as the properties hit maxima at or around these atomic numbers (46) as a consequence of optimal orbital occupancy. This effect is not observed in Pt-Rh binary alloys, as in most cases the average atomic number of the alloy is not close to the aforementioned Z numbers (Table I). As shown in the table, the existing Pt-Rh alloys can have higher Hardness, E, and UTS with the decrease of the average atomic number. In other words, the mechanical properties of the alloys increase with decreasing the total number of electrons (average atomic number) of the alloy. Non-valence electrons do not contribute to bonding and together with the protons comprise the ion kernels in the metallic bonding of the transition metal alloys.
Decreasing the non-valence electrons or the size of the kernels at constant (or nearly constant) valence electron numbers leads to stronger elastic bonding (45, 46). This, in turn, means that the resistance to atomic displacement, crystal shape and volume change will be higher (at least in some crystallographic directions) to result in the improved mechanical properties. The presence of Rh (Z = 45) compared to Pt (Z = 78) in the alloys causes the total number of non-valence electrons to extensively decrease due to its lower Z (Table I).

3.2. Number of Valence Electrons

Pt-Rh Alloys with 0 to 100 at% Rh were included in this study. In the transition alloys with respect to their number of valence electrons, a wide range can be observed (3 ≤ e_v ≤ 12) as categorised by Zarinejad and Liu (36, 44). The alloys were divided into low (e_v/a < 5), medium (5 ≤ e_v ≤ 7.50) and high (e_v > 7.50) valence electron groups. Following this categorisation, Pt-Rh binary alloys all belong to the high valence electron group with their (e_v/a > 7.50) in a range between 9 and 10 (Table I, Figure 2).
By increasing Rh content percentage in the binary alloys, the number of valence electron of the alloy decreases as the number of valence electrons of Pt (s+d orbital electrons) is 10 and that of Rh is 9. By decreasing the number of valence electrons of the alloys, the Hardness, Elastic modulus (E) and Ultimate Tensile Strength (UTS) of the alloys is consistently increased (Table I). This is indicative of the dependence of the mechanical properties on number of valence electrons of the binary solid solution alloy, and that although the number of e_v is a factor in bonding, its effect must be studied along with other influencing factors such as the average atomic number (Z). Increasing the Rh content percentage of the binary alloys accompanied by lowering e_v results in a lower average Z for the alloy crystal. These two opposing trends of change with the composition of Rh not only affect the number of valence and non-valence electrons of the alloys but also the dynamics of the metallic bonding. Decreasing the
number of non-valence electrons (because of decrease in the average atomic number of the alloys), even when accompanied by slight reductions in the number of valence electrons, affect the interatomic bonding that keeps the ion kernels in the metallic bonds together as it affects the size and density of the kernels (41). The higher numbers of non-valence electrons and protons in this condition reduce the bonding effects of the valence electrons and therefore reduce the mechanical properties of the solid solution crystal at least in some crystallographic directions.

3.3. Valence Electron Ratio (VER)

Hardness

Depending on the atomic fractions of Rh in the Pt-Rh alloys, different VER values have resulted. These values for the alloys examined are tabulated in Table I. The variations of Hardness versus VER and versus atomic percentage of Rh in the alloy are plotted in Figure 3. A main trend is observed with increasing the VER. By increasing Rh content, the Hardness of the binary alloy increases consistently from as low values as 45 (Hv) with VER 0.13 to as high values as 130 (Hv) with VER 0.20. The general trends of variation of Hardness with VER and the Rh at\% is identical (Figure 3). It is evident that the varying direction of Hardness with VER is an ascending trend. VER represents the compound effect of \( e_v \) and \( Z \) at the same time.
Tensile Strength and Elastic Modulus

Figure 4 shows the variation of Elastic Modulus (E) and Ultimate Tensile Strength (UTS) of the alloys as a function of at.% Rh of the alloy and VER. It is evident that both E and UTS increase with VER, which is brought about by increasing Rh content of the binary alloys. The gradient of UTS with increasing VER and Rh at.% is more pronounced than the gradient of E, though, in both cases the variations with VER as it represents chemical composition are remarkably high (Figure 4). It should be noted that microstructural factors including grain boundary characteristics and defect populations can have major influence especially on UTS. However, the intrinsic
properties of the solid solution are dictated by bonding and valence electron parameters.

![Graph showing the relationship between at% Rhodium and properties like Ultimate Tensile Strength (UTS) and Elastic Modulus (E).](image)

**Creep Rate and Rupture Time**

**Table II** presents the four binary platinum-rhodium (Pt-Rh) alloy compositions and their creep rate characteristics at 1500 °C, 1600 °C and 1700 °C (10, 11). **Table III** presents the seven binary platinum-rhodium (Pt-Rh) alloy compositions and their stress rupture time characteristics at various test temperatures from 1200 °C to 1700 °C (10, 11, 29). With reference to the tables, it is evident that the creep rate of the binary alloys at all the test temperature decreases with VER. This means that because of the presence of more Rh in the binary alloy the creep resistance of the alloy is
improved (Figure 5). Moreover, the stress rupture time of binary alloys at any temperature of creep testing (1200 °C to 1700 °C) increases with VER and Rh at.% (Figure 6). In all the variations of mechanical properties, VER follows the change of Rh at. % and represents as a measure of Pt-Rh alloy composition. Hence, the relationship of VER and mechanical properties of Pt-Rh alloy is now discussed.
In metallic bonding, the valence electrons act like ‘glue’ to bond non-valence electrons and nuclei units together (45, 46), whereas non-valence electrons contribute to the total atomic volume of the alloy. Increasing VER could mean thickening of the ‘glue’ to bond the ionic kernels together. The elastic response coefficients are the most fundamental of all the properties of solid crystals. The most important subset of the properties are the shear and bulk moduli. Bulk modulus is a measure of the resistance of a solid to volume change. Shear modulus is a measure of resistance to shape change. Shear moduli have the highest influence on the mechanical properties of the crystals (45, 46). Furthermore, stacking-fault energy, dislocation mobility and plastic deformation characteristics of the crystals are also dictated by the metallic bonding (41). Bonding type (metallic, covalent, ionic and molecular) and solidity index of a crystal (which is simply the ratio of the shear modulus to the bulk modulus, multiplied...
by a coefficient of the order of unity) have been used to classify crystals (46). Hardness, tensile properties and other mechanical properties at elevated temperatures are also dominated by the nature and change in the metallic bonding in transition metal alloys. The metallic bonding is in turn controlled by valence electrons, which are altered by the chemistry of the alloys. The chemical factors that affect the mechanical properties of Pt-Rh-based alloys in this study are discussed as follows.

An established empirical relationship between the valence electron density and bulk modulus of metallic materials and intermetallic compounds is known. Higher VER usually results in higher bulk and therefore higher shear moduli (46). Increasing VER of the Pt-Rh alloys, therefore, is expected to result in higher elastic and shear moduli, lower dislocation mobility and more difficult local plastic deformation at least in some crystallographic directions. The change of VER by altering Pt/Rh ratio in the alloy is accompanied by a change in the elastic properties, dislocation mobility and stacking-fault energy as the interatomic bonding is affected. A key factor controlling the bonding is the VER of the alloy. When these properties of solid solution crystal of Pt-Rh alloys are enhanced because of higher VER, the resistance to shape or volume change of the crystal, atomic displacement, and dislocation mobility increases. In this way the mechanical properties such as Hardness, Elastic Modulus, tensile strength, and creep rate are enhanced. More Rh content in the alloy increases VER and contributes to an improvement of the mechanical properties. From the work of Okamoto (24), we know that Pt-Rh are complete solid solutions and second phase precipitation does not take place at any Rh at.%. Therefore, all the Rh contributes to the change in VER and the mechanical properties. We assume that impurity trace elements at very low
concentrations do not contribute significantly to grain boundary precipitations in the alloys. The comprehensive work of Termic et. al. (50) has shown that impurity elements might influence the mechanical properties by the formation of grain boundary effects. However, addition of any other element to this binary system that may cause precipitation can change the influence of the VER and warrants further study. The VER dependence of mechanical properties discussed hereinabove is limited to Pt-Rh binary alloys, though, it might be extended to other solid solution alloy systems after careful future studies. The shown trends are general and indicative of the major underlying influence of VER on the intrinsic mechanical properties of Pt-Rh alloy system.

4. Conclusions

The main correlations shown in this study reveal clear dependence of the intrinsic creep, tensile and hardness properties of binary Pt-Rh solid solution alloys on valence electron ratio (VER). Alloy chemistry influences the number and ratio of valence electrons, and average atomic number of Pt-Rh alloys and thereby changes the mechanical properties of the solid solution alloy crystals. All the mechanical properties are improved with increasing VER of the binary Pt-Rh alloys. VER presents itself as a dominant intrinsic parameter that can be utilised to take steps toward successful alloy design to achieve the desired mechanical properties.
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Table I

Number of valence electrons (e\textsubscript{v}), average atomic number (Z), valence electron ratio (VER) and mechanical properties of binary Pt-Rh alloys from (31, 32, 48, 49)

<table>
<thead>
<tr>
<th>Pt-Rh (wt.%)</th>
<th>Pt-Rh (at.%)</th>
<th>e\textsubscript{v}</th>
<th>Z</th>
<th>VER</th>
<th>Hardness (Hv)</th>
<th>E (GPa)</th>
<th>UTS (MPa)</th>
<th>Reference</th>
</tr>
</thead>
<tbody>
<tr>
<td>0</td>
<td>0</td>
<td>10</td>
<td>78</td>
<td>0.128</td>
<td>45</td>
<td>151.7</td>
<td>144.7</td>
<td>(31) (31) (31)</td>
</tr>
<tr>
<td>5</td>
<td>9.1</td>
<td>9.909</td>
<td>74.997</td>
<td>0.132</td>
<td>63</td>
<td>172.4</td>
<td>206.8</td>
<td>(31) (31) (31)</td>
</tr>
<tr>
<td>10</td>
<td>17.4</td>
<td>9.826</td>
<td>72.258</td>
<td>0.136</td>
<td>79</td>
<td>191.7</td>
<td>292.3</td>
<td>(48) (31) (48)</td>
</tr>
<tr>
<td>10.01</td>
<td>17.5</td>
<td>9.825</td>
<td>72.225</td>
<td>0.136</td>
<td>80</td>
<td></td>
<td></td>
<td>(49)</td>
</tr>
<tr>
<td>13</td>
<td>22.1</td>
<td>9.779</td>
<td>70.707</td>
<td>0.138</td>
<td>82</td>
<td>196.5</td>
<td>318.5</td>
<td>(31) (31) (31)</td>
</tr>
<tr>
<td>15</td>
<td>25.1</td>
<td>9.749</td>
<td>69.717</td>
<td>0.140</td>
<td>86</td>
<td>201.3</td>
<td>343.3</td>
<td>(48) (31) (48)</td>
</tr>
<tr>
<td>18.1</td>
<td>29.5</td>
<td>9.705</td>
<td>68.265</td>
<td>0.142</td>
<td>88</td>
<td>206.8</td>
<td>355</td>
<td>(48) (31) (48)</td>
</tr>
<tr>
<td>20</td>
<td>32.2</td>
<td>9.678</td>
<td>67.374</td>
<td>0.144</td>
<td>90</td>
<td>213.7</td>
<td>372.3</td>
<td>(31) (31) (31)</td>
</tr>
<tr>
<td>25</td>
<td>38.8</td>
<td>9.612</td>
<td>65.196</td>
<td>0.147</td>
<td>97</td>
<td>218</td>
<td>386.1</td>
<td>(31) (31) (31)</td>
</tr>
<tr>
<td>30</td>
<td>44.9</td>
<td>9.551</td>
<td>63.183</td>
<td>0.151</td>
<td>102</td>
<td>221</td>
<td>413.7</td>
<td>(31) (31) (31)</td>
</tr>
<tr>
<td>35</td>
<td>50.6</td>
<td>9.494</td>
<td>61.302</td>
<td>0.155</td>
<td>105</td>
<td></td>
<td></td>
<td>(31, 32)</td>
</tr>
<tr>
<td>40</td>
<td>55.9</td>
<td>9.441</td>
<td>59.553</td>
<td>0.159</td>
<td>108</td>
<td></td>
<td></td>
<td>(31, 32)</td>
</tr>
<tr>
<td>50</td>
<td>65.5</td>
<td>9.345</td>
<td>56.385</td>
<td>0.166</td>
<td>112</td>
<td></td>
<td></td>
<td>(31, 32)</td>
</tr>
<tr>
<td>60</td>
<td>74.1</td>
<td>9.259</td>
<td>53.547</td>
<td>0.173</td>
<td>118</td>
<td></td>
<td></td>
<td>(31, 32)</td>
</tr>
<tr>
<td>70</td>
<td>81.6</td>
<td>9.184</td>
<td>51.072</td>
<td>0.180</td>
<td>122</td>
<td></td>
<td></td>
<td>(31, 32)</td>
</tr>
<tr>
<td>80</td>
<td>88.4</td>
<td>9.116</td>
<td>48.828</td>
<td>0.187</td>
<td>124</td>
<td></td>
<td></td>
<td>(31, 32)</td>
</tr>
<tr>
<td>90</td>
<td>94.5</td>
<td>9.055</td>
<td>46.815</td>
<td>0.193</td>
<td>127</td>
<td></td>
<td></td>
<td>(31, 32)</td>
</tr>
<tr>
<td>100</td>
<td>100</td>
<td>9</td>
<td>45</td>
<td>0.2</td>
<td>130</td>
<td></td>
<td></td>
<td>(31, 32)</td>
</tr>
</tbody>
</table>
Table II

Valence electron ratio (VER) and creep rate of binary Pt-Rh alloys at different temperatures from (10, 11)

<table>
<thead>
<tr>
<th>Pt-Rh (wt.%Rh)</th>
<th>Pt-Rh (at.%Rh)</th>
<th>VER</th>
<th>Creep rate $\xi$ (%/h)</th>
<th>Reference</th>
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<td>(1600 °C)</td>
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<tr>
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<td>0.140</td>
<td>2.5</td>
<td>5.5</td>
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<tr>
<td>20</td>
<td>32.2</td>
<td>0.144</td>
<td>2</td>
<td>4</td>
</tr>
<tr>
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<td>44.9</td>
<td>0.151</td>
<td>0.8</td>
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<tr>
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<td>55.9</td>
<td>0.158</td>
<td>0.1</td>
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Table III

Valence electron ratio (VER), and stress rupture time of binary Pt-Rh alloys at different temperatures from (10, 11, 29)

<table>
<thead>
<tr>
<th>Pt-Rh (wt.%Rh)</th>
<th>Pt-Rh (at.%Rh)</th>
<th>VER</th>
<th>Rupture time (h)</th>
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<td>(1300 °C)</td>
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<Figure captions>

Fig. 1. Alloy atomic number: variations of hardness with average atomic number of binary Pt-Rh alloys (Z)

Fig. 2. Hardness vs. number of valence electrons: variations of hardness with number of valence electrons of binary Pt-Rh alloys (ev) and Rh content of the alloy (at.% Rh)

Fig. 3. Hardness vs. VER and Rh content: variations of hardness with valence electron ratio (VER) and Rh content of the of binary Pt-Rh alloys (at.% Rh)

Fig. 4. Ultimate Tensile Strength (UTS) and Elastic Modulus (E) vs. VER and Rh content: variations of UTS and E with valence electron ratio (VER) and Rh content of the of binary Pt-Rh alloys (at.% Rh)

Fig. 5. Creep rate vs. VER and Rh content: variations of creep rate with valence electron ratio (VER) and Rh content of the of binary Pt-Rh alloys (at.% Rh) at different temperatures

Fig. 6. Stress rupture time vs. VER and Rh content: variations of stress rupture time with valence electron ratio (VER) and Rh content of the of binary Pt-Rh alloys (at.% Rh) at different temperatures