

https://dspace.org/

# Investigation of the Pt-Al-Cr system as part of the development of the Pt-Al-Cr-Ru thermodynamic database

**Suss, Rainer**

**2008-09-03T11:52:13Z**
http://hdl.handle.net/10539/5591

Downloaded from a DSpace repository. https://dspace.org/

# PART FOUR: SELECTED MECHANICAL PROPERTIES

## 1. HARDNESS

Since the hardness of a metal depends on the ease with which it plastically deforms, there is an empirical relationship between hardness and strength. Since the hardness test is much simpler than a tensile test it is therefore often used by engineers to obtain an easily measured and specified quantity which indicates something about the strength and heat treatment of a metal [1988Die, 1990Smi].

### 1.1. Experimental procedure

The hardness of the alloys was measured using a Vickers Ltd. Vickers hardness tester with a 10 kg load, with at least six analyses carried out to obtain an average hardness value.

### 1.2. Results and discussion

#### *1.2.1. As-cast*

The results of hardness measurements on the annealed samples are given in Table 4.1. The average values are superposed on the solidification projection in Figure 4.1.

*Table 4.1. Hardness values of as-cast Pt-Cr-Al alloys ($HV_{10}$).*

| Alloy | As cast hardness | Phases present |
|---|---|---|
| $Pt_{10}:Al_{10}:Cr_{80}$ | 704 ± 16 | (Cr), ~PtAl |
| $Pt_{10}:Al_{30}:Cr_{60}$ | 675 ± 17 | (Cr), ~$PtAl_2$ |
| $Pt_{10}:Al_{60}:Cr_{30}$ | 699 ± 63 | ~$Cr_5Al_8$, ~$PtAl_2$ |
| $Pt_{10}:Al_{80}:Cr_{10}$ | 367 ± 20 | ~$CrAl_5$, ~$Pt_8Al_{21}$, (Al), ~$PtAl_2$ |
| $Pt_{20}:Al_{20}:Cr_{60}$ | 760 ± 36 | (Cr), ~PtAl |
| $Pt_{20}:Al_{40}:Cr_{40}$ | 777 ± 7 | ~$PtAl_2$, ~PtAl, (Cr) |
| $Pt_{30}:Al_{50}:Cr_{20}$ | 806 ± 8 | ~$PtAl_2$, ~PtAl, (Cr) |
| $Pt_{40}:Al_{10}:Cr_{50}$ | 749 ± 13 | ~CrPt, ~$Pt_2Al$ |
| $Pt_{40}:Al_{30}:Cr_{30}$ | 743 ± 13 | T1 |
| $Pt_{40}:Al_{50}:Cr_{10}$ | 841 ± 76 | ~$Pt_2Al_3$, ~PtAl |

*Table 4.1.(cont.) Hardness values of as-cast Pt-Cr-Al alloys ($HV_{10}$).*

| **Alloy** | **As-cast hardness** | **Phases present** |
|---|---|---|
| $Pt_{50}:Al_{10}:Cr_{40}$ | 572 ± 61 | ~CrPt, ~$Pt_2Al$ |
| $Pt_{65}:Al_5:Cr_{30}$ | 322 ± 21 | ~$Pt_3Cr$, ~$Pt_3Al$ |
| $Pt_3:Al_{65}:Cr_{32}$ | 670 ±32 | ~$Cr_4Al_9$, ~$PtAl_2$ |
| $Pt_3:Al_{35}:Cr_{62}$ | 637 ±26 | ~$Cr_2Al$, ~$PtAl_2$, T2≈$Cr_3Al_2$ |
| $Pt_{10}:Al_{50}:Cr_{40}$ | 762 ±16 | T2≈$Cr_3Al_2$, ~$PtAl_2$, ~$Cr_5Al_8$ |
| $Pt_{12}:Al_{18}:Cr_{70}$ | 758 ±50 | (Cr), ~$PtAl_2$, ~PtAl |
| $Pt_{17}:Al_{68}:Cr_{15}$ | 666 ±16 | ~$PtAl_2$, ~$CrAl_4$, ~$Cr_4Al_9$ |
| $Pt_{18}:Al_2:Cr_{80}$ | 767 ±29 | ~CrPt, ~$Cr_3Pt$, (Cr) |
| $Pt_{28}:Al_{12}:Cr_{60}$ | 462 ±4 | ~CrPt, (Cr), T1 |
| $Pt_{28}:Al_{70}:Cr_2$ | 653 ±89 | ~$PtAl_2$, ~$Pt_8Al_{21}$ |
| $Pt_{35}:Al_{55}:Cr_{10}$ | 822 ±39 | ~$PtAl_2$, ~$Pt_2Al_3$, ~PtAl |
| $Pt_{38}:Al_{22}:Cr_{40}$ | 717 ±27 | T1, ~CrPt |
| $Pt_{43}:Al_{52}:Cr_5$ | 818 ±69 | ~$Pt_2Al_3$, ~PtAl |
| $Pt_{50}:Al_{35}:Cr_{15}$ | 739 ±14 | T1 |
| $Pt_{58}:Al_{10}:Cr_{32}$ | 697 ±18 | ~$Pt_3Al$, ~CrPt |
| $Pt_{60}:Al_2:Cr_{38}$ | 333 ±35 | ~CrPt |
| $Pt_{63}:Al_{32}:Cr_5$ | 591 ±65 | ~$Pt_2Al$, T1 |
| $Pt_{63}:Al_{22}:Cr_{15}$ | 673 ±6 | ~$Pt_3Al$, ~$Pt_2Al$ |
| $Pt_{78}:Al_{17}:Cr_5$ | 407 ±6 | ~$Pt_3Al$, (Pt) |
| $Pt_{75}:Al_{10}:Cr_{15}$ | 880 ±10 | ~$PtAl_2$, ~PtAl, (Cr) |
| $Pt_3:Al_{79}:Cr_{18}$ | 425 ± 111 | ~$CrAl_4$, T3≈$CrAl_3$, ~$CrAl_5$, ~$PtAl_2$ |
| $Pt_5:Al_{52}:Cr_{43}$ | 726 ± 30 | T2≈$Cr_3Al_2$, ~$PtAl_2$, ~$Cr_5Al_8$ |
| $Pt_{13}:Al_{45}:Cr_{42}$ | 688 ± 42 | ~$PtAl_2$, ~$Cr_2Al$ |
| $Pt_{15}:Al_5:Cr_{80}$ | 632 ± 4 | (Cr), ~CrPt, T1 |
| $Pt_{34}:Al_{27}:Cr_{39}$ | 670 ± 9 | T1, (Cr) |
| $Pt_{37}:Al_{59}:Cr_4$ | 707 ± 32 | ~$Pt_2Al_3$ |
| $Pt_{45}:Al_{35}:Cr_{20}$ | 628 ± 38 | T1 |
| $Pt_{52}:Al_{43}:Cr_5$ | 788 ± 45 | T1 |
| $Pt_{55}:Al_{25}:Cr_{20}$ | 450 ± 75 | ~$Pt_2Al$ |
| $Pt_{55}:Al_{20}:Cr_{25}$ | 414 ± 61 | ~$Pt_2Al$ |
| $Pt_{64}:Al_{16}:Cr_{20}$ | 532 ± 15 | ~$Pt_3Al$, ~$Pt_3Cr$ |

Approximately 75% of the alloys in the as-cast condition had hardnesses above 600 $HV_{10}$, indicating that most phases in this system are fairly hard. Only alloy $Pt_{76}:Al_5:Cr_{19}$ had a hardness of less than 300 $HV_{10}$, being single phase ~$Pt_3Cr$. The high Al-containing alloys $Pt_3:Al_{79}:Cr_{18}$ and $Pt_{10}:Al_{80}:Cr_{10}$ were also relatively low in hardness. Five alloys had exceptionally high hardnesses (> 800 $HV_{10}$) compared to the rest, namely alloy $Pt_{30}:Al_{50}:Cr_{20}$, which contained a majority of ~$PtAl_2$; alloys $Pt_{40}:Al_{50}:Cr_{10}$ and $Pt_{43}:Al_{52}:Cr_5$ which contained ~$Pt_2Al_3$ and ~PtAl; and alloys $Pt_{35}:Al_{55}:Cr_{10}$ and $Pt_{75}:Al_{10}:Cr_{15}$ (actual $Pt_{34}:Al_{49}:Cr_{17}$), which

contained ~$PtAl_2$. Thus, ~$PtAl_2$, ~PtAl and ~$Pt_2Al_3$ were very hard phases compared to the others in the system. There was a variation in the hardness of the single-phase T1 alloys, from $628 \pm 38$ to $788 \pm 45$ $HV_{10}$, with no composition-related trend.

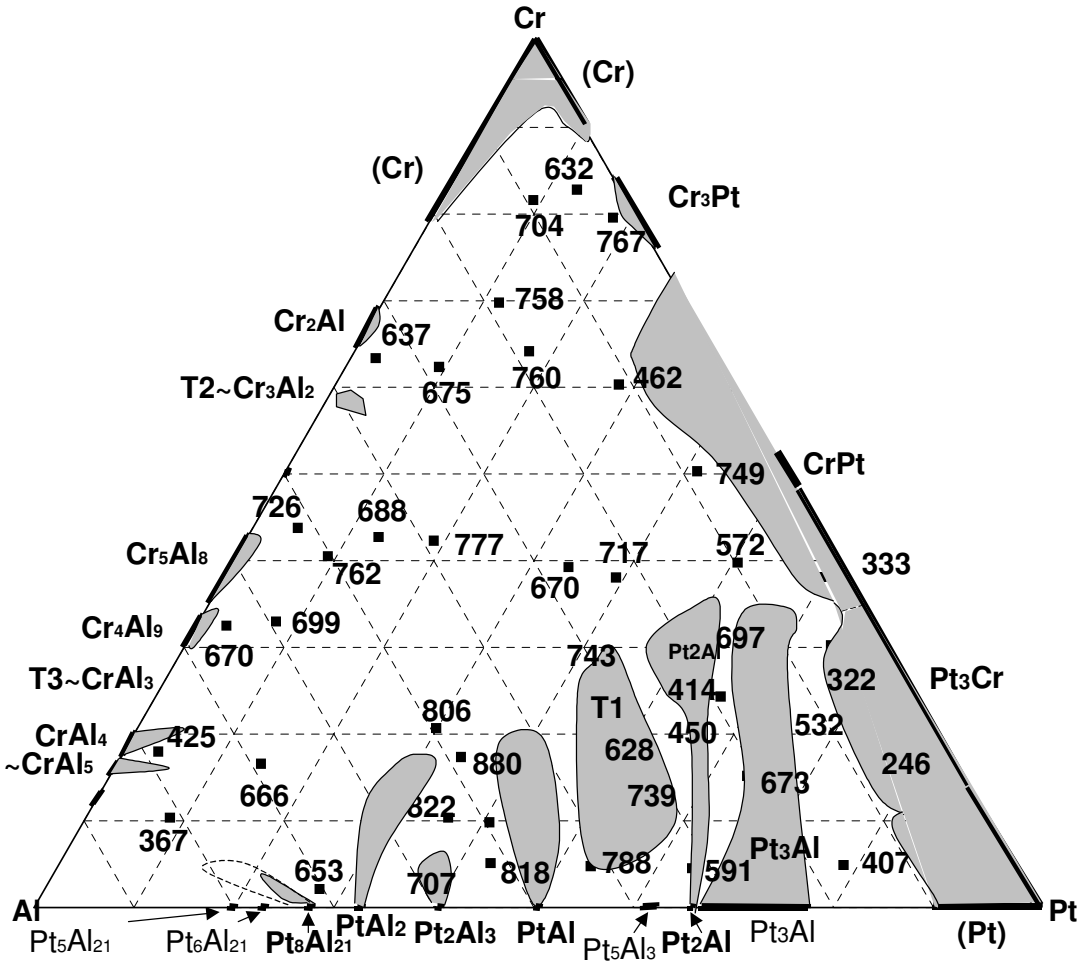



*Figure 4.1. Hardness values of as-cast Pt-Cr-Al alloys superposed on the solidification projection.*

### *1.2.2. Annealed at 1000 ℃*

The results of the hardness measurements on the 1000°C annealed samples are given in Table 4.2, compared to the relevant alloys' as-cast hardness values. The only alloys whose hardness did not change significantly during annealing at 1000°C were alloys $Pt_{65}$:$Al_5$:$Cr_{30}$, $Pt_{63}$:$Al_{32}$:$Cr_5$ and $Pt_{55}$:$Al_{25}$:$Cr_{20}$, even though, especially in the case of $Pt_{55}$:$Al_{25}$:$Cr_{20}$, the

microstructure had changed significantly. On the other hand, an alloy like $Pt_{10}$:$Al_{30}$:$Cr_{60}$ hardly changed during annealing, yet its hardness fell from 675 ± 17 to 241 ± 19 $HV_{10}$. This alloy was in fact very porous and the Vickers diamond indentor sank into the sample, and it is believed that the given hardness value is not a true indication of its hardness. The same argument could be used for the hardness of alloy $Pt_{50}$:$Al_{10}$:$Cr_{40}$ which seemed softer than expected. Over 75% of the alloys' hardness values decreased.

*Table 4.2. Hardness values of Pt-Cr-Al alloys annealed at 1000°C for 1000 hours ($HV_{10}$) compared to as-cast hardness values.*

| **Alloy** | **Annealed hardness and standard deviation** | **As-cast hardness and standard deviation** | **Phases present in 1000°C annealed samples** |
|---|---|---|---|
| $Pt_{10}$:$Al_{30}$:$Cr_{60}$ | 241 ± 19 | 675 ± 17 | (Cr), ~$PtAl_2$, ~$Cr_2Al$ |
| $Pt_{10}$:$Al_{80}$:$Cr_{10}$ | 575 ± 42 | 367 ± 20 | (Al), ~$CrAl_5$, ~$PtAl_2$ |
| $Pt_{30}$:$Al_{50}$:$Cr_{20}$ | 715 ± 12 | 806 ± 8 | ~$PtAl_2$, ~$Pt_2Al_3$, (Cr) |
| $Pt_{50}$:$Al_{10}$:$Cr_{40}$ | 320 ± 42 | 572 ± 61 | ~CrPt |
| $Pt_{65}$:$Al_5$:$Cr_{30}$ | 289 ± 7 | 322 ± 21 | ~$Pt_3Al$ |
| $Pt_3$:$Al_{65}$:$Cr_{32}$ | 556 ± 27 | 670 ±32 | ~$Cr_4Al_9$, ~$PtAl_2$ |
| $Pt_3$:$Al_{35}$:$Cr_{62}$ | 432 ± 32 | 637 ±26 | (Cr), ~$PtAl_2$, ~$Cr_2Al$/T2≈$Cr_3Al_2$ |
| $Pt_{18}$:$Al_2$:$Cr_{80}$ | 882 ± 10 | 767 ±29 | ~$Cr_3Pt$, ~CrPt, (Cr) |
| $Pt_{35}$:$Al_{55}$:$Cr_{10}$ | 755 ± 5 | 822 ±39 | ~$PtAl_2$, ~$Pt_2Al_3$, (Cr) |
| $Pt_{38}$:$Al_{22}$:$Cr_{40}$ | 629 ± 4 | 717 ±27 | T1, ~$Cr_3Pt$, (Cr) |
| $Pt_{43}$:$Al_{52}$:$Cr_5$ | 714 ± 20 | 818 ±69 | ~PtAl, ~$Pt_2Al_3$, (Cr) |
| $Pt_{50}$:$Al_{35}$:$Cr_{15}$ | 652 ± 19 | 739 ±14 | T1, ~PtAl |
| $Pt_{58}$:$Al_{10}$:$Cr_{32}$ | 581 ± 15 | 697 ±18 | ~CrPt, ~$Pt_3Al$ |
| $Pt_{63}$:$Al_{32}$:$Cr_5$ | 652 ± 23 | 591 ±65 | ~$Pt_2Al$ |
| $Pt_{63}$:$Al_{22}$:$Cr_{15}$ | 621 ± 11 | 673 ±6 | ~$Pt_2Al$, ~$Pt_3Al$ |
| $Pt_{75}$:$Al_{10}$:$Cr_{15}$ | 750 ± 18 | 880 ±10 | ~$Pt_2Al_3$, ~PtAl, (Cr) |
| $Pt_{15}$:$Al_5$:$Cr_{80}$ | 544 ± 18 | 632 ± 4 | ~$Cr_3Pt$, (Cr), ~PtAl |
| $Pt_{55}$:$Al_{25}$:$Cr_{20}$ | 458 ± 22 | 450 ± 75 | T1, ~$Pt_3Al$, ~$Pt_2Al$ |

Just over half the alloys had hardnesses above 600 $HV_{10}$, indicating that most phases in this system are fairly hard, which could be expected from intermetallic compounds. Only alloys $Pt_{50}$:$Al_{10}$:$Cr_{40}$ and $Pt_{65}$:$Al_5$:$Cr_{30}$ had hardnesses of less than 400 $HV_{10}$. Only three alloys had exceptionally high hardness (> 750 $HV_{10}$) compared to the rest, namely alloy $Pt_{18}$:$Al_2$:$Cr_{80}$, which contained a majority of ~$Cr_3Pt$; alloys $Pt_{35}$:$Al_{55}$:$Cr_{10}$ which contained ~$PtAl_2$ and ~$Pt_2Al_3$; and $Pt_{75}$:$Al_{10}$:$Cr_{15}$ (actual $Pt_{33}$:$Al_{51}$:$Cr_{16}$), which contained ~$PtAl_2$ and ~PtAl. As was

the case in the as-cast state, it was obvious that ~$PtAl_2$, ~PtAl and ~$Pt_2Al_3$ are very hard phases compared to the others in the system. ~$Cr_3Pt$ is also very hard. It was also interesting to see that ~75% of the alloys that were annealed at 1000°C softened during annealing. The only ones that became harder were $Pt_{10}$:$Al_{80}$:$Cr_{10}$ (~$Pt_8Al_{21}$ disappeared during annealing), $Pt_{18}$:$Al_2$:$Cr_{80}$ (the alloy almost turning into single-phase ~$Cr_3Pt$) and $Pt_{63}$:$Al_{32}$:$Cr_5$ (turning into single-phase ~$Pt_2Al$, T1 disappearing).

The average values are superposed on the 1000°C isothermal section in Figure 4.2.

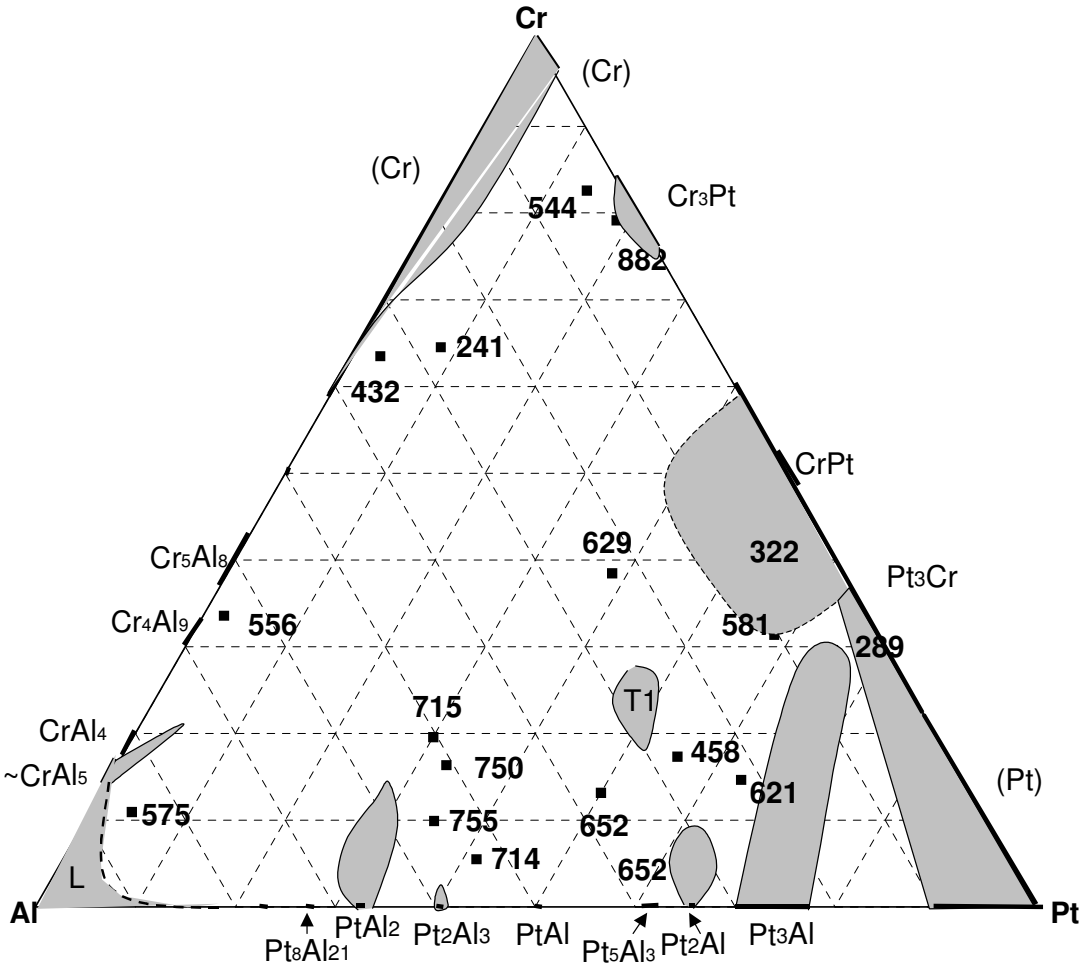



*Figure 4.2. Hardness values of Pt-Cr-Al alloys annealed at 1000°C for 1000 hours, superposed on the 1000°C isothermal section.*

### *1.2.3. Annealed at 600°C*

The results of the hardness measurements on the 600°C annealed samples are given in Table 4.3 (and superposed on the 600°C isothermal section in Figure 4.3), compared to the relevant alloys' as-cast and 1000°C annealed hardness values.

*Table 4.3. Hardness values of Pt-Cr-Al alloys annealed at 600°C for 2500 hours ($HV_{10}$) compared to as-cast and 1000°C hardness values.*

| **Alloy** | **Annealed (600°C) hardness and standard deviation** | **As-cast hardness and standard deviation** | **Annealed (1000°C) hardness and standard deviation** | **Phases present in 600°C annealed samples** |
|---|---|---|---|---|
| $Pt_{10}:Al_{30}:Cr_{60}$ | 760 ± 17 | 675 ± 17 | 241 ± 19 | ~$PtAl_2$, (Cr) |
| $Pt_{10}:Al_{60}:Cr_{30}$ | 728 ± 41 | 699 ± 63 | *Not annealed* | ~$PtAl_2$, ~$Cr_5Al_8$, ~$Cr_4Al_9$ |
| $Pt_{30}:Al_{50}:Cr_{20}$ | 853 ± 28 | 806 ± 8 | 715 ± 12 | ~$PtAl_2$, ~PtAl, (Cr) |
| $Pt_{50}:Al_{10}:Cr_{40}$ | 708 ± 56 | 572 ± 61 | 320 ± 42 | ~CrPt, ~$Pt_2Al$ |
| $Pt_{65}:Al_5:Cr_{30}$ | 327 ± 6 | 322 ± 21 | 289 ± 7 | ~$Pt_3Al$, ~$Pt_3Cr$ |
| $Pt_3:Al_{65}:Cr_{32}$ | 645 ± 31 | 670 ± 32 | 556 ± 27 | ~$Cr_4Al_9$, ~$PtAl_2$ |
| $Pt_3:Al_{35}:Cr_{62}$ | 576 ± 15 | 637 ± 26 | 432 ± 32 | (Cr), ~$PtAl_2$, ~$Cr_2Al$ |
| $Pt_{18}:Al_2:Cr_{80}$ | 962 ± 62 | 767 ± 29 | 882 ± 10 | ~CrPt, ~$Cr_3Pt$, (Cr) |
| $Pt_{35}:Al_{55}:Cr_{10}$ | 947 ± 30 | 822 ± 39 | 755 ± 5 | ~$PtAl_2$, ~PtAl, ~$Pt_2Al_3$ |
| $Pt_{38}:Al_{22}:Cr_{40}$ | 950 ± 28 | 717 ± 27 | 629 ± 4 | T1, ~CrPt, ~$Cr_3Pt$ |
| $Pt_{43}:Al_{52}:Cr_5$ | 914 ± 34 | 818 ± 69 | 714 ± 20 | ~PtAl, ~$Pt_2Al_3$ |
| $Pt_{75}:Al_{10}:Cr_{15}$ | 810 ± 116 | 880 ± 10 | 750 ±18 | ~$PtAl_2$, ~$Pt_2Al_3$, ~PtAl |
| $Pt_{50}:Al_{35}:Cr_{15}$ | 960 ± 14 | 739 ± 14 | 652 ± 19 | ~PtAl, T1 |
| $Pt_{58}:Al_{10}:Cr_{32}$ | 854 ± 6 | 697 ± 18 | 581 ± 15 | ~$Pt_3Al$, ~$Pt_3Cr$, ~CrPt |
| $Pt_{63}:Al_{32}:Cr_5$ | 617 ± 24 | 591 ± 65 | 652 ± 23 | ~$Pt_2Al$, T1 |
| $Pt_{63}:Al_{22}:Cr_{15}$ | 798 ± 22 | 673 ± 6 | 621 ± 11 | ~$Pt_3Al$, ~$Pt_2Al$ |
| $Pt_{15}:Al_5:Cr_{80}$ | 901 ± 13 | 632 ± 4 | 544 ± 18 | (Cr), ~CrPt, T1, ~$Cr_3Pt$ |
| $Pt_{55}:Al_{25}:Cr_{20}$ | 650 ± 33 | 450 ± 75 | 458 ± 22 | ~$Pt_2Al$, T1 |

Over 70% of the alloys had hardnesses above 700 $HV_{10}$, once again an indication of the hard intermetallic compounds present in the system. Only alloys $Pt_3:Al_{35}:Cr_{62}$ and $Pt_{65}:Al_5:Cr_{30}$ had hardnesses of less than 600 $HV_{10}$. Several alloys had exceptionally high hardness (> 900 $HV_{10}$) compared to the rest, namely alloys $Pt_{15}:Al_5:Cr_{80}$, $Pt_{18}:Al_2:Cr_{80}$, $Pt_{75}:Al_{10}:Cr_{15}$ (actual $Pt_{33}:Al_{50}:Cr_{17}$), $Pt_{38}:Al_{22}:Cr_{40}$, $Pt_{43}:Al_{52}:Cr_5$ and $Pt_{50}:Al_{35}:Cr_{15}$. It is unclear why alloy $Pt_{75}:Al_{10}:Cr_{15}$ showed such a large standard deviation on hardness - maybe subsurface porosity played a role. The presence of intermetallic compounds like ~$PtAl_2$, PtAl and ~CrPt are responsible for these high values, as well as the presence of T1. Only alloys $Pt_3:Al_{65}:Cr_{32}$,

$Pt_3$:$Al_{35}$:$Cr_{62}$ and $Pt_{75}$:$Al_{10}$:$Cr_{15}$ softened during annealing at 600°C. The softening is probably due to the loss of ~$Pt_2Al_3$ during annealing in the latter, and the disordering of ~$Cr_2Al$ into (Cr) in alloy $Pt_3$:$Al_{35}$:$Cr_{62}$. It is unclear why alloy $Pt_3$:$Al_{65}$:$Cr_{32}$ softened.

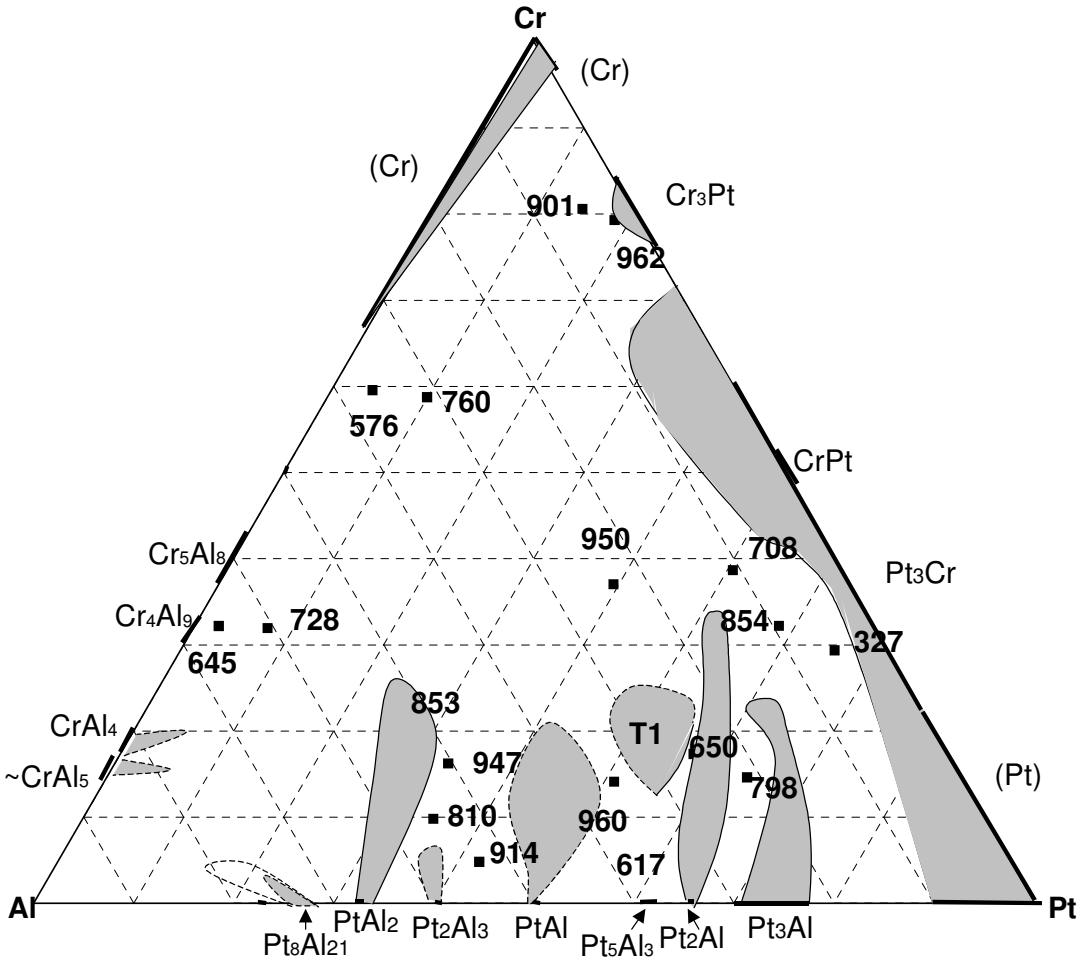



*Figure 4.3. Hardness values of Pt-Cr-Al alloys annealed at 600°C for 2500 hours, superposed on the 600°C isothermal section.*

### 1.3. Conclusions

Platinum is significantly hardened by alloying with Cr and Al. To put it in perspective, all the measured hardnesses were significantly higher than the 40-50 HV of pure Pt in the soft state [2007Int]. Most of the alloys were harder than the 360 $HV_{10}$ hardness of $Pt_{84}$:$Al_{11}$:$Ru_2$:$Cr_3$ [2004Süs3], the most promising Pt-based alloy thus far for potential application in high temperature environments. In the case of $Pt_{84}$:$Al_{11}$:$Ru_2$:$Cr_3$, the strengthening is the result of precipitation hardening, while the high hardnesses of alloys in the Pt-Al-Cr system is caused by the formation of high hardness intermetallic compounds.

## 2. TOUGHNESS

By classifying the deformation lines around a hardness indentation, one can get a basic idea about the toughness of a material (i.e. resistance to fracture). Cracking around an indentation is obviously an indication of brittleness. Straight lines around an indentation indicate *planar slip* on the primary slip system (moderate toughness), while wavy lines (*wavy slip*) indicates deformation on multiple slip systems whereby more increased plastic deformation is possible.

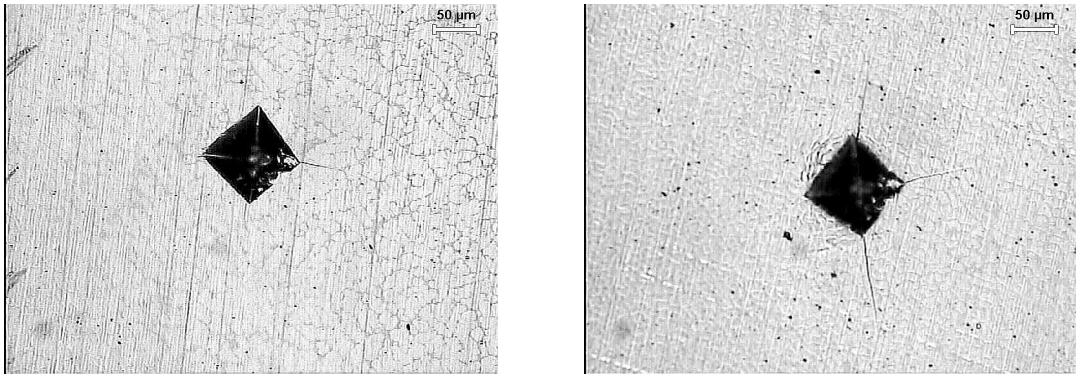
### 2.1. Experimental procedure

In order to get a qualitative evaluation of the alloys' toughness, photographs were taken of the hardness indentations via a JVC TK138E Color Video Camera connected to an Olympys Vanox-T light microscope, and the slip mode around the indentations classified. Note that the classification "no discernible slip" refers to cases where the relevant slip mechanism could not be identified because neither wavy nor planar slip was observed under the optical microscope, although slip would obviously have occurred.

### 2.2. Results and discussion

#### *2.2.1. As-cast*

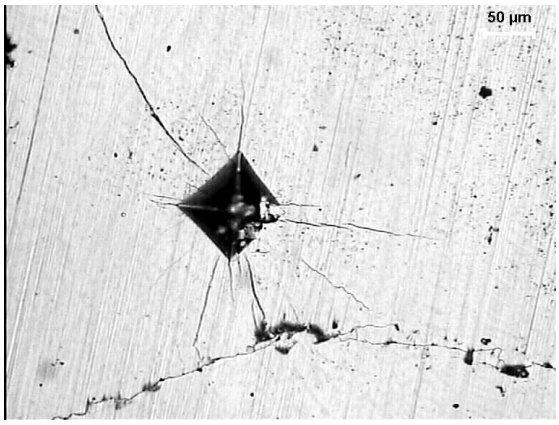
Figure 4.4 summarises the results of the measurements on the as-cast alloys, showing the relevant hardness indentations and slip modes.




$Pt_{10}:Al_{10}:Cr_{80}$
Cracking

$Pt_{10}:Al_{30}:Cr_{60}$
Major cracking and wavy slip

*Figure 4.4. Optical micrographs for comparison of the hardness indentations in as-cast Pt-Cr-Al alloys.*



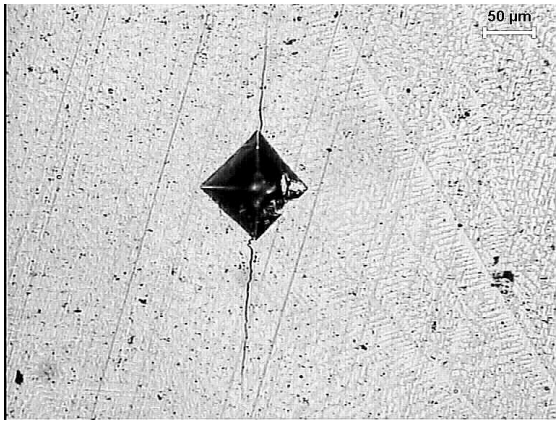

$Pt_{10}:Al_{60}:Cr_{30}$

Major cracking



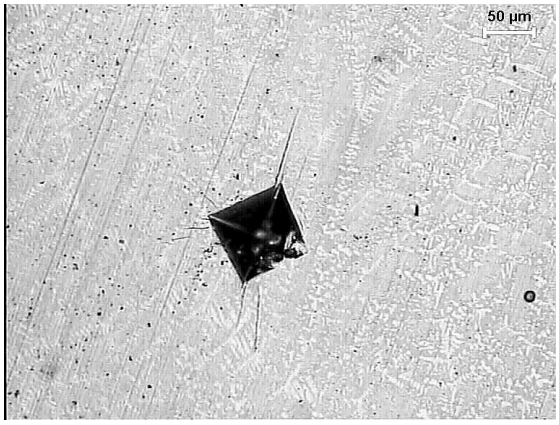

$Pt_{10}:Al_{80}:Cr_{10}$

Major interdendritic cracking



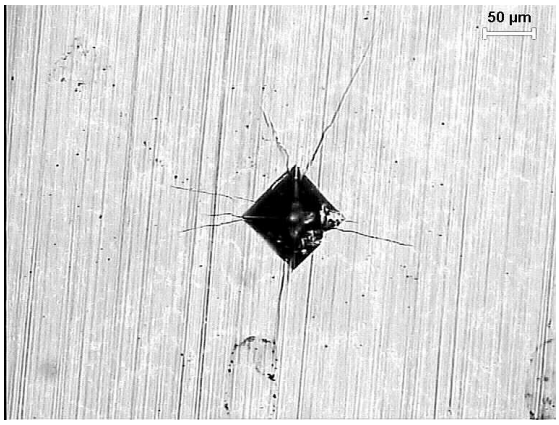

$Pt_{20}:Al_{20}:Cr_{60}$

Major cracking



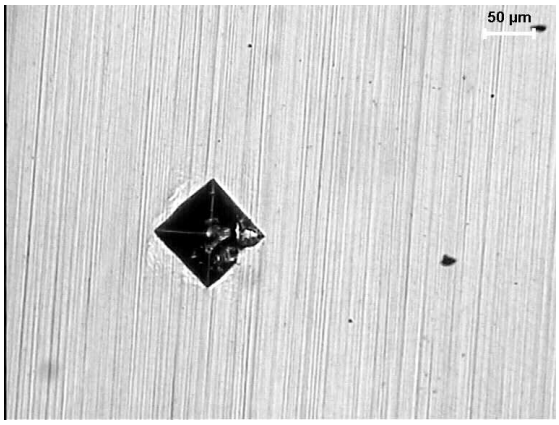

$Pt_{20}:Al_{40}:Cr_{40}$

Major cracking




$Pt_{30}:Al_{50}:Cr_{20}$

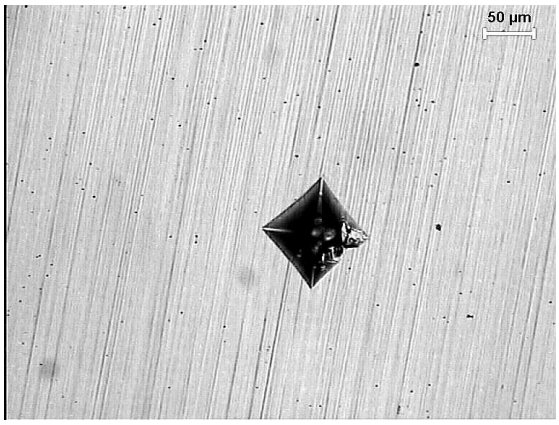
Major cracking




$Pt_{40}:Al_{10}:Cr_{50}$

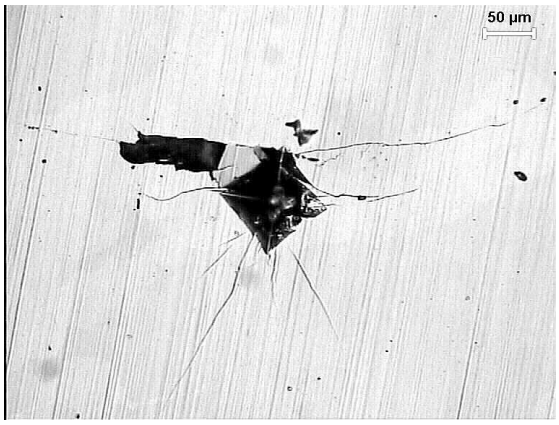
Wavy slip

*Figure 4.4. (cont.). Optical micrographs for comparison of the hardness indentations in as-cast Pt-Cr-Al alloys.*



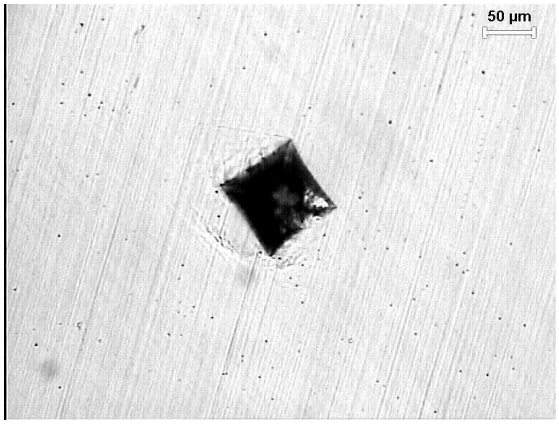

$Pt_{40}:Al_{30}:Cr_{30}$

No discernible slip



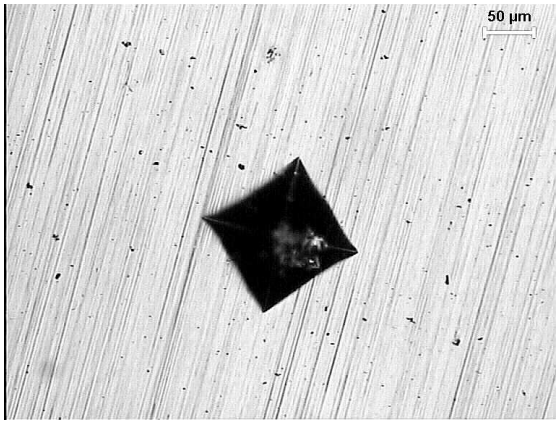

$Pt_{40}:Al_{50}:Cr_{10}$

Major cracking



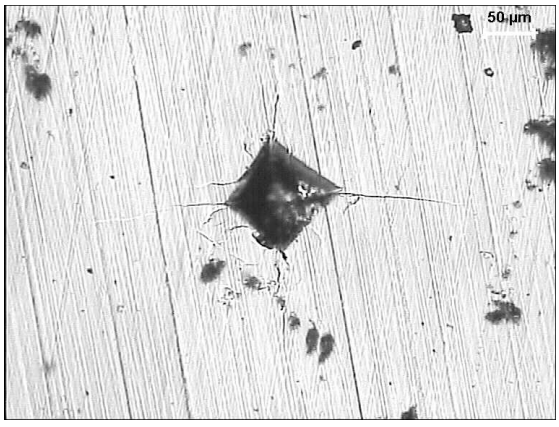

$Pt_{50}:Al_{10}:Cr_{40}$

Wavy slip



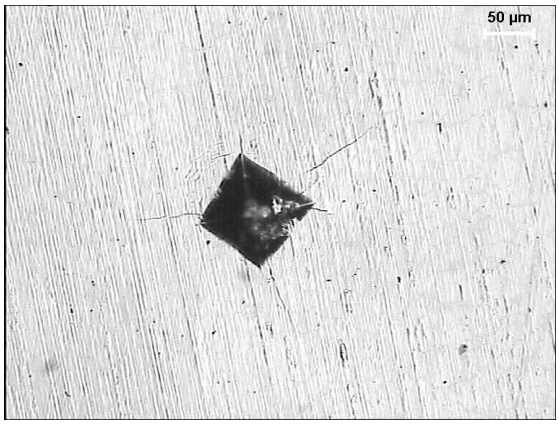

$Pt_{65}:Al_{5}:Cr_{30}$

No discernible slip




$Pt_{3}:Al_{65}:Cr_{32}$

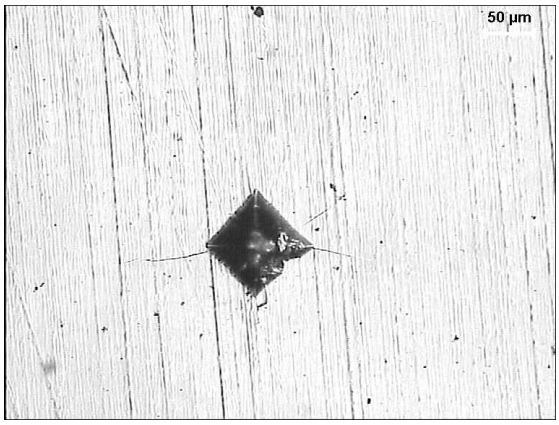
Major cracking




$Pt_{3}:Al_{35}:Cr_{62}$

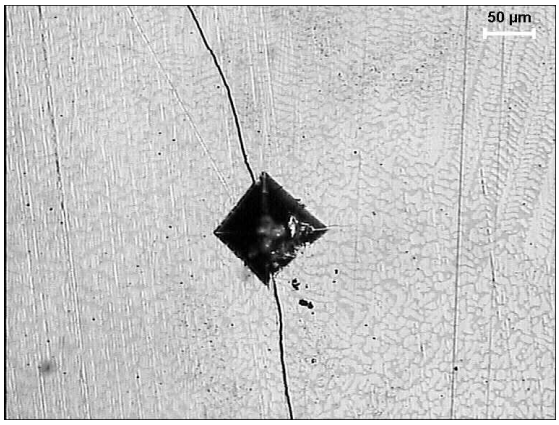
Wavy slip and major cracking

*Figure 4.4. (cont.). Optical micrographs for comparison of the hardness indentations in as-cast Pt-Cr-Al alloys.*



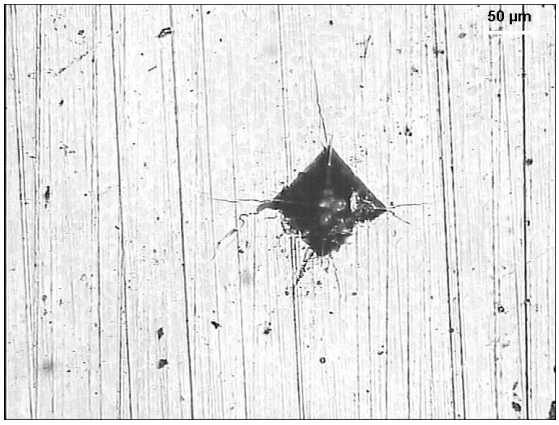

$Pt_{10}:Al_{50}:Cr_{40}$

Major cracking



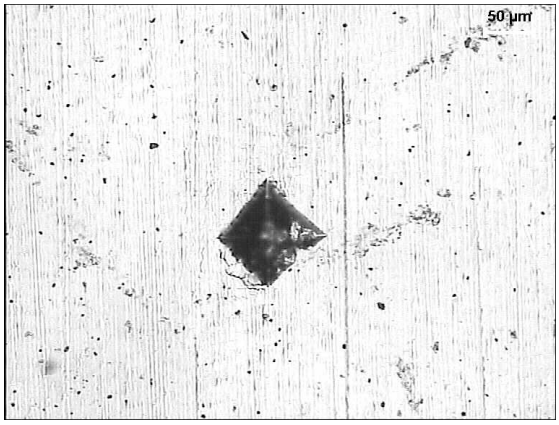

$Pt_{12}:Al_{18}:Cr_{70}$

Major cracking



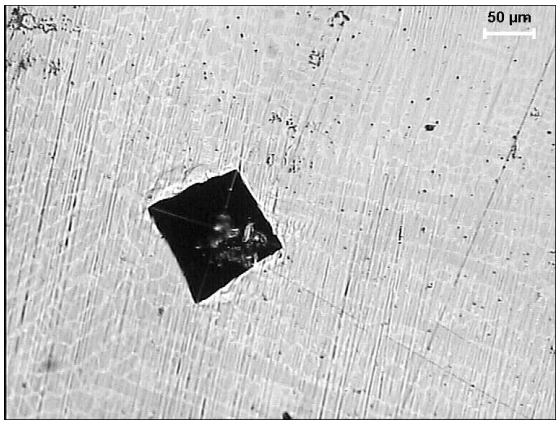

$Pt_{17}:Al_{68}:Cr_{15}$

Major cracking



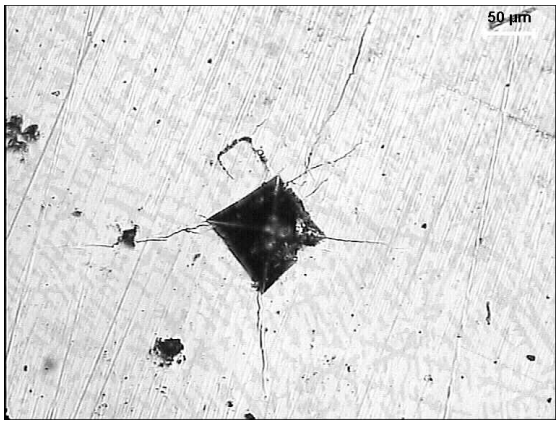

$Pt_{18}:Al_{2}:Cr_{80}$

Wavy slip




$Pt_{28}:Al_{12}:Cr_{60}$

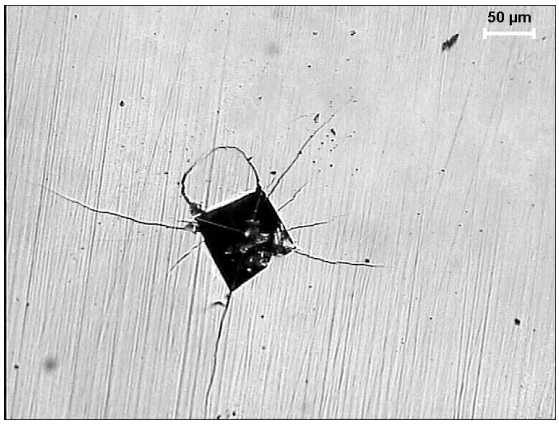
Wavy slip




$Pt_{28}:Al_{70}:Cr_{2}$

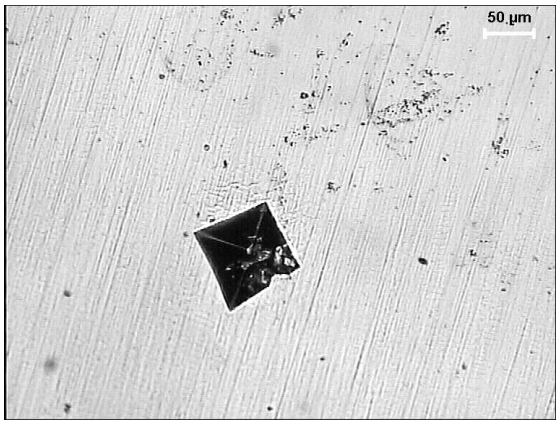
Major cracking

*Figure 4.4. (cont.). Optical micrographs for comparison of the hardness indentations in as-cast Pt-Cr-Al alloys.*



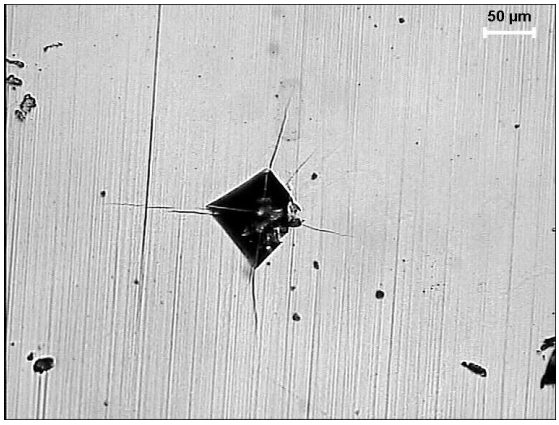

$Pt_{35}:Al_{55}:Cr_{10}$

Major cracking



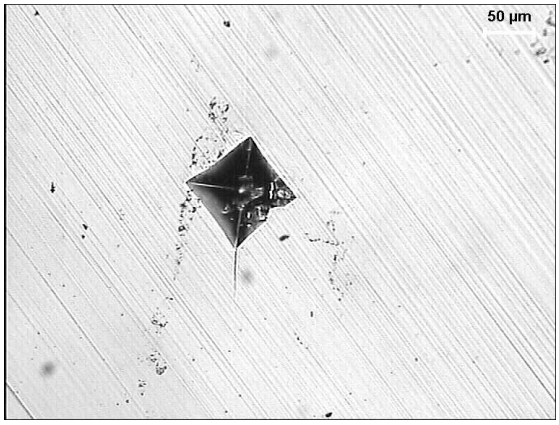

$Pt_{38}:Al_{22}:Cr_{40}$

Wavy slip



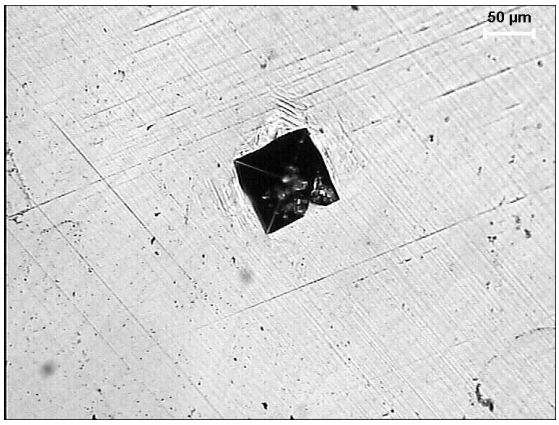

$Pt_{43}:Al_{52}:Cr_{5}$

Major cracking



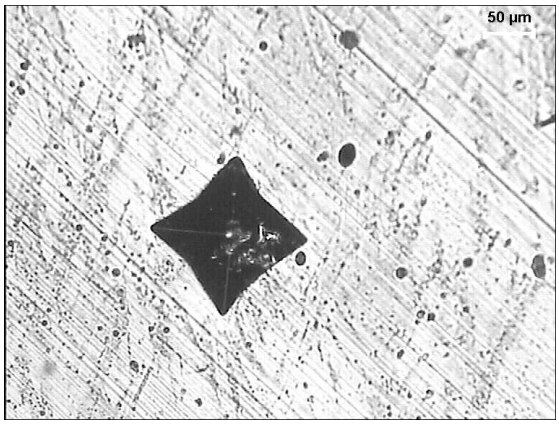

$Pt_{50}:Al_{35}:Cr_{15}$

Cracking




$Pt_{58}:Al_{10}:Cr_{32}$

Wavy and planar slip




$Pt_{60}:Al_{2}:Cr_{38}$

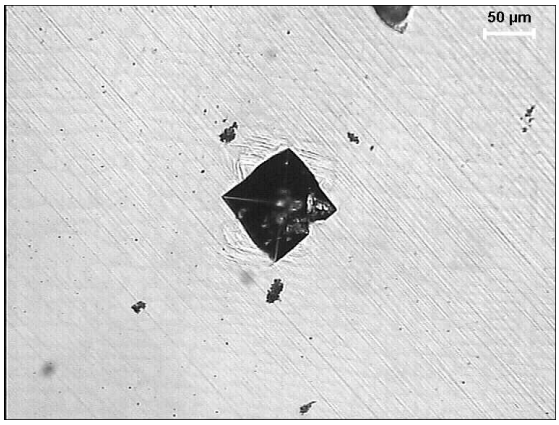
No discernible slip

*Figure 4.4. (cont.). Optical micrographs for comparison of the hardness indentations in as-cast Pt-Cr-Al alloys.*



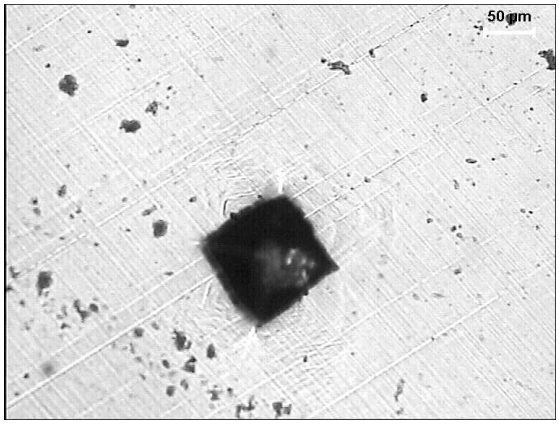

$Pt_{63}:Al_{32}:Cr_5$

Planar slip



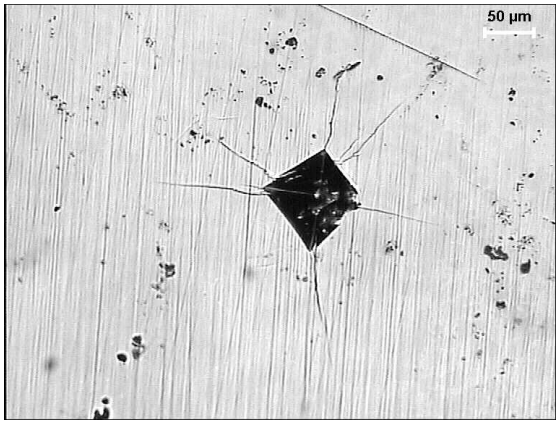

$Pt_{63}:Al_{22}:Cr_{15}$

Wavy slip



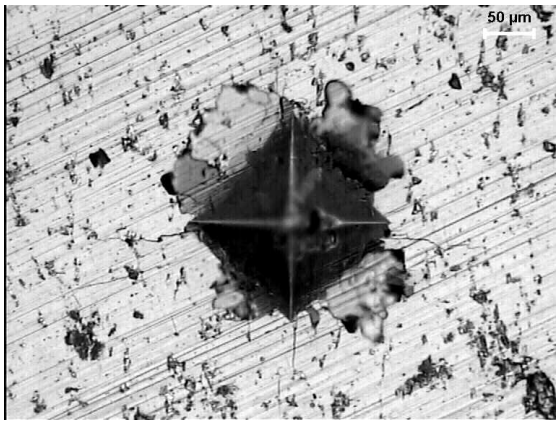

$Pt_{78}:Al_{17}:Cr_5$

Wavy slip



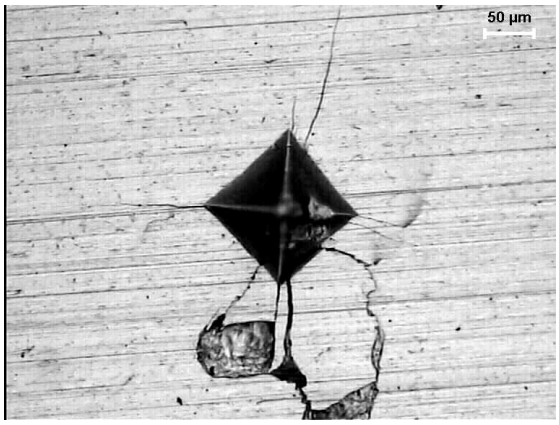

$Pt_{75}:Al_{10}:Cr_{15}$

Major cracking




$Pt_3:Al_{79}:Cr_{18}$

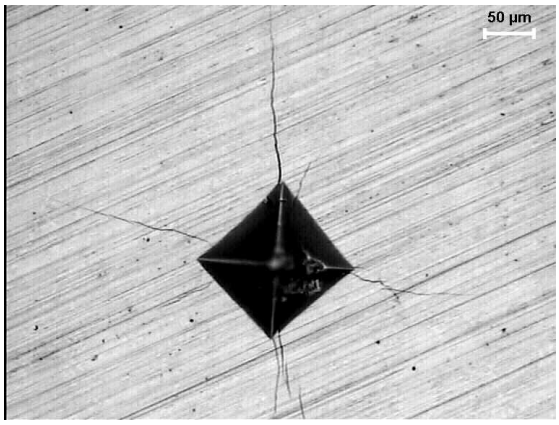
Major irregular cracking




$Pt_5:Al_{52}:Cr_{43}$

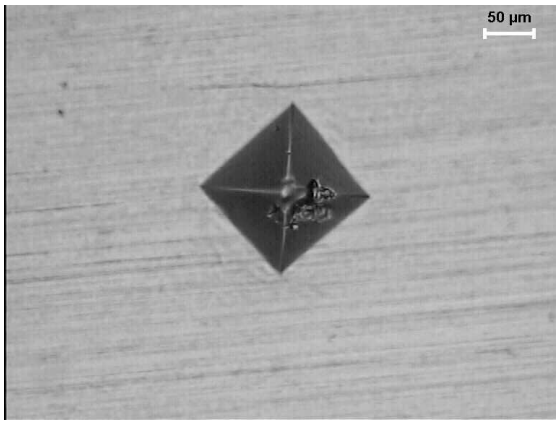
Major cracking

*Figure 4.4. (cont.). Optical micrographs for comparison of the hardness indentations in as-cast Pt-Cr-Al alloys.*



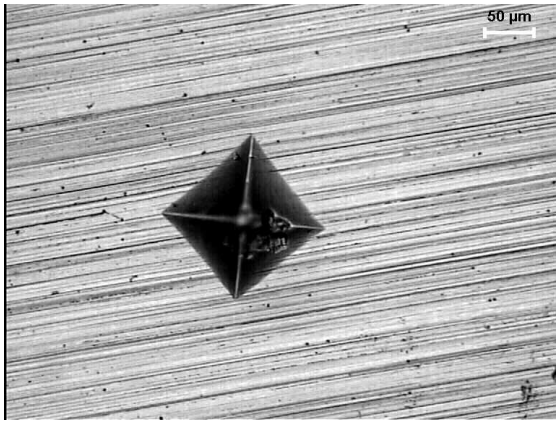

$Pt_{13}:Al_{45}:Cr_{42}$

Major cracking



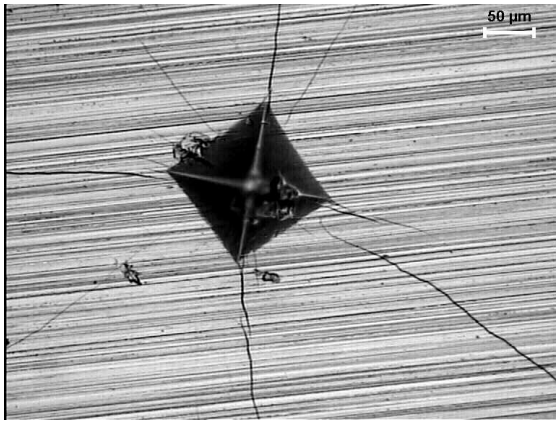

$Pt_{15}:Al_{5}:Cr_{80}$

Wavy slip



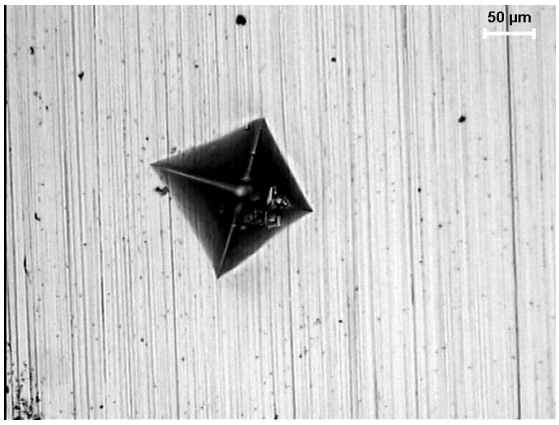

$Pt_{34}:Al_{27}:Cr_{39}$

No discernible slip



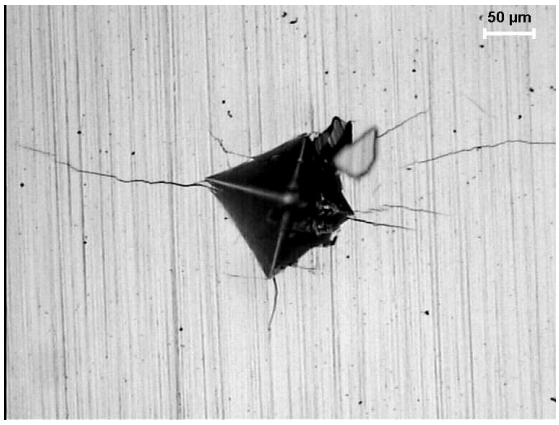

$Pt_{37}:Al_{59}:Cr_{4}$

Major cracking




$Pt_{45}:Al_{35}:Cr_{20}$

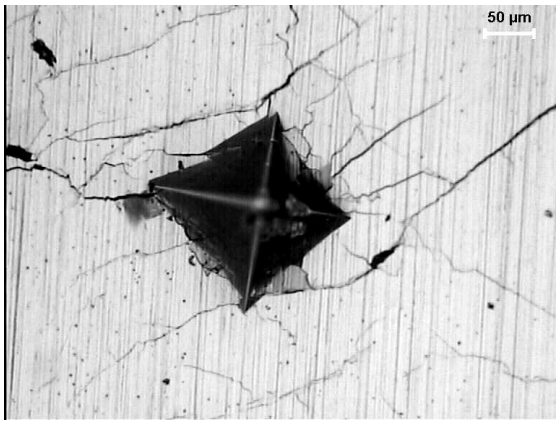
No discernible slip




$Pt_{52}:Al_{43}:Cr_{5}$

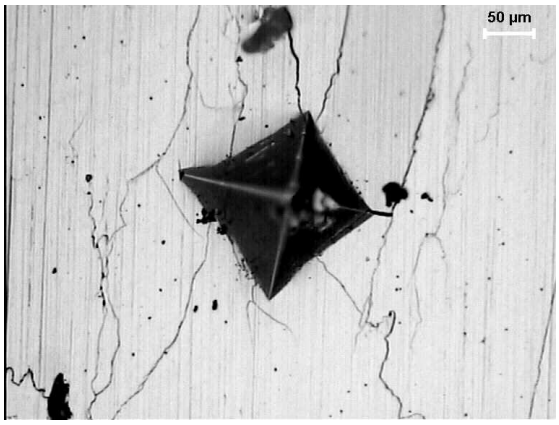
Major cracking

*Figure 4.4. (cont.). Optical micrographs for comparison of the hardness indentations in as-cast Pt-Cr-Al alloys.*



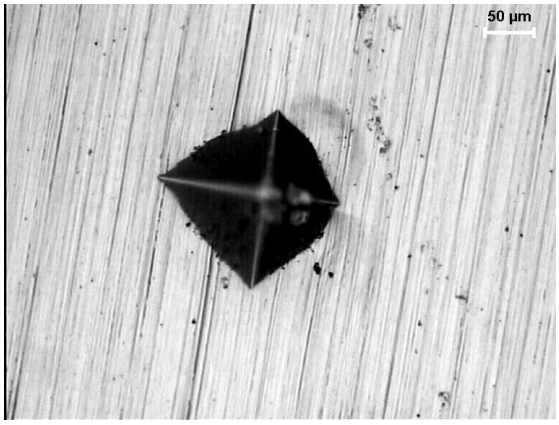

$Pt_{55}:Al_{25}:Cr_{20}$

Major irregular cracking



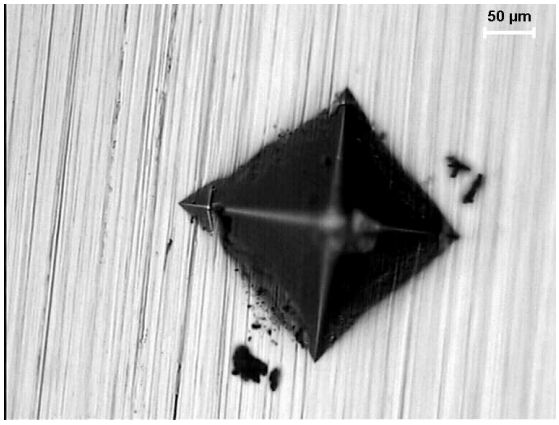

$Pt_{55}:Al_{20}:Cr_{25}$

Major irregular cracking




$Pt_{64}:Al_{16}:Cr_{20}$

Planar slip




$Pt_{76}:Al_5:Cr_{19}$

Cracking

*Figure 4.4. (cont.). Optical micrographs for comparison of the hardness indentations in as-cast Pt-Cr-Al alloys.*

It was interesting to note "pin-cushioning" of the hardness indentation of alloy $Pt_{60}:Al_2:Cr_{38}$, an anomaly typically observed with annealed material, when metal is sinking in around the faces of the indentor [1990Die]. Apart from alloy $Pt_{65}:Al_5:Cr_{30}$, alloy $Pt_{60}:Al_2:Cr_{38}$ was the softest in the as-cast condition (333 $HV_{10}$).

It is obvious that most alloys in the system are very brittle, since many of the alloys exhibited major cracking. The only alloys that stood out as having better toughness were the ones that contained ~CrPt (alloys $Pt_{18}:Al_2:Cr_{80}$, $Pt_{15}:Al_5:Cr_{80}$, $Pt_{38}:Al_{22}:Cr_{40}$, $Pt_{40}:Al_{10}:Cr_{50}$, and $Pt_{50}:Al_{10}:Cr_{40}$), $Pt_3Cr$ ($Pt_{65}:Al_5:Cr_{30}$ and $Pt_{76}:Al_5:Cr_{19}$) and ~$Pt_3Al$ ($Pt_{78}:Al_{17}:Cr_5$, $Pt_{63}:Al_{32}:Cr_5$, $Pt_{63}:Al_{22}:Cr_{15}$, $Pt_{64}:Al_{16}:Cr_{20}$ and $Pt_{60}:Al_2:Cr_{38}$) showing wavy slip in most cases. Considering

the alloys Mintek is targeting for high temperature applications are based on high Pt content ~$Pt_3Al$ containing alloys, this was most encouraging. The different slip modes of the as-cast alloys are superposed on the solidification projection in Figure 4.5.

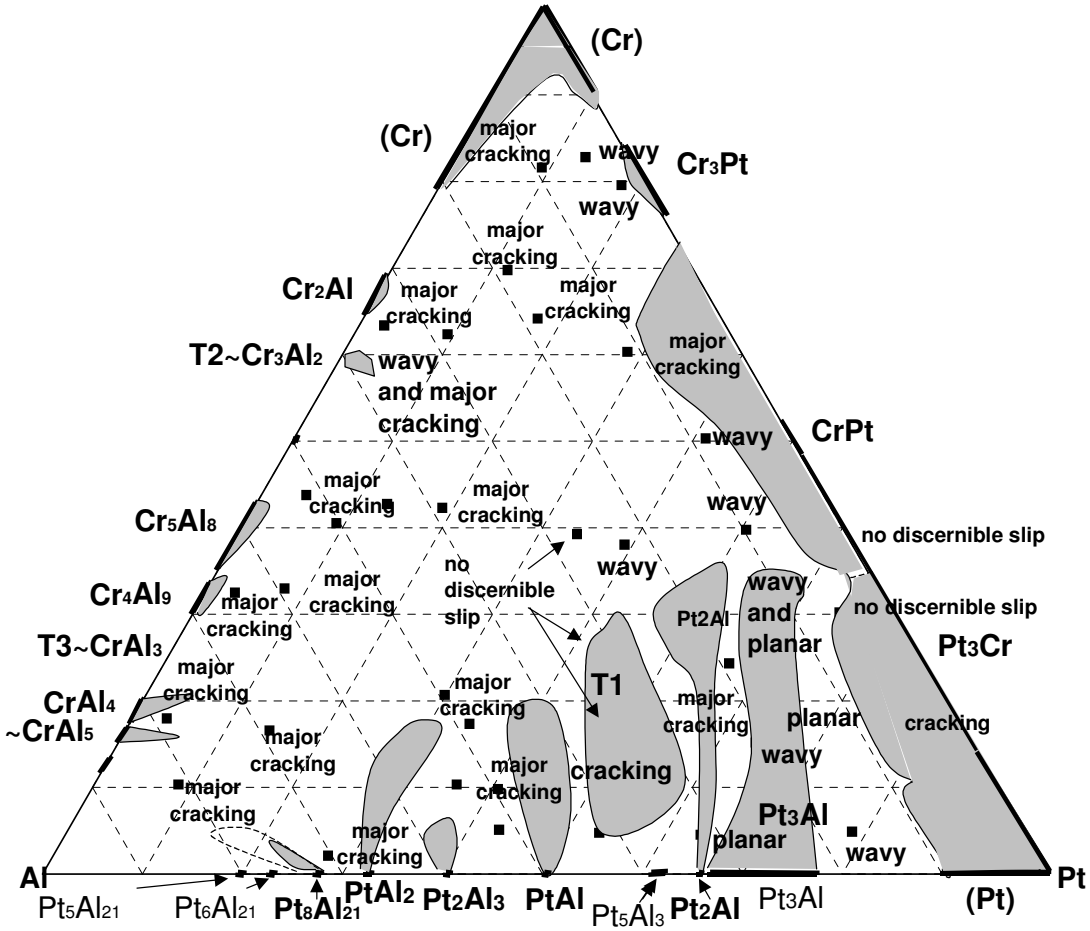
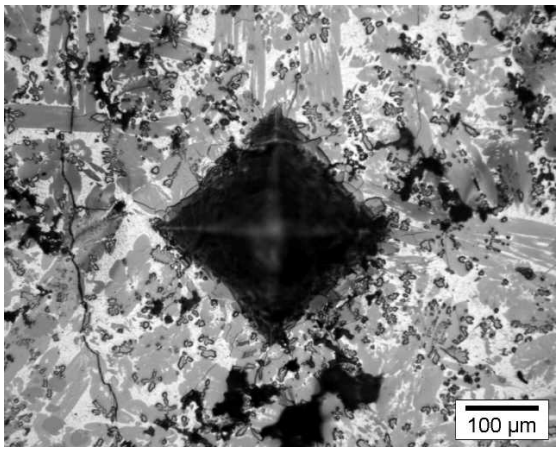


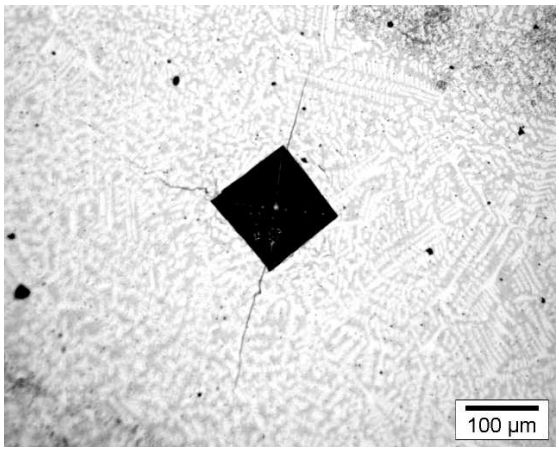

*Figure 4.5. Summary of the slip modes of as-cast Pt-Cr-Al alloys, superposed on the solidification projection.*

### *2.2.2. Annealed at 1000 ℃*

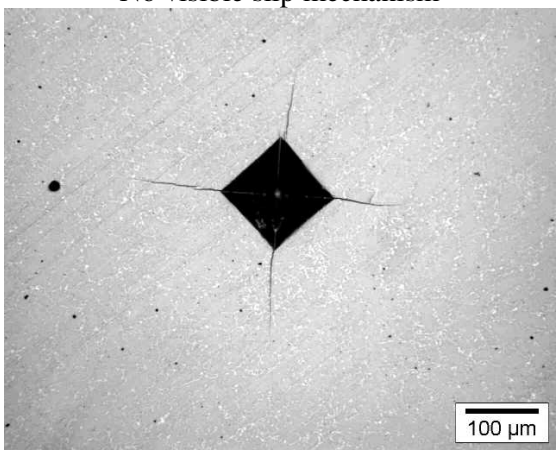
Figure 4.6 summarises the results of the measurements on the annealed alloys, showing the relevant hardness indentations and slip modes.



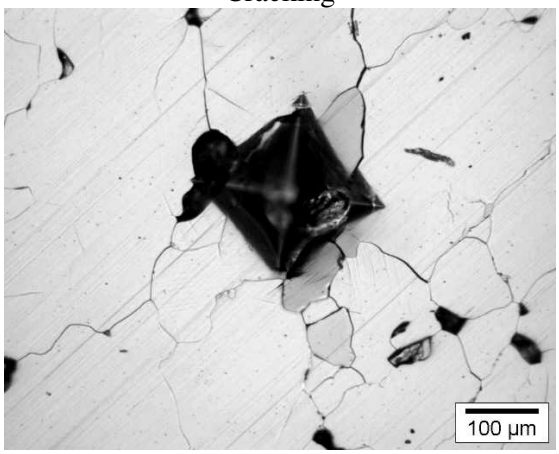

$Pt_{10}:Al_{30}:Cr_{60}$
No visible slip mechanism



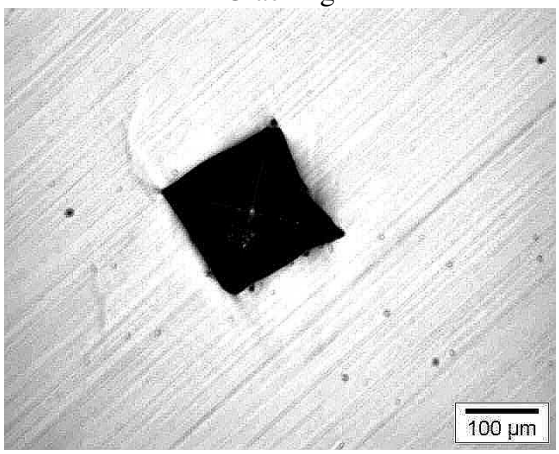

$Pt_{10}:Al_{80}:Cr_{10}$
Cracking



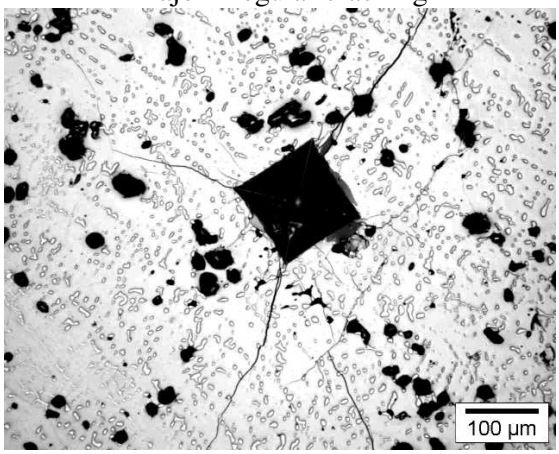

$Pt_{30}:Al_{50}:Cr_{20}$
Cracking




$Pt_{50}:Al_{10}:Cr_{40}$
Major irregular cracking

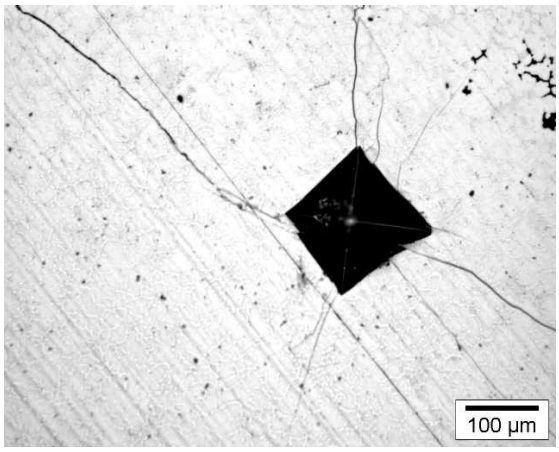



$Pt_{65}:Al_{5}:Cr_{30}$
Wavy slip

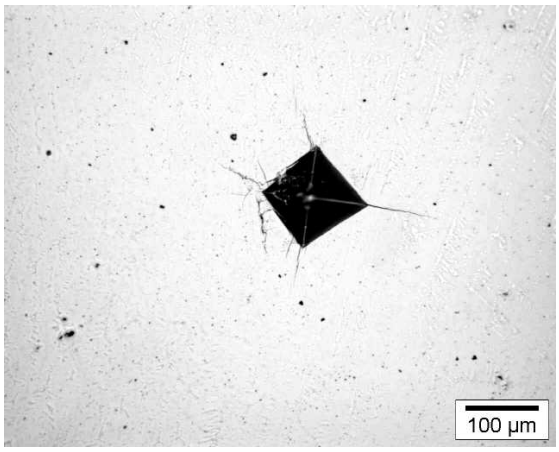



$Pt_{3}:Al_{65}:Cr_{32}$
Major cracking

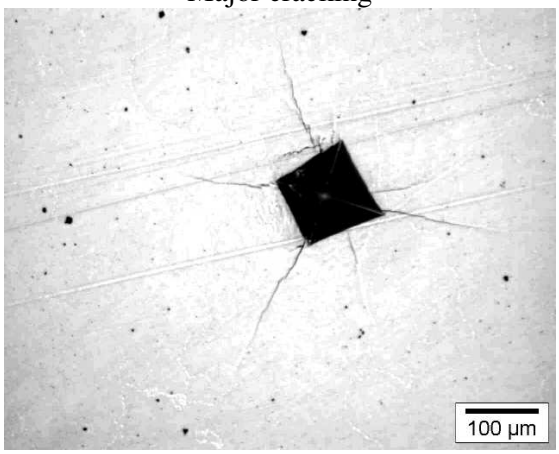
*Figure 4.6. Optical micrographs for comparison of the hardness indentations in Pt-Cr-Al alloys annealed at 1000℃ for 1000 hours.*



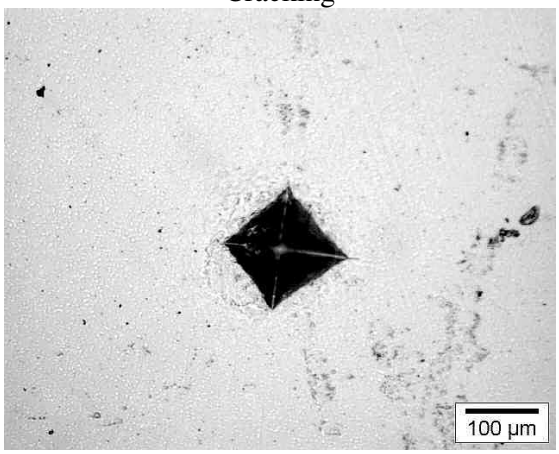

$Pt_3:Al_{35}:Cr_{62}$
Major cracking



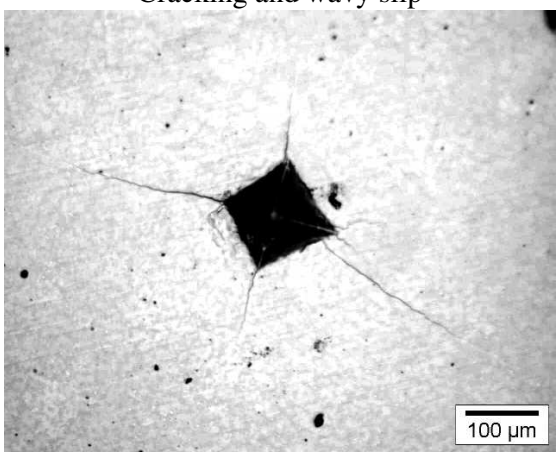

$Pt_{18}:Al_2:Cr_{80}$
Cracking



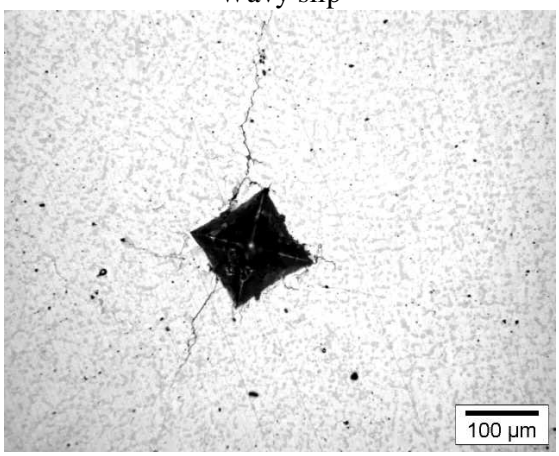

$Pt_{35}:Al_{55}:Cr_{10}$
Cracking and wavy slip




$Pt_{38}:Al_{22}:Cr_{40}$
Wavy slip

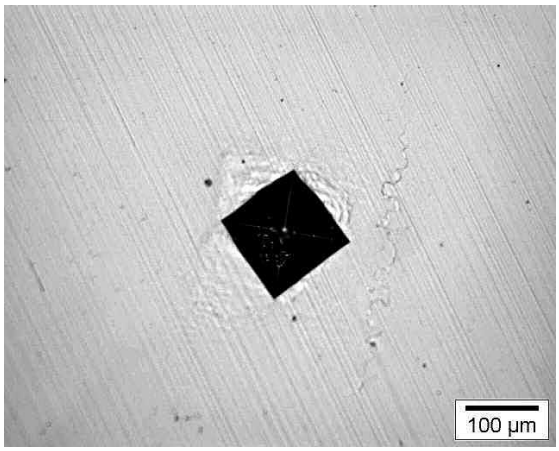



$Pt_{43}:Al_{52}:Cr_5$
Cracking and wavy slip

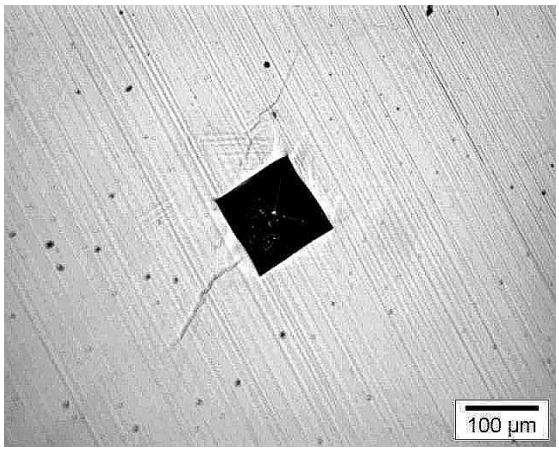



$Pt_{50}:Al_{35}:Cr_{15}$
Cracking (interdendritic)

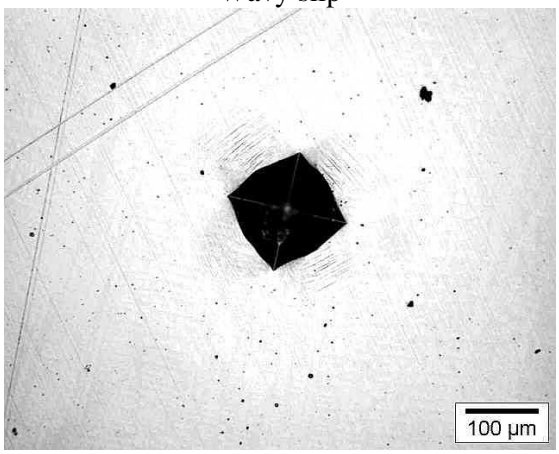
*Figure 4.6. (cont.) Optical micrographs for comparison of the hardness indentations in Pt-Cr-Al alloys annealed at 1000℃ for 1000 hours.*



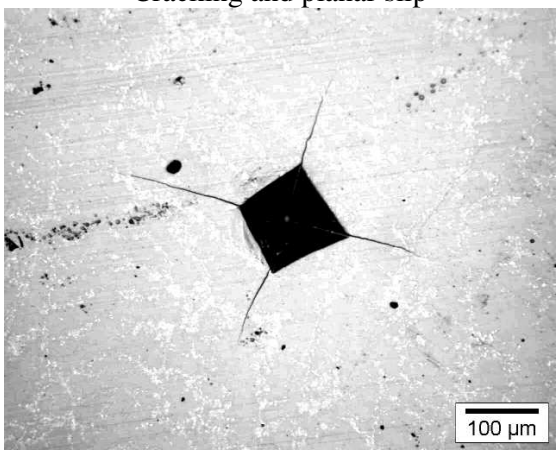

$Pt_{58}:Al_{10}:Cr_{32}$
Wavy slip



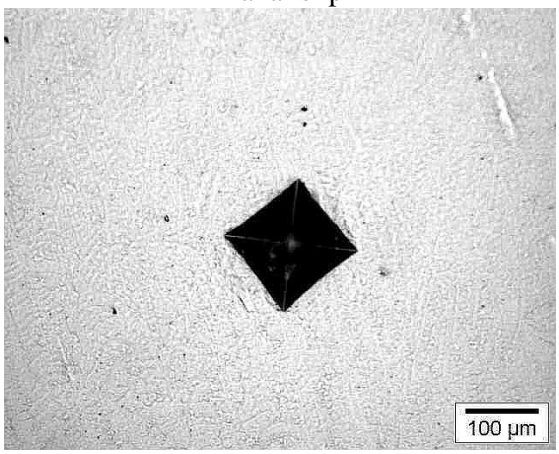

$Pt_{63}:Al_{32}:Cr_{5}$
Cracking and planar slip



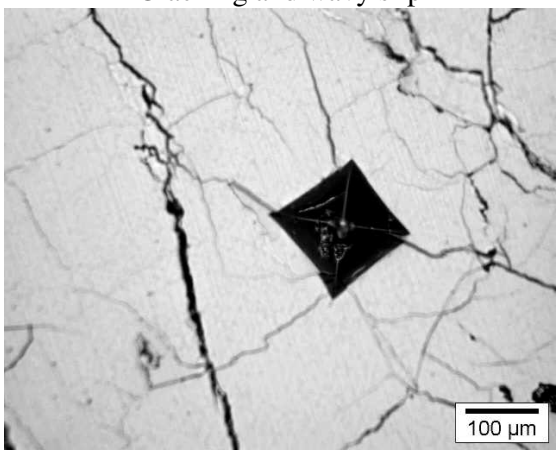

$Pt_{63}:Al_{22}:Cr_{15}$
Planar slip




$Pt_{75}:Al_{10}:Cr_{15}$
Cracking and wavy slip




$Pt_{15}:Al_{5}:Cr_{80}$
Wavy slip




$Pt_{55}:Al_{25}:Cr_{20}$
Major cracking

*Figure 4.6. (cont.) Optical micrographs for comparison of the hardness indentations in Pt-Cr-Al alloys annealed at 1000℃ for 1000 hours.*

It was interesting to note "barrelling" of the hardness indentation of alloy $Pt_{63}$:$Al_{22}$:$Cr_{15}$, an anomaly normally observed with cold-worked material, when metal is piling up around the faces of the indentor [1990Die]. The alloy had quite a high annealed hardness (621 $HV_{10}$). The different slip modes of the annealed alloys are superposed on the preliminary 1000°C isothermal section in Figure 4.7.

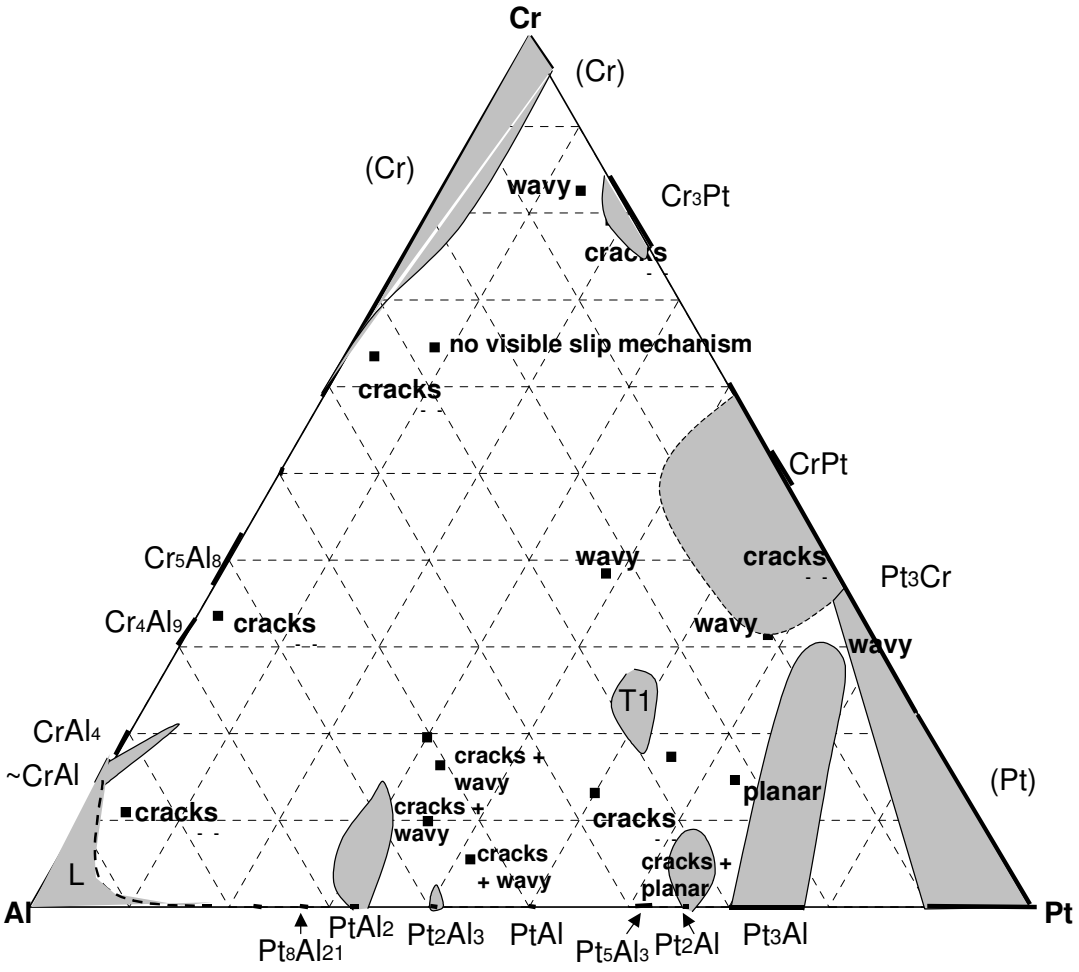
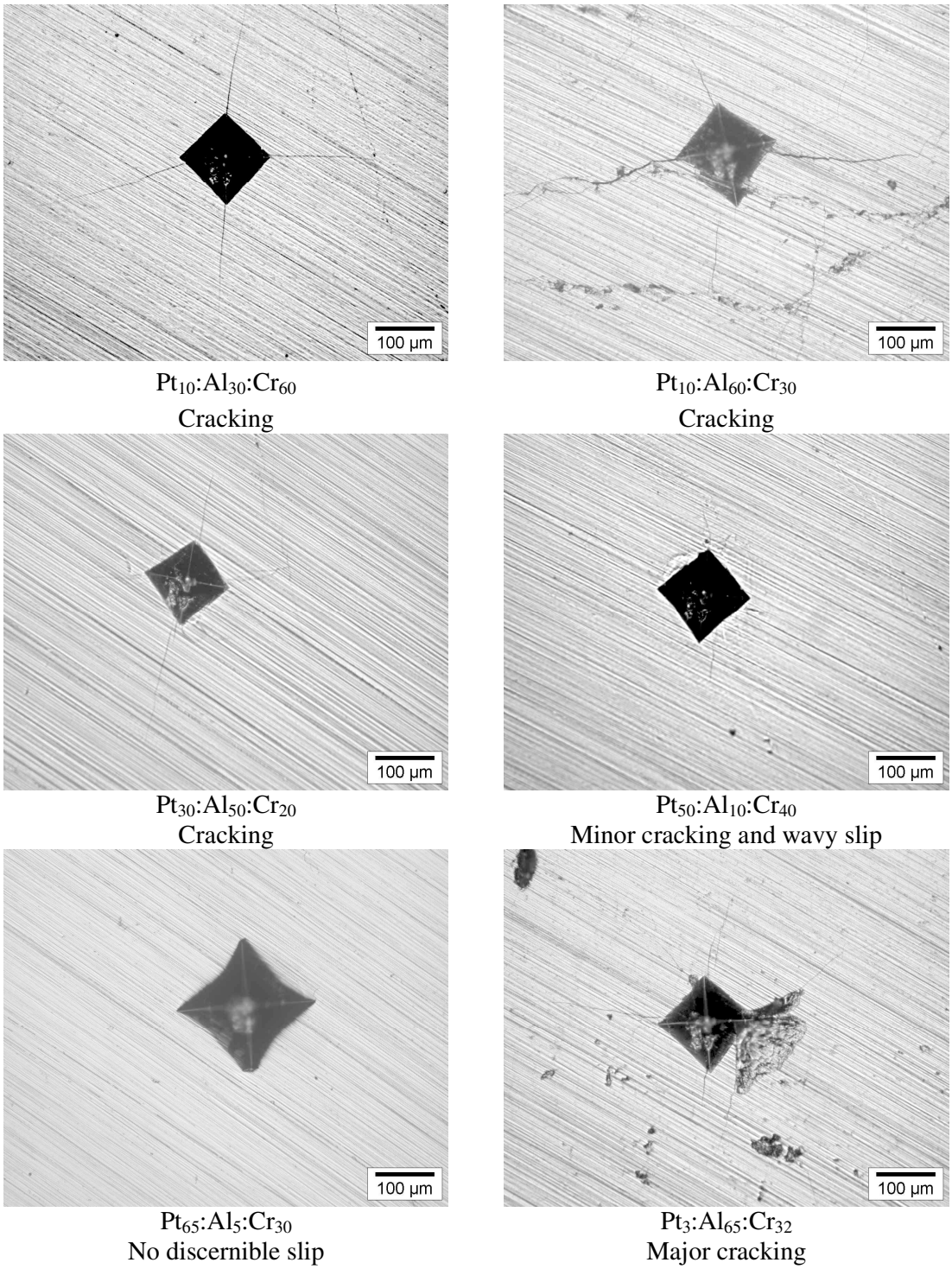



*Figure 4.7. Summary of the slip modes of Pt-Cr-Al alloys annealed at 1000°C for 1000 hours, superposed on the 1000°C isothermal section.*

It is obvious that most alloys in the system are very brittle, since many of the alloys exhibited failry major cracking. The only alloys that stood out as having better toughness were the ones that contained ~$Pt_3Al$ ($Pt_{58}$:$Al_{10}$:$Cr_{32}$ (wavy slip), $Pt_{63}$:$Al_{22}$:$Cr_{15}$ (planar slip) and $Pt_{65}$:$Al_5$:$Cr_{30}$ (wavy slip). Once again, this was encouraging for the Pt-based alloys that are being developed by Mintek.

### *2.2.3. Annealed at 600 ℃*

Figure 4.8 summarises the results of the measurements on the 600℃ annealed alloys, showing the relevant hardness indentations and slip modes.




$Pt_{10}:Al_{30}:Cr_{60}$
Cracking

$Pt_{10}:Al_{60}:Cr_{30}$
Cracking

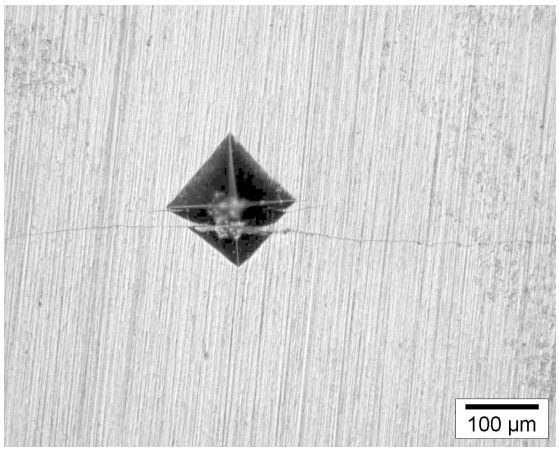
$Pt_{30}:Al_{50}:Cr_{20}$
Cracking

$Pt_{50}:Al_{10}:Cr_{40}$
Minor cracking and wavy slip

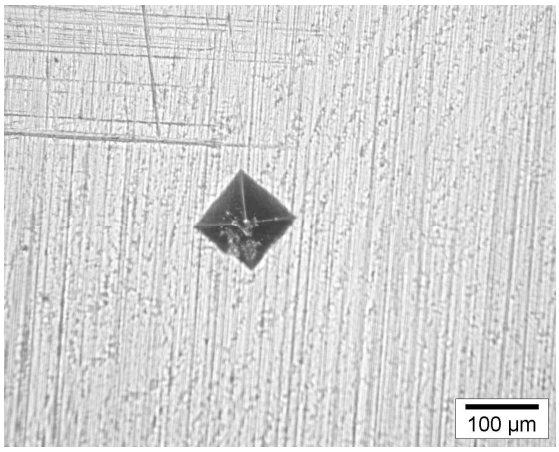
$Pt_{65}:Al_{5}:Cr_{30}$
No discernible slip

$Pt_{3}:Al_{65}:Cr_{32}$
Major cracking

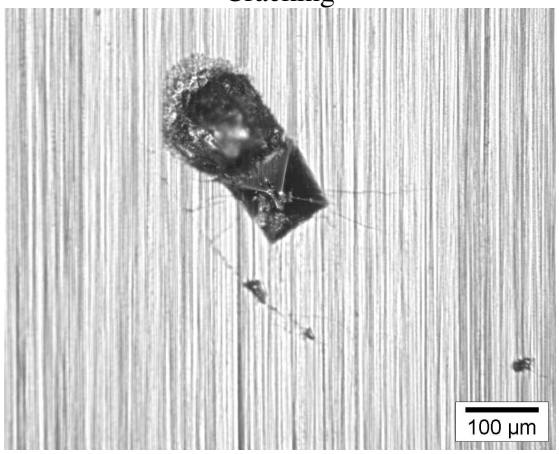
*Figure 4.8. Optical micrographs for comparison of the hardness indentations in Pt-Cr-Al alloys annealed at 600℃ for 2500 hours.*




$Pt_3:Al_{35}:Cr_{62}$
Cracking



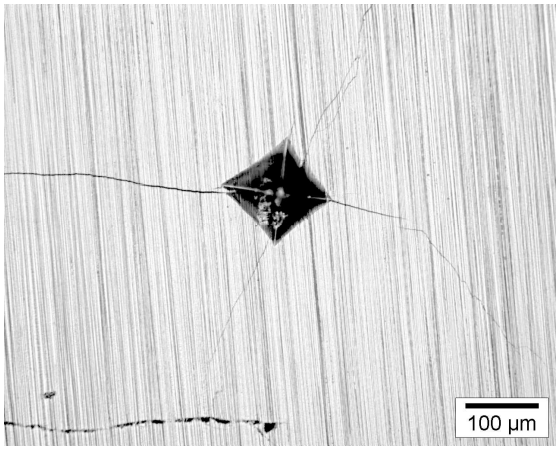

$Pt_{18}:Al_2:Cr_{80}$
No discernible slip



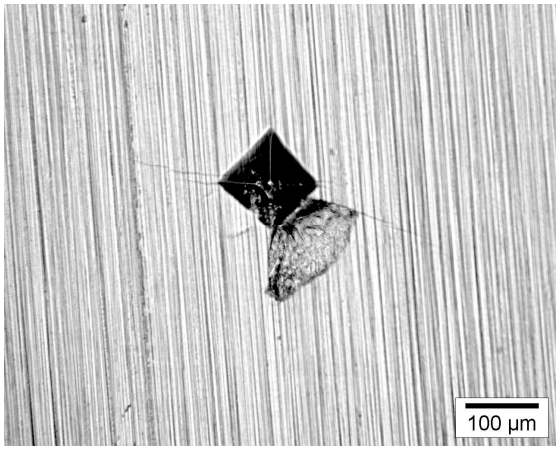

$Pt_{35}:Al_{55}:Cr_{10}$
Major cracking

*No picture taken*

$Pt_{38}:Al_{22}:Cr_{40}$

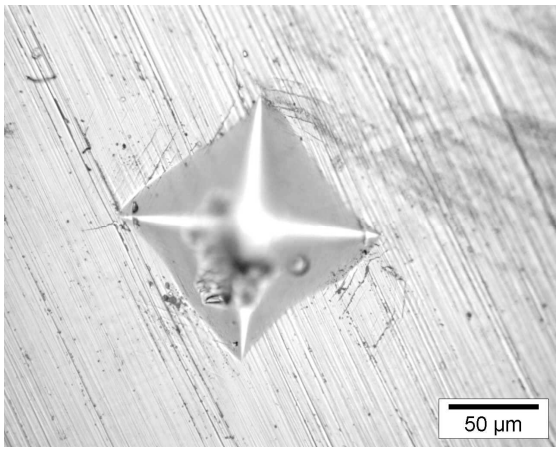



$Pt_{43}:Al_{52}:Cr_5$
Cracking

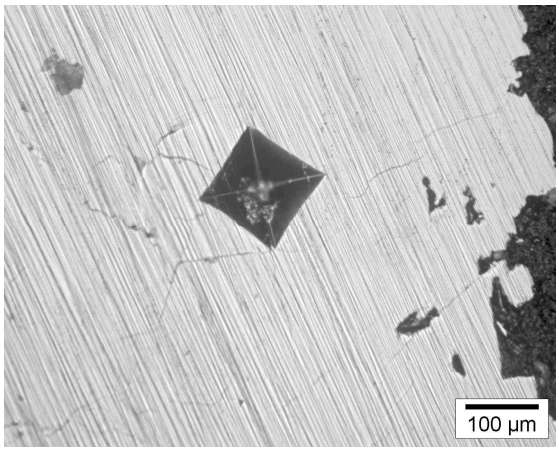



$Pt_{75}:Al_{10}:Cr_{15}$
Major cracking

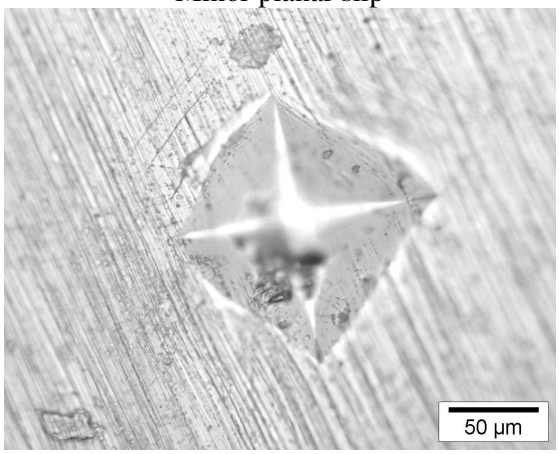
*Figure 4.8. (cont.) Optical micrographs for comparison of the hardness indentations in Pt-Cr-Al alloys annealed at 600℃ for 2500 hours.*



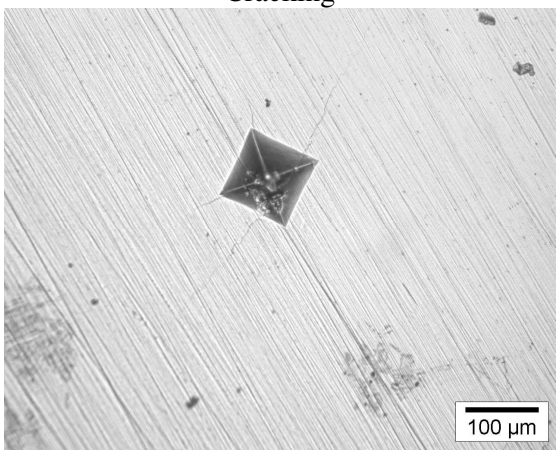

$Pt_{58}:Al_{10}:Cr_{32}$
Minor planar slip



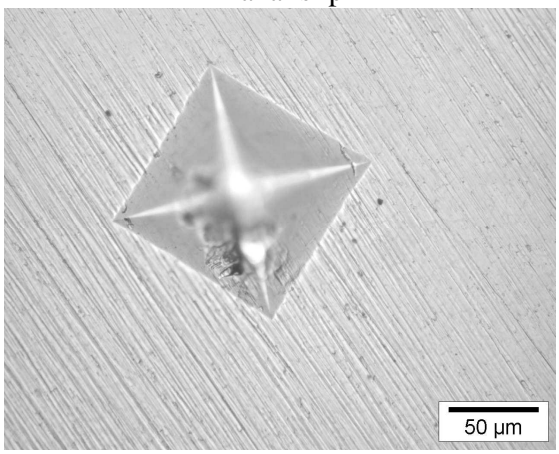

$Pt_{63}:Al_{32}:Cr_{5}$
Cracking



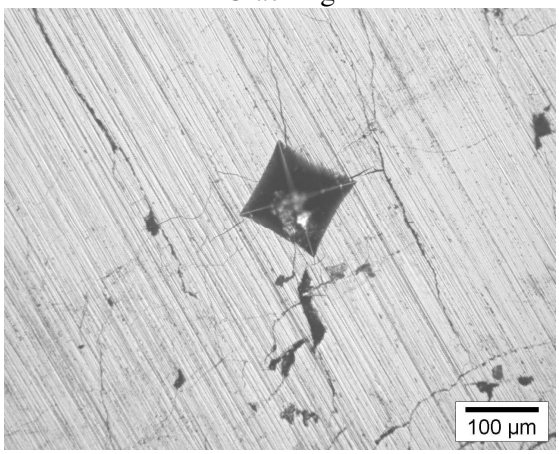

$Pt_{63}:Al_{22}:Cr_{15}$
Planar slip




$Pt_{50}:Al_{35}:Cr_{15}$
Cracking




$Pt_{15}:Al_{5}:Cr_{80}$
No discernible slip




$Pt_{55}:Al_{25}:Cr_{20}$
Major cracking

*Figure 4.8. (cont.) Optical micrographs for comparison of the hardness indentations in Pt-Cr-Al alloys annealed at 600℃ for 2500 hours.*

It was interesting to note "pin-cushioning" of the hardness indentation of alloy $Pt_{65}$:$Al_5$:$Cr_{30}$, an anomaly typically observed with annealed material, when metal is sinking in around the faces of the indentor [1990Die]. The alloy was the softest in the 600°C annealed condition (327 $HV_{10}$).

The different slip modes of the 600°C annealed alloys are superposed on the preliminary 600°C isothermal section in Figure 4.9. It is obvious that most alloys in the system are very brittle, since many of the alloys exhibited fairly major cracking. The only alloys that stood out as having better toughness were $Pt_{58}$:$Al_{10}$:$Cr_{32}$ (planar slip), $Pt_{63}$:$Al_{22}$:$Cr_{15}$ (planar slip) and $Pt_{50}$:$Al_{10}$:$Cr_{40}$ (wavy slip). The latter alloy contained ~CrPt, while the other two contained ~$Pt_3Al$.

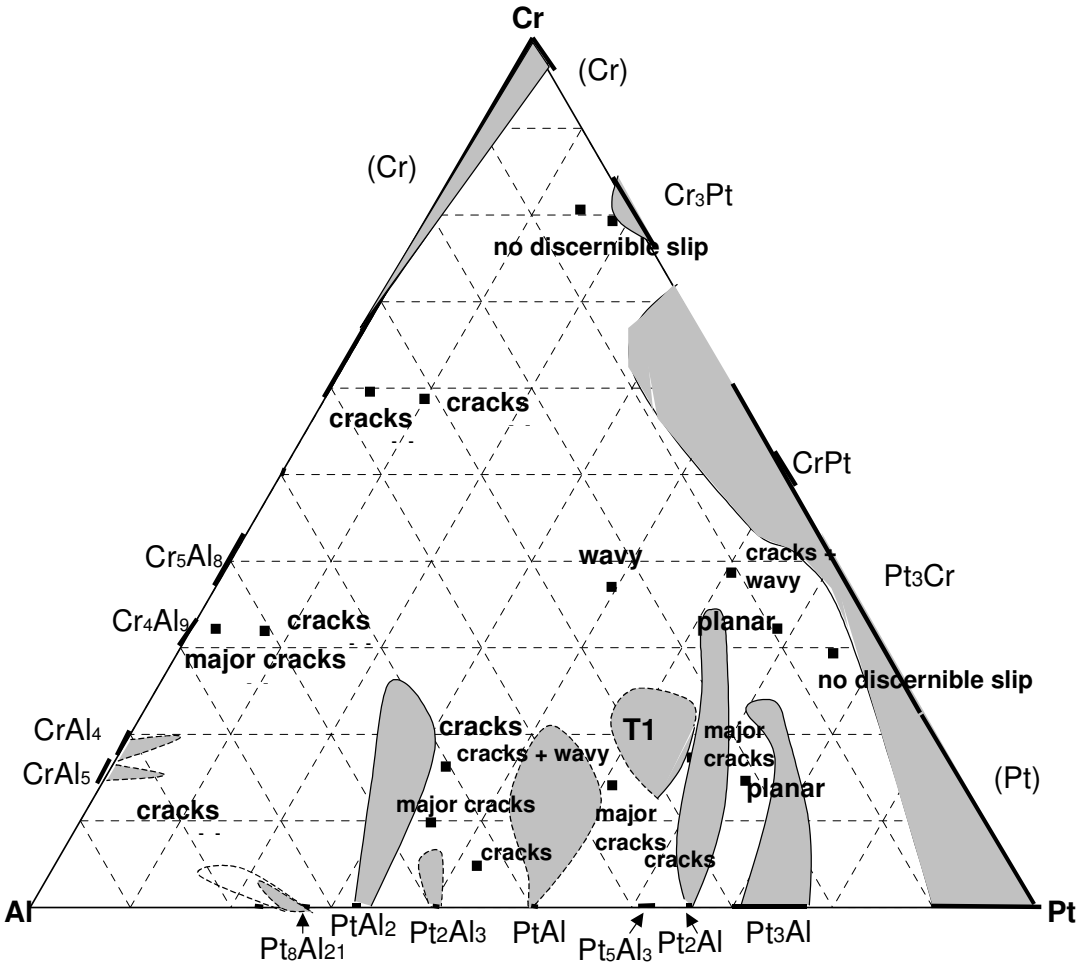



*Figure 4.9. Summary of the slip modes of Pt-Cr-Al alloys annealed at 600°C for 2500 hours, superposed on the 600°C isothermal section.*

## 2.3. Conclusions

Based on the examination of hardness indentations, alloys in the Pt-Al-Cr system generally seemed to be brittle regardless of their state of heat treatment. This was evident from the cracking that was observed in the majority of samples. This was expected considering the high hardness values that were obtained for the system. Most of the intermetallic compounds in the system are hard and decrease the toughness of most alloys. Generally, those alloys containing ~CrPt and in particular ~$Pt_3Al$ showed much better toughness. The fact that alloys containing ~$Pt_3Al$ showed better behaviour with regard to toughness was encouraging for the Pt-based alloys that are being developed by Mintek.

# PART FIVE: GENERAL CONCLUSIONS

- After using SEM, EDX and XRD on a selection of alloys, the following diagrams were successfully constructed for the Pt-Al-Cr system:
  - solidification projection
  - liquidus surface projection
  - isothermal sections at 600°C and 1000°C.
- It was concluded that all phase regions were identified correctly since the results were self-consistent.
- None of the diagrams were dominated by any particular phase.
- Three ternary phases were found in the Pt-Al-Cr system.
- The ~CrPt/~$Pt_3Cr$ and ~$Pt_3Cr$/(Pt) boundaries were shown as dashed lines, indicating either the uncertainty of where the ordering reactions of Massalski [1990Mas] occur, or the estimated positions of the ~CrPt/~$Pt_3Cr$ and ~$Pt_3Cr$/(Pt) two-phase regions of Zhao [2005Zhao].
- 19 ternary invariant reactions were identified in the Pt-Al-Cr system.
- It was confirmed that the two eutectic temperatures in the published Pt-Cr system [1990Mas] are the wrong way around [2004Süs1, 2005Nzu, 2005Süs, 2006Süs1].
- Single-phase alloys suggested the congruent melting of ternary phase T1, which confirmed a ternary phase, rather than a peritectically formed binary phase. Work is being done to get more precise crystallographic data for the phase [2007Ngw].
- Based on the examination of hardness indentations, alloys in the Pt-Al-Cr system generally seemed to be brittle regardless of their state of heat treatment due to the presence of hard intermetallic compounds.
- Alloys containing ~$Pt_3Al$ showed better behaviour with regard to toughness which was encouraging for the Pt-based alloys that are being developed by Mintek.
- A thermodynamic database was developed for the Pt-Al-Cr system using Thermo-Calc. The database could be used to get a very good prediction of phase relations between 600°C and 1000°C, and even up to temperatures close to the melting point, reasonable results would be obtained.

- The calculated results complimented the experimental work significantly and the value of the CALPHAD method as a tool in alloy design has been clearly demonstrated.
- However, the match between the calculated and experimental diagrams could be improved.
- The fact that the stability range of $Pt_3Al$, (Pt), $Pt_3Cr$ and CrPt (the ordered and disordered fcc phases in the Al-Pt and Cr-Pt systems) were inconsistent with regard to the experimental results clearly showed that the 4SL-CEF model description for L12 was problematic. This was underlined when attempting to calculate a liquidus surface projection using both Thermo-Calc and Pandat.
- As with the Cr-Pt-Ru system, problems with the constituting binary systems seems to be the major cause for problems encountered in the modelling.
- Currently, it would be a waste of time to optimise the databases (both Pt-Al-Cr and Cr-Pt-Ru) for the intermetallic phases any further because there are too many unknowns in the binary systems.
- Only once the Al-Pt and especially the Cr-Pt and Cr-Ru binary phase diagrams are confirmed more rigorously, the calculated ternary phase diagrams could be worked on with more confidence, which should make extrapolation into the quaternary not only easier, but also more valid.
- It is therefore recommended to:
  - Undertake slow scanning rate DTA for samples in the Cr-Pt and Cr-Ru systems to obtain reaction temperatures.
  - Undertake phase diagram studies in the Cr-Pt and Cr-Ru systems to obtain better phase equilibria data.
  - Consider the use of differential scanning calorimetry (DSC) to obtain thermodynamic values (enthalphy of formation) for phases in the Pt-Al-Cr and Pt-Cr-Ru systems.
  - Consider reassessing the Cr-Pt model with regard to Zhao's results and evaluating the effect on the overall system.
- Work on a thermodynamic database is seldom considered "complete"; there is always more work to undertake. Since there were very few data prior to this investigation, the results obtained here are significant.

**REFERENCES**


[1888Bar] C. Barus, *Am. J. Sci.,* 36 (1888) 427-442.

[1930Mül] L. Müller, *Ann. Phys*. (Leipzig), **7**(5) (1930) 9-47.

[1934Nem] W.A. Nemilow, *Z. Anorg. Allg. Chem.*, 218 (1934) 33-44.

[1935Fri] E. Friederich, A. Kussman, *Phys. Z.*, **36**(6) (1935) 185-192.

[1937Zin] E. Zintl, A. Harder and W. Haucke, *Z. Phys. Chem*., B35 (1937) 354.

[1940Geb] E. Gebhardt, Köster, *Z. Metallkd*., 32 (1940) 262-264.

[1948Red] O. Redlich and A.T. Kister, *Ind. Eng. Chem.* (2) (1948), 345.

[1955Rau] E. Raub, W. Mahler, *Z. Metallkd*., 46 (1955) 210-255.

[1956Gre] P. Greenfield, P.A. Beck, *Trans. AIME*, 206 (1956) 265-276.

[1956Sch] K. Schubert, W. Burkhardt, P. Esslinger, E. Gunzel, H. Meissner, W. Schutt, J. Wegst and M. Wilkens, *Naturwissenschaften*, 43 (1956) 248-249.

[1960Kub] O. Kubaschewski, G. Heymer, *Trans. Faraday Soc.,* 56 (1960) 473-478.

[1962Pic] S.J. Pickart, R. Nathans, *J. Appl. Phys*., **33**(3) (1962) 1336-1338.

[1962Bro] W. Bronger and W. Klemm, *Z. Anorg. Alg. Chem*., 319 (1962) 58.

[1963Fer] R. Ferro and R. Capelli, *Rend. Acad. Naz. Lincei*., 34 (1963) 659.

[1963Koe] W. Koester, E. Watchel, K. Grube, *Z. Metallkd*., 54 (1963) 393-401.

[1963Mag] A. Magneli, L. Edshammer and T. Dagerhamm, *Final technical report no. 1 under contract no dA-91-591-EUC-2734 (AD426927)* (1963) 44-50.

[1963Pic] S.J. Pickart, R. Nathans, *J. Appl. Phys.,* **34**(4) (1963) 1203-1204.

[1964Com] J.J. Comer, *Acta Cryst*., 17 (1964) 444-445.

[1965Sch] K. Schwerdfeger, A. Maun, *Trans. AIME*, 233 (1965) 1904-1906.

[1968Eds] L. Edshammer, *Acta Chem. Scand*., 22 (1968) 2374-2375.

[1964Huc] R. Huch and W. Klemm, *Z. Anorg. Alg. Chem*., 329 (1964) 123-135.

[1968Fer] R. Ferro, R. Gapelli, A. Borsese and G. Centineo, *Ren. Della Classe di Sci. Fis. Mat e Nat, VII* (1968) 10-15.

[1968Joh] W. Johnson, K. Komarek, E. Miller, *Trans. Met. Soc. AIME*, 242 (1968) 1685-1688.

[1968Kus] A. Kussman, K. Müller, E. Raub, *Z. Metallkd*., 59 (1968) 859-863.

[1970Dar] A.S. Darling, G.L. Selman and R. Rushforth, Plat. *Met. Rev*., 14 (1970) 124-130.

[1970Hil] M. Hillert and L.I. Staffanson, *Acta Chem. Scand*., 24 (1970) 3618-3626.

[1970Kay] D.A.R. Kay, A.K., Mohanty, *Metall. Trans.* 1 (1970) 303-304.

[1970Nag] H. J. Nagasawa, *Phys. Soc. Jpn*., **28**(5) (1970) 1171-1180.

[1971Sam] V.V. Samokhval, A.A Vecher, *Izv. Akad. Nauk, Metally*, 6 (1971) 118-120.

[1972Sta] W.M. Star, E. De Vroede, C. Van Baarle, *Physica*, 59 (1972) 128-154.

[1973Bes] M.J. Besnus, A.J.P. Meyer, Phys. *Status solidi (b),* 58 (1973) 533-542.

[1973Kue] R. Kuentzler, A.J.P. Meyer, *Phys. Lett. A*, **43**(1) (1973) 3-4.

[1973Wat] R.M. Waterstrat, *Metall. Trans*., 4 (1973) 1585-1592.

[1974Kue] R. Kuentzler and D.E. Moody, *Tr. Mezhdunar. Konf. Mag*., 6 (1974) 312-314.

[1975Cha1] T. Chattopadyay and K. Schubert, *J. Less-Common Met*., 41 (1975) 19-32.

[1975Mug] Y.M. Muggianu, M. Gambino, J.-P. Bros, *J. Chim. Phys. Phys.-Chim. Biol. (France)*, **72**(1), (1975), 83-88.

[1975Ohn] T. Ohnishi, Y. Nakatani, K. Okabayashi, *Bull. Univ. Osaka Prefect*, 24 (1975) 183-191.

[1975Ton] A.M. Tonejc, A. Tonejc and A. Bonifacic, *J. Material Sci*., 9 (1975) 535-526.

[1976Bag] J. Baglin, *et al*., *J. Electrochem. Soc*. 125 (1976) 1854.

[1976Cha] T. Chattopadyay and K. Schubert, *J. Less-Common Met.*, 45 (1976) 79-83.

[1976Gue] P. Guex and P. Feschotte, *J. Less-Common Met*.,46 (1976) 101-116.

[1977Bag] J. Baglin, F. d'Heurle, W.Hammer, S. Zirinsky*, Proc. 7th Int. Vacuum Congress and 3rd Int. Conf. Solid surfaces*, 3 (1977) 2127-2130.

[1977Bra] J.K. Brandon, W.B. Pearson, P.W. Riley, C. Chieh, R. Stokhuyzen, *Acta Crystallogr.*, 3B (1977) 1088-1095.

[1977Got] T. Goto, *J. Phys. Soc. Jpn*., 43 (1977) 1848-1853.

[1977Mie] A.R. Miedema, F.R. de Boer, R. Boom, *Calphad*, 1 (1977) 341-359.

[1977Pel] A.D. Pelton, C.W. Bale and W.T. Thompson, NBS SP-496, *Applic. of Phase. Diags. in Metall. & Ceramics, F'roc. NBS* Workshop Gaithersburg, 1977, p 1077-1089.

[1978Bag1] J. Baglin, J. Dempsey, F. d'Heurle, W. Hammer and S. Zirinsky, *Proc. Electrochem. Soc*., 78-2 (1978) 185-198.

[1978Bag2] J. Baglin, F. d'Heurle, W. Hammer and S. Zirinsky, *Proc. Electrochem. Soc.,* 125 (1978) 1854-1859.

[1978Bah] S. Bahn and H. Kudielka, *Z. Metallkde*, 69 (1978) 333-334.

[1978Sch] K. Schubert, *Z. Krist.,* 70 (1978) 318.

[1979Cha] T. Chattopadyay and P. Mamachandrarao, *Mater. Sci. Eng.,* 38 (1979) 7-17.

[1979Ole] A. Oles, A. Bombik, *Phys. Status Solidi* (b), 92 (1979) K81-K83.

[1980But] A.K. Butylenko, V.V. Nevdacha, *Dop. Akad. Nauk Ukr. RSR A, Fiz.-Mat. Tekh*., **42**(5) (1980) 66-69.

[1980Pia] G. Piatti anf G. Pellegrinin, *J. Mater. Sci*., 15 (1980) 2403-2408.

[1981Den] F.J.A. den Broeder, G. van Tendeloo, S. Amelinckx, J. Hornstra, R. de Ridder, J. van Landuyt, H.J. van Daal, *Phys. Stat. Sol.(a),* 67 (1981) 233-248.

[1981Kue] R. Kuentler, *Physics of Transition metals*, P. Rhodes, ed., Institute of Physics, Bristol, UK (1981) 397-400.

[1981Sun] B. Sundman and J. Agren, J. Phys. Chem. Solids, 42 (1981) 297-.

[1981Van] G. van Tendeloo, F.J.A den Broeder, S. Amelinckx, R. de Ridder, J. van Landuyt, H.J. Daal, *Phys. Stat. Sol*.(a), 67 (1981) 217-232.

[1982DeB] F.R. de Boer, R., Boom, A.R., Miedema, *Physica*, 113B, 18-41 (1982).

[1982Ell] M. Ellner, U. Kattner and B. Predel, *J. Less-common Metal*., 87 (1982) 305-325.

[1985Dun] R.A. Dunlap, K. Dini, *Can. J. Phys*., 63 (1985) 1267-1269.

[1985Sun] B. Sundman, B. Jansson and J.O. Andersson, *Calphad*, 9 (1985) 153.

[1985Vil] P. Villars and L.D. Calvert (eds.) *Pearson's Handbook of Crystallographic data for Intermetallic phases*, Vol. 2 Ohio, USA, ASM (1985).

[1985Vil1] P. Villars and L.D. Calvert (eds.) *Pearson's Handbook of Crystallographic data for Intermetallic phases*, *Vol. 2,* Ohio, USA, ASM (1985) 1850.

[1985Vil2] P. Villars and L.D. Calvert (eds.) *Pearson's Handbook of Crystallographic data for Intermetallic phases*, *Vol. 2,* Ohio, USA, ASM (1985) 1890.

[1985Vil3] P. Villars and L.D. Calvert (eds.) *Pearson's Handbook of Crystallographic data for Intermetallic phases*, *Vol. 3,* Ohio, USA, ASM (1985) 3044.

[1986Ben] L. Bendersky, R.J. Schaefer, F.S. Biancaniello, D. Shechtman, *J. Mat. Sci*., 21 (1986) 1889-1896.

[1986And] J-O. Andersson, A.F. Guillermet, M. Hillert, B. Jasson, B. Sundman, *Acta Metall.,* 34 (1986) 437-445.

[1986Lil] D.A. Lilienfeld, M. Nastasi, H.H. Johnson, D.G. Ast, J.W. Mayer, J. Mater. Res., **1**(2) (1986) 237-242.

[1986Mca] A.J. McAlister and D.J. Kahan*, Bull. Alloy Phase Diagr*., 7 (1986) 47-51.

[1986Mis] Y. Mishima, Y. Oya, T. Suzuki, *Proceedings of the International Conference on Martensitic Transformations*, Japan Institute of Metals (1986) 1009.

[1986Sau] N. Saunders, V.G. Rivlin, *Mater. Sci. Technol*., 2 (1986) 521-527.

[1987Oya] Y. Oya, Y. Mishima and T. Suzuki*, Z. Metalktd*, 78 (1987) 485-490.

[1987Sau] N. Saunders, V.G. Rivlin, *Z. Metallkde*., 78 (1987) 795-801.

[1987Sim] C.T. Sims, N.S. Stoloff, and W.C. Hagel, *Superalloys II*, Wiley Interscience, USA (1987).

[1988DeB] F.R. de Boer, R. Boom, W.C.M. Maartens, A.R. Miediema and A.K. Niessen, *Cohesion in Metals: Cohesion and Structure Vol. 1,* Elsevier Science, Amsterdam (1988).

[1988Smi] William F. Smith, Principles of Materials Science and Engineering, 2nd ed., McGraw-Hill, Singapore (1988), p. 272.

[1988Zha] H. Zhang, D.H. Wang, K.H. Kuo, *Phys. Rev. B*., 37 (1988) 6220-6225.

[1989Din] A.T. Dinsdale, S.M. Hodson, T.I.. Barry, J .R. Taylor, *Computer Software in Chemical and Exfractive Metallurgy,* (Pergamon press, Oxford, 1989), pp. 59-74.

[1989Ell] M. Ellner, J. Braun, B. Predel, *Z. Metallkde*., **80**(5) (1989) 374-383.

[1989Sok] E.M. Sokolovskaya, E.F. Kazakova, E.I. Podd'yakova, *Met. Sci. and Heat Treatment,* 31 (1989) 837-839.

[1990Die] George E. Dieter, Mechanical Metallurgy, SI Metric ed., McGraw-Hill, London (1990), p. 325.

[1990Eri] G. Eriksson and K. Hack, *Metall. Trans. B*, 21B (1990) 1013-1023.

[1990Mas] Massalski, T.B. (Ed.-in-chief), Binary Alloy Phase Diagrams, 2nd edition, Ohio, USA, Amer. Soc. Metals.

[1990Sud] V.S. Sudavtsova, A.V. Shuvalov, N.O. Sharkina, *Rasplavy*, 4 (1990) 97-99.

[1990Ter] S.V. Terekhov, V.N. Radchenko, *Russ. Metall*., 5 (1990) 44-46.

[1990Ven] M. Venkatraman, J.P. Neumann, *Bull. Alloy Phase Diagrams*, **11**(1) (1990) 16-21.

[1991Din] A.T. Dinsdale, *Calphad*, 15 (1991) 317-425.

[1991Din] A.T. Dinsdale, *Calphad*, 17 (1991) 319.

[1991Jun] W-G. Jung, O.J. Kleppa and L. Topor, *J. Alloys and Compounds*, 176 (1991) 404-414.

[1992Bar] A. Baran, H.L. Alberts, A.M. Strydom,., P. de V du Plessis, *Phys. Rev. B*, **45**(18) (1992) 10473-10484.

[1992Bra] J. Braun, M. Ellner, B. Predel, *J. Alloys and Compounds*, 183 (1992) 444-448.

[1992Cos] J.G. Costa Neto, S. Gama, C.A. Ribeiro, *J. Alloys and Compounds*, 182 (1992) 271-280.

[1992Wen] K.Y. Wen, Y.L.,Chen, K.H. Kuo, *Met. Trans. A*, 23A (1992) 2437-2445.

[1993Cho] J.D. Choi, J.S. Kwak, J.S. Hong, E.J. Chi, S.W. Park, H.K. Baik, K.H. Chae, S.M. Jung, C.N. Whang, *J. of the Korean Inst. of Met. and Mater*., **31**(8) (1993) 1004-1013.

[1993Mes] S.V. Meschel and O.J. Kleppa, *J. Alloys and Compounds,* 197 (1993) 75-81.

[1994Abr] V.O. Abramov, F. Sommer, *Materials Letters*, 20 (1994) 251-255.

[1994Dia] B.J. Diak, M. Whitehead, S. Saimoto*, Experimental Methods of Phase Diagram Determination*, J.E. Morral, R.S. Schiffman, S.M. Merchant, (Eds.), The Minerals, Metals and Materials Society (1994).

[1994Mes] S.V. Meschel, O.J. Kleppa, *Metallic Alloys: Experimental and Theoretical Perspectives*, J.S., Faulkner, R.G. Jordan, (Eds.), Kluwer, Dordrecht, 103-112 (1994).

[1994Sel] H. Selke, U. Vogg, P.L Ryder, *Phys. Stat. Sol. (a)* **141**(31) (1994) 31-41.

[1994Zub] A.A. Zubkov, *J. Chem. Thermodynamics*, 26 (1994) 1267-1274.

[1995Aud] M. Audier, M. Durand-Charre, E. Laclau, H. Klein, *J. Alloys and Compounds*, 220 (1995) 225-230.

[1996Lee] J.S. Lee, S.L. Kwun, *J. of the Korean Inst. of Met. and Mater*., **34**(4) (1996) 433-439.

[1997Ans] I. Ansara, N. Dupin, H.L. Lukas and B. Sundman, *J. Alloys and Compounds,* 247 (1997) 20-30.

[1997Li] X.Z. Li, K. Sugiyama, K. Hiraga, A. Sato, A. Yamamoto, H.X Sui, K.H Kuo, *Z. Kristallogr.,* 212 (1997) 628-633.

[1998Ans] I. Ansara, A.T. Dinsdale, M.H. Rand, *EUR 18171 - COST507*: *Thermochemical Database for Light Metal Alloys (Volume 2),* European Communities, 23-27 (1998).

[1998Li] X.Z. Li, H.X Sui, K.H. Kuo, K. Sugiyama, K. Hiraga, *J. Alloys and Compounds*, 364 (1998) L9-L12.

[1998Mur] J.L. Murray, *J. Phase Equil*., **19**(4) (1998) 368-375.

[1998Spe] Noble Metal Database, The Spencer Group, 1995.

[1998Sun] B. Sundman, S.G. Fries and W.A. Oates, *Calphad,* 22 (1998) 335-354.

[1998Wol] I.M. Wolff, Private Communication to S. Prins [2004Pri].

[1999Hel] T. Helander, O. Tolochko, *J. Phase Equilibria*, **20**(1) (1999) 57-60.

[2000Com1] D.N. Compton, L.A. Cornish and M.J. Witcomb, *Microscopy and Microanalysis 2000*, Volume 6, Supplement 2, 370-371, Philadelphia, Pennsylvania, USA, 13th-17th August 2000.

[2000Com2] D.N. Compton, L.A. Cornish and M.J. Witcomb, *Proc. Microsc. Soc. South. Afr.,* 30 (2000) 9.

[2000Hil1] P.J. Hill, L.A. Cornish and M.J. Witcomb, *International Symposium on High Temperature Corrosion and Protection 2000*, Rusutsu Resort Hotel, 185-190, Japan, 17th-22nd September 2000.

[2000Jcp] JCPDS – ICDDD Powder Diffraction File, 2000.

[2000Mah] K. Mahdouk, J.-C. Gachon, *J. Phase Equil.*, **21**(2) (2000) 157-166.

[2000Sha1] G. Shao, P. Tsakiropoulos, *Acta Mater.*, 48 (2000) 3671-3685.

[2000Sha2] G. Shao, D. Nguyen-Manh, D.G. Pettifor, P. Tsakiropoulos, *Phil. Mag. Let.*, **80**(11) (2000) 703-710.

[2000Sub] N. Subasic, B. Sundman, *Proc. Meet. Thermodyn. Alloys,* (2000) 42.

[2000Uch] M. Uchida, Y. Matsui, *Acta Cryst.*, B56 (2000) 654-658.

[2000Wol] I.M. Wolff and P.J. Hill, *Plat. Metals Rev.*, **44**(4) (2000) 158-166.

[2000Wu] K. Wu and Z. Jin, *J. Phase Equilibria*, 21 (2000) 221.

[2001Big] T. Biggs, *An investigation into displacive transformations in platinum alloys*, Ph.D. thesis, University of the Witwatersrand, (2001).

[2001Com] D.N. Compton, L.A. Cornish and M.J. Witcomb, *Microscopy and Microanalysis 2001*, Vol. 7, Supplement 2, 1248-1249. Pub. Springer-Verlag, NY, Inc., Long Beach, California, USA.

[2001Dup] N. Dupin, I. Ansara, B. Sundman, Calphad, **25**(2) (2001) 279-298.

[2001Har] K.C. Hari Kumar and P. Wollants, *J. Alloys and Compounds*, 320 (2001) 189-198.

[2001Hil1] P.J. Hill, Y. Yamabe-Mitarai, H. Murakami, L.A. Cornish, M.J. Witcomb, I.M. Wolff and H. Harada, TMS, 527-533. Snow King Resort, Jackson Hole, Wyoming, USA, Sept 2001. Rescheduled for 28th April - 1st May 2002.

[2001Hil2] P.J. Hill, L.A. Cornish, M.J. Witcomb and P. Ellis, *J. Alloys and Compounds*, 322 (2001) 166-175.

[2001Hil3] P.J. Hill, L.A. Cornish and M.J. Witcomb, *Proc. Microsc. Soc. South. Afr.*, 31 (2001) 22.

[2001Hil4] P.J. Hill, *Superalloy analogues based on platinum for ultra-high temperature applications*, Ph.D. thesis, University of the Witwatersrand, (2001).

[2001Lab] J.L. Labar, A. Kovacs and P.B. Barna, *J. Appl. Physics*, 90 (2001) 6545-6547.

[2001Mes] S.V. Meschel, O.J. Kleppa, *J. Alloys and Compounds*, 321 (2001) 183-200.

[2001Oik] K. Oikawa, G.W. Qin, T. Ikeshoja, O. Kitakami, Y. Shimada, K. Ishida K. Fukamichi, *J. Magnetism and Magnetic Mat.*, 236 (2001) 220-233.

[2001Süs1] R. Süss, P.J. Hill, P. Ellis and I.M. Wolff, *Proc. of the 7th European Conference on Advanced Materials and Processes*, Rimini, Italy, 10th-14th June 2001. CD-ROM: ISBN 8885298397.

[2001Süs2] R. Süss, P.J. Hill, P. Ellis and L.A. Cornish, *Proc. Microsc. Soc. South. Afr.,* 31 (2001) 21.

[2002And] J-O. Andersson, T. Helander, L. Höglund, P. Shi and B. Sundman, *Calphad*, **26**(2) (2002) 273-312.

[2002Bal] C. W. Bale, P. Chartrand, S. A. Degterov, G. Eriksson, K. Hack, R. Ben Mahfoud, J. Melançon, A. D. Pelton and S. Petersen, *Calphad*, **26**(2) (2002) 189-228.

[2002Che] S. -L. Chen, S. Daniel, F. Zhang, Y. A. Chang, X. -Y. Yan, F. -Y. Xie, R. Schmid-Fetzer and W. A. Oates, *Calphad*, **26**(2) (2002) 175-188.

[2002Cor1] L.A. Cornish, J. Hohls, P.J. Hill, S. Prins, R. Süss and D. Compton, Presented at the 34th International October Conference on Mining and Metallurgy, Bor Lake, Yugoslavia, September 30 – October 3, 2002.

[2002Cor2] L.A. Cornish, P. Saltykov and G. Cacciamani, accepted by Materials Science International Services GmbH and the Max-Planck-Institut für Metallforschung, PML.

[2002Ngo] P. Ngoepe, Private Communication to S. Prins [2004Pri].

[2002Dav] R.H. Davies, A.T. Dinsdale, J.A. Gisby, J.A.J. Robinson and S.M. Martin, *Calphad*, **26**(2) (2002) 229-271.

[2002Pri1] S. Prins, L.A. Cornish, W. Stumpf and B. Sundman, *CALPHAD XXXI Programme and Abstracts*, Stockholm, May 5-10 2002.

[2002Pri2] S. Prins and L.A. Cornish, *ICEM 15, Proceedings of the 15th International Congress on Electron Microscopy*, 1st - 6th September 2002, Durban, South Africa.

[2002Sal] P. Saltykov, V.T. Witusiewicz, I. Arpshofen, H.J. Seifert, F. J. Aldinger, *Mat. Sci. Technol.*, 18 (2002) 167-170.

[2002Süs1] R. Süss, L.A. Cornish, L. Glaner and D.N. Compton, *ICEM 15, Proceedings of the 15th International Congress on Electron Microscopy*, 1st - 6th September 2002, Durban, South Africa.

[2002Süs2] R. Süss, D. Freund, R Völkl, B. Fischer, P.J. Hill, P. Ellis and I.M. Wolff, *Materials Science and Engineering A338* (2002) 133-141.

[2003Gla] U. Glatzel, S.N. Prins, *Calphad XXXII Program and Abstracts*, Quebec, Canada, May 25-30, 2003, 118.

[2003Pri] S.N. Prins, L.A. Cornish, W.E. Stumpf, B. Sundman, *Calphad 27*(1) (2003) 79-90.

[2003Süs1] R. Süss, L.A. Cornish and B. Joja. Proc. Microsc. Soc. South. Afr., 33 (2003) 13.

[2003Süs2] R. Süss, U. Glatzel, U., S.N. Prins, L.A. Cornish. *Proc. 2nd International Conference of the African Materials Society,* Johannesburg, 2003, 141-142.

[2003Süs3] R. Süss, L.A. Cornish and B. Joja. *Proc. 2nd International Conference of the African Materials Society*, Johannesburg, 2003. p. 138-139.

[2004Pri1] S.N. Prins, *The Al-Pt-Ru ternary phase diagram*, M.Sc. dissertation, University of Pretoria, Pretoria, South Africa, 2004.

[2004Pri2] S.N. Prins, Private Communication to L.A. Cornish, October 2004.

[2004Süs1] R. Süss, *Investigation of the Pt-Cr-Ru system*, M.Sc. dissertation, University of the Witwatersrand, 2004.

[2004Süs2] R. Süss, L.A. Cornish and U. Glatzel, *CALPHAD XXXIII Program and Abstracts*, 34, Krakow, Poland, 30th May - 4th June 2004.

[2004Süs3] R. Süss, A. Douglas and L.A. Cornish, *Proc. Microsc. Soc. South. Afr.*, 34 (2004) 10.

[2004Zhao] J.-C. Zhao, Journal of Materials Science, 39 (2004) 3913 – 3925.

[2005Nzu] M. Nzula and L.A. Cornish, *Proc. Microsc. Soc. South. Afr.*, 35 (2005) 8.

[2005Pri] S. N. Prins, L.A. Cornish and P. Boucher, *J. Alloys and Compounds,* 403 (2005) 245-252.

[2005Süs] R. Süss and L.A. Cornish, *Proc. Microsc. Soc. South. Afr.*, 35 (2005) 9.

[2005Zha] J.-C. Zhao, X. Zeng and D. Cahill, *Materials Today*, October 2005, 28-37.

[2006Cor] L.A. Cornish, R. Süss, A. Watson and S.N. Prins, Building a database for the prediction of phases in a Pt-based Superalloys, Southern African Institute of Mining and Metallurgy SAIMM conference “Platinum Surges Ahead”, Sun City, 8th – 12th October 2006, Symposium Series S45, 91-102.

[2006Pre] J. Preussner, M. Wenderoth, S. Prins, R. Völkl and U. Glatzel, Platinum alloy development - the Pt-Al-Cr-Ni system, Southern African Institute of Mining and Metallurgy SAIMM conference “Platinum Surges Ahead”, Symposium Series S45, 91-102, Sun City, 8th – 12th October 2006, p. 103-4.

[2006Sch] R. Schmid-Fetzer, D. Andersson, P.Y. Chevalier, L. Eleno, O. Fabrichnaya, U.R. Kattner, B. Sundman, C. Wang, A. Watson, L. Zabdyr and M. Zinkevich, *Computer Coupling of Phase Diagrams and Thermochemistry,* 31 (2007) 38-52.

[2006Süs1] R. Süss, L.A. Cornish and M.J. Witcomb. *J. Alloys and Compounds,* 416(1-2) (2006) 80-92.

[2006Süs2] R. Süss and L.A. Cornish, *Proc. Microsc. Soc. South. Afr.*, 36 (2006) 14.

[2006Tsh] W. Tshawe, A. Douglas, B. Joja and L.A. Cornish, *Proc. Microsc. Soc. South. Afr.*, 36 (2006) 15.

[2006Wat] A. Watson, L.A. Cornish, and R. Süss, *Rare Metals*, 25(5) (2006) 1-11.

[2007Int] Internet URL: http://www.platinum.matthey.com/applications/properties.html (Accessed January 2007).

[2007Ngw] T.B. Ngwenya, *Extending the x-ray diffraction database for the PGM-based alloys*, M.Sc. dissertation, University of the Western Cape, 2007.

# APPENDICES

## APPENDIX A

Publications

## APPENDIX B

Thermodynamic databases for Pt-Al-Cr (in TDB format)

## APPENDIX A

### Publications

### Conference abstracts (no proceedings)

[2004Süs2] R. Süss, L.A. Cornish and U. Glatzel, *CALPHAD XXXIII Program and Abstracts*, 34, Krakow, Poland, 30th May - 4th June 2004.

[2007Süs] R. Süss, L.A. Cornish and A. Watson, *CALPHAD XXXVI Program and Abstracts*, 146, The Pennsylvania State University, State College, Pennsylvania, 6th - 11th May 2007.

### Published conference proceedings

[2003Süs3] R. Süss, L.A. Cornish and B. Joja*. Proc. 2nd International Conference of the African Materials Society*, Johannesburg, 2003. p. 138-139.

[2005Süs] R. Süss and L.A. Cornish, *Proc. Microsc. Soc. South. Afr.*, 35 (2005) 9.

[2006Cor] L.A. Cornish, R. Süss, A. Watson and S.N. Prins, Southern African Institute of Mining and Metallurgy SAIMM conference "Platinum Surges Ahead", Sun City, 8th – 12th October 2006, Symposium Series S45, 91-102.

[2006Süs2] R. Süss and L.A. Cornish, *Proc. Microsc. Soc. South. Afr.*, 36 (2006) 14.

### Published journal papers

[2006Wat] A. Watson, L.A. Cornish, and R. Süss, *Rare Metals*, 25(5) (2006) 1-11.