

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 ₅ Al ₈ , ~PtAl ₂
Pt ₁₀ :Al ₈₀ :Cr ₁₀	367 ± 20	~CrAl ₅ , ~Pt ₈ Al 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 ₂ Al
Pt ₄₀ :Al ₃₀ :Cr ₃₀	743 ± 13	T1
Pt ₄₀ :Al ₅₀ :Cr ₁₀	841 ± 76	~Pt ₂ Al 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 ₂ Al
Pt ₆₅ :Al ₅ :Cr ₃₀	322 ± 21	~Pt ₃ Cr, ~Pt ₃ Al
Pt ₃ :Al ₆₅ :Cr ₃₂	670 ± 32	~Cr ₄ Al ₉ , ~PtAl ₂
Pt ₃ :Al ₃₅ :Cr ₆₂	637 ± 26	~Cr ₂ Al, ~PtAl ₂ , T2≈Cr ₃ Al ₂
Pt ₁₀ :Al ₅₀ :Cr ₄₀	762 ± 16	T2≈Cr ₃ Al ₂ , ~PtAl ₂ , ~Cr ₅ Al 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 ₄ Al ₉
Pt ₁₈ :Al ₂ :Cr ₈₀	767 ± 29	~CrPt, ~Cr ₃ Pt, (Cr)
Pt ₂₈ :Al ₁₂ :Cr ₆₀	462 ± 4	~CrPt, (Cr), T1
Pt ₂₈ :Al ₇₀ :Cr ₂	653 ± 89	~PtAl ₂ , ~Pt ₈ Al ₂₁
Pt ₃₅ :Al ₅₅ :Cr ₁₀	822 ± 39	~PtAl ₂ , ~Pt ₂ Al ₃ , ~PtAl
Pt ₃₈ :Al ₂₂ :Cr ₄₀	717 ± 27	T1, ~CrPt
Pt ₄₃ :Al ₅₂ :Cr ₅	818 ± 69	~Pt ₂ Al ₃ , ~PtAl
Pt ₅₀ :Al ₃₅ :Cr ₁₅	739 ± 14	T1
Pt ₅₈ :Al ₁₀ :Cr ₃₂	697 ± 18	~Pt ₃ Al, ~CrPt
Pt ₆₀ :Al ₂ :Cr ₃₈	333 ± 35	~CrPt
Pt ₆₃ :Al ₃₂ :Cr ₅	591 ± 65	~Pt ₂ Al, T1
Pt ₆₃ :Al ₂₂ :Cr ₁₅	673 ± 6	~Pt ₃ Al, ~Pt ₂ Al
Pt ₇₈ :Al ₁₇ :Cr ₅	407 ± 6	~Pt ₃ Al, (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 ₃ Al ₂ , ~PtAl ₂ , ~Cr ₅ Al ₈
Pt ₁₃ :Al ₄₅ :Cr ₄₂	688 ± 42	~PtAl ₂ , ~Cr ₂ Al
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 ₂ Al 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 ₂ Al
Pt ₅₅ :Al ₂₀ :Cr ₂₅	414 ± 61	~Pt ₂ Al
Pt ₆₄ :Al ₁₆ :Cr ₂₀	532 ± 15	~Pt ₃ Al, ~Pt ₃ Cr

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 Pt₇₆:Al₅:Cr₁₉ had a hardness of less than 300 HV_{10} , being single phase ~Pt₃Cr. The high Al-containing alloys Pt₃:Al₇₉:Cr₁₈ and Pt₁₀:Al₈₀:Cr₁₀ were also relatively low in hardness. Five alloys had exceptionally high hardnesses (> 800 HV_{10}) compared to the rest, namely alloy Pt₃₀:Al₅₀:Cr₂₀, which contained a majority of ~PtAl₂; alloys Pt₄₀:Al₅₀:Cr₁₀ and Pt₄₃:Al₅₂:Cr₅ which contained ~Pt₂Al₃ and ~PtAl; and alloys Pt₃₅:Al₅₅:Cr₁₀ and Pt₇₅:Al₁₀:Cr₁₅ (actual Pt₃₄:Al₄₉:Cr₁₇), which

contained $\sim\text{PtAl}_2$. Thus, $\sim\text{PtAl}_2$, $\sim\text{PtAl}$ and $\sim\text{Pt}_2\text{Al}_3$ 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 ± 38 to $788 \pm 45 \text{ HV}_{10}$, with no composition-related trend.

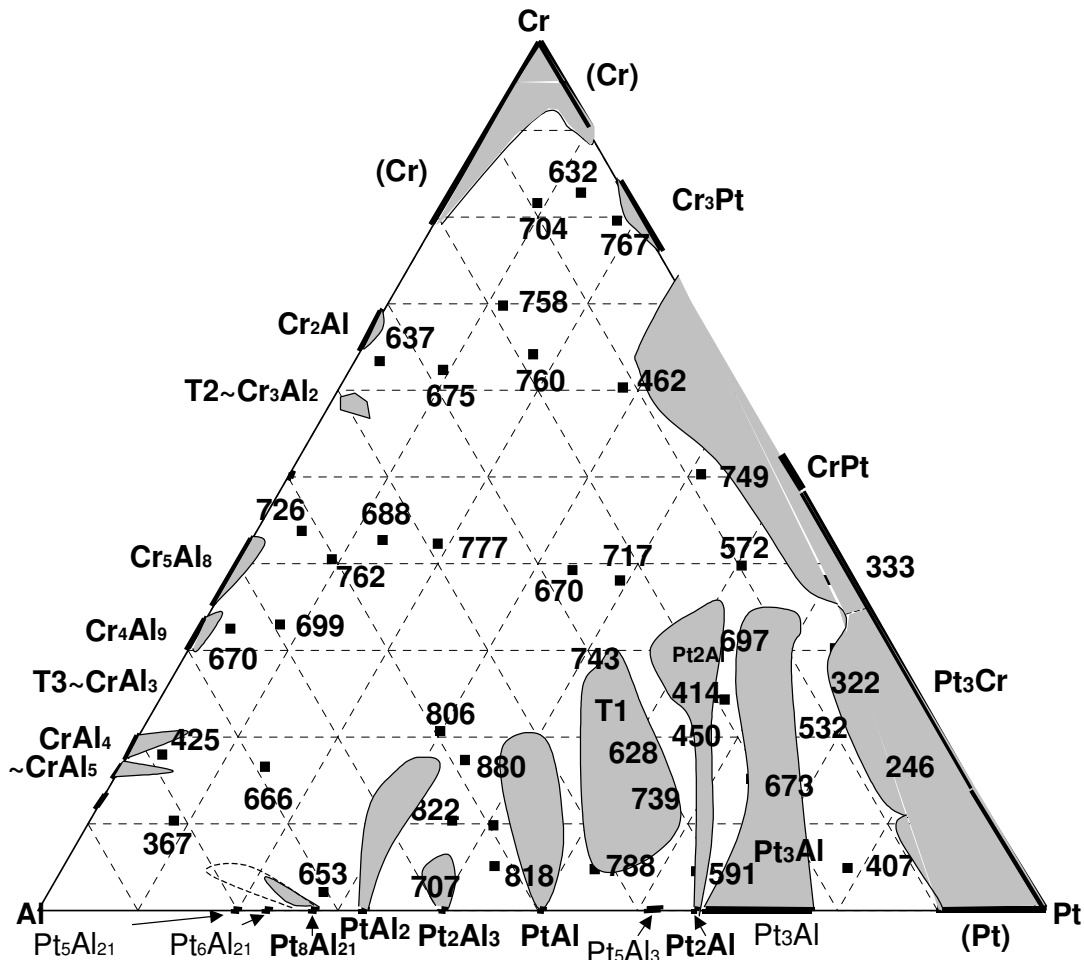


Figure 4.1. Hardness values of as-cast Pt-Cr-Al alloys superposed on the solidification projection.

1.2.2. Annealed at 1000 °C

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 $\text{Pt}_{65}:\text{Al}_5:\text{Cr}_{30}$, $\text{Pt}_{63}:\text{Al}_{32}:\text{Cr}_5$ and $\text{Pt}_{55}:\text{Al}_{25}:\text{Cr}_{20}$, even though, especially in the case of $\text{Pt}_{55}:\text{Al}_{25}:\text{Cr}_{20}$, the

microstructure had changed significantly. On the other hand, an alloy like Pt₁₀:Al₃₀:Cr₆₀ hardly changed during annealing, yet its hardness fell from 675 ± 17 to 241 ± 19 HV₁₀. This alloy was in fact very porous and the Vickers diamond indenter 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 Pt₅₀:Al₁₀:Cr₄₀ 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 (HV₁₀) 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 ₂ Al
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 ₂ Al ₃ , (Cr)
Pt ₅₀ :Al ₁₀ :Cr ₄₀	320 ± 42	572 ± 61	~CrPt
Pt ₆₅ :Al ₅ :Cr ₃₀	289 ± 7	322 ± 21	~Pt ₃ Al
Pt ₃ :Al ₆₅ :Cr ₃₂	556 ± 27	670 ± 32	~Cr ₄ Al ₉ , ~PtAl ₂
Pt ₃ :Al ₃₅ :Cr ₆₂	432 ± 32	637 ± 26	(Cr), ~PtAl ₂ , ~Cr ₂ Al/T ₂ ~Cr ₃ Al ₂
Pt ₁₈ :Al ₂ :Cr ₈₀	882 ± 10	767 ± 29	~Cr ₃ Pt, ~CrPt, (Cr)
Pt ₃₅ :Al ₅₅ :Cr ₁₀	755 ± 5	822 ± 39	~PtAl ₂ , ~Pt ₂ Al ₃ , (Cr)
Pt ₃₈ :Al ₂₂ :Cr ₄₀	629 ± 4	717 ± 27	Tl, ~Cr ₃ Pt, (Cr)
Pt ₄₃ :Al ₅₂ :Cr ₅	714 ± 20	818 ± 69	~PtAl, ~Pt ₂ Al ₃ , (Cr)
Pt ₅₀ :Al ₃₅ :Cr ₁₅	652 ± 19	739 ± 14	Tl, ~PtAl
Pt ₅₈ :Al ₁₀ :Cr ₃₂	581 ± 15	697 ± 18	~CrPt, ~Pt ₃ Al
Pt ₆₃ :Al ₃₂ :Cr ₅	652 ± 23	591 ± 65	~Pt ₂ Al
Pt ₆₃ :Al ₂₂ :Cr ₁₅	621 ± 11	673 ± 6	~Pt ₂ Al, ~Pt ₃ Al
Pt ₇₅ :Al ₁₀ :Cr ₁₅	750 ± 18	880 ± 10	~Pt ₂ Al ₃ , ~PtAl, (Cr)
Pt ₁₅ :Al ₅ :Cr ₈₀	544 ± 18	632 ± 4	~Cr ₃ Pt, (Cr), ~PtAl
Pt ₅₅ :Al ₂₅ :Cr ₂₀	458 ± 22	450 ± 75	Tl, ~Pt ₃ Al, ~Pt ₂ Al

Just over half the alloys had hardnesses above 600 HV₁₀, indicating that most phases in this system are fairly hard, which could be expected from intermetallic compounds. Only alloys Pt₅₀:Al₁₀:Cr₄₀ and Pt₆₅:Al₅:Cr₃₀ had hardnesses of less than 400 HV₁₀. Only three alloys had exceptionally high hardness (> 750 HV₁₀) compared to the rest, namely alloy Pt₁₈:Al₂:Cr₈₀, which contained a majority of ~Cr₃Pt; alloys Pt₃₅:Al₅₅:Cr₁₀ which contained ~PtAl₂ and ~Pt₂Al₃; and Pt₇₅:Al₁₀:Cr₁₅ (actual Pt₃₃:Al₅₁:Cr₁₆), which contained ~PtAl₂ and ~PtAl. As was

the case in the as-cast state, it was obvious that $\sim\text{PtAl}_2$, $\sim\text{PtAl}$ and $\sim\text{Pt}_2\text{Al}_3$ are very hard phases compared to the others in the system. $\sim\text{Cr}_3\text{Pt}$ is also very hard. It was also interesting to see that $\sim 75\%$ of the alloys that were annealed at 1000°C softened during annealing. The only ones that became harder were $\text{Pt}_{10}\text{:Al}_{80}\text{:Cr}_{10}$ ($\sim\text{Pt}_8\text{Al}_{21}$ disappeared during annealing), $\text{Pt}_{18}\text{:Al}_{2}\text{:Cr}_{80}$ (the alloy almost turning into single-phase $\sim\text{Cr}_3\text{Pt}$) and $\text{Pt}_{63}\text{:Al}_{32}\text{:Cr}_5$ (turning into single-phase $\sim\text{Pt}_2\text{Al}$, T1 disappearing).

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

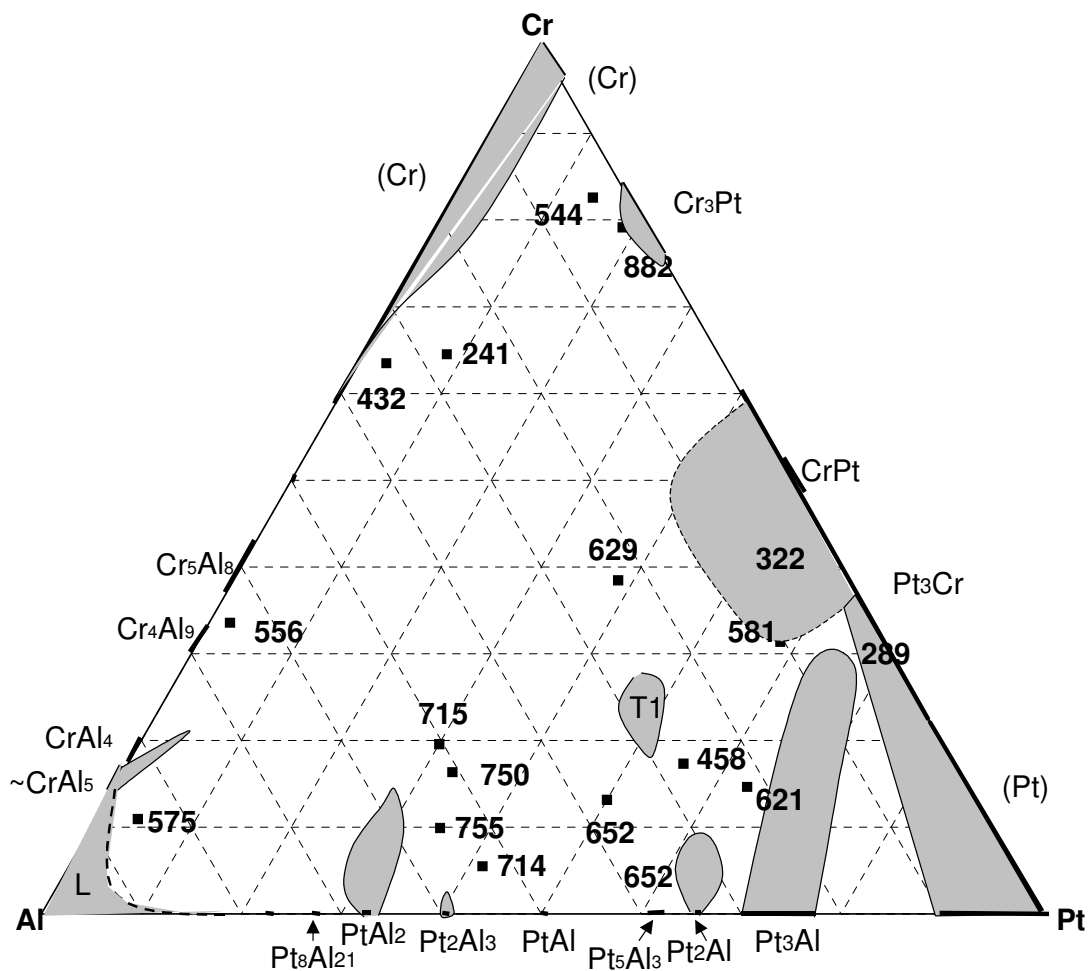


Figure 4.2. Hardness values of Pt-Cr-Al alloys annealed at 1000°C for 1000 hours, superposed on the 1000°C isothermal section.

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	<i>Not annealed</i>	~PtAl ₂ , ~Cr ₅ Al ₈ , ~Cr ₄ Al 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 ₂ Al
Pt ₆₅ :Al ₅ :Cr ₃₀	327 ± 6	322 ± 21	289 ± 7	~Pt ₃ Al, ~Pt ₃ Cr
Pt ₃ :Al ₆₅ :Cr ₃₂	645 ± 31	670 ± 32	556 ± 27	~Cr ₄ Al ₉ , ~PtAl ₂
Pt ₃ :Al ₃₅ :Cr ₆₂	576 ± 15	637 ± 26	432 ± 32	(Cr), ~PtAl ₂ , ~Cr ₂ Al
Pt ₁₈ :Al ₂ :Cr ₈₀	962 ± 62	767 ± 29	882 ± 10	~CrPt, ~Cr ₃ Pt, (Cr)
Pt ₃₅ :Al ₅₅ :Cr ₁₀	947 ± 30	822 ± 39	755 ± 5	~PtAl ₂ , ~PtAl, ~Pt ₂ Al ₃
Pt ₃₈ :Al ₂₂ :Cr ₄₀	950 ± 28	717 ± 27	629 ± 4	T1, ~CrPt, ~Cr ₃ Pt
Pt ₄₃ :Al ₅₂ :Cr ₅	914 ± 34	818 ± 69	714 ± 20	~PtAl, ~Pt ₂ Al ₃
Pt ₇₅ :Al ₁₀ :Cr ₁₅	810 ± 116	880 ± 10	750 ± 18	~PtAl ₂ , ~Pt ₂ Al 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 ₃ Al, ~Pt ₃ Cr, ~CrPt
Pt ₆₃ :Al ₃₂ :Cr ₅	617 ± 24	591 ± 65	652 ± 23	~Pt ₂ Al, T1
Pt ₆₃ :Al ₂₂ :Cr ₁₅	798 ± 22	673 ± 6	621 ± 11	~Pt ₃ Al, ~Pt ₂ Al
Pt ₁₅ :Al ₅ :Cr ₈₀	901 ± 13	632 ± 4	544 ± 18	(Cr), ~CrPt, T1, ~Cr ₃ Pt
Pt ₅₅ :Al ₂₅ :Cr ₂₀	650 ± 33	450 ± 75	458 ± 22	~Pt ₂ Al, 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 Pt₃:Al₃₅:Cr₆₂ and Pt₆₅:Al₅:Cr₃₀ had hardnesses of less than 600 HV_{10} . Several alloys had exceptionally high hardness (> 900 HV_{10}) compared to the rest, namely alloys Pt₁₅:Al₅:Cr₈₀, Pt₁₈:Al₂:Cr₈₀, Pt₇₅:Al₁₀:Cr₁₅ (actual Pt₃₃:Al₅₀:Cr₁₇), Pt₃₈:Al₂₂:Cr₄₀, Pt₄₃:Al₅₂:Cr₅ and Pt₅₀:Al₃₅:Cr₁₅. It is unclear why alloy Pt₇₅:Al₁₀:Cr₁₅ showed such a large standard deviation on hardness - maybe subsurface porosity played a role. The presence of intermetallic compounds like ~PtAl₂, PtAl and ~CrPt are responsible for these high values, as well as the presence of T1. Only alloys Pt₃:Al₆₅:Cr₃₂,

$\text{Pt}_3\text{Al}_{35}\text{Cr}_{62}$ and $\text{Pt}_{75}\text{Al}_{10}\text{Cr}_{15}$ softened during annealing at 600°C . The softening is probably due to the loss of $\sim\text{Pt}_2\text{Al}_3$ during annealing in the latter, and the disordering of $\sim\text{Cr}_2\text{Al}$ into (Cr) in alloy $\text{Pt}_3\text{Al}_{35}\text{Cr}_{62}$. It is unclear why alloy $\text{Pt}_3\text{Al}_{65}\text{Cr}_{32}$ softened.

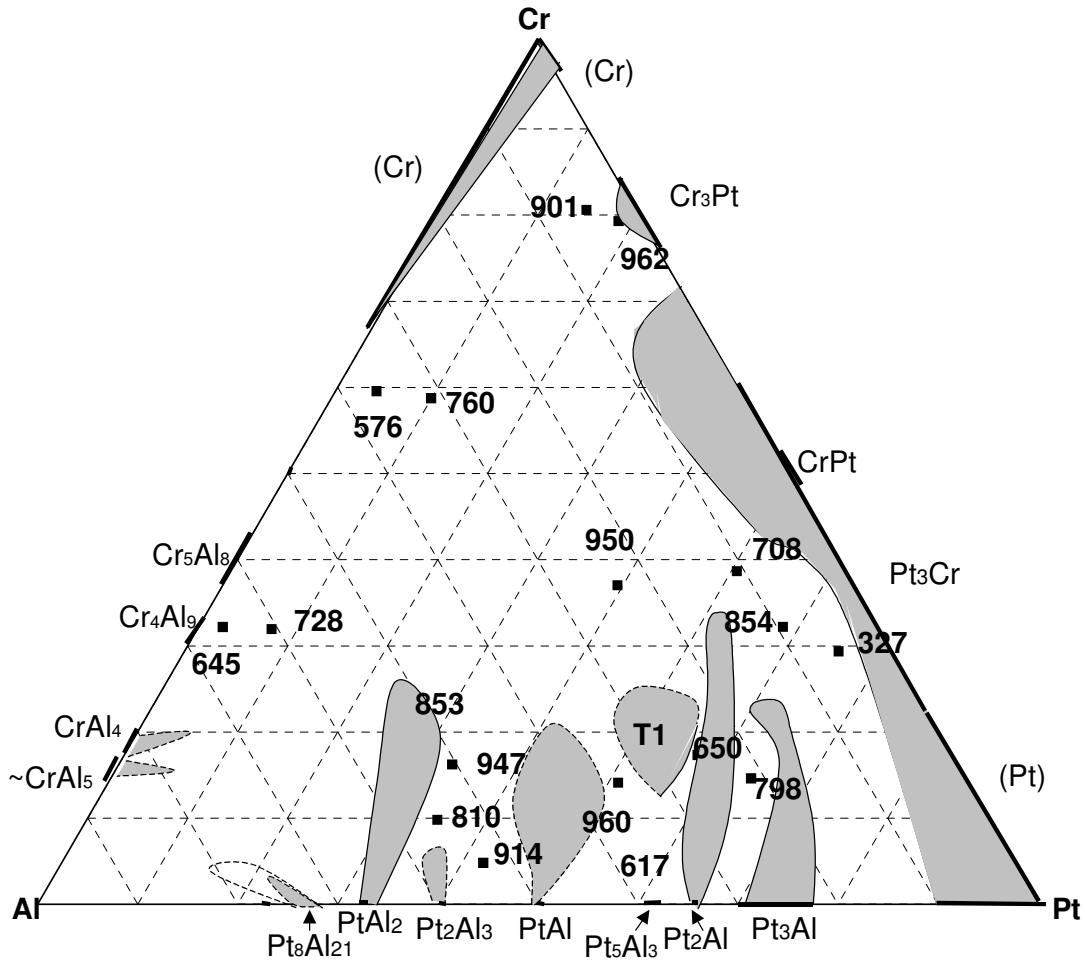


Figure 4.3. Hardness values of Pt-Cr-Al alloys annealed at 600°C for 2500 hours, superposed on the 600°C isothermal section.

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 HV₁₀ hardness of $\text{Pt}_{84}\text{Al}_{11}\text{Ru}_2\text{Cr}_3$ [2004Süs3], the most promising Pt-based alloy thus far for potential application in high temperature environments. In the case of $\text{Pt}_{84}\text{Al}_{11}\text{Ru}_2\text{Cr}_3$, 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.

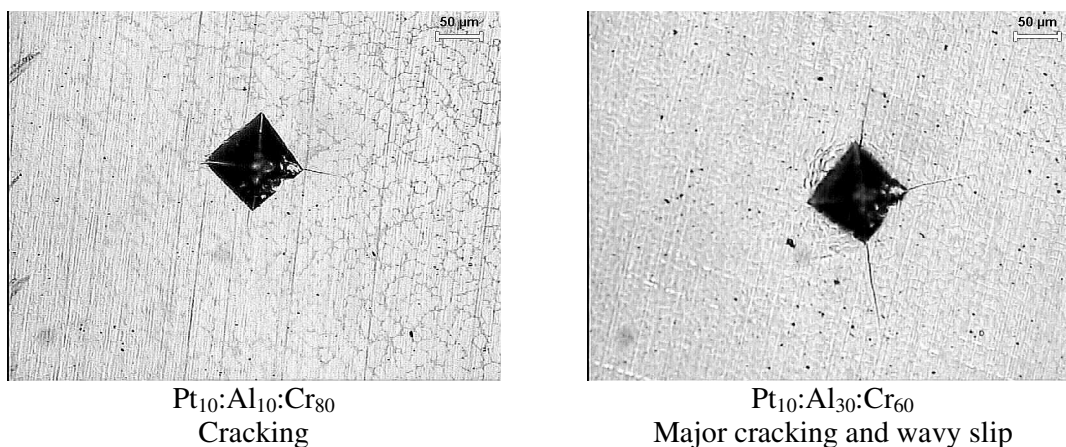
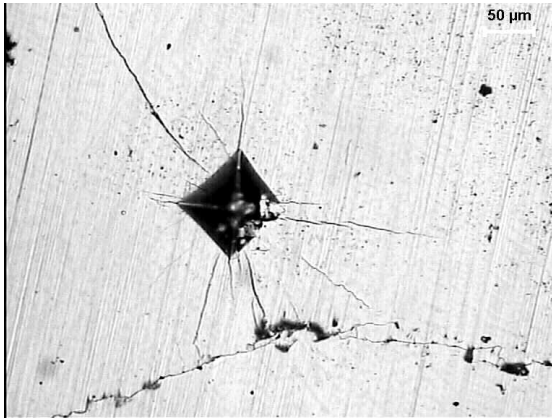


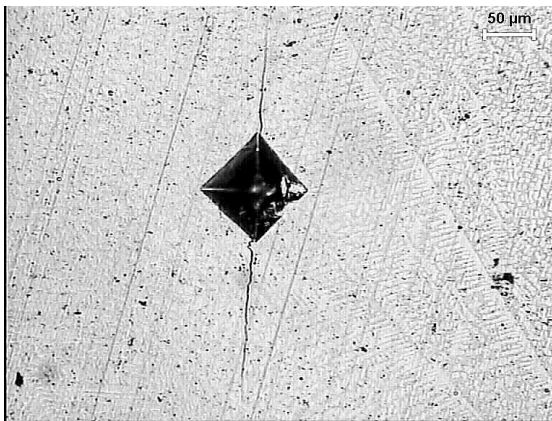
Figure 4.4. Optical micrographs for comparison of the hardness indentations in as-cast Pt-Cr-Al alloys.



Pt₁₀:Al₆₀:Cr₃₀
Major cracking



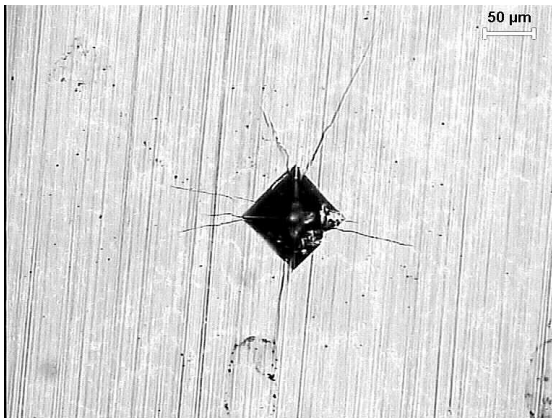
Pt₁₀:Al₈₀:Cr₁₀
Major interdendritic cracking



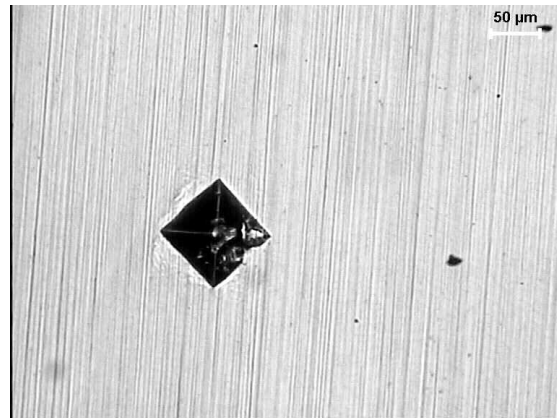
Pt₂₀:Al₂₀:Cr₆₀
Major cracking



Pt₂₀:Al₄₀:Cr₄₀
Major cracking



Pt₃₀:Al₅₀:Cr₂₀
Major cracking

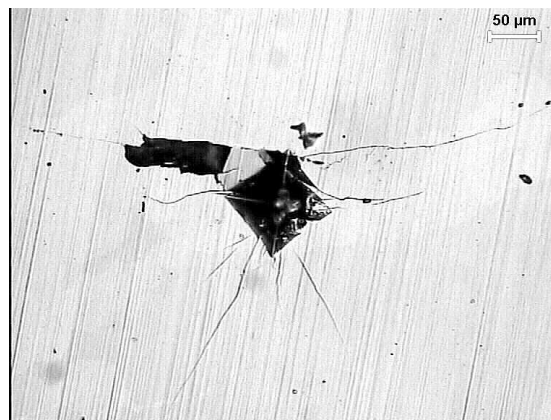


Pt₄₀:Al₁₀:Cr₅₀
Wavy slip

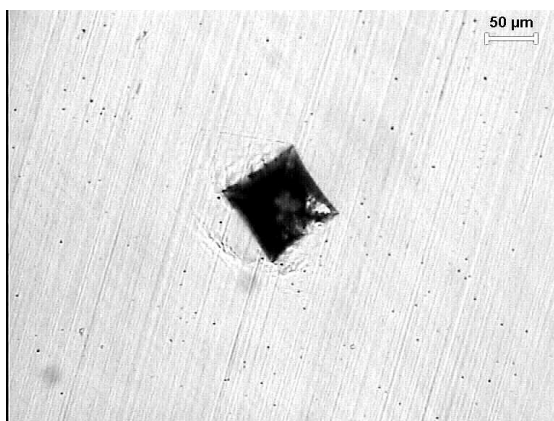
Figure 4.4. (cont.). Optical micrographs for comparison of the hardness indentations in as-cast Pt-Cr-Al alloys.



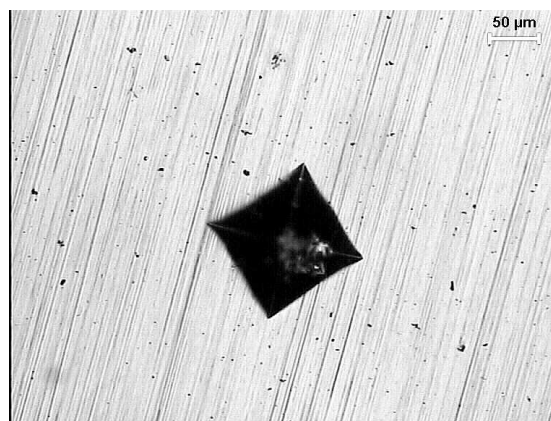
Pt₄₀:Al₃₀:Cr₃₀
No discernible slip



Pt₄₀:Al₅₀:Cr₁₀
Major cracking



Pt₅₀:Al₁₀:Cr₄₀
Wavy slip



Pt₆₅:Al₅:Cr₃₀
No discernible slip

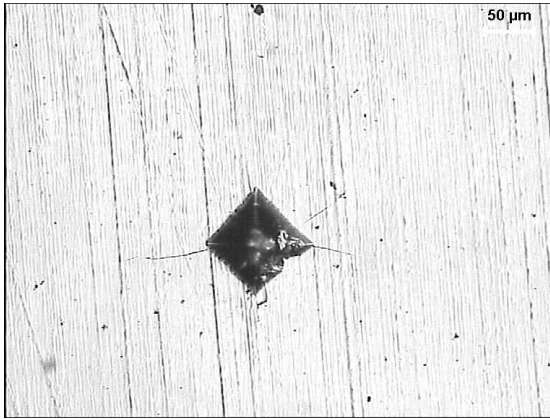


Pt₃:Al₆₅:Cr₃₂
Major cracking

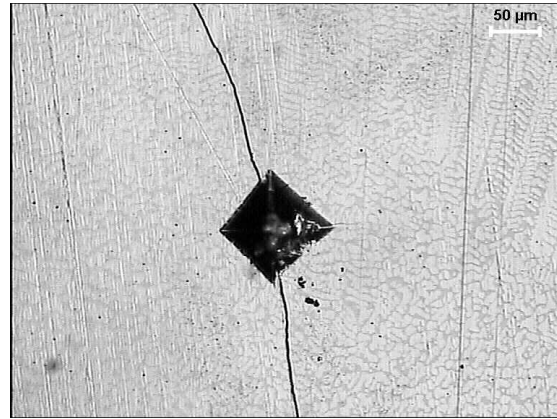


Pt₃:Al₃₅:Cr₆₂
Wavy slip and major cracking

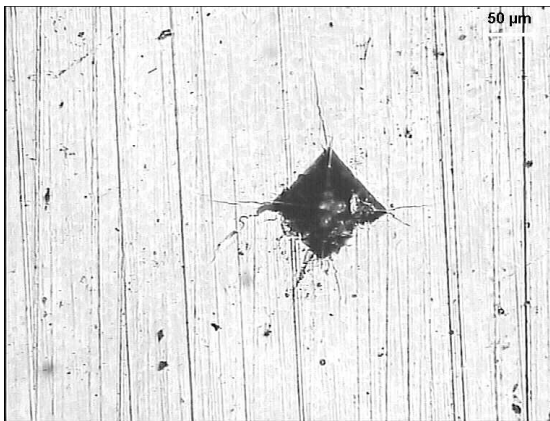
Figure 4.4. (cont.). Optical micrographs for comparison of the hardness indentations in as-cast Pt-Cr-Al alloys.



Pt₁₀:Al₅₀:Cr₄₀
Major cracking



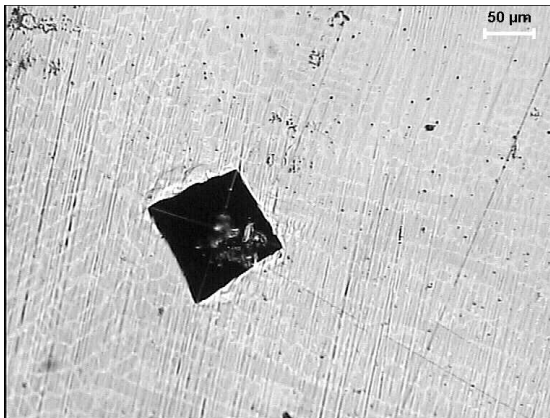
Pt₁₂:Al₁₈:Cr₇₀
Major cracking



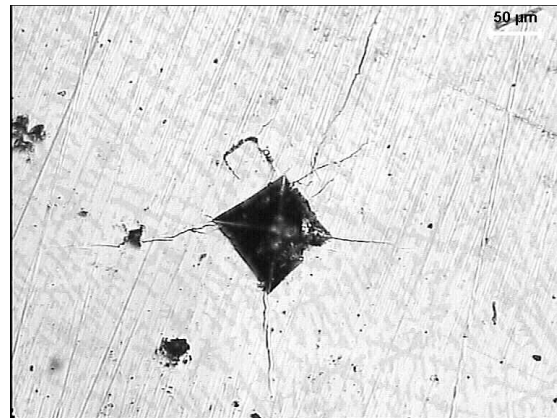
Pt₁₇:Al₆₈:Cr₁₅
Major cracking



Pt₁₈:Al₂:Cr₈₀
Wavy slip

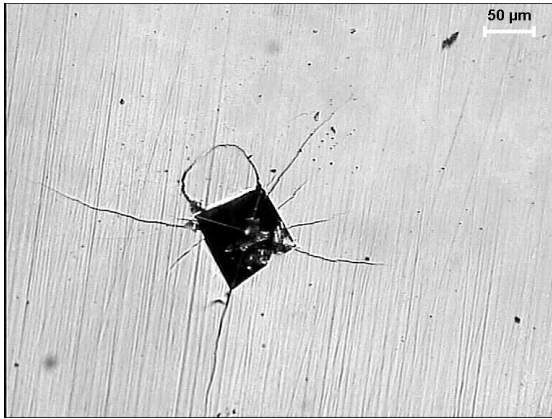


Pt₂₈:Al₁₂:Cr₆₀
Wavy slip

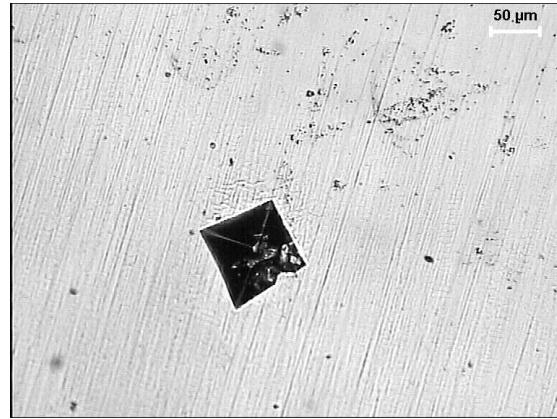


Pt₂₈:Al₇₀:Cr₂
Major cracking

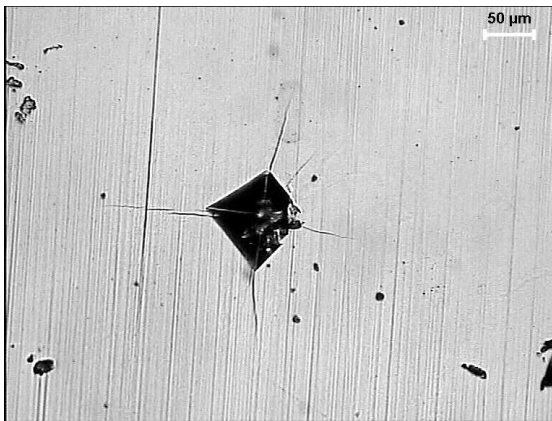
Figure 4.4. (cont.). Optical micrographs for comparison of the hardness indentations in as-cast Pt-Cr-Al alloys.



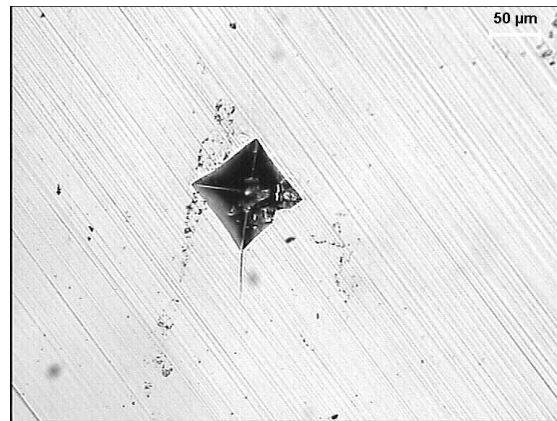
Pt₃₅:Al₅₅:Cr₁₀
Major cracking



Pt₃₈:Al₂₂:Cr₄₀
Wavy slip



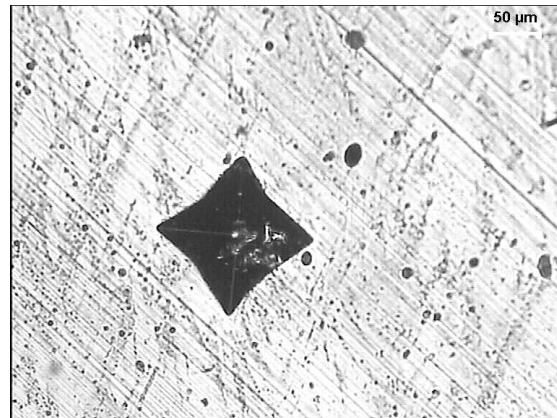
Pt₄₃:Al₅₂:Cr₅
Major cracking



Pt₅₀:Al₃₅:Cr₁₅
Cracking

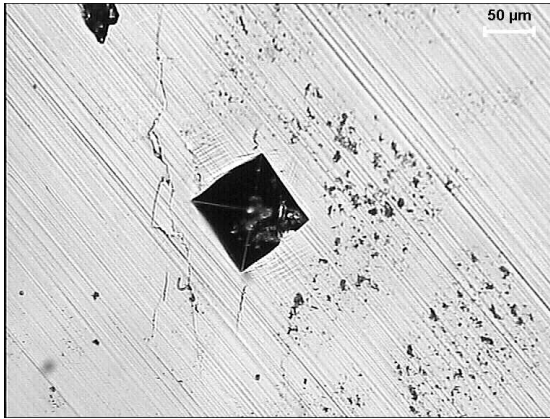


Pt₅₈:Al₁₀:Cr₃₂
Wavy and planar slip

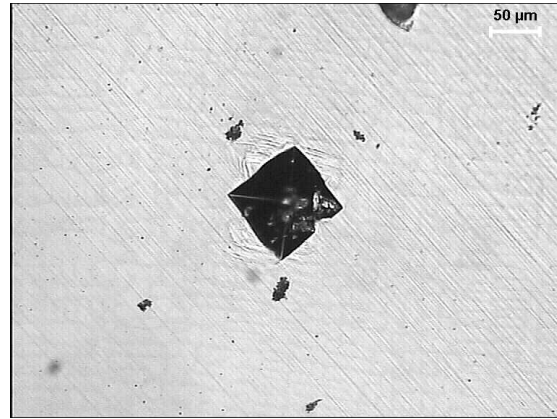


Pt₆₀:Al₂:Cr₃₈
No discernible slip

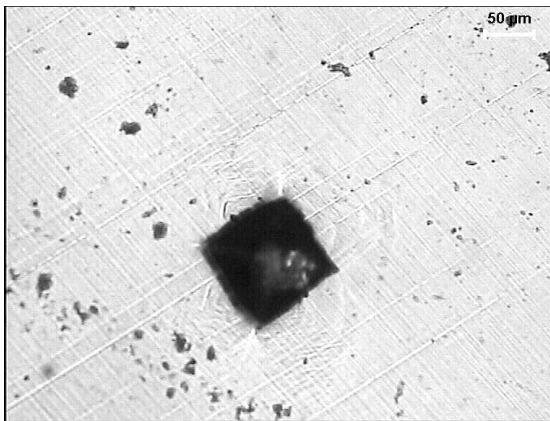
Figure 4.4. (cont.). Optical micrographs for comparison of the hardness indentations in as-cast Pt-Cr-Al alloys.



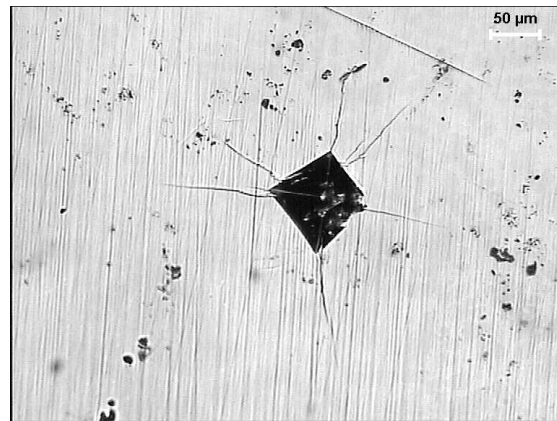
Pt₆₃:Al₃₂:Cr₅
Planar slip



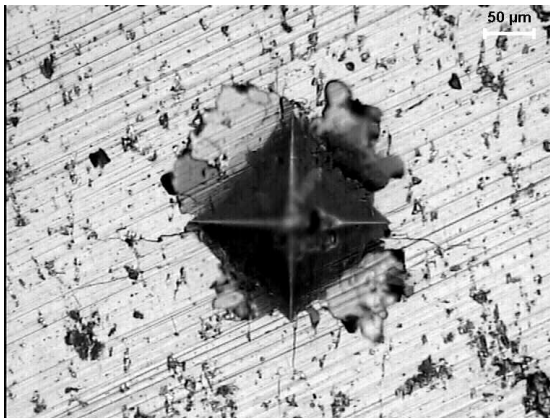
Pt₆₃:Al₂₂:Cr₁₅
Wavy slip



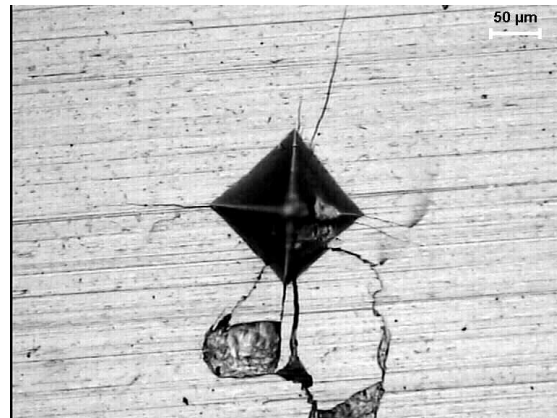
Pt₇₈:Al₁₇:Cr₅
Wavy slip



Pt₇₅:Al₁₀:Cr₁₅
Major cracking

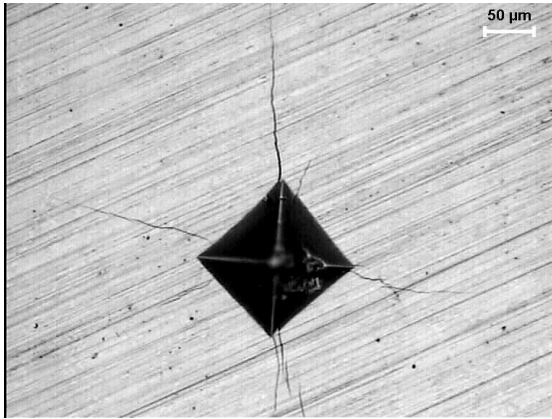


Pt₃:Al₇₉:Cr₁₈
Major irregular cracking

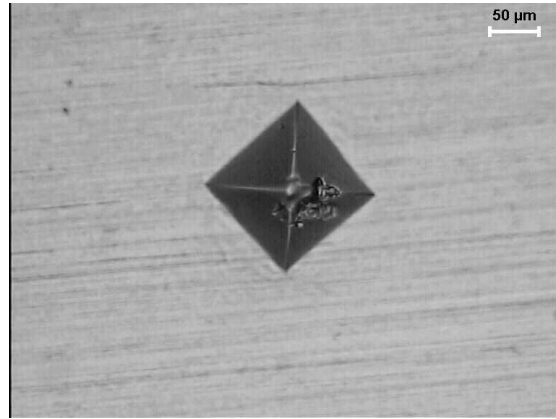


Pt₅:Al₅₂:Cr₄₃
Major cracking

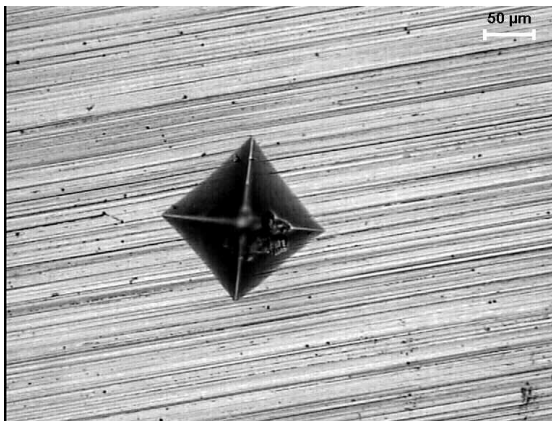
Figure 4.4. (cont.). Optical micrographs for comparison of the hardness indentations in as-cast Pt-Cr-Al alloys.



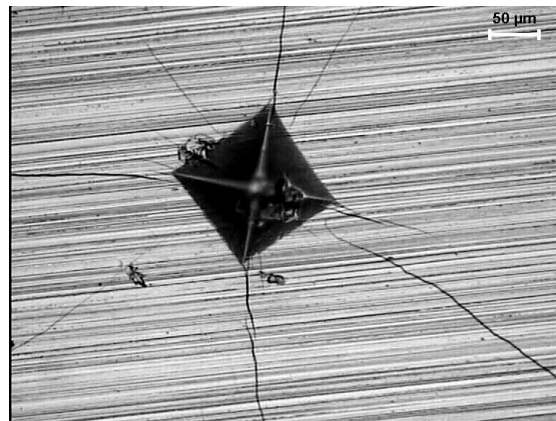
Pt₁₃:Al₄₅:Cr₄₂
Major cracking



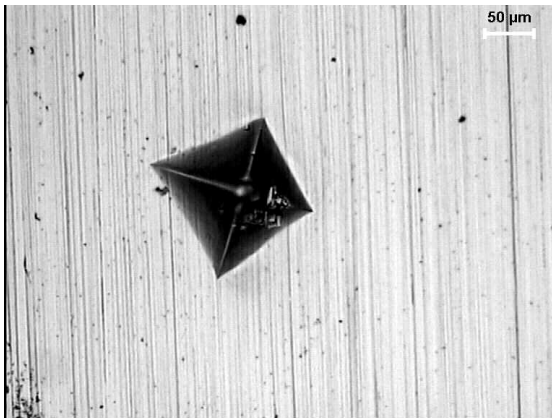
Pt₁₅:Al₅:Cr₈₀
Wavy slip



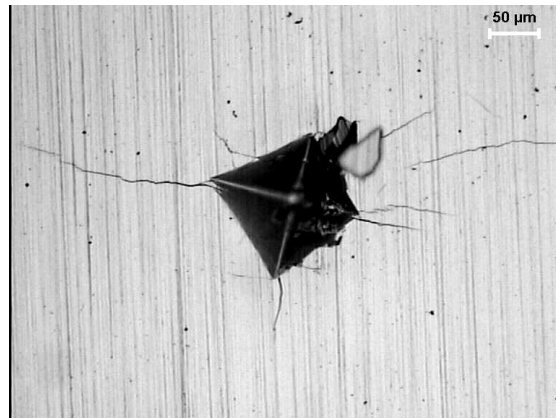
Pt₃₄:Al₂₇:Cr₃₉
No discernible slip



Pt₃₇:Al₅₉:Cr₄
Major cracking



Pt₄₅:Al₃₅:Cr₂₀
No discernible slip



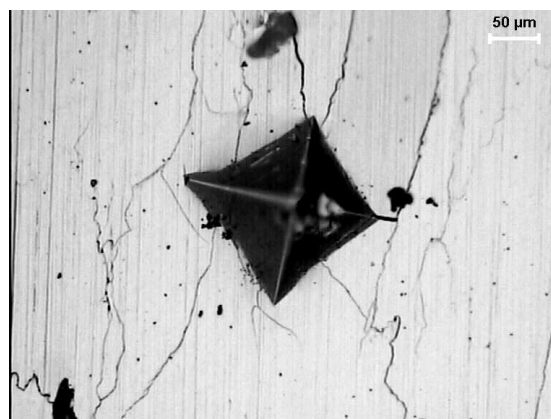
Pt₅₂:Al₄₃:Cr₅
Major cracking

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



Pt₅₅:Al₂₅:Cr₂₀

Major irregular cracking



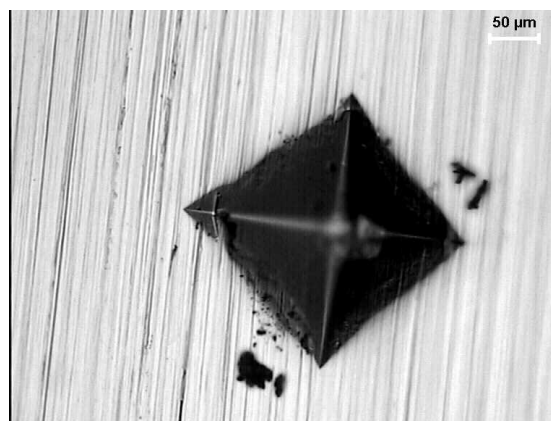
Pt₅₅:Al₂₀:Cr₂₅

Major irregular cracking



Pt₆₄:Al₁₆:Cr₂₀

Planar slip



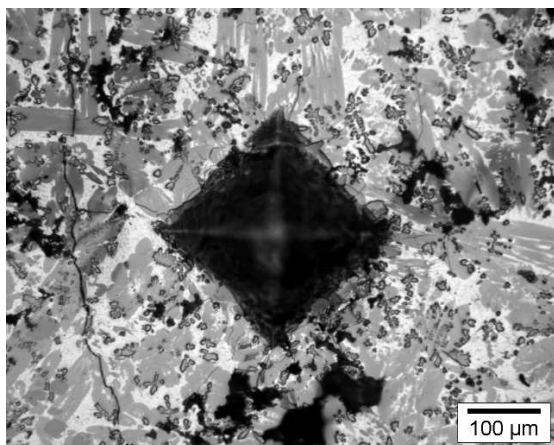
Pt₇₆:Al₅:Cr₁₉

Cracking

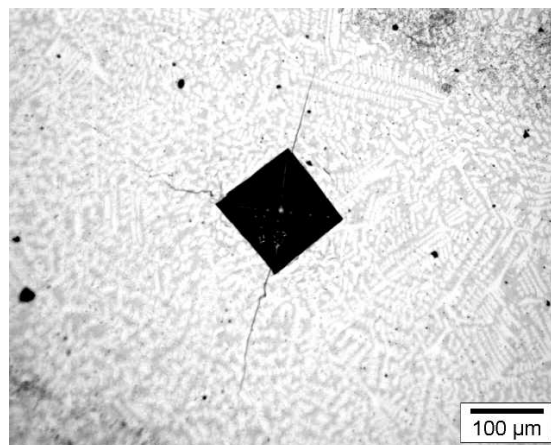
Figure 4.4. (cont.). Optical micrographs for comparison of the hardness indentations in as-cast Pt-Cr-Al alloys.

It was interesting to note "pin-cushioning" of the hardness indentation of alloy Pt₆₀:Al₂:Cr₃₈, an anomaly typically observed with annealed material, when metal is sinking in around the faces of the indenter [1990Die]. Apart from alloy Pt₆₅:Al₅:Cr₃₀, alloy Pt₆₀:Al₂:Cr₃₈ was the softest in the as-cast condition (333 HV₁₀).

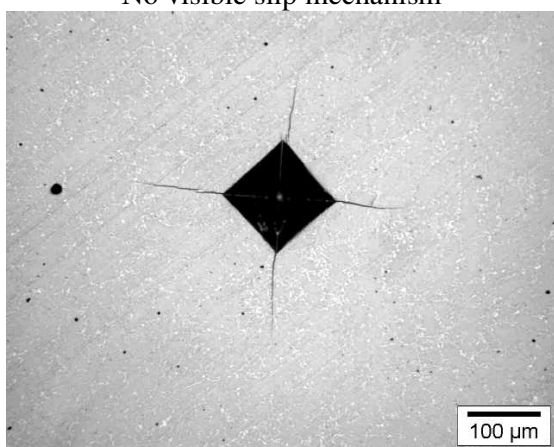
It is obvious that most alloys in the system are very brittle, since many of the alloys exhibited major cracking. The only alloys that stood out as having better toughness were the ones that contained ~CrPt (alloys Pt₁₈:Al₂:Cr₈₀, Pt₁₅:Al₅:Cr₈₀, Pt₃₈:Al₂₂:Cr₄₀, Pt₄₀:Al₁₀:Cr₅₀, and Pt₅₀:Al₁₀:Cr₄₀), Pt₃Cr (Pt₆₅:Al₅:Cr₃₀ and Pt₇₆:Al₅:Cr₁₉) and ~Pt₃Al (Pt₇₈:Al₁₇:Cr₅, Pt₆₃:Al₃₂:Cr₅, Pt₆₃:Al₂₂:Cr₁₅, Pt₆₄:Al₁₆:Cr₂₀ and Pt₆₀:Al₂:Cr₃₈) showing wavy slip in most cases. Considering



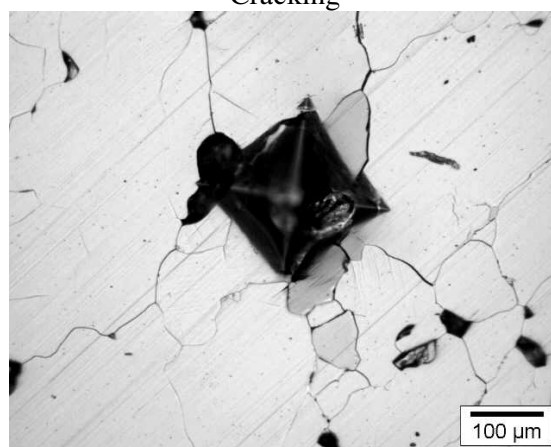
Pt₁₀:Al₃₀:Cr₆₀
No visible slip mechanism



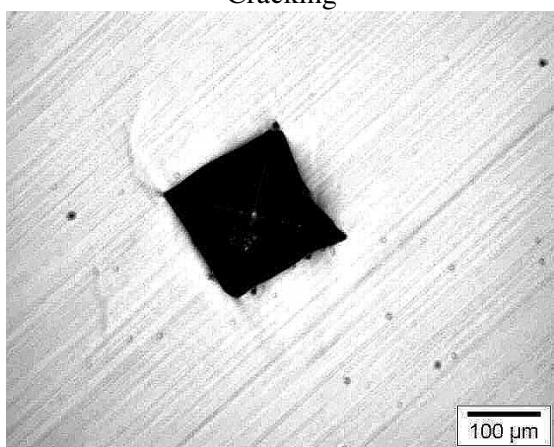
Pt₁₀:Al₈₀:Cr₁₀
Cracking



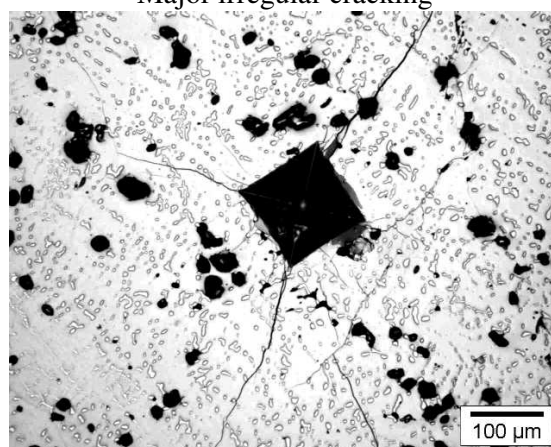
Pt₃₀:Al₅₀:Cr₂₀
Cracking



Pt₅₀:Al₁₀:Cr₄₀
Major irregular cracking

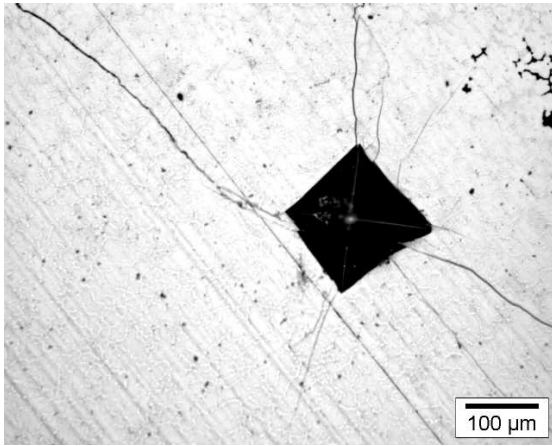


Pt₆₅:Al₅:Cr₃₀
Wavy slip

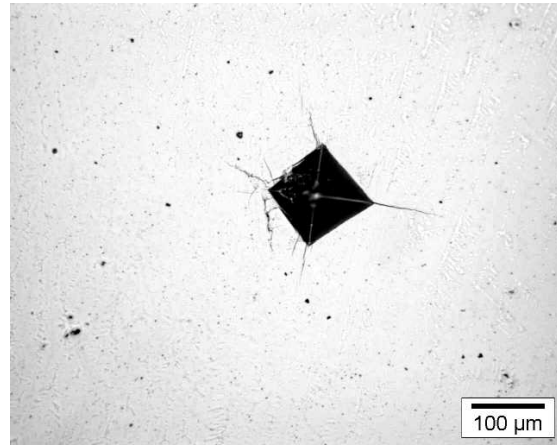


Pt₃:Al₆₅:Cr₃₂
Major cracking

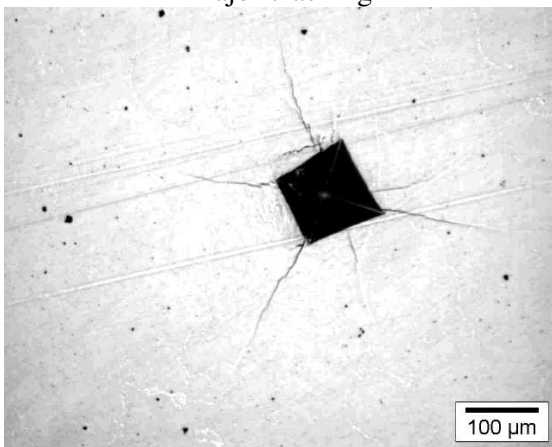
Figure 4.6. Optical micrographs for comparison of the hardness indentations in Pt-Cr-Al alloys annealed at 1000 °C for 1000 hours.



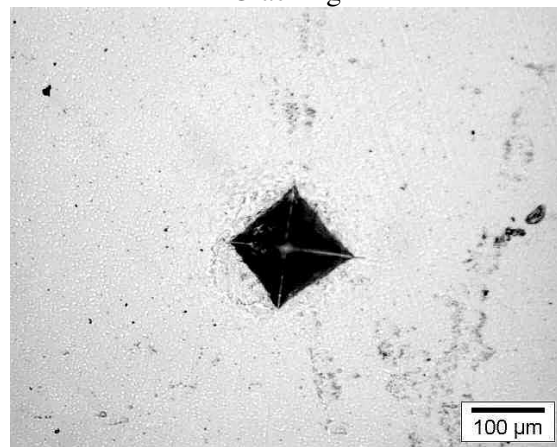
Pt₃:Al₃₅:Cr₆₂
Major cracking



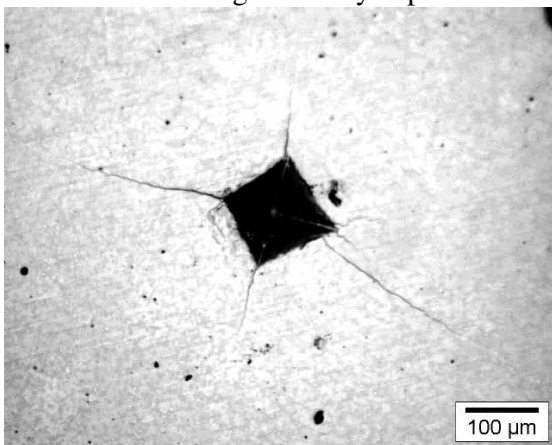
Pt₁₈:Al₂:Cr₈₀
Cracking



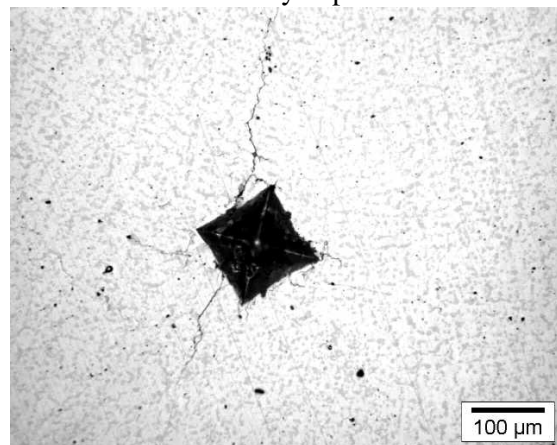
Pt₃₅:Al₅₅:Cr₁₀
Cracking and wavy slip



Pt₃₈:Al₂₂:Cr₄₀
Wavy slip

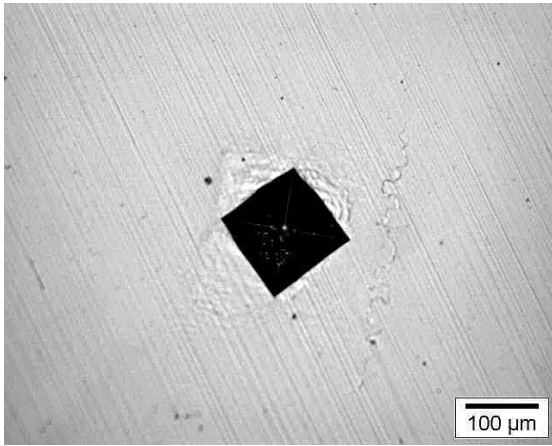


Pt₄₃:Al₅₂:Cr₅
Cracking and wavy slip

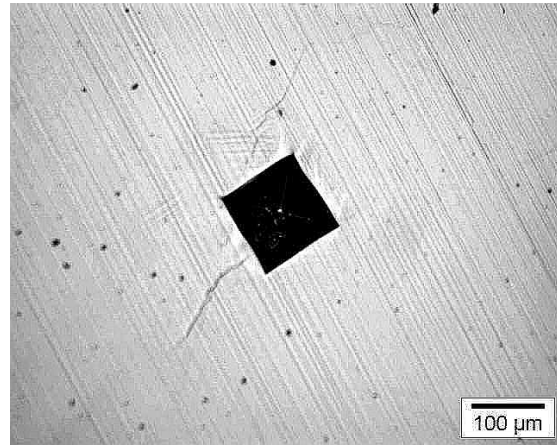


Pt₅₀:Al₃₅:Cr₁₅
Cracking (interdendritic)

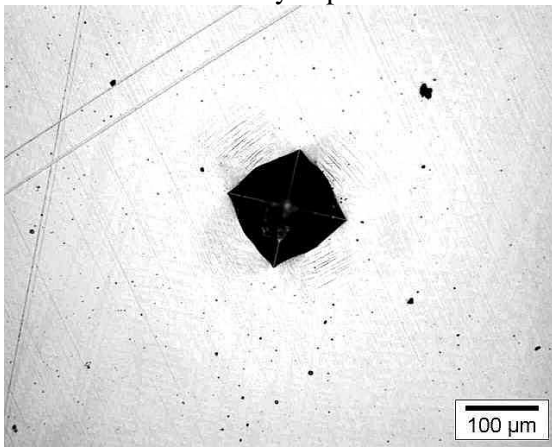
Figure 4.6. (cont.) Optical micrographs for comparison of the hardness indentations in Pt-Cr-Al alloys annealed at 1000°C for 1000 hours.



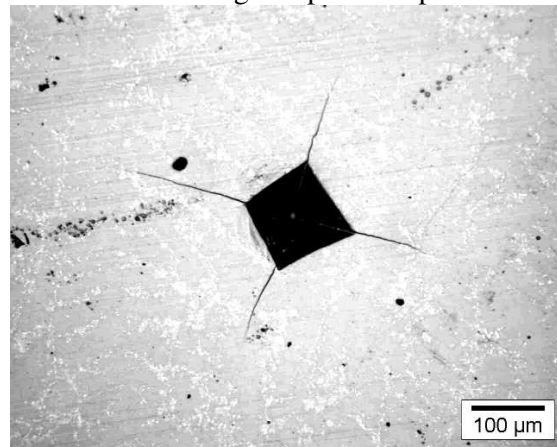
Pt₅₈:Al₁₀:Cr₃₂
Wavy slip



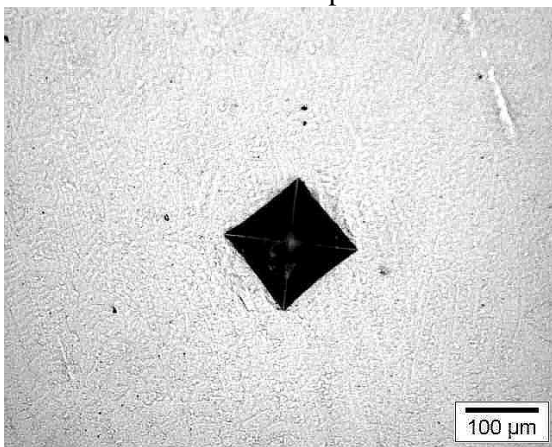
Pt₆₃:Al₃₂:Cr₅
Cracking and planar slip



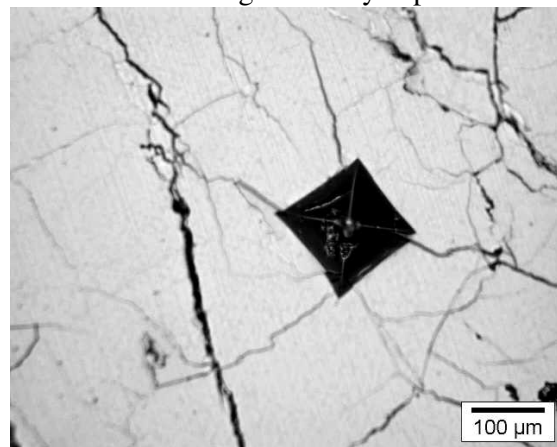
Pt₆₃:Al₂₂:Cr₁₅
Planar slip



Pt₇₅:Al₁₀:Cr₁₅
Cracking and wavy slip



Pt₁₅:Al₅:Cr₈₀
Wavy slip



Pt₅₅:Al₂₅:Cr₂₀
Major cracking

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

It was interesting to note "barrelling" of the hardness indentation of alloy $\text{Pt}_{63}:\text{Al}_{22}:\text{Cr}_{15}$, an anomaly normally observed with cold-worked material, when metal is piling up around the faces of the indenter [1990Die]. The alloy had quite a high annealed hardness (621 HV₁₀). The different slip modes of the annealed alloys are superposed on the preliminary 1000°C isothermal section in Figure 4.7.

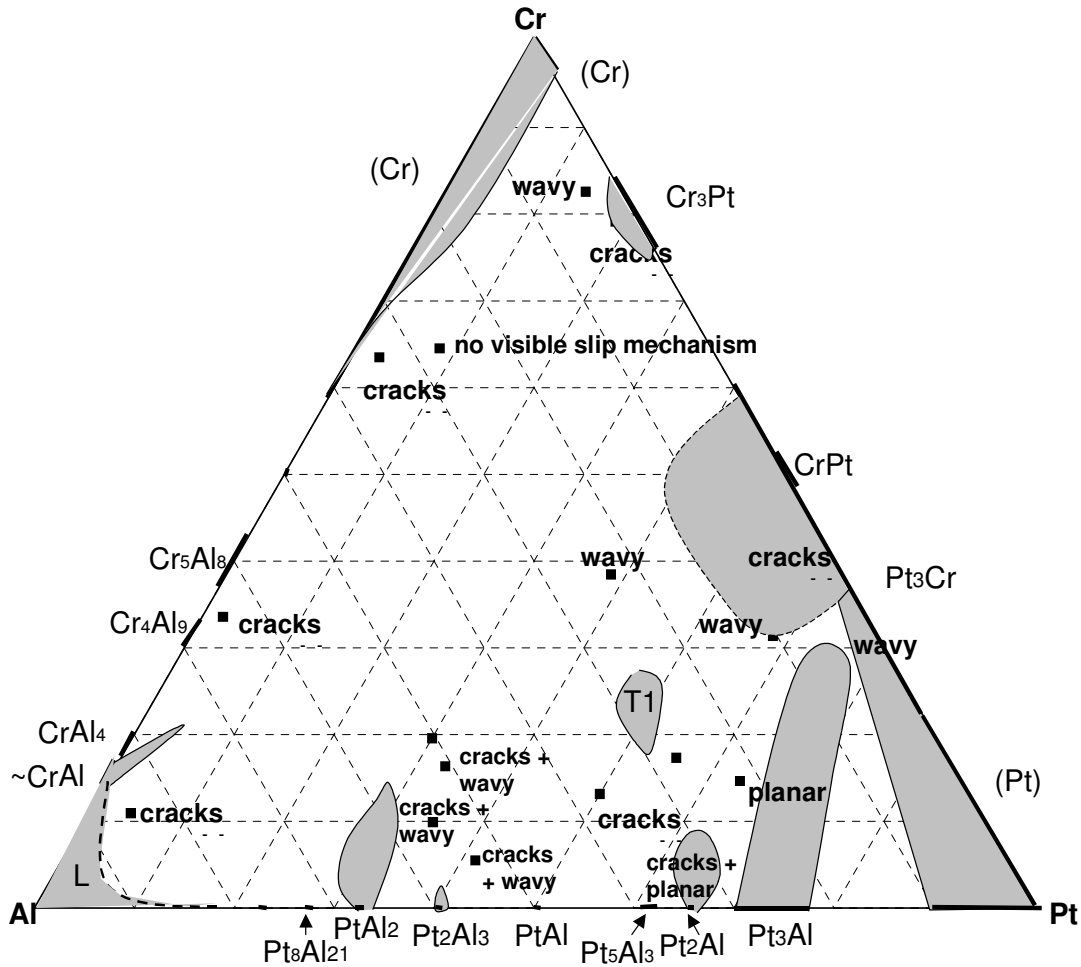


Figure 4.7. Summary of the slip modes of Pt-Cr-Al alloys annealed at 1000 °C for 1000 hours, superposed on the 1000 °C isothermal section.

It is obvious that most alloys in the system are very brittle, since many of the alloys exhibited fairly major cracking. The only alloys that stood out as having better toughness were the ones that contained $\sim\text{Pt}_3\text{Al}$ ($\text{Pt}_{58}:\text{Al}_{10}:\text{Cr}_{32}$ (wavy slip), $\text{Pt}_{63}:\text{Al}_{22}:\text{Cr}_{15}$ (planar slip) and $\text{Pt}_{65}:\text{Al}_5:\text{Cr}_{30}$ (wavy slip). Once again, this was encouraging for the Pt-based alloys that are being developed by Mintek.

2.2.3. Annealed at 600 °C

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

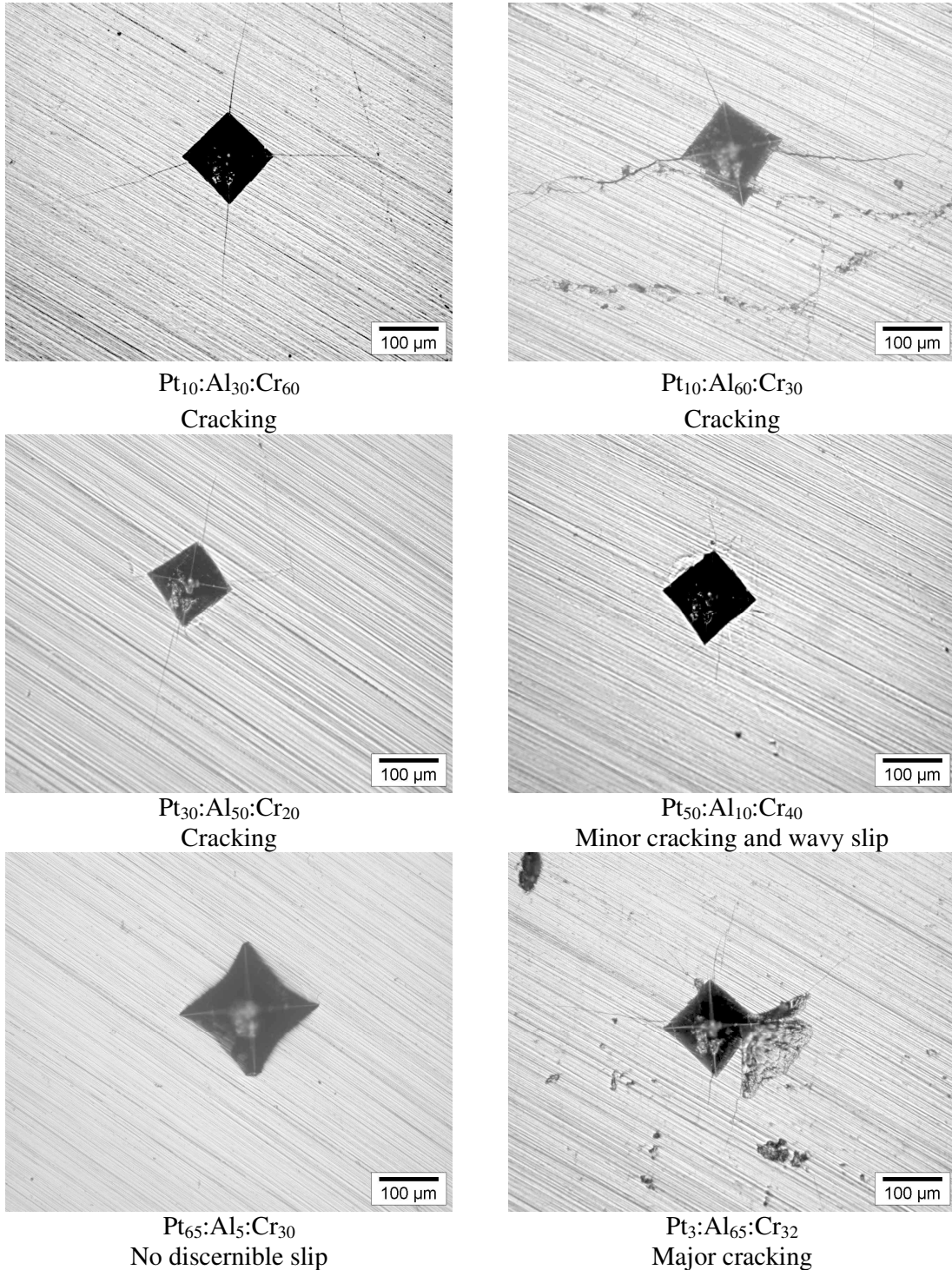
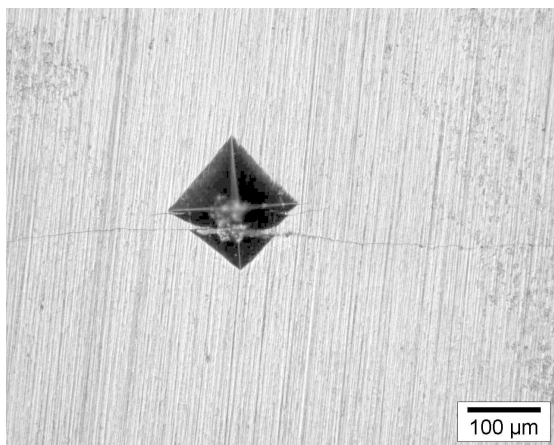
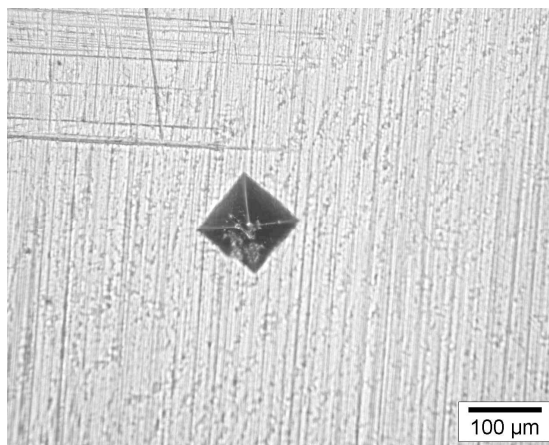


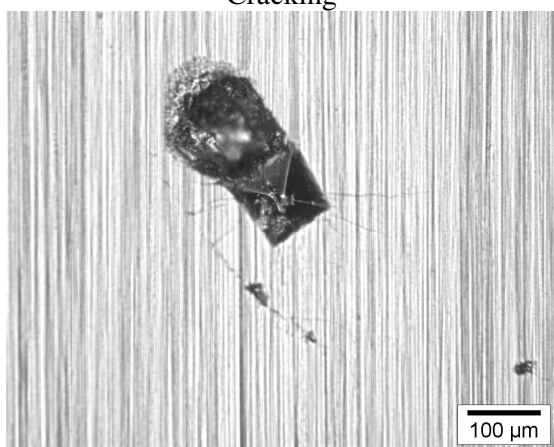
Figure 4.8. Optical micrographs for comparison of the hardness indentations in Pt-Cr-Al alloys annealed at 600 °C for 2500 hours.



Pt₃:Al₃₅:Cr₆₂
Cracking



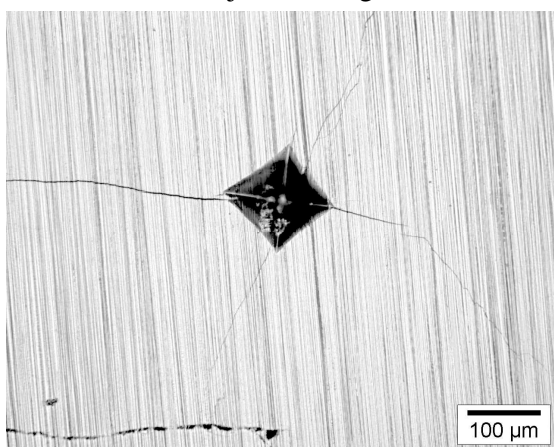
Pt₁₈:Al₂:Cr₈₀
No discernible slip



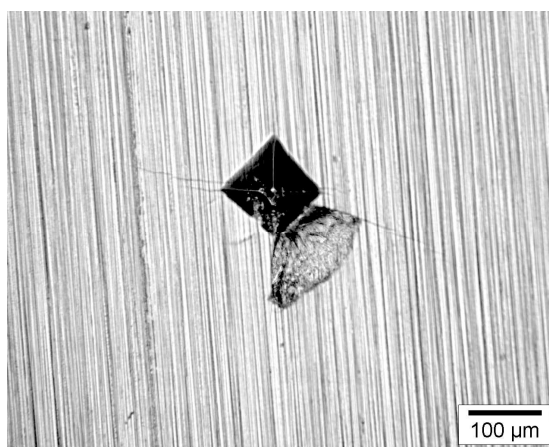
Pt₃₅:Al₅₅:Cr₁₀
Major cracking

No picture taken

Pt₃₈:Al₂₂:Cr₄₀

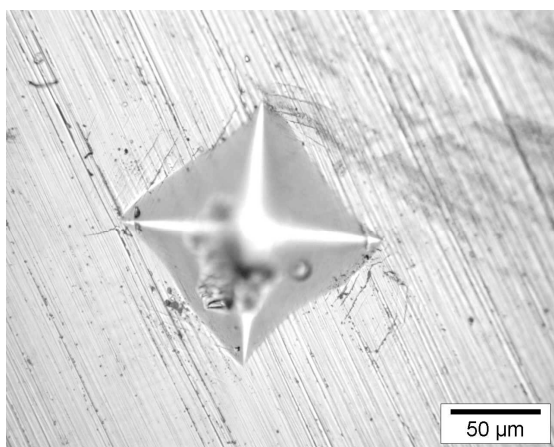


Pt₄₃:Al₅₂:Cr₅
Cracking

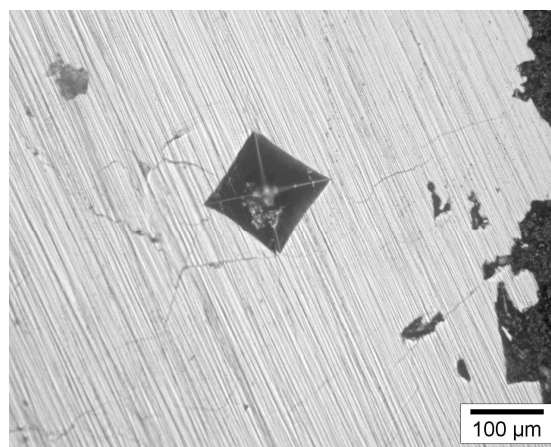


Pt₇₅:Al₁₀:Cr₁₅
Major cracking

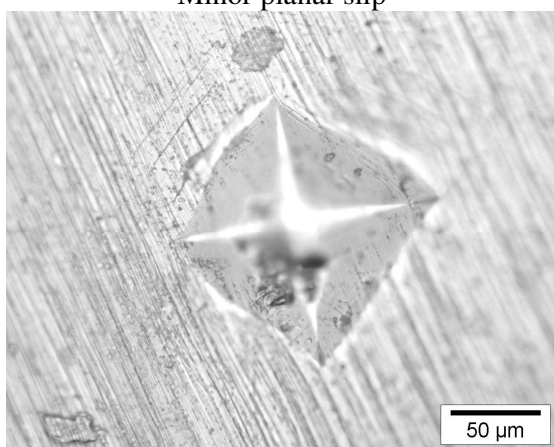
Figure 4.8. (cont.) Optical micrographs for comparison of the hardness indentations in Pt-Cr-Al alloys annealed at 600 °C for 2500 hours.



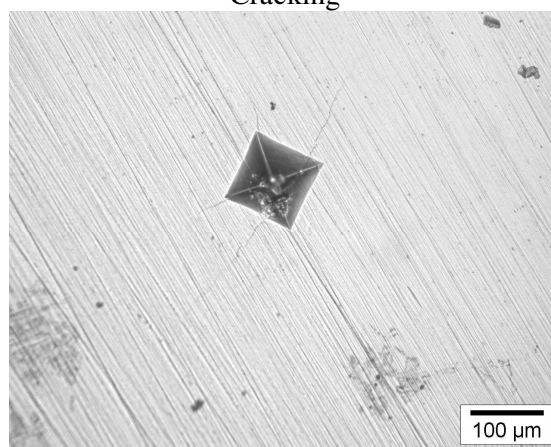
Pt₅₈:Al₁₀:Cr₃₂
Minor planar slip



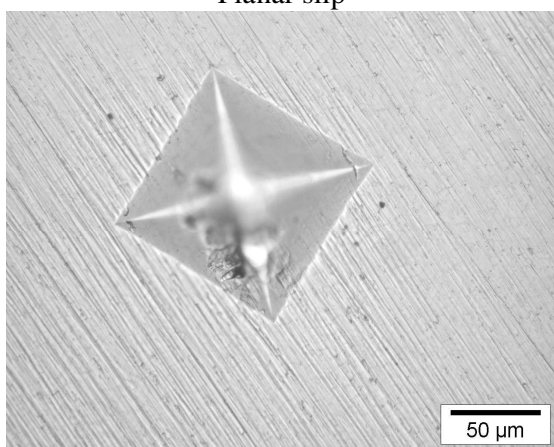
Pt₆₃:Al₃₂:Cr₅
Cracking



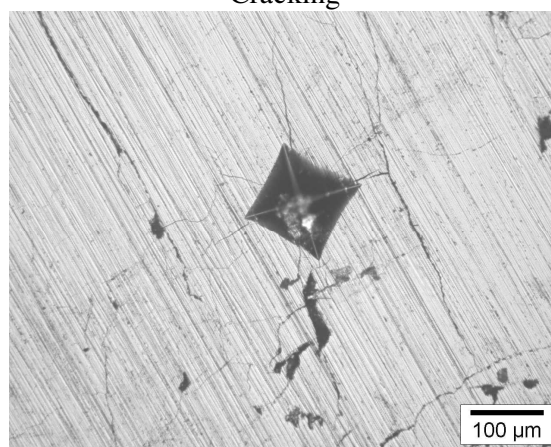
Pt₆₃:Al₂₂:Cr₁₅
Planar slip



Pt₅₀:Al₃₅:Cr₁₅
Cracking



Pt₁₅:Al₅:Cr₈₀
No discernible slip



Pt₅₅:Al₂₅:Cr₂₀
Major cracking

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

It was interesting to note "pin-cushioning" of the hardness indentation of alloy $\text{Pt}_{65}\text{Al}_5\text{Cr}_{30}$, an anomaly typically observed with annealed material, when metal is sinking in around the faces of the indenter [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 $\text{Pt}_{58}\text{Al}_{10}\text{Cr}_{32}$ (planar slip), $\text{Pt}_{63}\text{Al}_{22}\text{Cr}_{15}$ (planar slip) and $\text{Pt}_{50}\text{Al}_{10}\text{Cr}_{40}$ (wavy slip). The latter alloy contained $\sim\text{CrPt}$, while the other two contained $\sim\text{Pt}_3\text{Al}$.

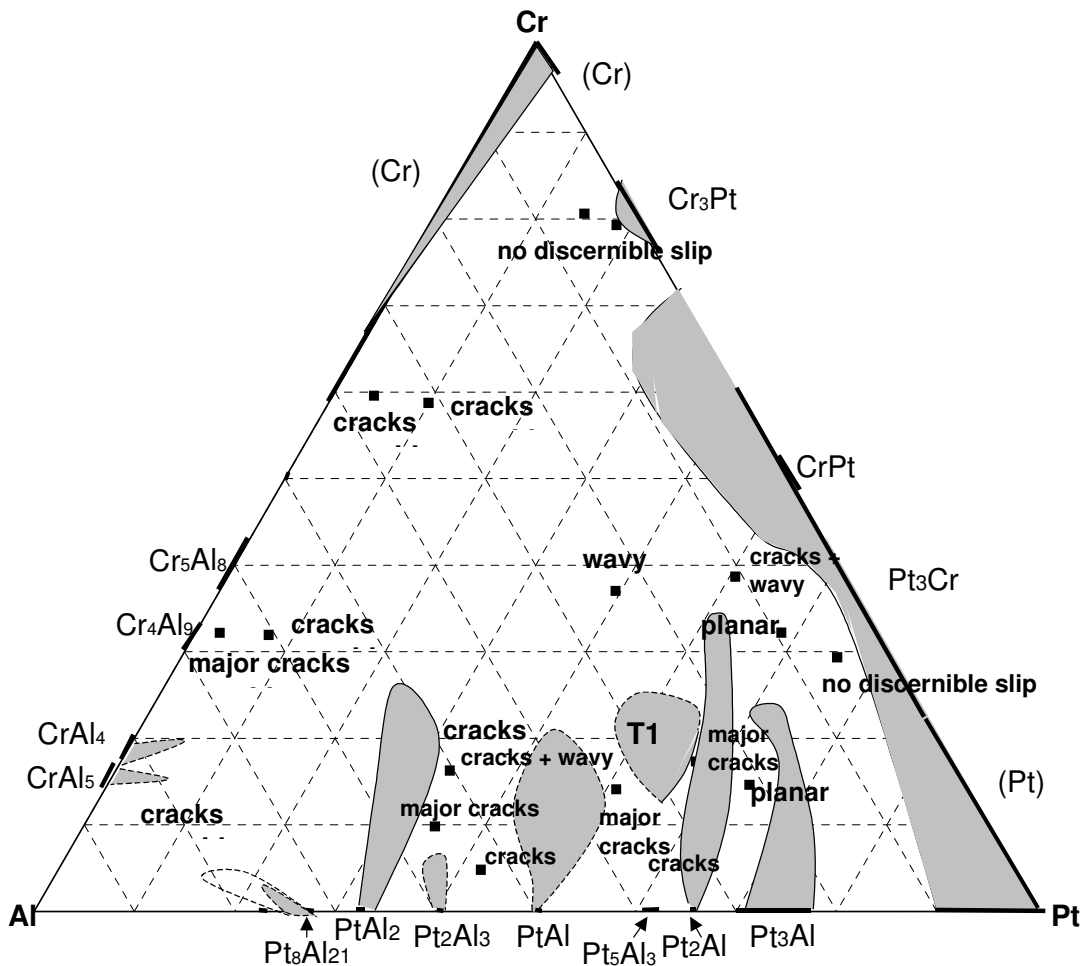


Figure 4.9. Summary of the slip modes of Pt-Cr-Al alloys annealed at 600°C for 2500 hours, superposed on the 600°C isothermal section.

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 $\sim$ CrPt and in particular $\sim$ Pt₃Al showed much better toughness. The fact that alloys containing $\sim$ Pt₃Al 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 $\sim\text{CrPt}/\sim\text{Pt}_3\text{Cr}$ and $\sim\text{Pt}_3\text{Cr}/(\text{Pt})$ 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 $\sim\text{CrPt}/\sim\text{Pt}_3\text{Cr}$ and $\sim\text{Pt}_3\text{Cr}/(\text{Pt})$ 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 $\sim\text{Pt}_3\text{Al}$ 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 (enthalpy 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.

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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.

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