ISSN : 0974 - 7486 Volume 9 Issue 8

Trade Science Inc.

Materials Science

An Indian Journal

Full Paper

MSAIJ, 9(8), 2013 [304-311]

Thermal expansion of selected parent dental alloys used for fixed partial denture

Lionel Aranda[1], Pascal De March[2], Patrice Berthod[1]*
[1]Institut Jean Lamour (UMR 7198), Team 206 "Surface and Interface, Chemical Reactivity of Materials"
Faculty of Science and Technologies, University of Lorraine, B.P. 70239, 54506 Vandoeuvre-lès-Nancy, (FRANCE)
[2]Faculty of Dentistry, Department of Prostheses, University of Lorraine, 96 avenue de Lattre De Tassigny, B.P. 50208, 54000 Nancy, (FRANCE)
E-mail: patrice.berthod@univ-lorraine.fr

ABSTRACT

The dimensional variation of the different materials included in the ceramic-metallic dental prostheses is of a great importance since manufacturing them involves several heating phases until rather high temperatures are reached (near 1000°C) and subsequent cooling phases down to room temperature, for heat-treating porcelain to achieve the required properties and aspects without damaging it because of too great difference of thermal expansion behaviour with the internal strengthening metallic framework. The present work consists in studying the thermal expansion and retraction behaviours of eight parent alloys the thermal dimensional variations of which are the one of the whole framework since they represent almost its whole length. This was done by reproducing the temperature cycling known by real prostheses after porcelain covering. It appears that the dimensional evolution can be different among the studied alloys since the thickness of some of them decreases during the first thermal cycles while this never occurs for other parent alloys. Further the average thermal expansion and retraction coefficients vary among the different classes of nobility of the alloys as well as between the alloys of a same nobility class. An attempt was done for establishing an empiric correspondence between the thermal expansion coefficient of each parent alloy and the one of the main elements of its chemical composition. A rather good agreement was additionally found between the measured values and the ones of the manufacturer.

KEYWORDS

Ceramic-metallic prostheses;
Dental alloys;
Thermal expansion;
Thermal cycling.

INTRODUCTION

In some cases metallic frameworks are inserted in dental prostheses in order to strengthen them against the mechanical solicitations induced by chewing, by taking benefit of both the intrinsic high resistance and the high ductility of metallic alloys. This allows them enduring such high intensity of cyclic compression and flexure over very long times, more precisely at least ten years generally. The main metallic material present in the framework is a parent alloy, more or less noble depending on its contents in elements such as gold or platinum or in contrast as nickel and chromium, which represents the greatest part of the framework, the other alloys also present being simply thin solder joints[1,2]. The assemblage realized by using these solder alloys either before (pre-soldering) or after (post-soldering) the ceramic (or porcelain) covering (the artificial dentition) allows the correction of the distortion of the framework which may occur during the foundry step of elaboration[3], the improvement of the seating accuracy[4] and the correction of the teeth's movement possibly occurring before the prosthesis cementation[5].

After the deposit of ceramic over the metallic framework the prostheses are subjected to heat-treatments in five steps, each of them being characterized by a heating up to about 900°C in the case of some Ivoclar-Vivadent alloys. Such temperature evolution necessarily induces dimensional changes which may be not compatible with the own dimensional changes of the ceramic cover, with as possible consequences a loss of adherence between the framework and the artificial teeth, and even local ruptures of the ceramic covering the metallic framework, the more intense thermal expansion (respectively retraction) of which subjects the fragile porcelain in traction (resp. compression). This is the reason why the thermal expansion behavior of dental materials destined to ceramic-metallic prostheses has been from several decades the purpose of many studies[6-8].

The subject of the present work is precisely to better know the thermal expansion behavior of selected alloys representing the greatest part of the metallic framework (the "parent alloys") and belonging to different classes of nobility, not only for a single heating-cooling cycle but for several cycles reproducing, with a fidelity high enough, the real thermal cycles encountered by the prosthesis to wholly thermally treat the porcelain. In this field (high temperature behavior of framework's alloys) the present work comes thus completing a recent other one which dealt with the characterization of the melting ranges of the same alloys[9].

EXPERIMENTAL DETAILS

The studied alloys

The alloys concerned by the present thermodilatometry study were supplied by the Ivoclar-Vivadent company. They were remelted and investment cast in order to obtain parallelepipeds of about 10mm × 10mm × 1mm. Investment casting was performed by preparing resin models with a resin injected in a metallic mould (resin Pattern from GC, Tokyo, Japan). These patterns or model were coated (FugiVest II from GC) to obtain the final moulds in which the liquid alloy will be poured. For this filling operation a casting machine equipped with a centrifugal arm (Minicast from Uger) was used.

Five out of these alloys are named "High Noble" since they contain more than 60 wt.% of gold, platinum and/or palladium (cumulated content > 60wt.%): the IPS dSIGN98 alloy (about 86Au-12Pt-2Zn in wt.%), the IPS dSIGN91 one (about 60Au-31Pd-8In, wt.%), the Aquarius Hard one (about 86Au-9Pt-3Pd-1In, wt.%), the Lodestar one (52Au-39Pd-9In-2Ga, wt.%) and the W one (54Au-26Pd-16Ag-3Sn-2In). One out of them is named "Noble" alloy since it contains more than 25wt.% Au and/or Pt and/or Pd: the dSIGN59 one (59Pd-28Ag-8Sn-3In-1Zn). To finish, two out of them are named "Predominantly Base" alloys since they contain less than 25wt.% of Au+Pt+Pd; more precisely they are both {nickel + chromium}-based: the 4ALL alloy (about 61Ni-26Cr-11Mo-2Si, wt.%) and the Pisces Plus one (about 62Ni-22Cr-11W-3Si-2Al, wt.%). More detailed chemical compositions for these alloys were already given in an earlier work[10] in which the microstructures of the re-solidified alloys are also described.

The thermodilatometry tests

After the deposit of porcelain the prostheses are subjected to different successive heat-treatments. These ones were already described in a previous work[10] but they can be summarized as follows:

- Heat-treatment 1 ("opaque")
  temperatures/baking service: 900-403°C, heating rate 80K/min, temperatures/vacuum: 450-899°C
- Heat-treatment 2 ("opaque wash")
  temperatures/baking service: 890-403°C, heating rate 60K/min, temperatures/vacuum: 450-889°C
- Heat-treatment 3 ("dentine I")
  temperatures/baking service: 870-403°C, heating rate 60K/min, temperatures/vacuum: 450-869°C

- Heat-treatment 4 (“dentine II”)
  temperatures/baking service: 870-403°C, heating rate 60K/min, temperatures/vacuum: 450-869°C
- Heat-treatment 5 (“glazing”)
  temperatures/baking service: 830-403°C, heating rate 60K/min, temperatures/vacuum: 450-869°C with, for all of the previous treatments, a stage duration of one minute.

To simulate the preceding thermal cycles the dilatometry runs which were done on the samples using a Setaram TMA 92-16.18 device, were:

- Cycle 1: heating from room temperature (20°C) up to 900°C at 20K/min, stage at 900°C during 1 minute, cooling at -20K/min down to 20°C, stage at 20°C during 10 minutes,
- Cycle 2: heating from 20°C up to 890°C at 20K/min, stage during 1 minute, cooling at -20K/min down to 20°C and stage during 10 minutes at this temperature,
- Cycle 3: heating from 20°C up to 870°C at 20K/min, stage at 870°C during 1 minute, cooling at -20K/min, stage at 20°C during 10 minutes,
- Cycle 4: identical to cycle 3
- Cycle 5: heating from 20°C up to 830°C at 20K/min, stage at 870°C during 1 minute, cooling at -20K/min, stage at 20°C during 10 minutes.

Some parameters are different from the ones of the heat-treatments really applied in practice (notably the heating and cooling rates, lower for the experiment than for the real conditions). This is in order to use the thermo-dilatometer in good conditions.

RESULTS AND DISCUSSION

The dilatometry curves plotted as deformation versus time

The results obtained for the five cycles for the eight alloys are presented in the {deformation = f(time)} scheme in Figure 1 for three of the High Noble alloys (Aquarius Hard, dSIGN91 and dSIGN98), in Figure 2 for the two other High Noble alloys (Lodestar and W) together with the single Noble alloy of this study (dSIGN59), and in Figure 3 for the two Predominantly Base alloys (4ALL and Pisces Plus).

It appears that the cooling leads, during the first cycle, to a loss of thickness for the sample much important than the thickness gain during the heating. This is reproduced too for the subsequent cycles but with each time a lower negative deformation. The behaviour of the dSIGN91 alloy is totally different since the return to room temperature allows for the sample the recovering of its initial thickness, this for each of the five cycles. The dSIGN98 alloy behaves similarly to the Aquarius Hard one, but with a slower loss of thickness per cycle.

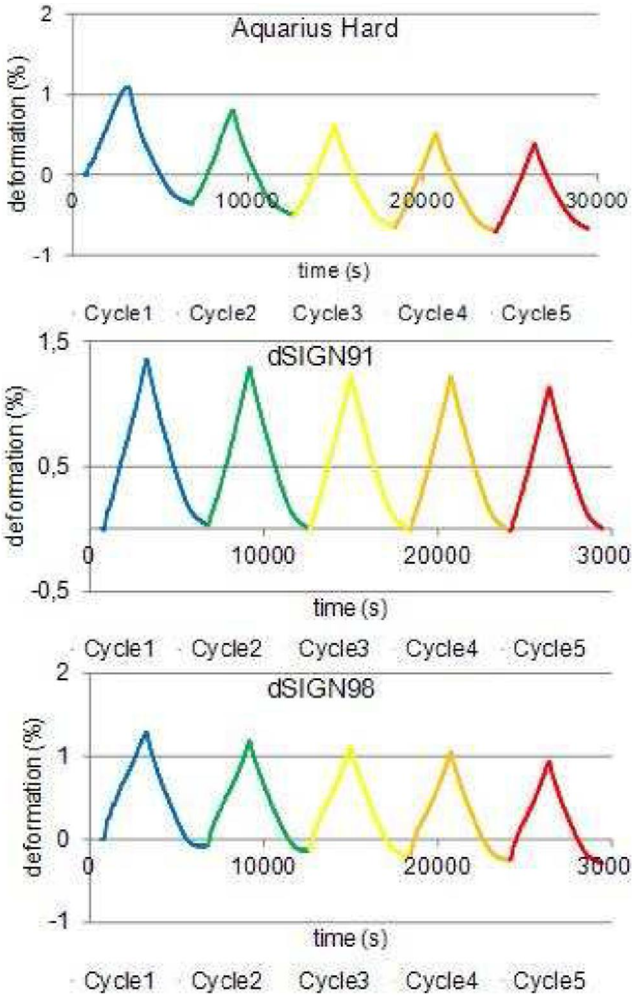


Figure 1 : The cumulated five successive {heating-cooling} thermodilatometric cycles represented as dimensional deformation versus time for three of the High Noble alloys. (top: Aquarius Hard, middle: dSIGN91, bottom: dSIGN98).

Concerning the two other High Noble alloys the phenomenon is found again but with intermediate negative deformation, as is to say higher than for the previous dSIGN91 alloy but lower than for Aquarius hard and similar to dSIGN98. The single Noble alloy of this study, dSIGN59, loses more thickness per cycle than the two previous High Noble alloys, but less than the previous Aquarius Hard alloy.

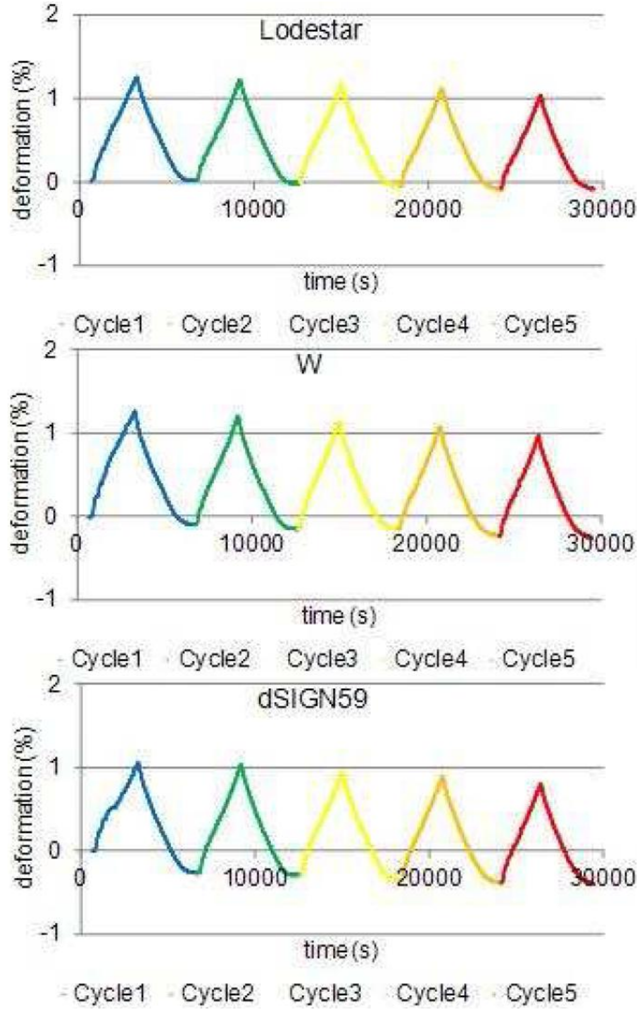


Figure 2 : The cumulated five successive {heating-cooling} thermodilatometric cycles represented as dimensional deformation versus time for the two other high noble alloys. (top: Lodestar, middle: W) and the Noble alloy dSIGN59 (bottom).

In contrast with many of the High Noble and Noble alloys of this study the two Predominantly Base alloys did not lose significant thickness during the five cycles and then they appeared as particularly stable dimensionally.

The dilatometry curves plotted as deformation versus temperature

The dilatometry results for the same eight alloys can be also presented in the {deformation = f(temperature)} scheme. This is done in Figure 4 for the Aquarius Hard, dSIGN91 and dSIGN98 alloys, in Figure 5 for the Lodestar, W and dSIGN59 alloys, and in Figure 6 for the 4ALL and Pisces Plus alloys.

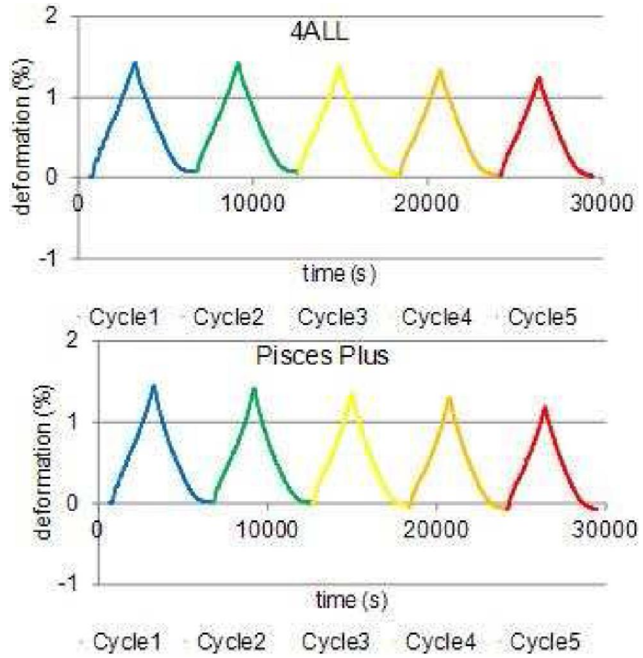


Figure 3 : The cumulated five successive {heating-cooling} thermodilatometric cycles represented as dimensional deformation versus time for the two Predominantly base alloys. (top: 4ALL, bottom: Pisces Plus).

Concerning the three first alloys one can see that the Aquarius Hard alloy presents a rather wide hysteresis for the first cycle, as well as for the second cycle, while the subsequent cycles have their heating and cooling parts closer to one another. A consequence of that is a significant residual negative deformation of the sample at the end of the whole experiment. In contrast, the dSIGN91 alloy has obviously the heating curve and the cooling curve superposed for all the five cycles, with thus no residual deformation after the whole test. The dSIGN98 shows here too a behaviour intermediate between the two previous ones.

Similar behaviours were encountered for the Lodestar alloy (small hysteresis, only for the first cycle), the W alloy (hysteresis more pronounced, for the first cycle) and for the Noble dSIGN59 alloy (especially for the first cycle but also for the subsequent ones).

In contrast the two Predominantly Base alloys present a much better reproducibility of the heating parts and of the cooling parts of their curves for all cycles, with no or rather small residual negative deformation.

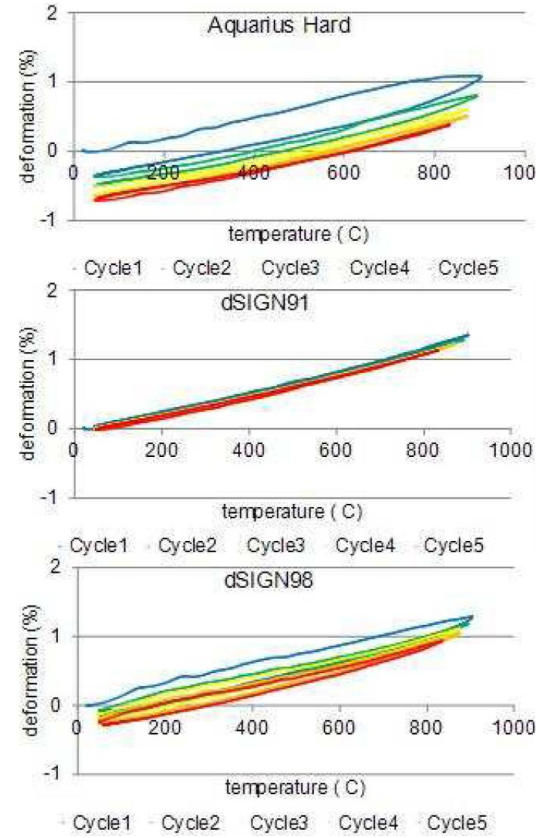


Figure 4 : The cumulated five successive {heating-cooling} thermodilatometric cycles represented as dimensional deformation versus temperature for three of the high noble alloys. (top: Aquarius Hard, middle: dSIGN91, bottom: dSIGN98).

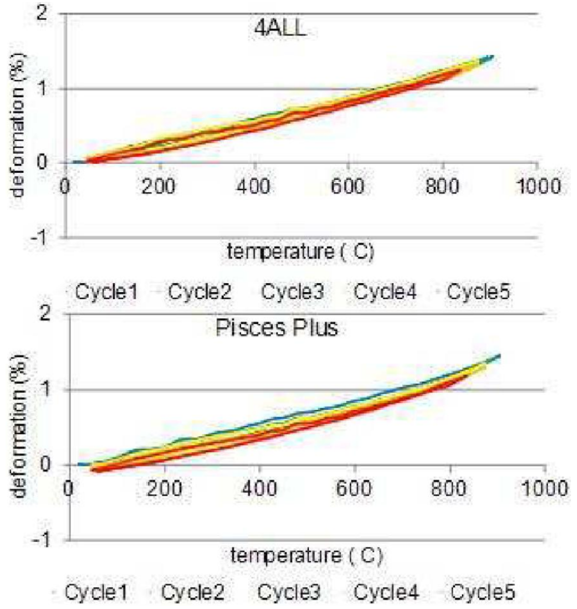


Figure 6 : The cumulated five successive {heating-cooling} thermodilatometric cycles represented as dimensional deformation versus temperature for the two Predominantly base alloys. (top: 4ALL, bottom: Pisces Plus).

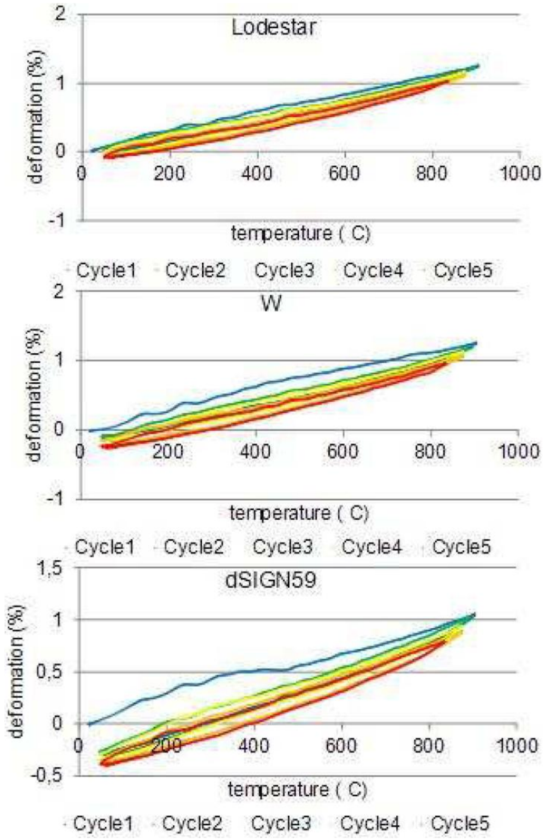


Figure 5 : The cumulated five successive {heating-cooling} thermodilatometric cycles represented as dimensional deformation versus temperature for the two other High Noble alloys. (top: Lodestar, middle: W) and the Noble alloy dSIGN59 (bottom).

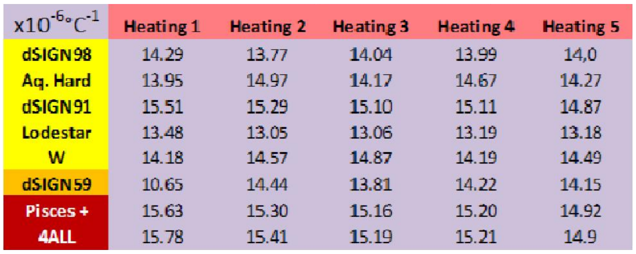
The thermal expansion coefficients

The dilatometry results obtained for each alloy were exploited in order to determine an average value of two thermal expansion/retraction coefficients per alloy and per cycle, one for the heating part and one for the cooling part. The five thermal expansion coefficients obtained for each alloy during the heating are presented in TABLE 1 and the five thermal retraction coefficients during the cooling for each alloy again are given in TABLE 2.

One can see that, if in some cases the thermal expansion coefficient becomes stabilized after one or two cycles (e.g. dSIGN98 and dSIGN91 for heating and cooling, Lodestar for heating only...) this coefficient remains variable all along the five cycles (e.g. Aquarius Hard and W at heating...). In addition there are also alloys the thermal expansion coefficients of which continuously decrease cycle after cycle, as it is the case for the two Predominantly Base alloys (Pisces Plus and

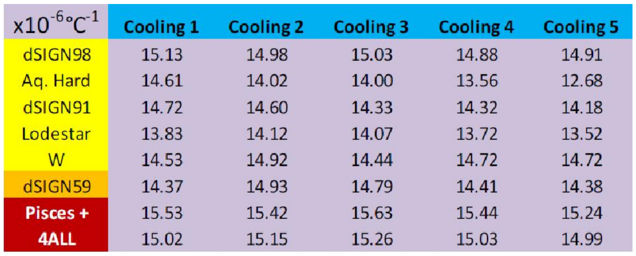
4ALL) in the heating phase.

TABLE 1 : The successive average thermal expansion coefficients determined on the heating parts of the five dilatometry curves of each alloy.



$x10^{-6}°C^{-1}$	Heating 1	Heating 2	Heating 3	Heating 4	Heating 5
dSIGN98	14.29	13.77	14.04	13.99	14,0
Aq. Hard	13.95	14.97	14.17	14.67	14.27
dSIGN91	15.51	15.29	15.10	15.11	14.87
Lodestar	13.48	13.05	13.06	13.19	13.18
W	14.18	14.57	14.87	14.19	14.49
dSIGN59	10.65	14.44	13.81	14.22	14.15
Pisces +	15.63	15.30	15.16	15.20	14.92
4ALL	15.78	15.41	15.19	15.21	14.9

TABLE 2 : The successive average thermal expansion coefficients determined on the cooling parts of the five dilatometry curves of each alloy.



$x10^{-6}°C^{-1}$	Cooling 1	Cooling 2	Cooling 3	Cooling 4	Cooling 5
dSIGN98	15.13	14.98	15.03	14.88	14.91
Aq. Hard	14.61	14.02	14.00	13.56	12.68
dSIGN91	14.72	14.60	14.33	14.32	14.18
Lodestar	13.83	14.12	14.07	13.72	13.52
W	14.53	14.92	14.44	14.72	14.72
dSIGN59	14.37	14.93	14.79	14.41	14.38
Pisces +	15.53	15.42	15.63	15.44	15.24
4ALL	15.02	15.15	15.26	15.03	14.99

By considering, for a given alloy, the average value of the five heating and of the five cooling thermal expansion/retraction coefficients, it appears that the Lodestar alloy is the one which dimensionally varies the least (low coefficients for heating and also for cooling: less than 14×10^{-6} K^{-1}) and that the two Predominantly Base alloys are the ones which vary the most (more than 15×10^{-6} K^{-1}).

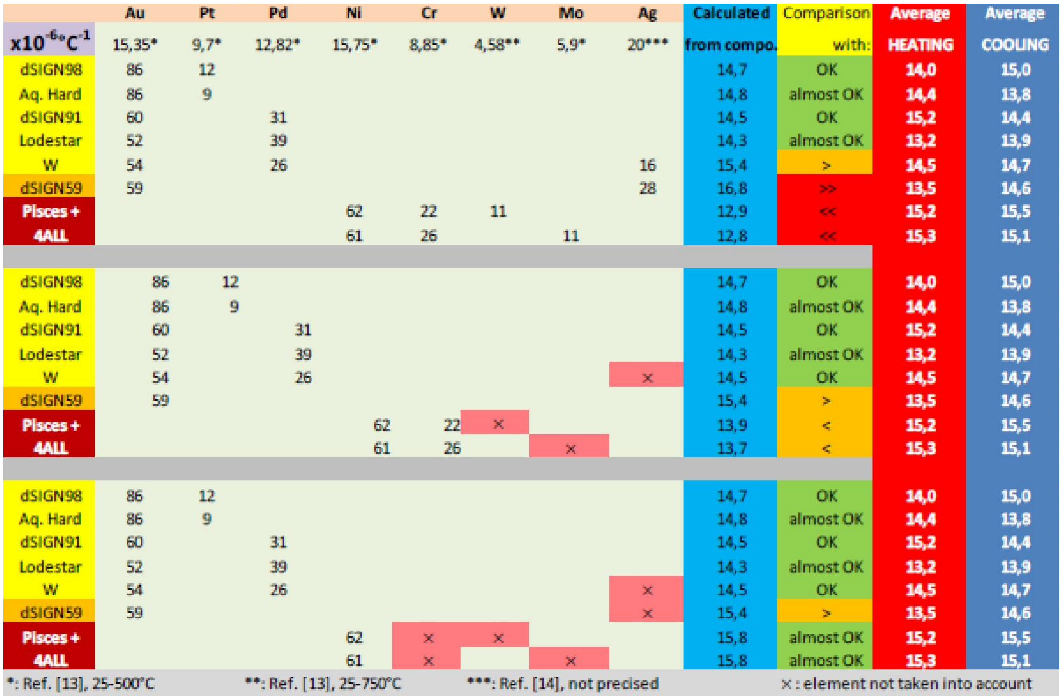
General commentaries

First the dilatometry results obtained present different behaviours. If in all cases there are never discontinuities during thermal expansion or retraction (such as it may occur in case of crystallographic change), there is a decrease in room temperature thickness after one cycle or two. This may be attributed to a possible lack of mechanical resistance of the concerned alloys when temperature has become rather high, leading to a visco-plastic compressive deformation under the small load (10g) applied by the thermo-dilatometer (or intrinsically by the microstructure itself as this was seen previously for metallic alloys containing carbides with fractions high enough[11,12]). This possibility was thereafter further investigated and it appears that it seems existing a correlation between the temperature of fusion start of the alloys (determined in a previous work[9]) and the loss of thickness after the first one or two cycles. Indeed the room temperature thickness of the {low fusion start temperature: 1031°C}-alloy Aquarius Hard was significantly reduced after the first cycles, the one of the {slightly higher fusion start temperature: 1036°C}-dSIGN98 was less reduced, and the ones of the {high fusion start temperature}-alloys dSIGN91 (1094°C) and Lodestar (1132°C), and of the {very high fusion start temperatures}-alloys 4ALL (1277°C) and Pisces Plus (1278°C), were absolutely not changed after all cycles. But there are two exceptions, the {high fusion start temperature}-alloys dSIGN59 (1174°C) and W (1193°C) have known a significant thickness reduction and a small one, respectively. But this can be explained by the fact that these two latter alloys are single-phased while all the other contained two different phases in their microstructures[10] (which may be a source of mechanical resistance).

Second there are obviously different values of the average thermal expansion coefficient among the studied alloys. It appears that the alloy's family has a noticeable importance (e.g. the two Predominantly Base alloys are the ones with the higher values), as is to say the chemical composition type, which may involve elements with rather high thermal expansion coefficients (Ag, Ni, Au...) or other elements with rather low ones (Pd, Pt, Cr, Mo, W...) when these elements are pure solids[11,12]. To further study a possible effect of the chemical composition it was attempted to calculate a kind of theoretical thermal expansion coefficients from the ones of the main elements[11,12], weighted by their contents (re-calculated by suppressing all minor elements). The results are presented in TABLE 3 which is divided in three parts. It appeared in a first time that the obtained values were in good agreement with the average values of thermal expansion/retraction coefficients measured in this work, only for the five High Noble elements (top part). A first improvement was obtained by suppressing the W, Mo and Ag elements (middle part of TABLE 3), and the best correspondence for all the alloys was obtained by suppressing also Cr (bottom part of TABLE 3).

Third the average thermal expansion coefficients measured in this work were compared to the ones given by the manufacturer (Figure 7). It appears that there is often a good agreement between these sets of data, except for the W and dSIGN59 alloys for which there are significant mismatches, which remain to be explained.

TABLE 3: Attempt of prevision of the average alloy's thermal expansion coefficient from the chemical composition of the alloy (main elements only) and the thermal expansion coefficient of these elements when pure solids[13,14]; (top part of the table: all main elements taken into account; middle part: W, Mo and Ag not taken into account despite they are present; bottom part: Cr, W, Mo, Ag not taken into account despite they are present)



	Au	Pt	Pd	Ni	Cr	W	Mo	Ag	Calculated	Comparison	Average	Average
x10^{-6}°C^{-1}	15,35*	9,7*	12,82*	15,75*	8,85*	4,58**	5,9*	20***	from compo.	with:	HEATING	COOLING
dSIGN98	86	12							14,7	OK	14,0	15,0
Aq. Hard	86	9							14,8	almost OK	14,4	13,8
dSIGN91	60		31						14,5	OK	15,2	14,4
Lodestar	52		39						14,3	almost OK	13,2	13,9
W	54		26					16	15,4	>	14,5	14,7
dSIGN59	59							28	16,8	>>	13,5	14,6
Pisces +				62	22	11			12,9	<<	15,2	15,5
4ALL				61	26		11		12,8	<<	15,3	15,1
dSIGN98	86	12							14,7	OK	14,0	15,0
Aq. Hard	86	9							14,8	almost OK	14,4	13,8
dSIGN91	60		31						14,5	OK	15,2	14,4
Lodestar	52		39						14,3	almost OK	13,2	13,9
W	54		26					×	14,5	OK	14,5	14,7
dSIGN59	59								15,4	>	13,5	14,6
Pisces +				62	22	×			13,9	<	15,2	15,5
4ALL				61	26		×		13,7	<	15,3	15,1
dSIGN98	86	12							14,7	OK	14,0	15,0
Aq. Hard	86	9							14,8	almost OK	14,4	13,8
dSIGN91	60		31						14,5	OK	15,2	14,4
Lodestar	52		39						14,3	almost OK	13,2	13,9
W	54		26					×	14,5	OK	14,5	14,7
dSIGN59	59							×	15,4	>	13,5	14,6
Pisces +				62	×	×			15,8	almost OK	15,2	15,5
4ALL				61	×		×		15,8	almost OK	15,3	15,1

*: Ref. [13], 25-500°C **: Ref. [13], 25-750°C ***: Ref. [14], not precised ×: element not taken into account

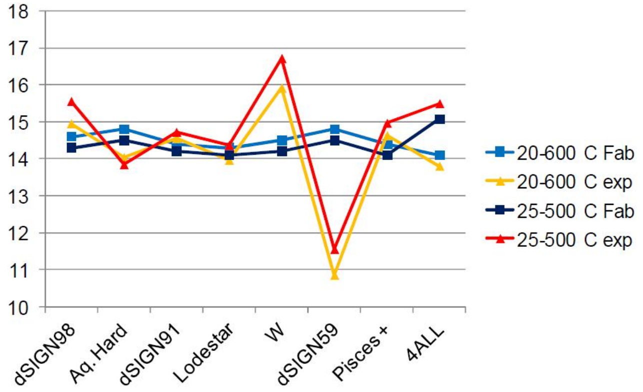


Figure 7 : Comparison between the average thermal expansion coefficients measured in this work ("exp") with the ones given by the manufacturer ("Fab") for two temperature ranges (25 to 500°C) and (25 to 600°C).

CONCLUSION

The present study, by thermo-dilatometric experiments almost reproducing the thermal cycles known by the prostheses during the different heat-treatments applied after deposit of the porcelain (the cosmetic part), showed that the main part of the metallic framework dimensionally behaves differently depending on the identity of the parent alloy. Some of them know a possible viscous-plastic deformation seemingly due to a rather low fusion start temperature and a microstructure less favorable to high mechanical properties at high temperature. This is maybe both a bad thing since this may induces dimensional instabilities and a good thing since the stresses induced for the fragile porcelain can be lowered. The real dimensional behavior must be anyway better known than the sole indication of average thermal coefficients which are, it is true, of a first great importance for seeing the compatibility with the one of the porcelain.

ACKNOWLEDGEMENTS

The authors would like thank very much the Ivoclar Vivadent company who offered them the alloys for this study.

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