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MEASUREMENTS AND CALCULATIONS OF STRESSES IN METAL-CERAMIC SYSTEMS

P. DORSCH

Vaduz, Fürstentum Liechtenstein

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Deflection changes dependent on temperature and thickness of ceramics have been measured on ceramic-coated metal strips, using a modified commercial dilatometer. The deflections are not only dependent on the difference in the thermal expansion coefficients of the two materials, but are also influenced by the thickness ratio of the ceramic to the metal. The stresses existing in the ceramic have been calculated for the surface layer and for the layer in the transition zone ceramic/metal. The results have shown that there is no proportional relation between the value of deflection and the stresses in the ceramic; however, the maxima in the deflection curves coincide with the peaks shown in the stress curves. From a certain thickness ratio of ceramic to metal — determined by the Young's moduli of the materials — tensile stresses in the surface of the ceramic occur even at the higher expansion coefficient of the metal.

As for the enamel techniques, the adjustment of the expansion values of metal and ceramic materials is of great importance in the production of metal-ceramic restorations, such as artificial teeth [1–3]. It is necessary to keep the stresses as small as possible that occur due to the different thermal contractions in the compound during the cooling phase. An exact conformity of the dilatation values cannot be technically realized.

Most ceramic compounds can take compressive stresses of approximately four (4) times higher compared to tensile stresses. In general, systems where the coefficient of expansion of the alloy is slightly higher than the one of ceramics, are strived for. Then, after the firing process, the metal contracts more than the ceramic and thus induces compressive stresses in the dental ceramic compound.

A standard method for optimization of metal/ceramic systems exists in the comparison of the individual values of the materials which constitute the compound and production of dental-ceramic restorations, whereby the tolerable differences of the expansion coefficients can be determined.

Under the heading "Warp-Test" [4–7], "Split Ring Test" [8–10] and "Steger Test" [11–13], measuring methods in the enamel techniques have been developed to evaluate the stresses present in a specimen. These methods are based on the fact that an enamel-coated metal body suffers deformations caused by temperature changes, from which conclusions can be drawn on the type and size of stresses occurring in the two layers.

These measurements require special equipment. A method is described herein to measure the deflection and thus the stress changes, dependent on the temperature, in a bi-material strip, conducted on a commercial dilatometer.

Experimental

To perform the test, small metal plates of $l = 20 \pm 0.1$ mm, $b = 3 \pm 0.05$ mm and $d = 1 \pm 0.01$ mm, and 1.5 ± 0.01 mm were prepared from a Ni-base alloy coated with the dental-ceramic material "A" and "B" respectively, and fired. The length of the ceramic material was 12 mm.

To obtain the desired layer thicknesses of 0.2 mm, 0.4 mm, 0.6 mm and 0.8 mm a surplus of ceramic was used, which after firing was ground to the intended layer thickness with a precision of ± 0.01 mm. A further firing process followed to produce a stress in the samples according to the thickness of the ceramic layer.

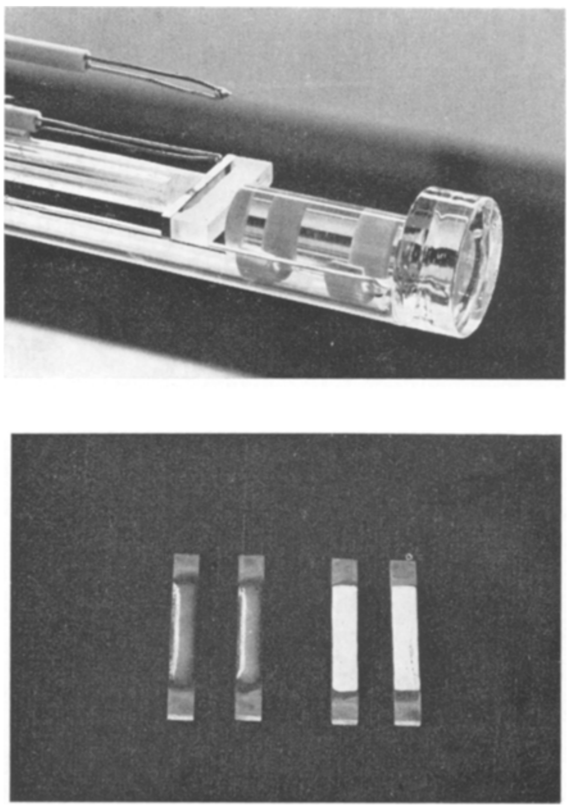

Fig. 1. Sample support (on top) and shape of the samples (bottom) used for the measurements of deflection

Table 1

Difference of the relative thermal expansions $(\Delta l/l)_{Ceramic} - (\Delta l/l)_{Metal}$ between ambient temperature and T, °C

T, °C	Alloy/Ceramic A	Alloy/Ceramic B
250	$-0.32 \cdot 10^{-3}$	$-0.05 \cdot 10^{-3}$
400	-0.36	$+0.30$
500	-0.63	$+0.20$
550	-1.02	$+0.01$
575	-1.25	-0.07
600	-1.40	-0.01
625	-1.38	$+0.18$
650	-1.35	$+0.25$
700	-1.87	-0.20

This was necessary as the stresses existing in the specimen were changed by the partial removal of the ceramic material.

Figure 1 shows the shape of the samples. The difference in the relative thermal expansions between the Ni-based alloy and the two ceramic substances used for the test can be seen in Table 1. The deflection changes dependent on the temperature in the samples were determined by using a NETZSCH Electronic Dilatometer, Model 402 E, with a slightly modified sample support. The illustration in Fig. 1 shows that the samples, with the surface carrying the ceramic material, were placed against two supports with a bearing surface of 2×3 mm^2 each and a distance of 16 mm. On the opposite surface a scanning rod picked up the deflection changes that are superimposed by the thermal expansion of the metal substratum. If the sample is regarded as part of a circular arc, having the ceramic material on the outside, an increase in the bend radius should correspond to positive deflections.

The relative thermal expansions of the alloy and the two types of ceramic were measured on test bodies with a length of 28 mm and a cross section of 4×5 mm^2. As for the determination of the deflection changes the contact pressure of the scanning rod was 0.5 N and the heating rate 5 K/min. The usual instrument correction for dilatometric measurements was not made, as the results obtained from the two different systems were regarded separately.

Results and discussion

In Fig(s) 2 to 5 the measured relative thermal expansions of the standard rods of the alloy and the ceramic substance, as well as of the small metal plates, are plotted over the temperature. Furthermore, the apparent $\Delta l/l$ curves of the bimaterial bodies, representing the deflection changes and thermal expansion of the metal substratum, are outlined in these diagrams.

Figure 5 shows only the deflection curves for specimens with 0.20 mm and 0.60 mm thickness of ceramic, because the curves with the other two ceramic thicknesses show an almost identical process, and thus a graphical distinction was not possible.

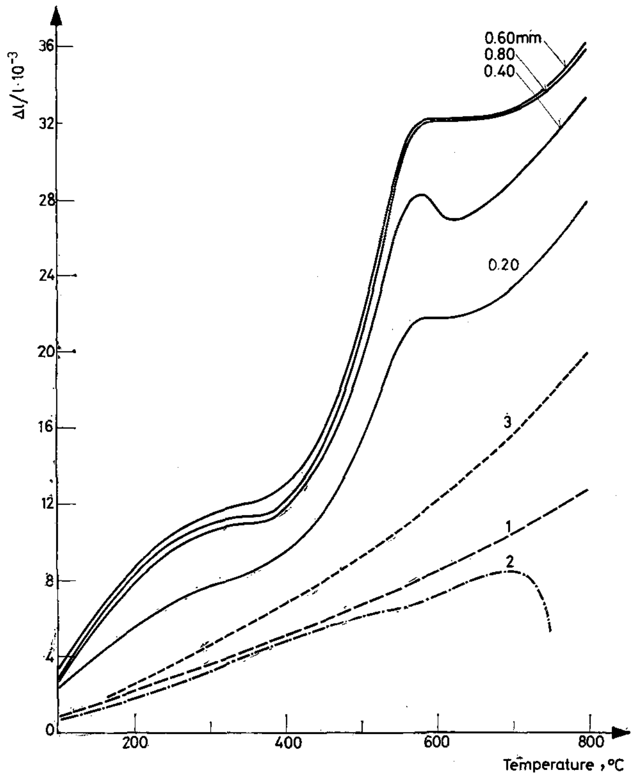

Fig. 2. Relative deflections plus superimposed thermal expansions of the specimens in the system 1.00 mm "alloy/ceramic A", with the ceramic thickness as a parameter, as well as relative thermal expansions of the standard samples: alloy (1), ceramic (2) and the small metal plates (3)

For the calculation of these apparent deflection curves the measuring values were divided by the thickness of the metal substratum. Thus, the pure deflection part can be ascertained by subtraction of the $\Delta l/l$ values of the small metal plates and multiplication by the thickness of them.

A characteristic in the curves of the specimens is that the expansion, when compared to the expansion curve of the metal substratum, increases at first up to 250°, passes through a lower value at 400°, and at 575° shows a further maximum. Starting at about 650° the rising tendency of this curve follows the metal substratum. The shape of the specimen curves can be explained by the material characteristics of the individual components and be qualitatively explained using the example of

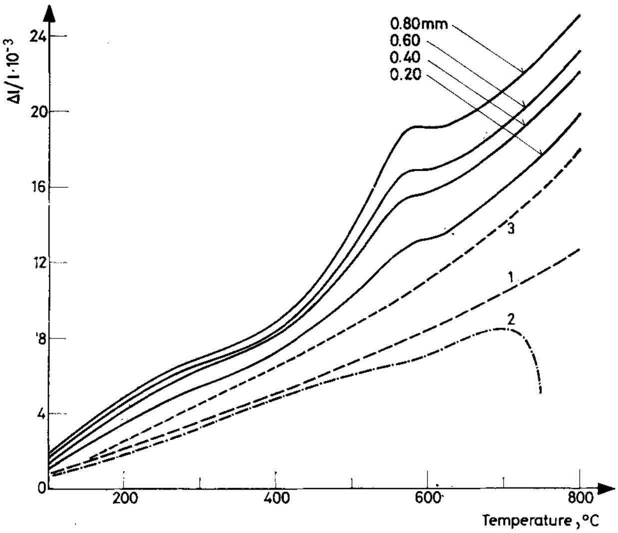

Fig. 3. Relative deflections plus superimposed thermal expansions of the specimens in the system 1.50 mm "alloy/ceramic A" with the ceramic thickness as a parameter, as well as relative thermal expansions of the standard samples: alloy (1), ceramic (2) and the small metal plates (3)

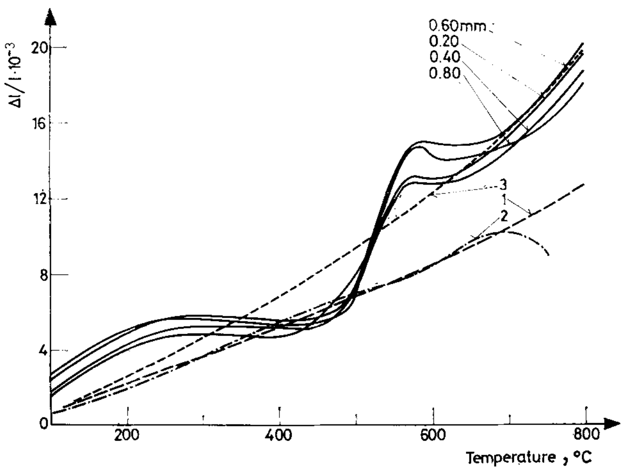

Fig. 4. Relative deflections plus superimposed thermal expansions of the specimens in the system 1.00 mm "alloy/ceramic B" with the ceramic thickness as a parameter, as well as relative thermal expansions of the standard samples: alloy (1), ceramic (2) and the small metal plates (3)

the system of 1.00 mm "alloy/ceramics A". According to curves 1 and 2 in Fig. 2 describing the characteristics of the material, the ceramic is under compressive stress and the metal component under tensile stress after cooling from the tempering firing process which takes place at 940°. As a consequence of this, the specimen forms a circular arc with the porcelain on the outside circumference. If the speci-

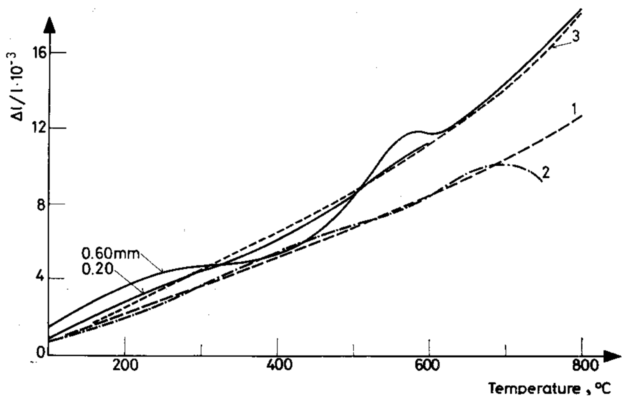

Fig. 5. Relative deflections plus superimposed thermal expansions of the specimens in the system 1.50 mm "alloy/ceramic B" with the ceramic thickness as a parameter, as well as relative thermal expansions of the standard samples: alloy (1), ceramic (2), and the small metal plates (3)

men is heated up to 250° an increase in the bend radius, and thus in the deflection will take place due to the higher relative thermal expansion of the metal.

Within the temperature range of 250° and 400° the thermal expansions of the alloy and the ceramics are almost equal, and therefore only a slight change of deflection takes place. This can be seen in the almost parallel shape of the specimen curves compared to the curve of the metal substratum. Between 400° and 575° the alloy again has the higher value and therefore a further positive deflection occurs leading to a negative bend radius, causing the ceramic to be temporarily placed under tensile stress. The decrease of deflection between 575° and 650° is based on the higher thermal expansion and the beginning of softening of the ceramic, which occurs in this temperature interval. At approximately 650° the deflection curves take a parallel course to the expansion curve of the metal substratum due to a decrease in the viscosity of the ceramic, after which there are no further deflections. As previously published [14] a reasonable conformity exists, up to the transformation temperature of the ceramic, between the deflection part and the value calculated from the differences in the relative thermal expansions.

As can be seen in Fig(s) 4 and 5, as well as Table 1, the system "alloy/ceramic B", compared to the one regarded previously, is distinguished by a considerably smaller difference in the thermal expansion between ambient temperature and approximately 650°. Also the thermal expansion of the ceramic material from ambient temperature to values between 300° and 550° is higher than that of the alloy. During heating of the specimens the ceramic material expands more within this temperature range than the alloy, and the change in deflection of these samples must be of a negative nature.

The measuring results reproduce these relations correctly because the deflection curves cross the curve of the metal substratum at approximately 325° and 525°.

The influence of the ceramic layer thickness, metal thickness and difference in the relative thermal expansions of these two materials on the value of deflection can be described by a comparison of Fig(s) 2 to 5 as follows:

Increasing the ceramic layer thickness produces larger deflections.

Thicker metal substrata lead to smaller deflections.

Larger differences in the relative thermal expansions result in higher deflections.

In the following, the connection between the deflection changes from ambient temperature to 700°, and the resulting stresses based on a calculation method [15] developed for bi-metals, shall be examined. If, at 700° a straight specimen is cooled to ambient temperature, the sample will change into a circular arc with the following bend:

$$\frac{l}{R} = \frac{(\Delta l/l)_M - (\Delta l/l)_K}{h_n}. \qquad (1)$$

Where $\Delta l/l$ is the relative thermal expansion of the materials and h_n the distance of the neutral fibres of both layers resulting from

$$h_n = \frac{2h}{3} + \frac{(E_M \cdot h_M^2 - E_K \cdot h_K^2)^2}{6 \cdot h \cdot h_M \cdot h_K \cdot E_M \cdot E_K}. \qquad (2)$$

In these formulas the subscripts M and K relate to the metal and ceramic respectively. E are the elasticity moduli and the description h the total thickness, or when subscripted, the thickness of the individual layers.

The bending radius R can be evaluated from the deflection changes "a" (see Table 2) measured between ambient temperature and 700°. For this it was assumed that the curve of the sample continues in tangents over the length of chord, $s = 12$ mm, up to the support in the measuring system. Using elementary geometric relations, and considering the sample as being supported on the inner edges of the sample carrier, the following equation may be written:

$$R = \frac{30 \text{ mm}^2}{a \text{ mm}}. \qquad (3)$$

With the formulas (1) to (3) and the hypothesis $E_K = 60.000$ N/mm^2, $E_M = 200.000$ N/mm^2 a theoretical difference $\Delta(\Delta l/l)$ of the relative thermal expansions of the compound components can be calculated from the measured deflections. The results are shown in Table 2.

Table 2

Theoretical difference in the relative expansion calculated from the measured deflection (a) $\Delta(\Delta l/l) = (\Delta l/l)_{\text{Metal}} - (\Delta l/l)_{\text{Ceramic}}$ between ambient temperature and 700°

Compounds consisting of	a, μm	$\Delta(\Delta l/l) \cdot 10^{-3}$
1.00 mm alloy with		
0.20 mm ceramic A	7.57	0.772
0.40 mm ceramic A	12.95	0.788
0.60 mm ceramic A	16.97	0.864
0.80 mm ceramic A	16.95	0.819
1.50 mm alloy with		
0.20 mm ceramic A	2.73	0.599
0.40 mm ceramic A	6.15	0.744
0.60 mm ceramic A	7.85	0.719
0.80 mm ceramic A	10.71	0.854
mean value		0.770
standard deviation		±0.085
1.00 mm alloy with		
0.20 mm ceramic B	−0.37	−0.038
0.40 mm ceramic B	−1.33	−0.081
0.60 mm ceramic B	0.01	+0.001
0.80 mm ceramic B	−0.89	−0.043
1.50 mm alloy with		
0.20 mm ceramic B	0.33	0.073
0.40 mm ceramic B	0.85	0.103
0.60 mm ceramic B	0.47	0.043
0.80 mm ceramic B	−0.05	−0.004
mean value		0.007
standard deviation		±0.062

Taking into consideration that the standard deviation of approximately $0.08 \cdot 10^{-3}$ corresponds to a difference in the expansion coefficients of approximately $0.12 \cdot 10^{-6} \cdot K^{-1}$, the conformity of the values measured from the deflections of samples, with different thickness ratios of metal to ceramic, is within the precision of dilatometric measurements.

With the theoretical $\Delta(\Delta l/l)$ value of $0.77 \cdot 10^{-3}$, obtained for the material combination "alloy/ceramic A", the deflections of the small metal plates with different thicknesses were calculated as a function of the thickness of ceramic. In comparison to this, the stresses in the ceramic at its surface and in the contact face to the metal may be calculated as follows:

$$\sigma = \frac{E_K(\Delta l/l)_M - (\Delta l/l)_K \cdot Y_i}{h_n} \qquad (4)$$

with

$$Y_1 = \frac{h_K}{2} - \frac{E_K \cdot h_k^3 \cdot + E_M \cdot h_M^3}{6 \cdot h \cdot h_K \cdot E_K} \tag{5}$$

$$Y_2 = \frac{h_K}{2} + \frac{E_K \cdot h_K^3 + E_M \cdot h_M^3}{6 \cdot h \cdot h_K \cdot E_K} \tag{6}$$

where Y_1 signifies the distance of the neutral fiber in the ceramic from its surface, and Y_2 from the contact face [15].

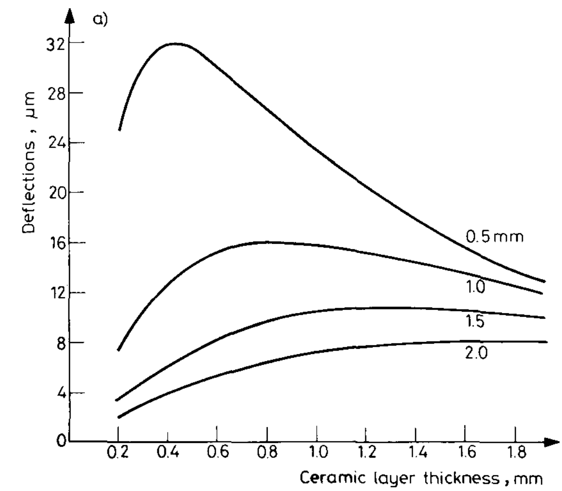

Fig. 6a. Evaluated deflections for specimens dependent on the thickness of the ceramic layer with the metal thickness as a parameter

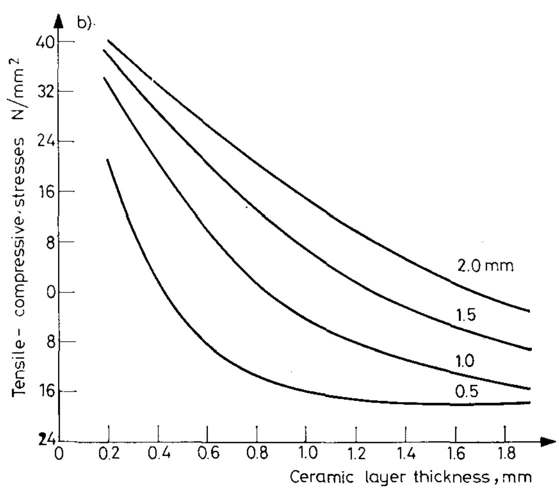

Fig. 6b. Evaluated stresses in the surface of the ceramics dependent on the thickness of the ceramic layer with the metal thickness as a parameter

The results of these calculations are graphically shown in Fig(s) 6a to 6c. The deflections pass through a maximum which lies at a value of 0.85 in the layer thickness ratio, and which increases the smaller the thickness of the metal substratum becomes. On the surface of the ceramic, in thin ceramic layers, compressive stresses

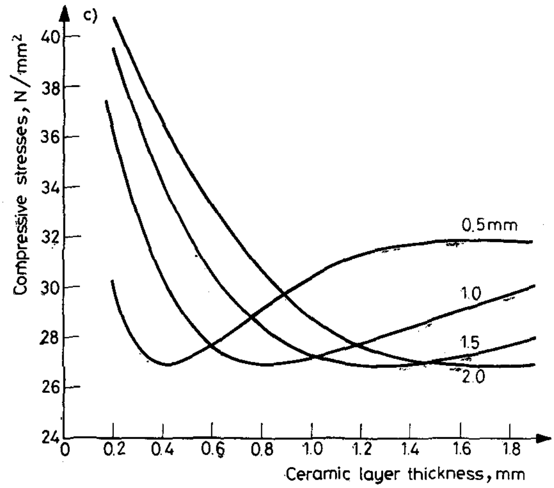

Fig. 6c. Evaluated stresses in the contact face of the ceramics dependent on the thickness of the ceramic layer with the metal thickness as a parameter

exist at first, changing into tensile stresses when surpassing a critical thickness ratio. In the transition zone between ceramic and metal, the compressive stresses pass a minimum which lies at the same thickness ratio. Contrary to the stresses on the surface, the change becomes considerably smaller with increasing ceramic thickness and no tensile stresses are occurring in this zone. Therefore, the surface of the ceramic has to be considered as a critical zone, because in such cases where the thermal contraction of the metal is higher than that of the ceramic, from a certain ceramic thickness, tensile stresses occur to which ceramic materials are especially sensitive.

According to formula (4), by using the same materials and the same layer thicknesses, the stresses are directly linear proportional to the difference in the relative thermal expansions. In the system "alloy/ceramic B" this theoretical value calculated from the deflections is $0.007 \cdot 10^{-3}$, whereby a virtually stressless condition would exist. Taking into consideration the standard deviation of $0.062 \cdot 10^{-3}$, stresses up to approximately 10% of the values calculated for the system "alloy/ceramics A" would be expected.

The tests have shown that the stresses in a compound are not only determined by the coefficient of expansion but also that the layer thickness is influential in the development of compressive – or tensile – stresses in the ceramic. To estimate the stress situation in the ceramic material, which is considered the critical component, the measurement of the deformation of a specimen under the influence of different thermal expansion coefficients is not sufficient.

It is also necessary to approach the problem mathematically, for which the measuring method herein described will give sufficiently precise foundations in addition to the methods already known.

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Résumé — On a mesuré, sur des bandes de métal recouvertes de céramique et en se servant d'un dilatomètre commercial modifié, les changements de déflection qui dépendent de la température et de l'épaisseur des céramiques.

Les déflections dépendent non seulement de la différence des coefficients de dilatation thermique des deux matériaux, mais aussi du rapport des épaisseurs respectives de la céramique et du métal. Les contraintes existant dans la céramique ont été calculées pour la couche superficielle et pour la couche de la zone de transition céramique/métal. Les résultats ont montré qu'il n'y a pas de relation de proportionnalité entre la valeur de la déflection et les contraintes dans la céramique; cependant, les maximums des courbes de déflection coïncident avec les pics des courbes de contrainte. A partir d'un certain rapport d'épaisseur de la céramique au métal — déterminé par les modules d'Young des matériaux — les contraintes d'allongement à la surface de la céramique se produisent même si le métal possède un coefficient de dilatation plus élevé.

Zusammenfassung — An mit Keramik beschichteten Metallstreifen wurden in einem modifizierten, handelsüblichen Dilatometer Ausbiegungsänderungen in Abhängigkeit von der Temperatur und der Keramikdicke gemessen. Die Verformungen hängen nicht allein von der Differenz der thermischen Ausdehnungskoeffizienten der beiden Werkstoffe ab, sondern werden auch durch das Dickenverhältnis von Keramik zu Metall beeinflusst. Die in der Keramik vorhandenen Spannungen wurden für die Oberflächenschicht und für die Schicht in der Grenzzone Keramik/Metall berechnet. Die Ergebnisse haben gezeigt, daß kein proportionaler Zusammenhang zwischen der Grösse der Ausbiegung und den Spannungen in der Keramik vorhanden ist. Maxima in den Ausbiegungskurven fallen jedoch mit ausgezeichneten Punkten in den Spannungskurven zusammen. Ab einem durch die Elastizitäts-Moduln der Werkstoffe bestimmten Dickenverhältnis von Keramik zu Metall treten auch bei einem grösseren Ausdehnungskoeffizienten des Metalls Zugspannungen in der Oberfläche der Keramik auf.

Резюме — С помощью видоизмененного дилатометра были измерены изменения прогиба металлических фотм с керамическим покрытием в зависимости от температуры и толщины керамики. Прогибы зависят не только от различия коэффициентов термического расширения двух материалов, но и от соотношения толщины керамики и металла. Были вычислены существующие в керамике напряжения для поверхностного слоя и для слоя в переходной зоне керамика/металл. Рерультаты показали, что нет прямой зависимости между значением прогиба и напряжениями в керамике. Вместе с тем показано, что максимум на кривых прогиба совпадает с пиками на кривых напряжения. Из соотношения толщины керамики и металла определено, с помощью модулей Юнга этих материалов, растягивающее усилие на поверхности керамики, чпоисходящее даже при более высоком коэффициенте расширения металла.