© Strojniški vestnik 48(2002)1,2-8
ISSN 0039-2480
UDK 53.089:539.37
Izvirni znanstveni članek (1.01)

© Journal of Mechanical Engineering 48(2002)1,2-8
ISSN 0039-2480
UDC 53.089:539.37
Original scientific paper (1.01)

Eksperimentalno ovrednotenje analitičnega preračuna deformacije krogle zaradi tipalne sile pri kalibraciji

The Experimental Validation of an Analytical Calculation of Sphere's Deformation that Results from Probing Force During Calibration

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Kalibracija premera majhnih kroglic je z vidika merilne negotovosti zelo problematična, kar dokazujejo rezultati številnih mednarodnih laboratorijskih primerjav. Posebni problem pomeni določitev deformacije zaradi merilne sile. Vzrok je predvsem v netočnem poznavanju mehanskih lastnosti materialov tipal merilne naprave in kroglice, ki jo kalibriramo. V prispevku je predstavljen postopek za eksperimentalno določitev deformacije krogle med kalibracijo in rezultati analize na primeru tipalne kroglice iz rubina. Prikazana je tudi primerjava z rezultati analitičnega preračuna, v katerem smo uporabili vrednosti mehanskih lastnosti materialov, ki smo jih dobili od različnih proizvajalcev merilne opreme.

(Ključne besede: sile merilne, deformacije, kalibriranje premerov, negotovosti merilne)

The calibration of a sphere of a small diameter is very problematic in terms of the uncertainty of the measurement. This fact has often been demonstrated during numerous international interlaboratory comparisons. A particular problem occurs when calculating the deformation is caused by the measurement force. The reason for this is that we do not know enough about the mechanical properties of the probes of the measurement device or the sphere that is being calibrated. This paper introduces a procedure for the experimental determination of a sphere's deformation during a calibration and an analysis of the results of an example of a ruby probe sphere. A comparison of these results with analytical calculation results is also presented. The analytical calculations were based on the material's mechanical properties which were provided by different measurement-equipment manufacturers.

(Keywords: measurement force, deformations, diameter calibrations, uncertainty of measurements)

0 UVOD

Kalibracija premera krogle je pomembna predvsem z vidika točne določitve dimenzij kroglic merilnih tipal, ki jih uporabljamo za točne meritve v dimenzionalni merilni tehniki. Posebni merilni problemi terjajo določitev premera tipalne kroglice z negotovostmi pod 0,5 μm. Če hočemo doseči takšno točnost merjenja premera kroglice, moramo določiti deformacijo zaradi merilne sile z negotovostjo, manjšo od 0,2 μm. Ta naloga ni lahka, ker se pri kalibraciji majhnih premerov na standardnih merilnih napravah pojavljajo zelo velike deformacije (pri kalibraciji rubinaste kroglice premera 0,3 mm s silo 1,5 N je deformacija 1 μm).

Z uporabo analitičnih obrazcev ali z metodo končnih elementov lahko sicer točno izračunamo deformacijo, vendar moramo zelo dobro poznati module elastičnosti in Poissonove količnike

0 INTRODUCTION

Sphere's diameter calibration is important because we need to determine that exact dimensions of the probe spheres used for precise measurements in dimensional measurement techniques. Special measurement problems require very exact diameter determination with uncertainties under 0,5 μm. If such diameter measurement accuracy is demanded, the deformation caused by the probing force needs to be determined with an accuracy of better than 0,2 μm. This task is not easy, because big deformations occur during the calibration of small diameters on conventional measurement machines (e.g. 1 μm when calibrating a ruby sphere with a diameter 0,3 mm using a measurement force of 1,5 N).

It is possible to calculate the deformation precisely using analytical formulae or the finite-element method, but only if the elasticity moduli and Poisson's ratia of the sphere and probe materials are materialov tipal merilne naprave in kroglice, ki ju kalibriramo. To pa je v praksi velik problem, ker tudi proizvajalci merilne opreme v mnogih primerih ne navajajo točnih vrednosti. Da bi lahko ovrednotili negotovost analitičnega izračuna, smo se odločili za izvedbo eksperimentalne meritve kroglic različnih premerov s stopnjevanjem merilne sile.

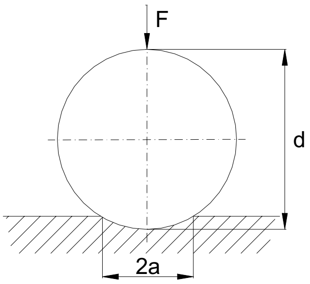
known exactly. This can, however, be a great problem because measurement-equipment producers do not usually give the exact values. In order to be able to evaluate the uncertainty of the analytical calculation, we decided to perform an experiment with spheres of different diameters, which were measured with different measurement forces.

1 ANALITIČNI IZRAČUN DEFORMACIJE

Zaradi merilne sile F, ki deluje na kroglico, se pojavi deformacija, ki je enaka vsoti sploščitve kroglice in vgrezu kroglice v merilno površino tipala ([1] in [4]). Na sliki 1 je predstavljen primer deformacije pri tipanju z eno merilno površino (enotočkovno tipanje). Razdalja med točko, v kateri deluje merilna sila, in merilno površino ni enaka premeru kroglice, ampak je zmanjšana za vrednost x, ki pomeni deformacijo. V primeru dvotočkovnega tipanja je ta deformacija dvakrat večja.

1 ANALYTICAL DEFORMATION CALCULATION

The measurement force F on the sphere causes a deformation, which is the sum of the sphere's deformation and the indentation into the probe surface ([1] and [4]). Figure 1 shows an example of probing with one measuring surface (one-point probing). The distance between the probing surface and the point where measurement force is acting is not equal to the sphere's diameter. It is reduced by an amount x, which represents the deformation. In the case of two-point probing this deformation is twice as big.



Sl. 1. *Deformacija krogle in merilne površine tipala zaradi merilne sile*
Fig. 1. *Deformations of a sphere and a probe surface, caused by a measurement force*

Deformacijo x za enotočkovno tipanje [1] izračunamo po enačbi:

The deformation x for one-point probing [1] is calculated using equation:

$$x = 1{,}04\sqrt[3]{\frac{F^2 C_E^{\ 2}}{d}} \qquad (1).$$

Količnik C_E v enačbi (1) opisuje mehanske lastnosti materialov:

The factor C_E in equation (1) describes the mechanical properties of the materials:

$$C_E = \frac{1-\nu_1^{\ 2}}{E_1} + \frac{1-\nu_2^{\ 2}}{E_2} \qquad (2).$$

V preglednici 1 je predstavljenih nekaj rezultatov izračunov za primer, ko je merjena kroglica iz rubina, tipali merilne naprave pa iz karbidne trdine. Iz preglednice je lepo razvidno, da so deformacije kritične pri merjenju majhnih premerov.

Table 1 presents some calculation results for the case where a ruby sphere is measured using hard metal probes. These results demonstrate clearly that deformations are critical for small sphere's diameters.

1.1 Negotovost izračuna deformacije

Izračunane vrednosti deformacije v preglednici 1 so točne ob predpostavki, da so točni podatki za modula elastičnosti E_1 in E_2 in Poissonova količnika ν_1 in ν_2 v enačbi (2) in uporabljeno silo F (en. 1). V praksi moramo predpostaviti, da teh podatkov ne poznamo absolutno točno. Še najbolj zanesljivo lahko

1.1 Uncertainty of the deformation calculation

The calculated values in Table 1 are only exact if the data for the elasticity moduli (E_1 and E_2), and Poisson's ratia (ν_1 and ν_2 in equation 2) and the force (F in Equation 1) are known with absolute accuracy. In reality this is never the case and we shall assume that these data are not known exactly. The most accurate

Preglednica 1. *Deformacije pri merjenju kroglice iz rubina s tipali iz karbidne trdine za različne premere merjene kroglice in različne tipalne sile*
Table 1. *Deformations during ruby sphere measurement by using hard metal probes for different ball diameters and different measurement forces*

x - µm										
d mm	F - N									
	0,1	0,2	0,5	0,7	0,8	1	1,5	2	5	10
0,1	0,2372	0,3766	0,6937	0,8681	0,9490	1,1012	1,4429	1,7480	3,2198	5,1112
0,2	0,1883	0,2989	0,5506	0,6890	0,7532	0,8740	1,1453	1,3874	2,5556	4,0567
0,3	0,1645	0,2611	0,4810	0,6019	0,6580	0,7635	1,0005	1,2120	2,2325	3,5439
0,4	0,1495	0,2372	0,4370	0,5469	0,5978	0,6937	0,9090	1,1012	2,0284	3,2198
0,5	0,1387	0,2202	0,4057	0,5077	0,5550	0,6440	0,8438	1,0222	1,8830	2,9890
0,7	0,1240	0,1969	0,3626	0,4538	0,4961	0,5756	0,7543	0,9138	1,6832	2,6719
1	0,1101	0,1748	0,3220	0,4030	0,4405	0,5111	0,6698	0,8113	1,4945	2,3724
1,5	0,0962	0,1527	0,2813	0,3520	0,3848	0,4465	0,5851	0,7088	1,3056	2,0725
2	0,0874	0,1387	0,2556	0,3198	0,3496	0,4057	0,5316	0,6440	1,1862	1,8830
5	0,0644	0,1022	0,1883	0,2356	0,2576	0,2989	0,3917	0,4745	0,8740	1,3874

določimo merilno silo, ki jo v večini primerov ustvarimo z utežjo. To utež lahko zelo točno izmerimo, preostane le določena sila trenja vrvice, prek katere je utež vezana na tipalo.

Če predpostavimo, da lahko silo določimo z relativnim pogreškom 5%, module elastičnosti in Poissonove količnike pa z relativnim pogreškom 10%, se pri izračunu deformacije za silo 1,5 N in premer kroglice 0,3 mm pojavi razpon rezultatov 0,18 µm. Ker ne poznamo statistične porazdelitve rezultatov, predpostavimo po celotnem intervalu enako verjetnost, kar pomeni, da je porazdelitev pravokotna. Standardno negotovost ([2], [3] in [5]) izračunamo po enačbi:

data is the measurement force, which is usually established with an appropriate weight. This weight can be measured very precisely, the only problem is the friction of the rope that binds the weight to the probe.

If it is assumed that the force can be determined with a relative error of 5% and the material properties (elasticity moduli and Poisson’s ratia) with a relative error of 10%, the result span of the deformation calculation for a probing force of 1,5 N and a sphere‘s diameter of 0,3 mm would be 0,18 µm. Since the statistical distribution is not known, an equal probability is assumed for the whole interval (rectangular distribution). The standard uncertainty ([2], [3] and [5]) is calculated using equation:

$$u = 0{,}09\ \ \mu m / \sqrt{3} = 0{,}05\ \ \mu m \qquad (3).$$

Ker so vrednosti relativnih pogreškov zgolj predpostavke, sta izračunana srednja vrednost deformacije in standardna negotovost vprašljivi. Zato smo skušali s preskusom dokazati pravilnost omenjenih izračunov.

Since the values of the relative errors are only assumptions, the validity of the calculated deformation and the standard uncertainty are doubtful. Therefore, an experiment was performed in order to prove the correctness of the above calculations.

2 PRESKUSNA DOLOČITEV DEFORMACIJE

2 EXPERIMENTAL DETERMINATION OF DEFORMATION

2.1 Opis preskusa

2.1 Description of the experiment

Preskus smo izvedli na univerzalni dolžinski merilni napravi Carl Zeiss ULM 01-600C. Uporabili smo 2 ravni tipali iz karbidne trdine (eno tipalo je pomično oz. merilno, drugo pa fiksno in rabi kot naslon), za dolžinski merilni sistem smo uporabili laserski interferometer HP 5528 A [5] . Za vzpostavitev osnovne merilne sile smo uporabili originalno utež merilne naprave z maso 150 g, ta ustvari merilno silo prek vrvice, ki je pritrjena na merilno tipalo. Merilno silo smo stopnjevali tako, da smo osnovni uteži

The experiment was performed on a Carl Zeiss ULM 01-600C universal measurement device. Two hard metal probes (one moving res. measuring probe and one fixed probe) were used with a linear measurement system that was based on a HP 5528 A laser interferometer [5]. The basic measurement force came from a weight of 150 g that was bound to the measuring probe with a rope. The force was then increased by adding 10 g weights, which were made especially for this experiment, to the 150 g weight.

dodajali uteži z maso 10 g, ki smo jih izdelali posebej za ta namen. Takšnih uteži je bilo 10, pred uporabo pa smo jih stehtali s standardno negotovostjo 10 mg. Merili smo tipalne kroglice iz rubina premerov 0,8 mm, 1 mm, 1,35 mm, 2 mm in 5 mm. Premere posameznih kroglic, ki smo jih izmerili z različnimi merilnimi silami, smo med seboj primerjali in na podlagi te primerjave izračunali deformacije. Te deformacije smo primerjali z deformacijami, ki smo jih izračunali po analitičnih obrazcih [1].

2.2 Izvedba preskusa

Vsako kroglico smo najprej izmerili z osnovno merilno silo 1,5 N, potem pa smo silo stopnjevali v desetih stopnjah po 0,1 N (dodajali smo uteži mase 10 g na osnovno utež). Meritev smo pri vsaki merilni sili ponovili 5-krat, celotno serijo meritev smo potem še enkrat ponovili, tako da smo za vsak premer in vsako merilno silo dobili 10 merilnih vrednosti. Po izvedbi ene serije meritev smo meritev vedno ponovili pri osnovni sili, da smo ocenili vpliv naključnih pogreškov na rezultate. Uporabili smo le tiste vrednosti, pri katerih sprememba med prvo in zadnjo meritvijo ni bila večja od 0,1 µm.

Skupna standardna negotovost meritve dolžine z laserskim interferometrom [5] v nadzorovanih razmerah, ki smo jo točno ovrednotili že v mnogih akreditiranih kalibracijskih postopkih, je znašala: $u = 0{,}01$ µm in je bila pri vrednotenju deformacij praktično zanemarljiva.

Primer beleženja rezultatov meritev za kroglico premera 1 mm je prikazan v preglednici 2.

There were ten such 10-g weights, each with a standard uncertainty of 10 mg. Ruby probe spheres with diameters of 0,8 mm, 1 mm, 1,35 mm, 2 mm, and 5 mm were measured. Each individual diameter was measured using different probing forces, the results were compared, and the deformations were calculated. These deformations were compared with the deformations that were calculated using analytical formulae [1].

2.2 Performance of the experiment

Each sphere was first measured with the initial force of 1,5 N. Subsequently, the force was increased in ten steps of 0,1 N (weights of 10 g were put on the 150-g weight). The measurement was repeated five times for each measurement force. After this the whole procedure was repeated once again, so that ten measurement values were obtained for each measurement force. After a single series of measurements was finished, the measurement was repeated with the 150-g weight in order to evaluate the influence of random deviations on the result. Only the values where the difference between the first and the last measurement did not exceed 0.1 µm were taken into account.

The combined standard uncertainty of the length measurement using the laser interferometer under the controlled environmental conditions [5], which was already precisely evaluated in many accredited calibration procedures, was: $u = 0{,}01$ µm and was practically negligible for the deformation evaluation.

An example of the measurement result record for the 1-mm sphere's diameter is shown in Table 2.

Preglednica 2. *Rezultati ene serije meritev za kroglico premera 1 mm*
Table 2. *Results of one series of measurements for a sphere's diameter of 1 mm*

Utež št.	Masa	**Razbirek/Indication - µm**				
Weight No.	Mass	M1	M2	M3	M4	M5
1	150 g	-0,06	-0,05	-0,05	-0,06	-0,03
2	160 g	-0,08	-0,08	-0,09	-0,09	-0,08
3	170 g	-0,1	-0,11	-0,14	-0,14	-0,1
4	180 g	-0,14	-0,14	-0,17	-0,16	-0,11
5	190 g	-0,18	-0,17	-0,21	-0,17	-0,15
6	200 g	-0,22	-0,19	-0,25	-0,2	-0,16
7	210 g	-0,25	-0,23	-0,3	-0,26	-0,18
8	220 g	-0,26	-0,27	-0,32	-0,32	-0,2
9	230 g	-0,28	-0,33	-0,36	-0,36	-0,22
10	240 g	-0,33	-0,36	-0,42	-0,38	-0,24
11	250 g	-0,36	-0,42	-0,45	-0,39	-0,26
0	150 g	-0,07	-0,14	-0,14	-0,09	0,06
Razlika/Difference 11-0		-0,29	-0,28	-0,31	-0,3	-0,32

2.3 Rezultati meritev

Pri preračunu deformacij smo predpostavili, da je premer kroglice enak imenskemu premeru, kar v praksi seveda ne drži. Zato je izračunana deformacija pri sili 1,5 N netočna in rabi le kot izhodišče za preračun relativnih deformacij pri večjih obremenitvah. Izračunane srednje deformacije iz dveh serij po 5 meritev so prikazane v preglednici 3.

2.3 Measurement results

The sphere‘s diameter that was used in the deformation calculation was the nominal diameter, however, this is not the true value. Therefore, the calculated deformation for the force of 1,5 N was not exact and served only as a starting point for the calculation of the relative deformations with greater forces. Calculated mean deformations for a series of five measurements are shown in Table 3.

Preglednica 3. *Srednje deformacije za različne premere kroglic in različne merilne sile*
Table 3. *Mean deviations for different sphere’s diameters and different measurement forces*

x - µm											
d mm	F - N										
	1,5	1,6	1,7	1,8	1,9	2	2,1	2,2	2,3	2,4	2,5
0,8	0,035	0,06	0,085	0,1	0,135	0,18	0,22	0,25	0,275	0,32	0,37
1	0,04	0,075	0,1	0,135	0,165	0,205	0,2275	0,2475	0,2675	0,3075	0,33
1,35	0,03	0,0525	0,075	0,1025	0,12	0,145	0,17	0,2075	0,235	0,275	0,305
2	0,05	0,0875	0,105	0,13	0,1575	0,19	0,2325	0,275	0,3	0,32	0,3675
5	0,035	0,0675	0,0975	0,1325	0,16	0,18	0,2125	0,24	0,2675	0,29	0,305

Standardno negotovost tega izračuna lahko izrazimo kot eksperimentalni standardni odmik ([2] in [3]), ki ga izračunamo iz desetih merilnih vrednosti za vsako kroglico in vsako merilno silo. Vrednosti so zbrane v diagramu na sliki 2. Iz diagrama je razvidno, da imamo največ težav prav pri kroglicah majhnega premera, kjer so tudi deformacije največje. Vendar pa je negotovost vedno precej nižja od spremembe deformacije.

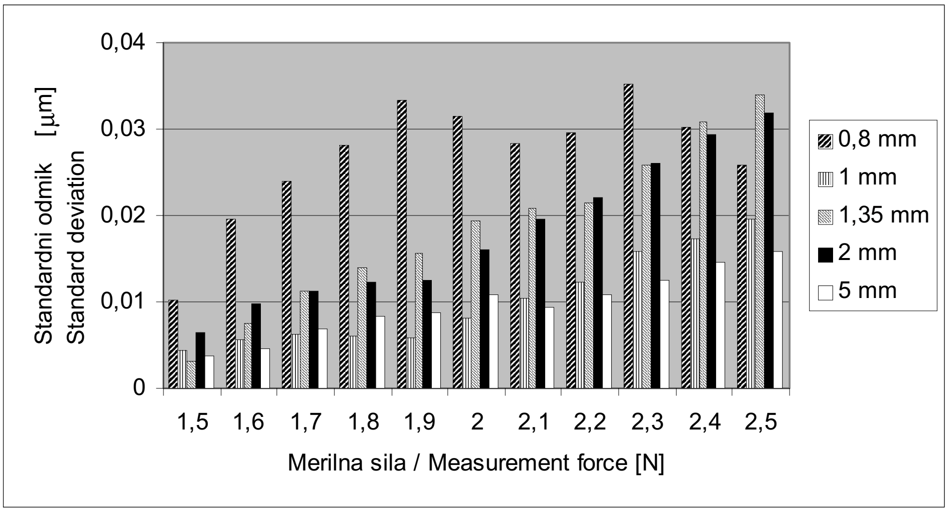
The standard uncertainty for this calculation can be expressed as a standard deviation ([2] and [3]) calculated from ten measurement values for each sphere‘s diameter and each measurement force. The values are collected in the diagram in Figure 2. This diagram shows that most of the problems occur at small diameters where the deformations are the biggest. However, the uncertainty is, in all cases, much lower than the change of the deformation.

3 PRIMERJAVA PRESKUSNIH VREDNOSTI DEFORMACIJ Z IZRAČUNANIMI ODMIKI

Primerjava rezultatov meritev in izračunanih rezultatov kaže, da so predpostavke glede

3 COMPARISON OF THE EXPERIMENTAL AND CALCULATED DEFORMATION DEVIATIONS

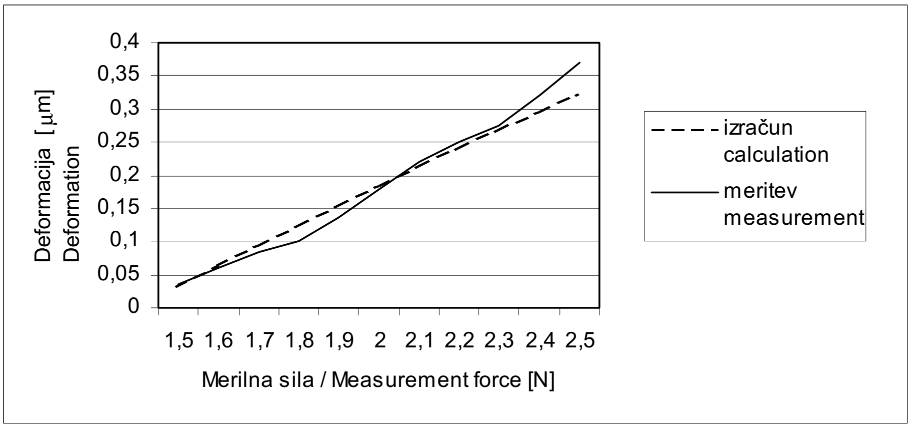
A comparison of the measurements and the calculated values proves that the assumptions



Sl. 2. *Standardni odmiki izmerjenih deformacij*
Fig. 2 *Standard deviations of measured deformations*

negotovosti določanja deformacije, ki smo jih navedli v točki 1.1, realne. Sklepamo lahko tudi, da z analitičnim preračunom ne presežemo določenega deleža skupne standardne negotovosti, ki sme znašati največ 0,2 μm. Slika 3 prikazuje primerjavo za kroglico s premerom 0,8 mm, slika 4 pa za kroglico s premerom 1,35 mm.

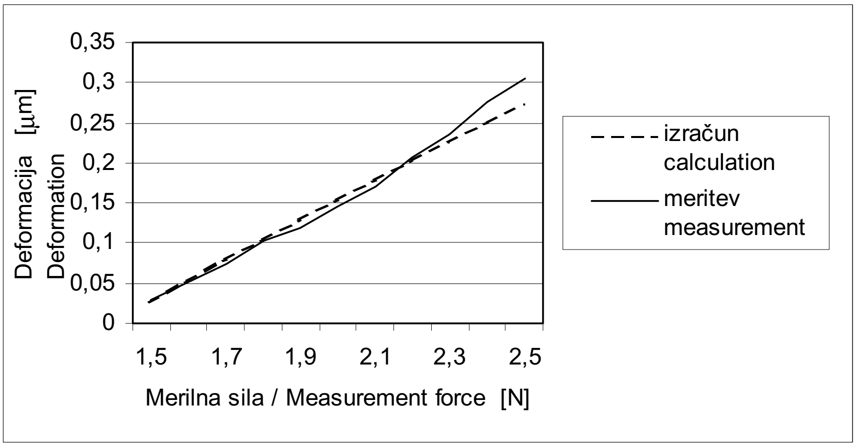
regarding the uncertainty of the deformation determination stated in section 1.1 are realistic. It can also be concluded that the supposed uncertainty contribution of less than 0,2 μm is not exceeded in the analytical calculation. Figure 3 shows a comparison for the sphere's diameter of 0,8 mm and Figure 4 for the diameter of 1,35 mm.



Sl. 3. *Primerjava izračunanih in izmerjenih deformacij za kroglico premera 0,8 mm*
Fig. 3. *Comparison of calculated and measured deformations for the sphere's diameter of 0,8 mm*

Največja razlika, ki se pojavi na obravnavanem območju sile, je 0,05 μm, kar je na ravni negotovosti izračunanih srednjih vrednosti izmerjenih deformacij. Pri kroglicah večjih premerov (npr. 5 mm) se pojavi največja razlika 0,15 μm, vendar pa pri teh kroglicah deformacija ni kritična.

The greatest difference in the whole range is 0,05 μm, which is approximately the level of the uncertainty of the calculated mean values of the measured deviations. The maximum difference for the bigger sphere's diameters (e.g. 5 mm) is 0,15 μm, but the deformation is not critical at these diameters.



Sl. 4. *Primerjava izračunanih in izmerjenih deformacij za kroglico premera 1,35 mm*
Fig. 4. *Comparison of calculated and measured deformations for the sphere's diameter of 1,35 mm*

4 SKLEP

S preskusno določitvijo deformacije pri merjenju premerov majhnih kroglic z metodo mehanskega dvotočkovnega tipanja smo želeli pokazati pravilnost ocene negotovosti izračuna z analitičnimi obrazci. Predpostavke o oceni območij, v katerih lahko pričakujemo prave vrednosti mehanskih lastnosti materialov, so se pokazale kot zelo

4 CONCLUSION

The aim of the experimental determination of the deformation during the measurement of small sphere's diameters with the method of mechanical two-point probing was to show the correctness of the uncertainty estimation of the analytical calculation. Assumptions about estimating intervals in which true values of the material's mechanical properties can be realistične. Vse dobljene razlike med izračunanimi in eksperimentalno določenimi deformacijami so bile znotraj območja standardne negotovosti. Rezultati preskusne analize deformacije in negotovosti določitve te deformacije bodo rabili kot dokaz o pravilnosti izračuna deformacije in ocene deleža merilne negotovosti pri akreditiranih kalibracijskih postopkih.

expected were found to be very realistic. All the differences between the calculated and the experimentally determined deformations were within the standard uncertainty interval. The results of the experimental analysis of the deformation and of the uncertainty of the deformation determination will serve as proof of the correctness of the deformation calculation and the uncertainty component estimation in the accredited calibration procedures.

5 OZNAKE
5 SYMBOLS

merilna sila	F	measurement force
deformacija pri tipanju krogle	x	deformation by the probing a sphere
premer deformiranega polja	$2a$	deformed area diameter
faktor mehanskih lastnosti materialov	C_E	material's mechanical property factor
premer krogle	d	sphere's diameter
modula elastičnosti	E_1, E_2	elasticity moduli
Poissonova količnika	ν_1, ν_2	Poisson's ratia
standardna negotovost	u	standard uncertainty
meritev 1 ... meritev 5	M1...M5	measurement 1 ... measurement 5

6 LITERATURA
6 REFERENCES

[1] Young, W. C. (1989) Roark's formulae for stress & strain, *McGraw-Hill International Editions.*

[2] Guide to the expression of uncertainty in measurement (1995), *ISO Guide, First Edition*, Switzerland.

[3] EAL-R2 (1997) Expression of the uncertainty of measurement in calibration, April 1997.

[4] Warnecke, H. J., W. Dutschke (1984) Fertigungsmeßtechnik - Handbuch für Industrie und Wissenschaft, *Springer Verlag*.

[5] Ačko, B., A. Šostar (1998) Uncertainty of measurement in calibration of one-coordinate measuring device with laser interferometer. *Proceedings of the 9th International DAAAM symposium, Cluj-Napoca, Romania.*

[6] Kovač, I., A. Frank (1999) Methods for calibration and testing of flexible arm measuring devices. *Proceedings of 4th International Conference on Laser Metrology and Machine Performance, University of Northumbria.*

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Prejeto:
Received: 30.5.2001

Sprejeto:
Accepted: 29.3.2002