Proceedings of the 17th International Conference on Force, Mass, Torque and Pressure Measurements,
IMEKO TC3, 17-21 Sept. 2001, Istanbul, Turkey

Determination of Elastic Properties of Piston Gauges Using the Strain Gauge Method

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Abstract

Applicability of strain gauge measurements to the determination of Young's modulus and Poisson's ratio of pressure-measuring piston-cylinder assemblies is studied. The method is qualified by comparing the results of the strain gauge measurements with those obtained for the same tungsten carbide samples or materials using the resonance vibration and ultrasonic pulse-echo-superposition methods. The elastic constants of the pistons of two piston-cylinder units used at the PTB for the realisation of the pressure scale up to 1 GPa are determined.

1. Introduction

The determination of Young's modulus (E) and Poisson's coefficient (μ) of materials of piston-cylinder assemblies used by national metrology institutes as primary pressure standards is an important task which is not, however, easy. These data are required to calculate the pressure distortion coefficient (λ) which is a dominant source of uncertainties at high pressures [1]. High-pressure piston-cylinder assemblies are usually manufactured from sintered tungsten carbide – cobalt hard alloys whose elasticity modulus may vary with the cobalt content in a broad interval between 720 GPa and 180 GPa, corresponding to pure WC and Co, respectively [2]. An estimation of the elastic properties from the Co content using literature data – a method usually applied by manufacturers of piston-cylinder assemblies – is a rather uncertain approach because the elastic constants additionally depend on the WC grain size and distribution as well as on the material porosity. Dynamic methods [3, 4] which allow brittle materials such as tungsten carbide to be characterised, put strict requirements on a sample as regards its dimensions, shape and surface quality, and therefore can be applied only if there is a specimen consisted of material identical with that of a piston-cylinder assembly. For most pressure-measuring piston-cylinder units which have been in use for some years or decades, the assembly material is not available and ordering it from the manufacturer does not give any guarantee that it is really identical. Consequently, the direct measurement on the piston and/or cylinder of the assembly is the only possibility of reliably determining the elastic constants.

In the present work, an examination of the applicability of the strain gauge method to the determination of Young's modulus and Poisson's ratio of WC materials of real high-pressure piston-cylinder units is presented.

2. Experimental

First, the method was applied to two WC samples 5 mm in diameter (d), whose elastic properties had previously been determined by the resonance vibration method. Then the measurements were carried out on the piston of the 400 MPa assembly Ruska 703/2 (d = 3.3 mm), the PTB standard for the 400 MPa pressure range, produced by the Ruska Company, USA, the material of which had been investigated earlier by the ultrasonic pulse-echo-superposition method. The measurements on these samples with known elastic properties were to show that accurate results can be achieved by the strain gauge method. Finally, the unknown elastic constants of the pistons of two 1 GPa standards, DH 17 and DH 7594, (d = 2.5 mm) manufactured by Desgrange et Huot, France, were measured.

Foil strain gauges with a polyimide base produced and characterised by Hottinger Baldwin Messtechnik GmbH, Darmstadt (HBM), in accordance with OIML IR 62 [5], each containing two constantan alloy measuring grids arranged perpendicular to each other, were used to measure the axial and tangential elongation of axially loaded cylindrical samples. Two strain gauges were bounded axially-symmetrically to a sample generatrix surface to compensate potential bending effects on the sample. For application, a solvent-free cyanide-acrylate adhesive was used which, owing to its solubility, for example in dimethyl formamide, allows strain gauges to be completely removed from the sample surface after experiments. To be certain that the sample surface is invariable, which is an indispensable precondition for measurements on real pistons, the condition of the sample surface was checked with a microscope before and after attachment of the strain gauges. The angle between sample and strain gauge axes due to imperfect strain gauge application was measured with a measurement microscope and used to calculate the sample's main strains from those monitored by the strain gauges. The resistance of the strain gauges was measured using an ASL F18 bridge with a relative uncertainty of $2.3 \cdot 10^{-7}$. The strain was calculated from the change in the strain gauge resistance using the gauge factor and the transverse sensitivity factor reported by the manufacturer [5]. In a screw press, the samples were subjected to compressive loads only because the tensile strength of tungsten carbide is rather low. The loading force was measured with a Z3 / 5 kN HBM force transducer calibrated to better than 10^{-3} in relative units. The sample ends were connected to the screw press loading bar and the force transducer supporting tack by means of ball-and-socket hinges, ensuring uniform loading of the sample butts and, therefore, nearly uniform stresses within the sample. Nevertheless, as a perfect, uniformly stressed state can hardly be achieved, the measurements were repeated several times, with the sample being rotated about its axis in 90° steps. Each series covered 12 load-elongation measurements at six equidistantly distributed increasing and then decreasing loads to study the hysteresis effect. The maximum load varied in dependence on the sample between 1 kN and 5 kN and was chosen so as to obtain a maximum longitudinal strain higher than $3.5 \cdot 10^{-4}$ but lower than the elastic buckling load by at least a factor of 7. Young's modulus was calculated as the slope of a linear fit of the longitudinal strain – stress dependence. Poisson's ratio was defined as the slope of tangential strain vs. longitudinal strain. The experiments were carried out in an air-conditioned room at nearly 20 °C; during a single measurement series the sample temperature did not vary by more than 0.1 °C.

3. Results and Discussion

The first precondition for reliable results is a well reproducible proportional dependence between the stresses and strains measured. Fig. 1 presents an example of stress-strain dependencies obtained for the piston of the DH 7594 assembly.

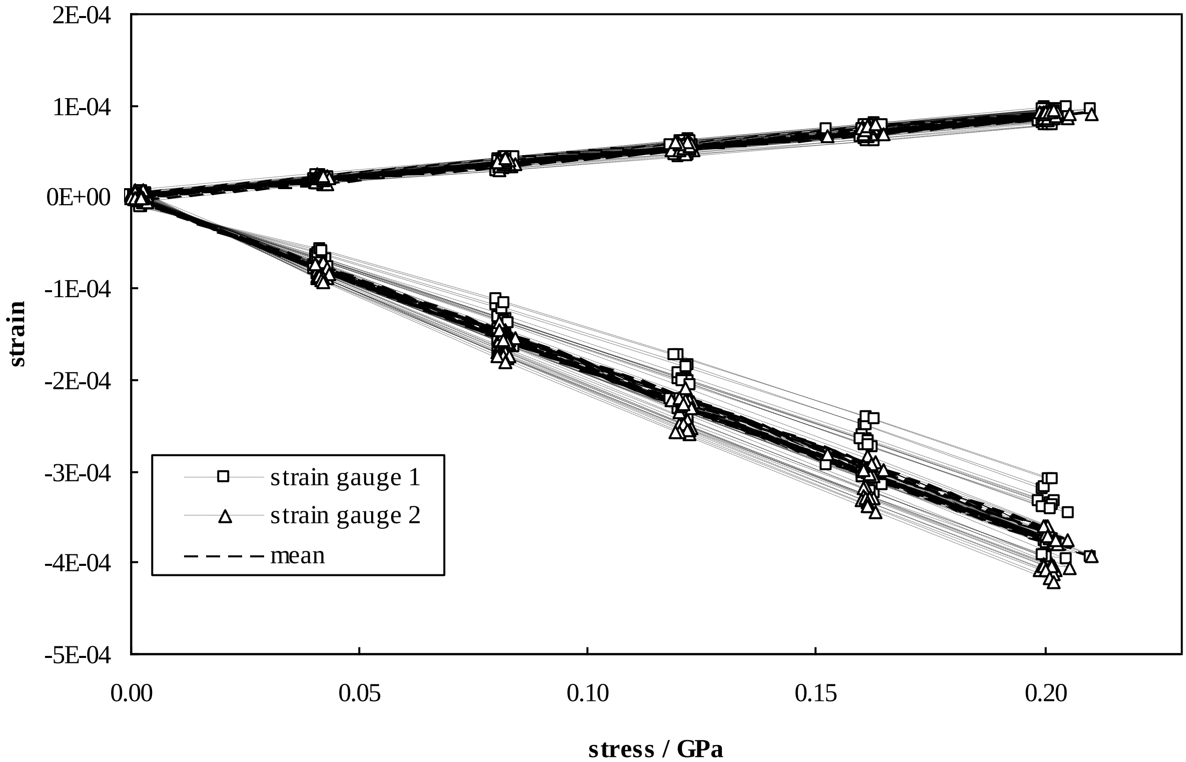

Figure 1. Strains of axially loaded piston of 1 GPa assembly DH 7594

Due to small diameter of the piston, the attachment of the strain gauges to this sample was highly complicated and the quality of application, which is of great importance for consistent results, was the worst among all the samples. In addition, compared with those for other samples, the results showed the highest scatter because the sample had the largest length-to-diameter ratio. Each series of 12 points obtained for an individual strain gauge looks well like a straight line. However, the slopes for different series, in particular for the axial strains, are rather different, furnishing a relatively broad interval for Young's modulus between 474 GPa and 666 GPa. This is evidently due to the fact that, under an axial compressive load, the relatively long sample undergoes a complex non-homogeneous deformation which can in first approximation be regarded as a combination of a uniaxial deformation and bending. Indeed, for the same measurement series, a higher slope obtained for one strain gauge was always accompanied by a lower slope for the opposite one so that the mean elongation vs. axial stress, which is shown in Fig. 1 by the thick dashed lines, is characterised by a significantly smaller scatter of slopes equivalent to a spread of E within ±13 GPa and μ within ±0.006. Sample bending can be seen particularly well in Fig. 2, which shows deviations of strains measured by two strain gauges and their mean values from a linear fit calculated for each separate measurement series. It demonstrates that the piston bends in different directions which depend on the sample's angular orientation in the screw press. The deviations of mean strains from the same linear fits and the hysteresis effects are smaller than those for single strain gauges by about one order of magnitude.

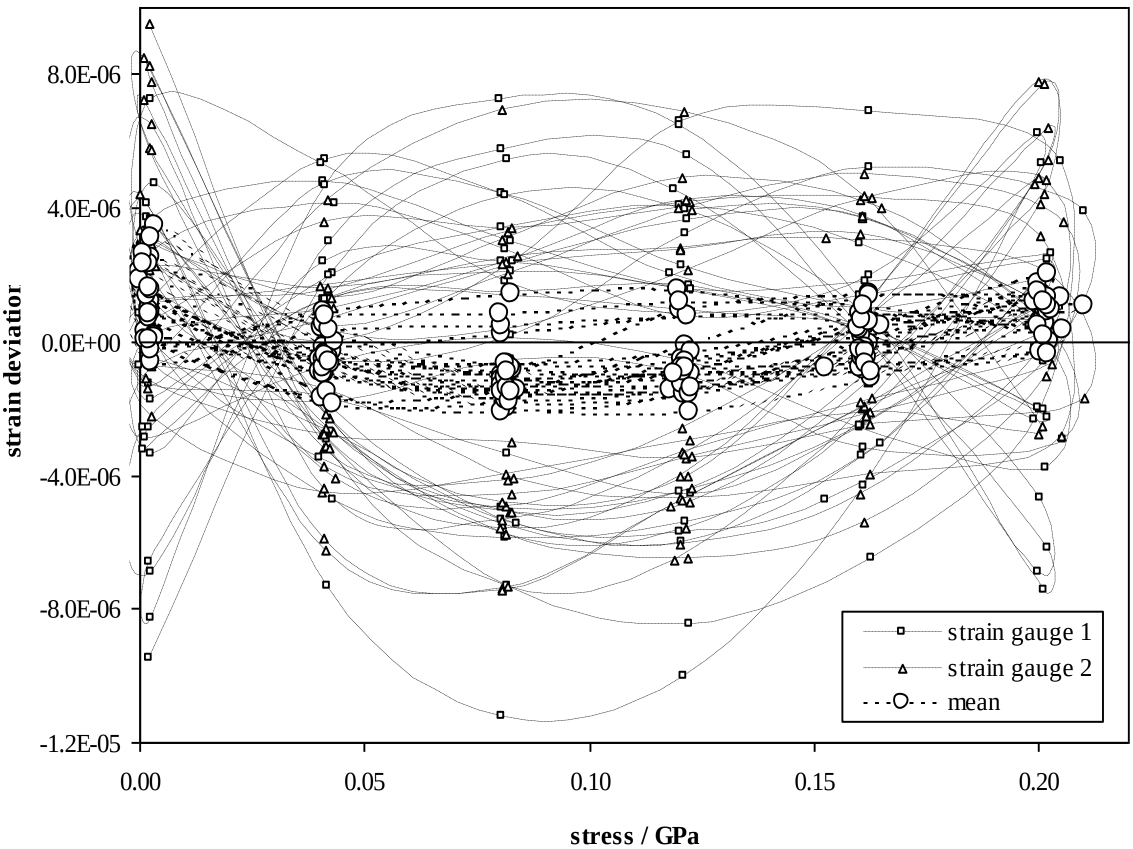

Figure 2. Deviations of axial strains measured on the piston of DH 7594 assembly with strain gauges 1 and 2 and their mean from the individual linear fit

To study the effect of strain gauge application on the elastic constants measured, the complete procedure, including strain gauge attachment and measurements, was carried out twice on one of the samples 5 mm in diameter and the piston of the DH 7594 assembly. No systematic difference between the results of the first and the second experiment was observed for both samples. For this reason, the results obtained in the first and the second experiment were combined (Figs. 1 and 2 present such combined results from the two experiments). Finally, the elasticity modulus was calculated from a linear fit of all available mean strain-stress points, with its A-type standard uncertainty taken as the standard deviation of the slope. The same evaluation procedure was used for calculating Poisson's ratio involving the axial and tangential strains. In the analysis of the uncertainty of the results, in addition to the A-type uncertainty the following systematic uncertainty sources were taken into account: gauge factor and transverse sensitivity factor of strain gauges, accuracy of the resistance measurement, the samples' thermal expansion due to temperature drift, force measurement, sample dimensions, angle between sample and strain gauge axes, axial asymmetry of two opposite strain gauges. The gauge factor was typically the main uncertainty source for Young's modulus, causing a relative uncertainty of about 0.4%. For Poisson's ratio, the gauge factor and the transverse sensitivity factor furnished the largest uncertainty contributions of 0.6% and 0.4%, respectively. All results obtained for the samples studied are summarised in Table 1.

Table 1. Elastic properties and their standard uncertainties of tungsten carbide samples determined using the strain gauge method, compared with available data

Sample	This work		Other sources	
	$[E \pm s(E)]$ / GPa	$\mu \pm s(\mu)$	$[E \pm s(E)]$ / GPa	$\mu \pm s(\mu)$
Samples 1+2, d = 5 mm	583 ± 6	0.219 ± 0.003	580 ± 6 [1)]	0.217 ± 0.017 [1)]
Piston Ruska 703/2	600 ± 4	0.229 ± 0.002	608 ± 5 [2)]	0.212 ± 0.01 [2)]
Piston DH 17	545 ± 4	0.244 ± 0.002	≈ 560 [3)]	≈ 0.218 [3)]
Piston DH 7594	543 ± 7	0.238 ± 0.002	≈ 630 [3)]	≈ 0.22 [3)]

[1)] resonance vibration method

[2)] ultrasonic pulse-echo-superposition method

[3)] estimation by the manufacturer on the basis of the Co content

For the materials investigated by other methods, samples with d = 5 mm and Ruska 703/2, good agreement between the results obtained with the strain gauge and the reference values is observed. The results obtained for the DH 17 and DH 7594 pistons demonstrate that the estimate of the elastic properties on the basis of the cobalt content in the alloy is very uncertain. It is interesting to note that the DH 17 and DH 7594 assemblies produced in 1988 and 1998, respectively, for which the manufacturer reported significantly different elastic properties, are found to practically have the same Young modulus and the same Poisson coefficient. The uncertainties of the elastic constants determined by strain gauge measurements are well acceptable because they are equivalent to a relative uncertainty of $1.6 \cdot 10^{-5}$ for a pressure of 1 GPa which thus is about six times lower than the actual uncertainty claimed by PTB for this pressure [6].

4. Conclusions

Estimation of the elastic properties of sintered tungsten carbide materials from the binder content runs a risk of large errors. Measurement of the distortion with strain gauges can be used to determine Young's modulus and Poisson's ratio of pressure-measuring piston-cylinder assemblies with the uncertainty comparable to that of the resonance vibration and ultrasonic pulse-echo-superposition methods. The determination of the elastic constants of two primary piston gauges operated at pressures of up to 1 GPa allows the uncertainty of their pressure distortion coefficients and, thus, of pressure measurements in this range to be significantly reduced.

5. References

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