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Absolute interferometric measurement of the dimensional and thermal stability of joning techniques

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ABSTRACT

We show how absolute length measurements by interferometry can be applied to measure the dimensional and thermal stability of joints. In order to investigate joining techniques, representative joints were fabricated by a number of methods including screwing and gluing. By using gauge blocks as joining parts parallelism and flatness were achieved which are needed for precision interferometric measurements. We were able to examine the dimensional behavior (i.e. change of length or orientation) of the sample joints on an accuracy level of about one nanometer. Stability has been investigated longitudinally and laterally to the connection interface, also mutual tilting of the parts was detected by analysis of the phase topographies. Measurement results of about one year show that screwed joints do not exhibit significant changes of length, orientation or response to temperature variation. This is different for adhesive joints where dimensional changes of up to 100 nm were observed.

Index Terms - absolute interferometry, adhesive, screw, joint, drift, thermal cycling

1. INTRODUCTION

Growing precision demands in engineering often lead to the insight that structures regarded as dimensionally stable, yesterday, cannot be regarded as stable anymore. The primary requirement to guaranty dimensional stability is a stable environment. Environmental parameters as temperature, pressure and humidity have to stay constant or, at least, have to be known very well. However, even when the length is extrapolated to a reference temperature and pressure, provided that the coefficients of thermal expansion (CTE) and compressibility are known, repeated length measurements may show drift in the nanometer range. Such measurements, preferably performed on gauge blocks (GBs), provide information about the intrinsic material stability. The intrinsic stability of a GB can be affected by internal structural changes of the respective material. Such changes can be influenced by external events like thermal or mechanical loading, as commonly existent in an industrial environment.

At PTB, interferometric length measurements with sub-nanometer precision are carried out under vacuum conditions, using an instrumentation similar to regular GB interferometers [1]. Due to growing demands on the precision of machine tools, semiconductor device manufacturing, scanning microscopes or various assemblies of optical components in ultrahigh-precision instruments, there is a need to investigate not only the stability of certain materials that they are made of but also of joints/connections. Generally, a joint consists of different materials, with different thermal expansion properties, interacting with each other at a common interface or interlayer. The overall behavior of a joint is not only the sum of the behavior of the parts but also of their interaction which mostly cannot be predicted reliably.

Until now there are very few published measurements concerning the dimensional and thermal behavior of joints, produced with techniques like gluing or screwing/bolting over a long-term period and with a precision as available for the length of GBs.

This paper describes the manufacturing of representative joints made of GBs and appropriate techniques that we have developed in order to achieve nanometer accuracy (or even sub-nanometer accuracy) of interferometric dimensional stability and thermal dilatation measurements performed on sample joints. Because the joints were made of GBs, it is possible to exploit the parallelism and flatness of GB surfaces which are needed for precision interferometric measurements. Fig. 1 shows the possible changes of length and angle that can occur between two connected parts. Two kinds of specimens had to be manufactured at which the stability could either be measured longitudinally or laterally to the connection interface, where the GBs have been joined with the end faces (as with ordinary wringing, cf. Fig. 2a) or with the side faces (Fig. 2b), respectively. The length is measured as the distance between the two opposed end faces of a GB, the so called "measurement faces". Additionally to the length, also the surface orientation of the joints can be detected by analysis of the interferograms at regions of the measurement faces.

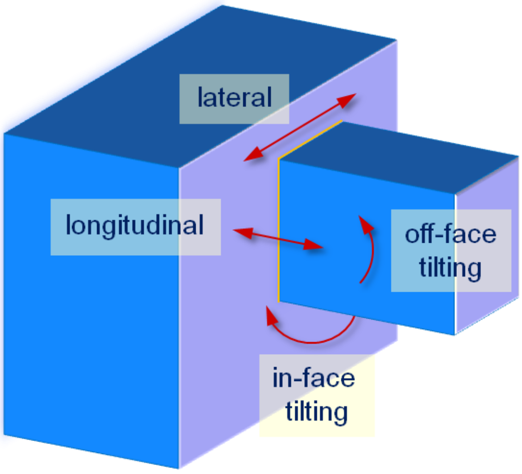


Figure 1. Stability of a joint: possible changes of length and angle

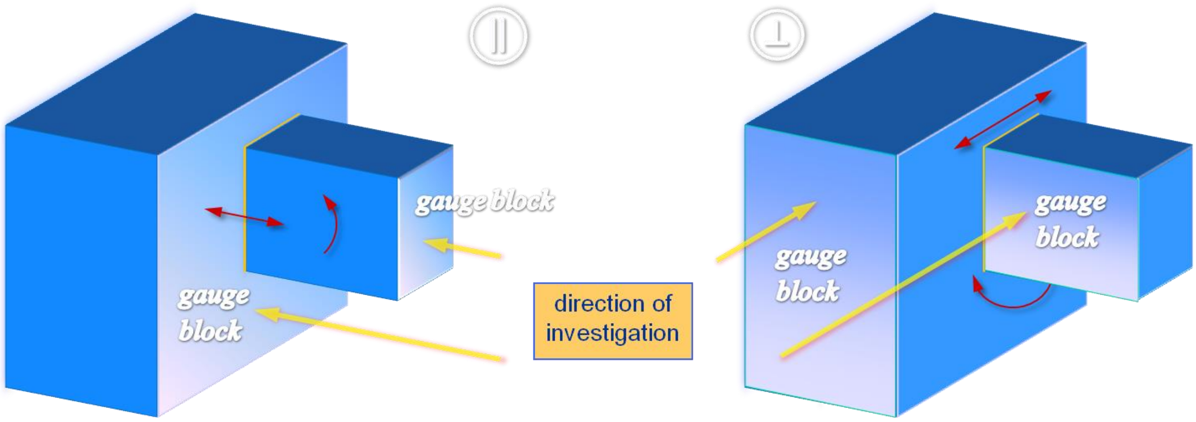


Figure 2. Stability of a joint: in order to measure all relevant changes of length and angle, gauge blocks have to be connected in two different ways - left: longitudinally, right: laterally

2. EXPERIMENTAL

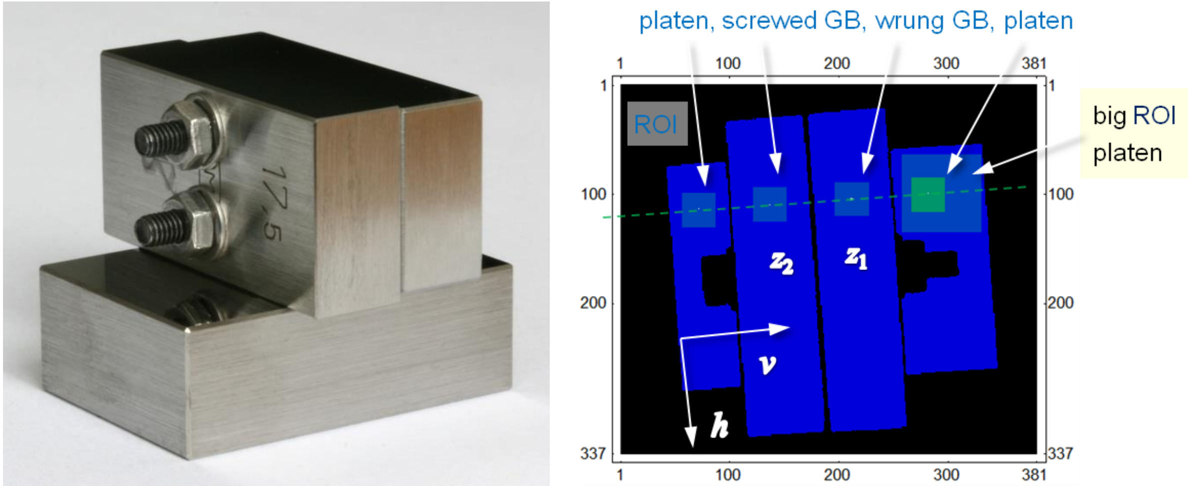
Measurements were performed at PTB's interference comparator INKO6 [1], the Precision Interferometer PI [2] and the Ultra Precision Interferometer UPI [3]. Three stabilized lasers of different wavelengths are used subsequently in the measurements, and imaging phase stepping interferometry is applied. The procedures of measuring the phase topography from interferogram digital images and other parameters like temperature are in principle similar as with regular GB calibrations and are described in the above mentioned references. The used GBs have rectangular end faces (mostly of 9 mm x 35 mm) and are made of steel or single-crystalline silicon.

For investigation of a specific joining technique two GB-shaped parts were connected to each other, in the case of *longitudinal* joints at the (polished) *end faces*, and in the case of *lateral* joints at the (unpolished) *side faces*. In the second case, a problem results from the fact that GBs have very parallel end faces but side faces are not very orthogonal to the former. According to ISO 3650, the measurement and side faces of a GB are only guaranteed to be perpendicular within ±50 µm (upper edges projected onto the measurement plane below). Consequently, the connection interface of the GBs is required to have a very accurate wedge, in order to achieve the required parallelism of the measurement faces. Therefore, the connections were aligned in an interferometer. In each case one of the (polished) end faces was attached to a flat platen (preferably made from the same material).

The length of a number of joints was measured several times within a period of about 1 year. The specimens were exchanged in the interferometer consecutively, while every specimen was placed again within 1 mm at it's original position. In the meantime, the specimens were stored at 20°C in air. According to ISO 3650 [4], calibration class K steel GBs (of small length) are only required to have a dimensional drift of $\Delta l < 20$ nm per year. To exclude phantom drift by inherent material instability, the stability of the individual steel GBs was investigated, starting several months before the joining, and a number of wrung GB pairs were also investigated simultaneously to the joints.

The length was extrapolated to a reference temperature of $\vartheta = 20$°C, in order to compensate for the effect of thermal dilatation. This involves a coefficient of thermal expansion (CTE) value for steel of $(11.5 \pm 0.5) \cdot 10^{-6}$ /K and for silicon of $2.56 \cdot 10^{-6}$ /K. The standard uncertainty of the 20°C related length changes is estimated to be 3 nm (INKO6) and 1 nm (PI, UPI) and below (materials e.g. Si or SiO_2).

The orientation (angels in both lateral directions) was determined from linear fitting at a certain position within the phase topography. An uncertainty for the angle measurement was estimated to ±0.2 arcsec.



a) b)

Figure 3: Lateral screw joint of two steel GBs, one GB wrung onto a platen:
a) photo; b) interference mask (areas of detected interference are colored), used for face center detection; ROIs, used for phase analysis; big ROI, used for orientation determination; dashed: pathway on platen, used for phase interpolation

3. ANALYSIS OF INTERFERENCE PHASE TOPOGRAPHIES

The phase topographies were investigated at different positions. In a first step, the face center and orientation of the visible GBs are determined in the interference mask (Fig. 3b). Regions of interest (ROIs) on the specimen surfaces are generated in a defined distance from the wrung GB, and a sub-pixel correction, related to the average phase within of each ROI, is extracted for the length evaluation [2]. In the case of *longitudinal* joints, the desired length which characterizes the stability of the joint is simply the difference between the center in the top face ROI, z_1, and the interpolated platen below the GB, $z_{P,1}$, at the same lateral position:

$l = (z_1 - z_{P,1})$.

For the *lateral* joints (e.g. the screwed joint in Fig. 3), the length difference, l, characterizing the stability of the joint was evaluated from the height difference between the neighboring GBs:

$l_{rel} = (z_2 - z_1) - z' \bullet (v_2 - v_1)$.

Here, the difference $z_2 – z_1$ was corrected for alignment rotation in the interferometer (the 2nd term involving $z' = \partial z / \partial v$), therefore, an orientation measure was defined by taking the orientation angle $\alpha = \arctan z'$ of the platen in a continuous large and flat area (cf. Fig. 3b). Especially for lateral joints, deformation or tilting can potentially influence the measured length. Therefore, the tilt angle difference $\alpha_{GB2} – \alpha_{GB1}$ between the top ROIs was observed to check for violation of the assumption that all parts adhere to a rigid-body rotation. The uncertainty of angles z', as estimated above, can lead to some nanometers of uncertainty for l_{rel}. As observed from the drift curve (Fig. 4b) l_{rel} is subject to a scatter of less than 4 nm.

4. RESULTS AND DISCUSSION

4.1 Screwed joints

The *longitudinally* screwed joint consists of a 12.5 mm steel GB bolted with two M3 screws and a torque of 1 Nm to a platen. No drift was detected at 20°C, also the angles in both directions remained constant (Fig. 4a). After 50 days, counted from the date of specimen manufacturing, one temperature cycle between 10°C...30°C was carried out. This did not cause any change, as was observed at the end of the temperature cycle at 20°C.
As already shown in Fig. 3, also a *lateral* joint of two steel GBs was produced. The mutual tilt was minimized by using a 10 µm precision gauge sheet, and the two screws were given different torques (1 Nm and 0.5 Nm). Within the measurement uncertainty no drift was detected during 450 days (Fig. 5b). Also the tilt angles between the GBs were found to remain constant in both space directions. After 330 days the temperature was cycled between 10°C...30°C. This did not cause any change, as was observed at the end of the temperature cycle at 20°C.

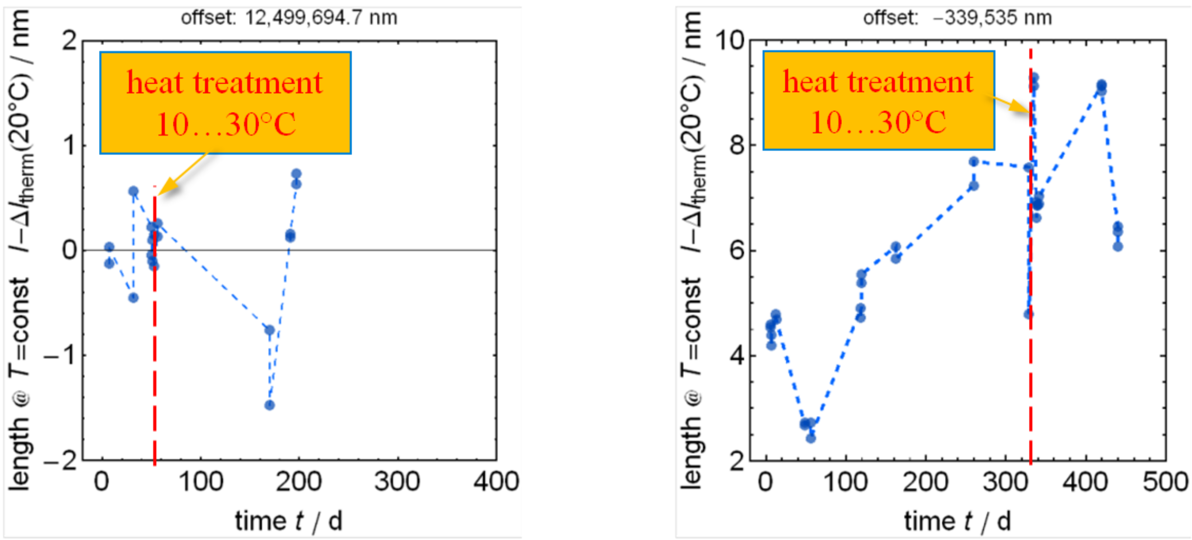


Figure 4. Screwed joints: length at 20°C (relative to given offset, above), heat treatment marked by red dashed line;
a) longitudinal joint; b) lateral joint (difference between GBs, corrected for rotation)

4.2 Adhesive joints

Two 12.5 mm steel GBs were *longitudinally* joined by a (8.2 ±0.4) µm layer of 2-component epoxy (EP) *UHU+ Endfest300* at 20°C. A length reduction of 25 nm (-0.3% of the layer thickness, due to epoxy curing) was detected during 100 days, while 90% of the shrinking took place within the first 50 days (Fig. 5a). After 100 days the joint was heat-treated at 50°C for 3 days. This resulted in a length increase of 10 nm followed by a relaxation with -16 nm during another 170 days. No tilting was detected.
A further joint involved 10 Vol.% of spacer spheres (glass beads, soda-lime glass, *HELIOS Optics*) which were added to the epoxy (Fig. 6). The glass beads had a nominal size distribution between 0...50 µm, as given by the manufacturer. The upper GB had a few hours time to settle down by it's own weight, until the epoxy was fully cured at 20°C. The adhesive layer had a final thickness of (70.6 ±0.3) µm, which approximately coincides with the largest

glass beads observed under the microscope. As with the pure epoxy, a curing relaxation was observed, but followed by a more complicated behavior. After 50 days, when a total length change of nearly -100 nm was reached, a halt of the shrinking and a following accelerated length increase until the end of measurement was observed. Moreover, these measurements show a significant tilting of $\Delta\alpha = 2$ arcsec. This could be explained by the relative humidity of the air under which the specimens are stored (40…60%) so that moisture might constantly diffuse into the glue joint. Because the joint is not fully symmetric and some adhesive was squeezed out forming a blob, one side might absorb more water leading to tilting. This potential explanation is also instructive to optimize adhesive joints with respect to stability, because a symmetric interlayer should result in a stable orientation of the joint.

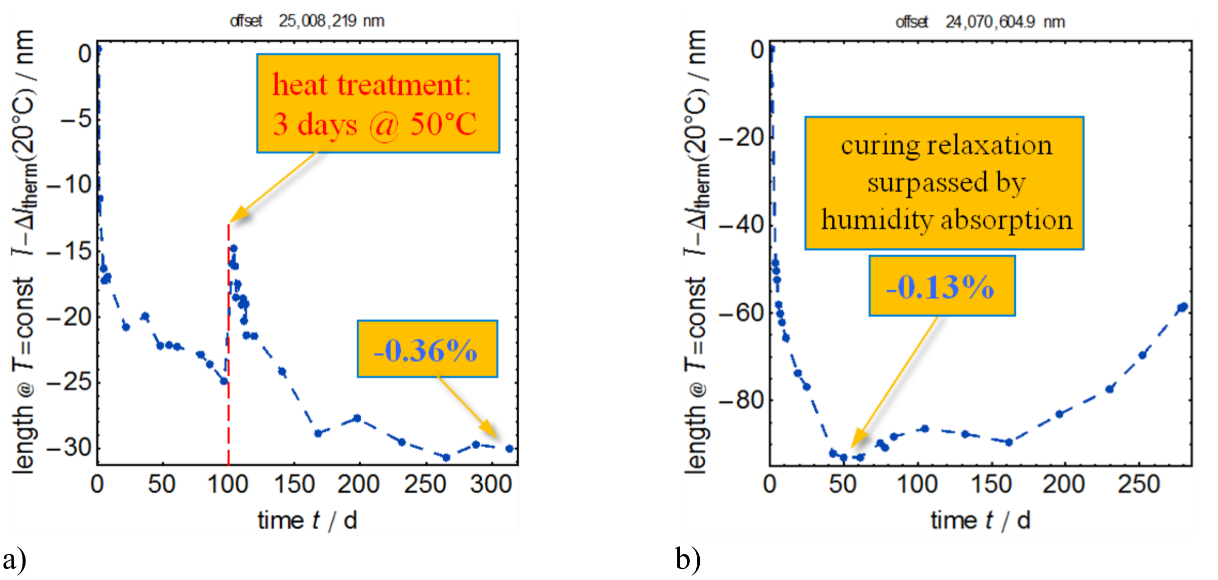


Figure 5. Longitudinal adhesive connections of steel GBs with EP: length at 20°C
a) 8.2 µm layer of pure EP; b) EP layer with 10% glass beads (0...70 µm diameter)

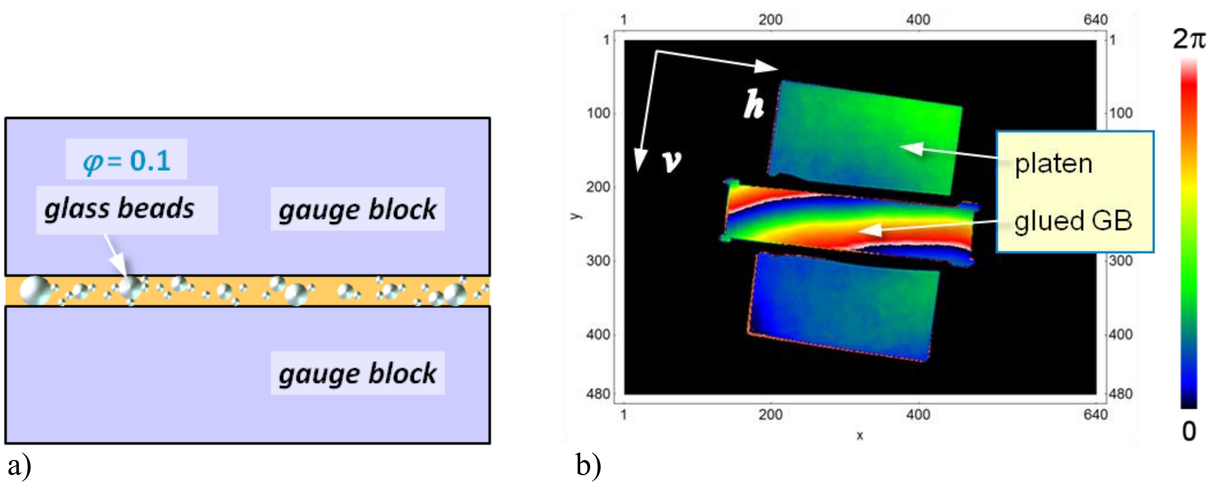


Figure 6. Longitudinal adhesive joint of steel GBs with EP, filled with glass beads as spacers:
a) schematic sketch; b) phase topography, $\lambda/2 = 266$ nm

Application of a dilute solution of synthetic resin, which was melted together with the joined parts at 150°C, turned out to be an effective way to produce stable adhesive joints. The resulting thickness of the adhesive layers was comparatively small ($d < 1$ µm). Two 15 mm silicon single crystal GBs were *longitudinally* joined in this way (Fig. 7). Length, as well as angles, stayed constant within 1 nm and 0.2 arcsec during 150 days of observation.

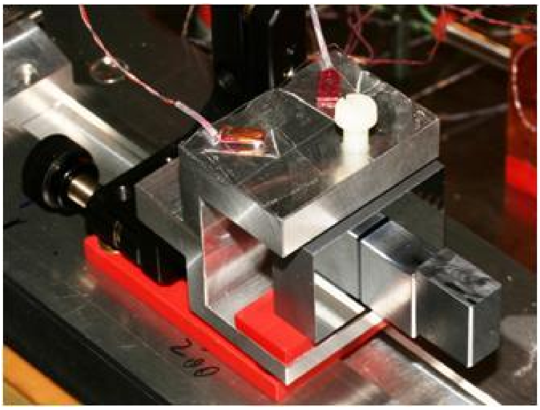


Figure 7. Adhesive connection of two silicon GBs á 15 mm length with synthetic resin, the joint is wrung onto a silicon platen which is mounted within the interferometer, two temperature sensors are attached on top of the mount

Finally, two steel GBs were *laterally* joined with EP, cured at 20°C. The observed relatively large length changes were difficult to analyze, because the adhesive layer varies in thickness by $d_{max}-d_{min} \approx 33$ µm along the z direction. This thickness variation leads to a drift of the respective tilt angle when the volume of the adhesive alters. That, in turn, leads to a lateral joint movement of $\Delta z_2 \approx 40$ nm as a result of heat treatment at 50°C. Without going into more detail, the source of this effect could partly be derived from an FEM model. This again points to the importance of producing a very symmetric and uniform glue distribution in order to optimize the dimensional and thermal stability of joints.

5. CONCLUSIONS

The stability of joints, produced with the techniques gluing and screwing, has been investigated for the first time with an accuracy of one or a few nanometers over a long-term period. Techniques were developed and specimens were manufactured exploiting the parallelism and flatness of gauge block measurement faces, allowing the joints to be investigated in an interferometer. The stability of length and angle was measured laterally and normally to the connection interface by analysis of phase topographies. At a constant temperature of 20°C, screwed joints have not shown a change of length or orientation in any direction. They also appeared stable between 10°C to 30°C concerning thermally-induced drift. Adhesive joints can behave very differently, dependent on curing and water absorption of the adhesive but also on the geometry of the glue joint. The use of glass beads as spacers did not improve the stability.

Though the aim of this study was primarily to demonstrate the feasibility of high-precision dimensional stability measurements, the results are also instructive to optimize joints with respect to stability. It should be possible also to adapt specimens for specialized joining techniques applied in ultra-high precision instruments.

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REFERENCES

[1] G. Bönsch, "Automatic gauge block calibrations by phase stepping interferometry with three laser wavelengths," Proc. SPIE 4401, Recent Developments in Traceable Dimensional Measurements, pp. 1-10, 2001.
[2] R. Schödel, "Ultra-high accuracy thermal expansion measurements with PTB's Precision Interferometer," Meas. Sci. Technol. 19, 084003, 2008.
[3] R. Schödel, A. Walkov, M. Zenker, G. Bartl, R. Meeß, D. Hagedorn, C. Gaiser, G. Thummes, and S. Heltzel, "A new Ultra Precision Interferometer for absolute length measurements down to cryogenic temperatures," Meas. Sci. Technol. 23, 094004, 2012.
[4] Geometrical Product Specification (GPS). Length Standards – Gauge Blocks (ISO 3650:1998)

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