Interferometric characterization of dimensional and thermal stability of materials and joints

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Abstract

Methods to measure the thermal and dimensional stability of materials and joining techniques have been developed. This concerns length measurements on gauge blocks made of metal, silicon or glasses. Representative joints between these gauge blocks have been manufactured by methods including screwing and gluing. With the use of these samples, elements frequently used in precision engineering can be examined carefully. The dimensional behaviour (i.e. change of length or orientation) of joints can be identified with about a 1 nm accuracy by analyzing phase topographies of precision interferometric measurements. Long-term measurements of drift behaviour in the range of months to years are being carried out, examples are shown.

1. Introduction

Increasing precision demands in engineering can lead to the discovery that structures regarded as dimensionally stable, yesterday, cannot be regarded as stable anymore. At PTB, the most precise interferometric length measurements with sub-nanometre precision are carried out under vacuum conditions, using an instrumentation similar to regular gauge block (GB) interferometers. Repeated length measurements provide information about the intrinsic stability of the GB which can be affected by internal structural changes of the material. Such processes can also be triggered by external events like thermal or mechanical loading, as common in an industrial environment. Due to growing demands on the precision of machine tools, semiconductor device manufacturing, optical instruments, scanning microscopy and other fields in precision engineering, there is a need to investigate not only the stability of materials but also of joints. Until now there exists very little published knowledge concerning the behaviour of joints, produced with techniques like gluing or screwing over a long-term period and with a precision as available for GBs. One of the goals of the European Joint Research Project “T3D” is to expand the knowledge base concerning the dimensional drift behaviour of joints.

This paper describes the manufacturing of representative joints made of GBs and appropriate techniques that we have developed in order to achieve sub-nanometer accuracy of interferometric stability and thermal dilatation measurements of sample joints. Two kinds of specimens had to be manufactured, at which the stability could either be measured longitudinally or laterally to the connection interface. Because only the end faces can be measured, the GBs have been joined with the end faces (as with ordinary wringing) or with the side faces (cf. Fig. 1), respectively. Additionally to the length, also the orientation of surfaces of the joints can be detected by analysis of the phase topographies.

2. Experimental

Measurements were performed at PTB’s interference comparator INKO6 [1] and the Precision Interferometer PI [2]. Three stabilized lasers of different wavelength are used subsequently in the measurements. The procedure of measuring interferograms and temperature is in principle similar as for “normal” GB calibrations. For investigation of a specific joining technique two gauge block shaped parts were connected to each other, in the case of longitudinal connections at the front faces, and in the case of lateral connections at the (unpolished) side faces. 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. To exclude phantom drift by inherent material instability, the stability of the individual steel GBs was investigated, starting several months before the joining. The length was extrapolated to a reference temperature of 20°C in order to reduce the effect of thermal dilatation. The latter was subject to a correction involving a CTE value for steel of $(11.5 \pm 0.5) \cdot 10^{-6}$/K. The standard uncertainty of the 20°C related length changes is estimated to be 3 nm (INKO6) and 1 nm (PI) and below (materials e.g. Si or SiO_2). An uncertainty for the angle measurement was estimated to ±0.2 arcsec.

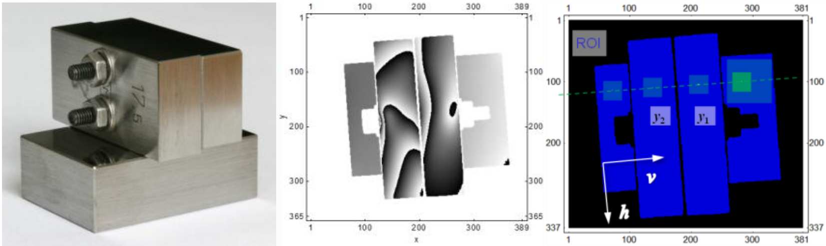

Figure 1: Screw joint of two GBs with the side faces, one GB wrung onto a platen:
a) photo; b) phase image, 532 nm; c) ROIs of phase analysis, interpolation path

3. Analysis of the phase topographies

The phase topography was investigated at different positions. In a first step, the face center and orientation of a GB are determinded in the camera image. Regions of interest (ROIs) are generated in a defined distance on the specimen surfaces, and a sub-pixel correction is extracted for the length evaluation. In the case of longitudinal joints, the length is simply the difference between the centre in the top face ROI, y_1, and the interpolated platen below the GB, $y_{P,1}$, at the same lateral position.

For the lateral joints (e.g. screwed joints), deformation or tilting can potentially affect the measured length. Therefore, the tilt angle difference between the top ROIs was observed for violation of rigid-body rotation. The length difference, Δl, which characterizes the stability of the joint was evaluated by the respective height differences between the GB surface and interpolated platen region below the GB, $\Delta l = (y_2 - y_{P,2}) - (y_1 - y_{P,1})$; as shown in Fig. 1c.

4. Results

4.1 Screw joints

The *longitudinal* joint consists of a 12.5 mm steel GB screwed with two M3 screws and a torque of 1 Nm to a platen. It shows a length reduction of 21 nm during the first 6 days. After this "setting", no drift was detected anymore. Also the angles in both directions remained constant. After 50 days the temperature was cycled between 10°C...30°C. This did not cause any change, when the temperature was back at 20°C.

A *lateral* joint of two steel GBs was produced (Fig. 1). Within the measurement uncertainty, no drift was detected during 250 days. Also the tilt between the GBs in both space directions was found to remain constant.

4.2 Adhesive joints

Two 15 mm Si GBs were *longitudinally* joined by a synthetic resin layer of $d < 1$ µm thickness. Length, as well as angles, stayed constant within 150 days of observation, and also after the temperature was raised to 30°C for one day.

Two 12.5 mm steel GBs were longitudinally joined by a (8.2 ±0.4) µm layer of 2-component epoxy *UHU+ Endfest300* at 20°C. A length reduction of 25 nm (-0.3% of the layer thickness due to epoxy curing) was detected, while 90% of that took place within the first 50 days. After 100 days the joint was heat treated at 50°C for 3 days. This resulted in a length increase of +0.12% followed by a relaxation by -0.17%. At t = 200 d, the total length reduction was 29 nm. No tilting was detected.

Further, 10 Vol.% of spacer spheres were added to the epoxy, which had a size distribution between 0...50 µm. A more complicated behaviour was observed, leading to a reduction of the curing relaxation by more than a half which was followed by a halt of the shrinking after 50 days. While the length keeps approximately constant, tilting of $\Delta\alpha \approx 1$ arcsec was observed.

Two steel GBs were *laterally* joined with epoxy at 20°C. The measured length changes were difficult to analyze, because the adhesive layer varies in thickness by $d_{\mathrm{max}} - d_{\mathrm{min}} \approx 33$ µm. This thickness variation leads to a drift of the respective tilt angle when the adhesive itself drifts and leads to a lateral joint movement of $\Delta l \approx 40$ nm. The source of this effect could be derived from an FEM model.

5. Conclusion

The stability of joints, produced with techniques like gluing and screwing, has been investigated for the fist time with nm accuracy over a long-term period. Techniques were developed and specimens were manufactured exploiting the parallelism of gauge block surfaces, 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. It should be possible also to adapt the specimens for specialized joining techniques applied in ultra precision instruments.

References:

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