Development of a New Interferometric Measurement System for Determining the Main Characteristics of Gauge Blocks

Y. Kuriyama[1], Y. Yokoyama[1], Y. Ishii[1], J. Ishikawa[2]
[1]Mitutoyo Corporation Tsukuba Laboratory, Tsukuba, Japan
[2]National Metrology Institute of Japan / AIST, Tsukuba, Japan
Submitted by H. Makino (1), Tokyo, Japan

Abstract

A new interferometric measurement system for gauge blocks which does not require wringing onto an auxiliary platen has been developed. The main characteristics of gauge blocks measured in this system are dimensions, coefficients of thermal expansion (CTE) and temporal stability. The repeatability is better than 3 nm for dimensional measurements and a comparison of this system to a conventional one showed good agreement. In CTE measurements, the expanded uncertainty is 3.5 x 10^{-8} / K. Precision temporal stability measurement is improved since wringing is not required. This interferometer enables better quality control in our gauge block production process.

Keywords:
Interferometry, Measurement, Gauge block

1 INTRODUCTION

As is well known, the length of a gauge block (henceforth, represented as GB) is defined in ISO 3650 as the distance between its one measuring face and the surface of an auxiliary platen on which the other measuring face has been wrung (Figure 1). Accordingly, in central length calibration of K-grade GBs using interferometry, it is required that they be wrung onto an auxiliary platen whose characteristics are the same as the measuring face of the GBs. According to this definition, the length of a GB consists of its mechanical length between two faces and the wringing film thickness. This definition is practical and reasonable in many cases because GBs are used as length standards with wringing. Also this calibration method has the advantage that the thickness of the wringing film is propagated appropriately when lower grade GBs are calibrated by comparison to higher grade GBs via a mechanical comparator. On the other hand, the thickness of the wringing film depends on a metrologist's manual skills. Wringing onto the platen many times also causes scratches and permanent damage to GB's measuring faces so that measurement values are varied, even if the measurement is performed carefully by highly skilled laboratories in an international round robin. The fluctuation in wringing film thickness influences the accuracy of calibrated values. It is apparent that wringing itself is one of the significant sources for reduced measuring reproducibility and increased uncertainty. Moreover, measuring apparatuses to be calibrated by using GBs as length standards are diverse. Hence, there are many cases of GB usage without need for wringing. In those cases, the wringing film thickness itself yields an unnecessarily deviation in the calibration value. It is also a serious problem that wringing is a laborious and time-consuming operation. After wringing, it is required to soak out the GBs until their temperature become the same as the room temperature and they equilibrate removing their thermal stress and deformation. This can take several hours. For laboratories and manufacturers who calibrate a large number of GBs, wringing prevents throughput improvement in the calibration process. In addition, recent market demands are for accurate values of GB's coefficient of thermal expansion (CTE). It is required not only for the length calibration of GBs in 20 °C but also the correction of the length to 23 °C which is widely used in electronics market. In a new standard of acceptance and reverification tests for CMMs (ISO10360-2), manufacturers are required to state the uncertainty in CTE of the artefacts used in their length calibration. One of the effective methods for above mentioned measurement is to measure GBs without wringing [1] [2]. This method eliminates the ambiguity of wringing film thickness so that higher reproducibility in the length measurements is obtained. Measurement without wringing also contributes to higher calibration throughput. Accordingly, to achieve higher quality control in our gauge block production process, a new gauge block

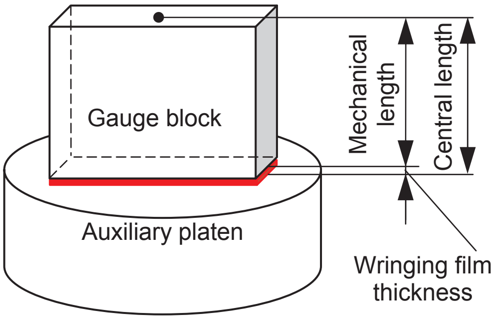

Figure 1: Definition of length of gauge block.

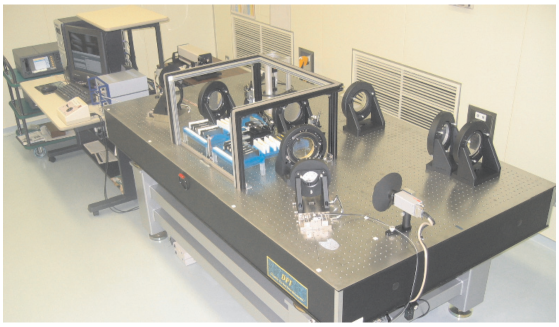

Figure 2: Appearance of new interferometer.

interferometer which measures both measuring faces simultaneously without need for wringing has been developed (Figure 2).

2 NEW LASER INTERFEROMETRIC MEASUREMENT SYSTEM FOR GAUGE BLOCKS WITHOUT NEED FOR WRINGING

2.1 Characteristics of gauge blocks to be measured

This system is a new gauge block laser interferometer which has an advantage of measuring GBs without wringing, and observing both ends at once.

Major characteristics measured are as follows.

- Absolute distance between any points on both ends
- Surface textures and flatness of both ends
- Coefficient of thermal expansion (CTE)
- Temporal stability

2.2 Measurement setup

The system diagram of our interferometer is shown in Figure 3. A commercial Iodine stabilized He-Ne laser light source, LIS-633, whose vacuum wavelength is 633nm is used. The beam is led to the interferometer by a single mode optical fibre. It is then collimated and sent into a triangle shaped optical path by the help of three half-silvered mirrors (HM1~HM3). A gauge block to be measured, up to the length of 508mm (20 in) in our present setup, is placed longitudinally along the base of the triangle optical path and is supported at Airy points. Light is reflected from both measuring faces and also propagates around the GB. The light is reflected from two reference mirrors (RM1, RM2) to create interference. Interferograms of both ends are captured by two CCD cameras located at both sides of the interferometer, and the images are stored on a PC via a framegrabber. To obtain phase maps, a N-Step least square PSI technique using PZT driven reference mirrors is used. By using above described method, the flatness of the end faces of GBs are measured. In addition, this interferometer yields the fringe fraction similarly to other gauge blocks interferometers. The approximate length is measured in advance using a mechanical comparator to obtain the interference order number.

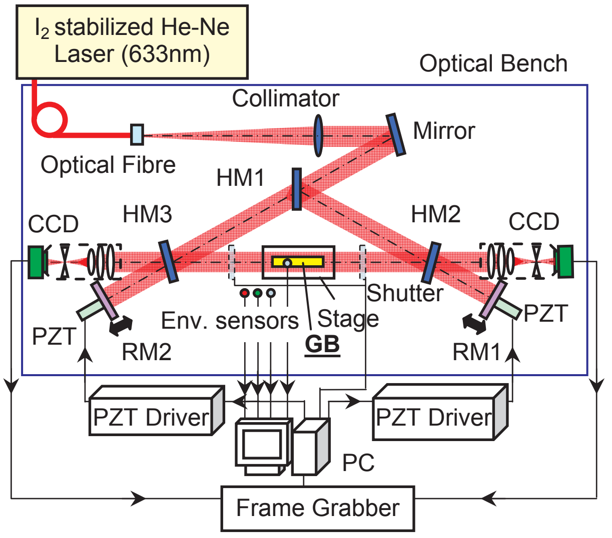

Figure 3: Scheme of system diagram.

2.3 Length determination principle

The length determination principle of this interferometer is given below. For clarity the area of the triangle shaped optical path is enlarged in Figure 4.

The optical length of the GB to be measured, P_B is calculated from four optical path lengths as follows.

P_1: HM1-->HM2-->GB's right end-->HM2

…Ray reflected from GB's right end

P_2: HM1-->HM2-->Passing around GB-->HM3

…Ray passing around GB from right to left

P_3: HM1-->HM3-->GB's left end-->HM3

…Ray reflected from GB's left end

P_4: HM1-->HM3-->Passing around GB-->HM2

…Ray passing around GB from left to right.

Taking cancellation into account the length is:

$$P_B = \frac{1}{2}\left(-P_1 + P_2 - P_3 + P_4\right) \tag{1}$$

Let the wavelength of the laser be L_0, each optical path length P_i is represented as,

$$P_i = L_0\left(N_i + e_i\right), \quad i = 1,\ldots,4 \tag{2}$$

Where, order numbers of each paths are N_1~N_4,

and fractions are e_1~e_4.

Hence, expression (1) may be rearranged as follows.

$$P_B = \frac{L_0}{2}\left[\left(-N_1 + N_2 - N_3 + N_4\right) + \left(e_4 - e_3\right) + \left(e_2 - e_1\right)\right] \tag{3}$$

The first term: ($-N_1+N_2-N_3+N_4$) is obtained from the approximate length determination by the comparators in advance. (e_4-e_3) and (e_2-e_1) are given by the phase differences between the center of the GB's face and the surrounding area in the phase map of both ends.

The absolute distance between two ends of GB is finally determined as the mechanical length of GB, what we would like to know, by applying a correction for it's thermal expansion and a phase shift correction for both ends (which will be discussed later) to optical length, P_B of the GB.

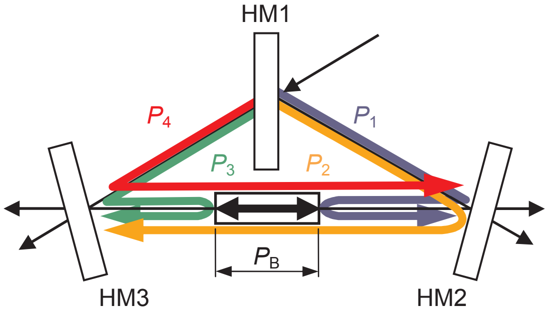

Figure 4: Explanation scheme of optical paths.

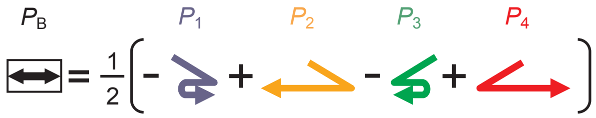

Figure 5: Optical path lengths calculation.

2.4 Flatness and surface profile measurement

When the value of flatness, surface texture profiles or checking for defects on the ends are required, previously each end had to be wrung onto a platen. However, this interferometer captures the images of both ends simultaneously so that these values are obtained directly.

3 RESULTS OF LENGTH MEASUREMENT

3.1 Measurement repeatability

The result of comparison between the two methods, without and with wringing, in length measurement repeatedly is shown in Figure 6. It shows that measurement repeatability of the present interferometer is less than 3 nm because of the wringing film thickness elimination. The conventional interferometer yields a repeatability 10 times worse.

3.2 Phase correction

Obtaining the value of phase correction is essential for the new interferometer. Because the phase shift takes place on both ends of the block the value must be doubled. The phase shift was investigated and calculated using the surface roughness and the complex refractive index of its material [3]. The average value of the phase correction for steel GBs in our products to be measured is 33.2 nm, and the standard deviation is 4.2 nm (Figure 7).

3.3 Absolute distance between two ends

The values of length of GBs measured by our new method were compared with those values given by the older wringing method (Figure 8). We can see that the results of the conventional method are larger than those obtained without wringing. The differences are about 20 nm in most cases. Since the wringing film thickness is normally in the range of 10 ~ 20 nm, these values coincide very well.

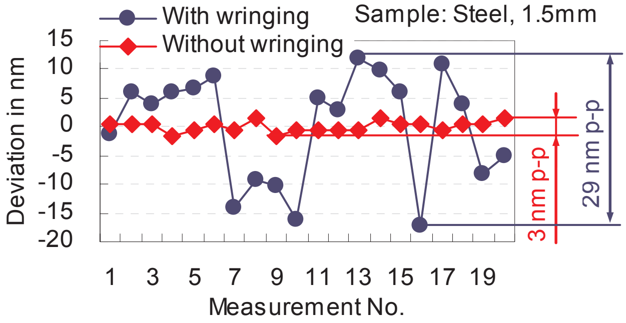

Figure 6: Repeatability in length measurement.

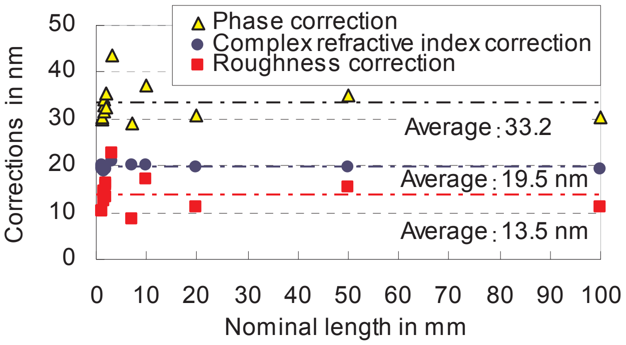

Figure 7: Result of phase correction measurement.

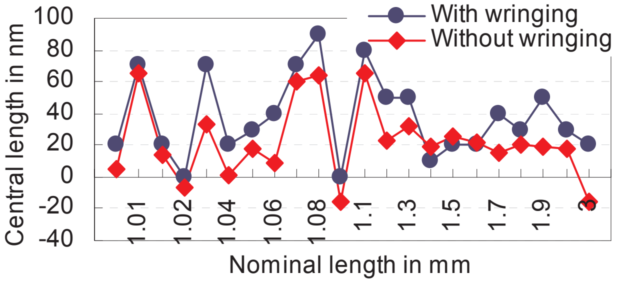

Figure 8: Result of comparisons in central length measurements of steel GBs.

4 MEASUREMENT OF COEFFICIENT OF LINEAR THERMAL EXPANSION

The coefficient of thermal expansion (CTE) is the material property which relates a material's temperature change to the length expansion caused by the temperature change. If it is measured over a wide temperature range, the value is usually expressed as a polynomial function with respect to its temperature. However, for practical reasons CTE is usually expressed as a constant value around a specified temperature which is sufficient in most cases. Hence, hereafter it is treated as a constant value although we can provide it as a polynomial expression.

CTE is represented as follows,

$$CTE = \frac{dL}{L} \cdot \frac{1}{dT} \tag{4}$$

Where, L : length of GB, dT : temperature change of GB, dL : length change of GB yielded by its thermal expansion

This time, CTE was measured around the temperature of 20 °C. The temperature changes of the GBs were obtained by changing the laboratory's temperature in the range of 17 °C to 23 °C with its air conditioner. To calculate CTE with the equation (3), parameters of L and dL were measured by this interferometer and dT was obtained by a commercial high accuracy thermometer which was installed in the system [4]. We compared this system to an existing highly accurate dilatometer. The results are shown in Table 1. The dilatometer which we compared with has been developed by AIST [5], and is one of the most accurate systems in the world. It has an expanded uncertainty of 0.007 x 10^{-6} /K (k=2). As we can see, both results agree well so that the measured values of CTE using our interferometer are sufficiently reliable.

GB	Materials and lengths	CTE （$\times 10^{-6}$ / °C）		
		Mitutoyo	AIST	Differences
S1	Steel 100 mm	10.778	10.77	0.008
S2		10.677	10.676	0.001
S3		10.739	10.737	0.002
S4		10.628	10.626	0.002
C1	Ceramics 100 mm	9.26	9.2418	0.019
C2		9.257	9.2322	0.025
C3		9.233	9.2253	0.007
C4		9.234	9.2171	0.017
C5		9.405	9.3813	0.024
C6		9.398	9.3787	0.02
C7		9.414	9.3836	0.03

Table 1: Comparison in CTE measurement.

Components	Uncertainty sources	Standard uncertainty $u(x_i)$		Sensitivity coefficients $C_i = df/x_i$		$u_i(L) = C_i \times u(x_i)$ nm		Type
$u(Lv)$	Wavelength of laser	3.65×10^{-9}	-		x L	3.65×10^{-9}	x L	A
$u(Lst)$	Longterm stability of system	0.8	nm	1		0.8		B
$u(e)$	Fringe fraction reading	0.9	nm	1		0.9		A
$u(E)$	Edlen's expression itself	1.00×10^{-8}	-		x L	1.00×10^{-8}	x L	B
$u(p)$	Air pressure	13.5	Pa	2.68×10^{-9}	x L	3.61×10^{-8}	x L	B
$u(t)$	Air temperature	6.90	mK	9.53×10^{-7}	x L	6.58×10^{-9}	x L	B
$u(h)$	Air humidity	89.6	Pa	3.61×10^{-10}	x L	3.23×10^{-8}	x L	B
$u(k)$	CO_2 density	8.66×10^{-3}	%	1.50×10^{-6}	x L	1.30×10^{-8}	x L	B
$u(a)$	CTE of GB	2.89×10^{-7}	1/K	(T - 20)	x L	5.77×10^{-8}	x L	B
$u(T)$	GB temperature	6.90	mK	1.08×10^{-5}	x L	7.45×10^{-8}	x L	B
$u(al1)$	Alignment of optical setup 1	0.62	nm	1		0.6		B
$u(al2)$	Alignment of optical setup 2	2.29×10^{-9}	-		x L	2.29×10^{-9}	x L	B
$u(oi)$	Optical imperfection	1.8	nm	1		1.8		A
$u(ph)$	Phase correction	5.9	nm	1		5.9		A

Table 2: Uncertainty budget in length measurement.

Moreover, the longest measurable length in our interferometer is 508 mm (20 in), but the dilatometer has only 100 mm. This point is a big advantage because we can provide CTE evaluated long GBs for CMM acceptance tests.

5 TEMPORAL STABILITY MEASUREMENT

To keep on measuring a certain GB for a prolonged period shows its temporal stability (length stability). However, the wringing film thickness variation takes place in each measurement so that it is difficult for the exiting conventional gauge blocks interferometer to distinguish small length changes clearly. On the other hand our interferometer doesn't require wringing itself, therefore length changes of less than 10 nm can be traced (Figure 9). The measurement data are fed back into our production process to provide better quality control.

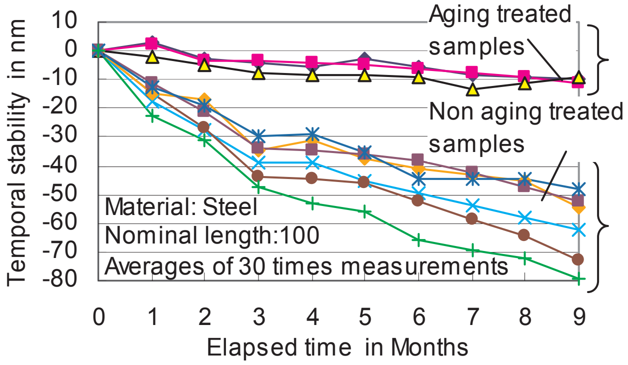

Figure 9: Example of temporal stability measurements.

6 UNCERTAINTY ESTIMATION

6.1 Length measurement

The uncertainty budget in length measurements is shown in Table 2. The expanded uncertainty (k=2) is estimated as,

$$U = 2\sqrt{39.8 + 1.16 \times 10^{-2} L^2} \text{ nm} \tag{5}$$

where, L is nominal length of GB in mm.

6.2 CTE measurement

The expanded uncertainty (k=2) in CTE measurements is estimated as,

$$U = 2\sqrt{2.1 + 1.2 \times 10^{-3} / L + 8.5 \times 10^{-1} \times dL / L} \times 10^{-8} / K \tag{6}$$

where, L: nominal length of GB in mm,
dL : amount of thermal expansion in mm.

The value of expanded uncertainty which is converted into the range of its longest measurable length of 508 mm (20 in) is 0.035 x 10^{-6} /K

7 CONCLUSIONS

A new gauge blocks interferometer which doesn't require wringing onto an auxiliary platen has been developed. The interferometer determines the main characteristics of gauge blocks such as dimensions, coefficient of thermal expansion and temporal stability. From the measurement data and uncertainty estimates, it is shown that the interferometer has lower uncertainty than conventional instruments.

8 ACKNOWLEDGEMENT

We greatly appreciate that Dr. Bitou of AIST gave us good suggestions regarding phase correction measurement.

9 REFERENCES

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