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Research Article

Uncertainty Estimation $U(L_g + L_w)$ due to Geometrical Imperfection and Wringing in Calibration of End Standards

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Uncertainty in gauge block measurement depends on three major areas, thermal effects, dimension metrology system that includes measurement strategy, and end standard surface perfection grades. In this paper, we focus precisely on estimating the uncertainty due to the geometrical imperfection of measuring surfaces and wringing gab $U(L_g + L_w)$ in calibration of end standards grade 0. Optomechanical system equipped with Zygo measurement interferometer (ZMI-1000A) and AFM technique have been employed. A novel protocol of measurement covering the geometric form of end standard surfaces and wrung base platen was experimentally applied. Surface imperfection characteristics of commonly used 6.5 mm GB have been achieved by AFM in 2D and 3D to be applied in three sets of experiments. The results show that there are obvious mapping relations between the geometrical imperfection and wringing thickness of the end standards calibration. Moreover, the predicted uncertainties are clearly estimated within an acceptable range from 0.132 μm, 0.164 μm and 0.202 μm, respectively. Experimental and analytical results are also presented.

1. Introduction

In nonmetrology, estimation of uncertainty in dimension measurements is a vital part in calibration processes. The uncertainty estimation is always influenced by the procedures and the conditions of length measurement. End-to-end effects in calibration of end standards are constantly a necessary part in length metrology. From the calibration of primary length standards (a stabilized laser wavelength) to the calibration of secondary end standards (gauge blocks, GBs), it was important to accurately identify the major impacts on the uncertainty estimation. There are many grades of gauge blocks (00, K, 0, and industrial grade) that are commonly working as end standards in different accurate industrial applications, especially in automotive and airspace industries. One must know the requirements of gauge blocks: (1) the surfaces must have a smooth finish, (2) the surfaces must be flat, (3) the double faces must be parallel, and (4) the actual size must be known as a natural expression of the nominal size [1, 2]. Materials of GBs are made including specific conditions such as hardness, temperature stability, corrosion resistance, and high-quality finish. Figure 1 emphasizes the truth of the metrologists saying "No surface is perfectly smooth." The surface of GB is rarely so flat or smooth, but most commonly it is a combination between the tolerances limits t_1 and t_2 due to the surface finish quality. In dimensional metrology, such calibration should be performed to specified tolerance (permissible deviation).

The main purpose of gauge blocks is to provide linear dimensions known within a given precise tolerance. The four grades of GBs include different tolerances "t_1 and t_2" as follows: reference grade $A^3 \equiv 00$ with higher tolerance $\pm 0.05\,\mu$m (50 nm), calibration grade $A^2 \equiv K$ with tolerance from $+0.10\,\mu$m to $-0.05\,\mu$m, inspection grade type $A \equiv 0$ with tolerance from $+0.15\,\mu$m to $-0.50\,\mu$m, and industrial workshop grade with the lowest tolerance (from $+0.25\,\mu$m to $-0.15\,\mu$m) [2, 3]. GB grade 0 is the most popular grade in the large range in length metrology; it is usually suitable for most applications and offers best combination of accuracy. Laser interferometer may be considered as a primary method in the calibration of end standards. One of the advantages in using Zygo interferometric system with a novel protocol is to avoid

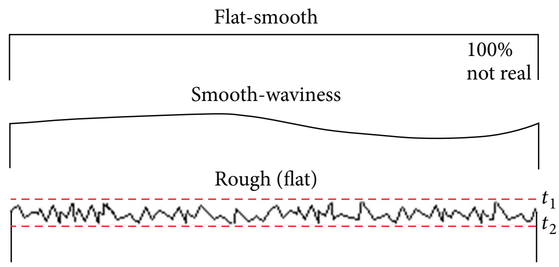


Figure 1: Surfaces of GB measuring faces are commonly a combination of tolerance limit.

the phase change effects which is an important condition to adhere/wring a gauge block to a base platen having the same material and surface perfections properties which is practically difficult to guarantee. Atomic force microscope (AFM) technique is an advanced nanometrology tool used for surface characterization of GBs faces in 2D and 3D profiles. Uncertainty evaluation for the measurement of GBs by popular optical laser measurement method is estimated [3, 4]. Multiwavelength interferometer using pattern analysis method based on fringe fraction method has been referenced [5]. While there are different measuring techniques that can be used for surface characterization in micro- and nanoscale [6]. Using compatible measuring technique including optomechanical system with Zygo measurement interferometer system will be possible to consider a new method.

Because of ultraflat surfaces of gauge blocks and base platen, they getting wrung to each other tightly with little force. Properly wrung locks may withstand a 330 N pull [7]. Indeed, the exact contact mechanism that causes wringing is as follows: (1) molecular attraction occurs when two very flat surfaces are brought into contact; this force causes GBs to adhere even without surface lubricants; (2) air pressure applies contact pressure between the blocks surfaces because the air is squeezed out of the joint. Giving quantitative information about the degree of imperfectness of geometric features on work pieces (gauge blocks-base platen) is very important for further improvement of accuracy on dimensional metrology. The traceability chain is achieved by calibration of the gauge blocks according to defined international standard ISO 3650 "the perpendicular distance between any particular point of the measuring face and the planar surface of an auxiliary plate of the same material and surface texture upon which the other measuring face has been wrung." One can say that, the minimum conditions for wringability (the ability of two surfaces to adhere tightly to each other in the absence of external means) are a surface finish of 0.025 μm or better and flatness of at least 0.13 μm [7, 8]. Recently, some published works interested in studying the surface profile of GB ends using AFM compared to reference flat mirror to verify standard/reference measurement accuracy [9–11]. However, the advanced technology that is employed in end standard surface mapping may require some additional investigations in order to guarantee the nanometric level of measurement accuracy.

In this paper, a novel measurement strategy uses compatible measuring technique to emphasize on accurate dimensions measurements in order to estimate the impacts of surface finishing imperfection (L_g) and of wringing gab (L_w) onto end standards; see the proposed method in Figure 2. The major advantage of the developed work is for estimate and accurate determine the actual empirical values of uncertainty using novel protocol include AFM and Optomechanical system equipped with Zygo measurement interferometer for further improvement of accuracy on dimensional metrology.

To achieve this goal, an equipped compatible measuring technique has been proposed. Characterization of surfaces imperfection of the commonly used 6.5 mm GB ends has also been investigated using AFM to be more suitable for the proposed three experimental sets. The estimated uncertainty $U(L_g + L_w)$ based on the previous mentioned conditions for a wide range of GBs was practically determined and interpreted.

2. The Conceptual Measurement Process

Traditionally, calibration of gauge blocks is very important for the traceability in length metrology. Geometric imperfections of end standard surfaces causes the most pronounced variation in gauge length which represents a value that should be considered. The slight deviations in end standard geometry by either imperfect flatness or parallelism of measuring faces have a gross contribution in an added uncertainty for the measured length [2, 12]. Figure 3 shows a plan of three experimental sets preserved for calibration. Three sets of gauge blocks including lengths 6.5 mm with 30.0 mm, 6.5 mm with 60.0 mm, and 6.5 mm with 90.0 mm have been selected. Indeed, three sets of wrung GBs 36.5 mm, 66.5 mm, and 96.5 mm were selected in order to cover a wide range of GBs in the short range. The shortest GB size 6.5 mm has been used in all sets of experiments to avoid any sources of other errors. Determination of L_w due to the wringing gab between measuring faces and L_g due to the geometrical form of surface imperfections for these wide ranges of GBs was the aim of these calibrations.

Practically, as described in the schematic diagram, we should measure L_{12} (two wrung gauges) in order to calculate L_w and L_g according to the mentioned in (1) and (2). It is important to take into consideration that the employed surfaces are of the same materials. The first rule is

$$L_w = (L_{12})_m - (L_1 + L_2)_{\text{Nom}}, \tag{1}$$

while the result to be reported was the deviation of measured length L_m from nominal length L_n to be Δ equal $L_w = L_m - L_{\text{Nom}}$. The measurements of Δ due to the wringing of each measurement face in turn to the reference flat and the average of the two wringings had to be reported. L_g practically represents (peak-to-valley) over the surface, so the appropriate computation function of the second rule is

$$L_g = \left(\int_{-t}^{+t} l_g \cdot dl \right), \tag{2}$$

where $\pm t$ represents the tolerance limits of GB. One can show explicitly that, (2) represents the surface imperfection

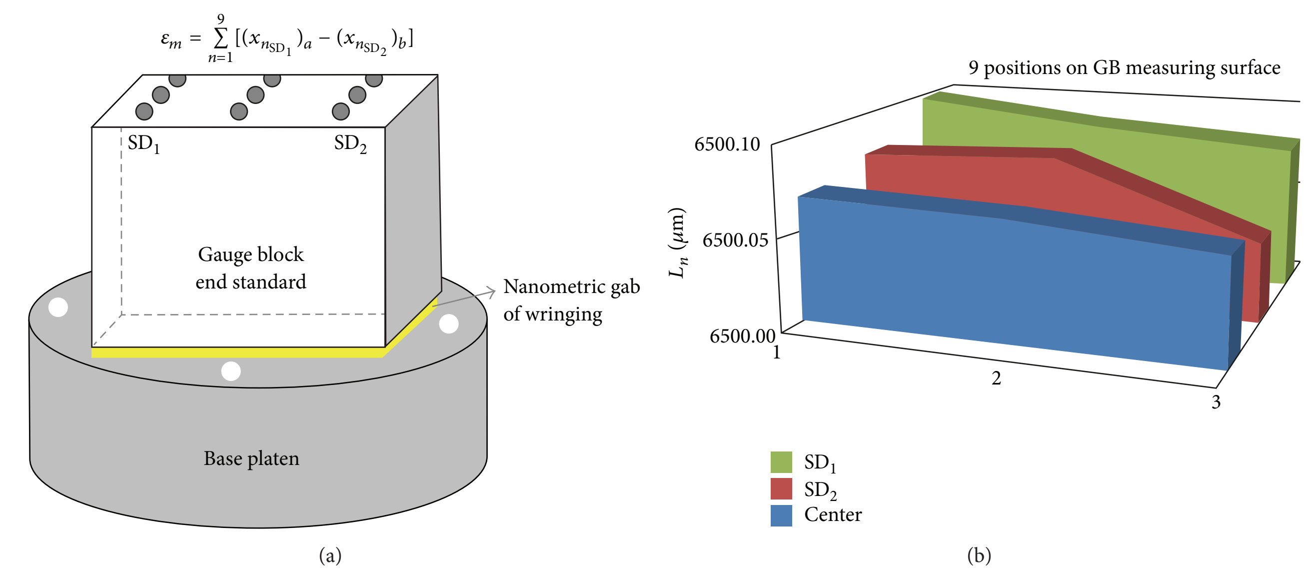


Figure 2: Novel protocol of gauge blocks calibration.

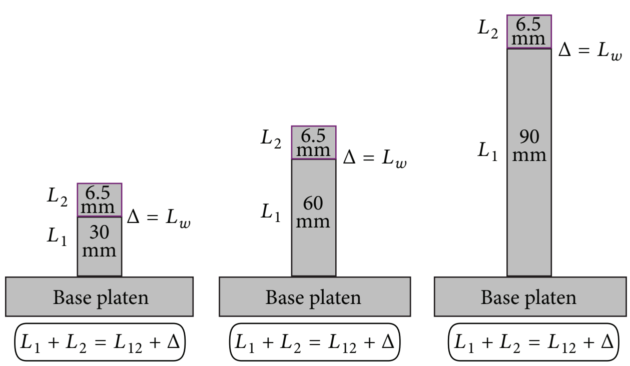


Figure 3: Schematic of three sets of gauge blocks (steel GBs on steel base platens).

contribution in terms of GB length; practically, we can suppose that

$$L_g = \sum_{i=1}^{9} \frac{x_i}{n}. \tag{3}$$

By using two steel surfaces of gauge block and base platen, the thermal expansion effects have been considered to be fixed effects for these measuring surfaces; for the different three sets of seventy-two readings of each gauge block (double faces), it gave reliability in the measurement results and was sufficient to estimate the contributions of the two studied parameters L_w and L_g based on an accurate estimate of the deviation error, ε_m, as follows:

$$\varepsilon_m = \sum_{i=1}^{9} \left[\left(x_{i_{SD_1}} \right)_a - \left(x_{i_{SD_2}} \right)_b \right], \tag{4}$$

where a expreses the first measured face of each GB and b is the second measured face. A lot of measured gauge blocks are screened differences in central length when wrung to one side as compared to the other side 42 nm. The measurement reproducibility for the central length of gauge blocks was better than the measurement results for the two other sides SD_1 and SD_2 of the two surfaces of measured gauge blocks as illustrated in the right part of Figure 2. The proposed design for this novel technique of calibration process of end standards is a compatible technique composed of an optomechanical measuring system equipped with Zygo measurement interferometer (ZMI-1000A). Figure 4 shows that optomechanical system has dual-wavelength laser heterodyne interferometer of linear measurement resolution 1.24 nm employed for gauge block measurements.

3. Experimental Work

Figures 2–4 illustrate the principles of proposed plan of the technical protocol using compatible technique. In this work, we assumed that thermal effects tend to be constant in measurement processes and could be fixed for the same materials of employed gauges. The used gauge blocks were of a rectangular cross section according to the ISO 3650. Mechanical predetermination of the length of employed gauge blocks was not needed because their nominal lengths are available. In order to achieve predictable uncertainty, lengths of reference standards should verify repeatability and reproducibility with high accuracy. So, even if the measurement is performed carefully by highly skilled laboratories in NMIs, the measurement values are expected to be varied, where wringing onto measuring platen surfaces many times may cause scratches and permanent damage to gauge block measuring faces. It is apparent that wringing is one of the significant sources for reduced measuring reproducibility and increased uncertainty. Calibration of highly graded end standards using laser interferometric techniques is strongly recommended for achieving reliability of experimental data

Table 1: Standards specifications and measured results of GBs (grade 0).

Nominal length (L), mm		Tolerance on length = 0.12 μm + 2 × 10^{-6} L, μm		Tolerance on parallelism = 0.10 μm + 3 × 10^{-7} L, μm	
Range	Referenced	Theoretical	Average measured error	Theoretical	Average measured error
0.5 → 50	6.5		+0.11	+0.10 → −0.10	0.06
	30.0	+0.10 → −0.10	+0.14	+0.10 → −0.10	0.07
50 → 150	60.0		+0.09	0.12	0.07
	90.0	+0.30 → −0.30	+0.20	0.12	0.10

Figure 4: Setting of optomechanical system with ZMI-1000A.

[12]. Figure 2(a) shows the measurement strategy for GB calibration using a novel measuring strategy, while Figure 2(b) shows gauge block surface profile according to nine points on one of its measuring surfaces. Referring to Figures 1 and 2, one can say that the deviation in flatness and parallelism encourage one to decide that the most appropriate points to precisely measure the length are always at the center of gauge blocks. Since surface roughness could be difficult to analyze quantitatively and GB surfaces may be entirely different, yet still provide the same measuring value.

Therefore, the novel protocol is proposed to cover many positions of effective points over the surfaces of gauge blocks to accurately estimate the uncertainty and its impacts in length measurement due to the geometrical imperfections using AFM images and the wringing process. Experimentally, we measured the impacts of surface finishing imperfections and wringing process for a specific grade “0” of end standards with respect to other input parameters of uncertainty estimation.

3.1. Surface Imperfection Measurement of GB Using AFM. Surface quality of GBs is an important parameter to qualify the surfaces perfection especially in uncertainty estimation of length measurement. Actually, AFM microscope technique is the advanced coordinate metrology tool for surface characterization of GBs faces. The shortest GB of 6.5 mm will be considered the main GB in all experimental sets in order to avoid any sources of other errors. Surface topography for two ends of 6.5 mm GB has been measured using AFM technique in the surface metrology laboratory at NIS. Representative AFM images of a GB at a greater magnification are shown in Figures 5 and 6. This is to indicate the range of imperfection deviation in the proposed three sets of experiments. Figure 5 shows the AFM images of the surfaces for center points of two coated faces for the shortest gauge block in 2D. Figure 6 illustrates the AFM 3D surface morphology of both sides for the 6.5 mm end standard. The structure of the faces surface of the 6.5 mm GB has been observed by AFM, taking advantage of its high sensitivity to small height variations in surface profiles. It clears that the scratches of the coated surfaces of GB in both 2D and 3D images in details. The predicted uncertainty of 6.5 mm GB due to surfaces imperfection is clearly measured within an acceptable range from 15 nm to 17 nm, respectively; see Figures 6(a) and 6(b).

3.2. Measurement of Instrument Errors (Electronic Uncertainty). The basis of length measuring interferometry system is the wavelength of employed laser source. The wavelength of employed laser source in the measurements is 632.991528 nm with resolution of 1.24 nm. Stability circuitry within laser head is designed to control the output frequency of the laser tube at fixed value. Zygo laser head has maximum frequency instability of 0.05 ppm/°C. In ZMI-1000A, the measurement board has a maximum electronic error in measurement of 1.3 counts. Therefore, the electronic uncertainty using a ZMI-1000A measurement board is 1.3 × 1.24 = 1.61 nm [4, 13]. The relative uncertainty due to instrument is 2.7 nm, laser 0.84 nm, electronics 1.61 nm, and interferometer polarization mixing 2.0 nm. In practice “instrument dependent—Figure 7,” it is found that relative stability is between 1 × 10^{-7} and 5 × 10^{-7}.

From the large number of measuring cycles, there was a natural tendency to collect data and statistically process these to compute a 2 sigma of repeatability. For accurately writing the specification standards of a specific “0” grade of end standards, it was important to practically measure and cover different lengths of GBs using different measuring techniques in order to judge your metrology tools traceability. The imperfection in GB surface may cause erroneous flatness and consequently end standard measurement that is definitely unacceptable in calibration process. Equation (5) could inform the right estimation of actual GB length as follows:

$$L_{\text{Act}} = \sum_{n=1}^{9} \left[\frac{\left(L_{\text{Nom}} \pm \varepsilon_m\right)}{n} \right], \tag{5}$$

where L_{Act} is the actual length, L_{Nom} is the nominal length, ε_m is measurement deviation error, and n integer number indicating the repeatability. The gauge blocks were obviously free of any damage at the beginning of the measurements. Table 1 presents the nominal and experimental measurement of different lengths of gauge blocks compared with the theoretical information according to ISO 3650.

The uncertainty evaluation is carried out in accordance with the ISO GUM, 2008 [1, 8]. The $U_{\text{Ex}} = \pm(0.08 + L/1000)\,\mu$m, where U_{Ex} is the expanded uncertainty using

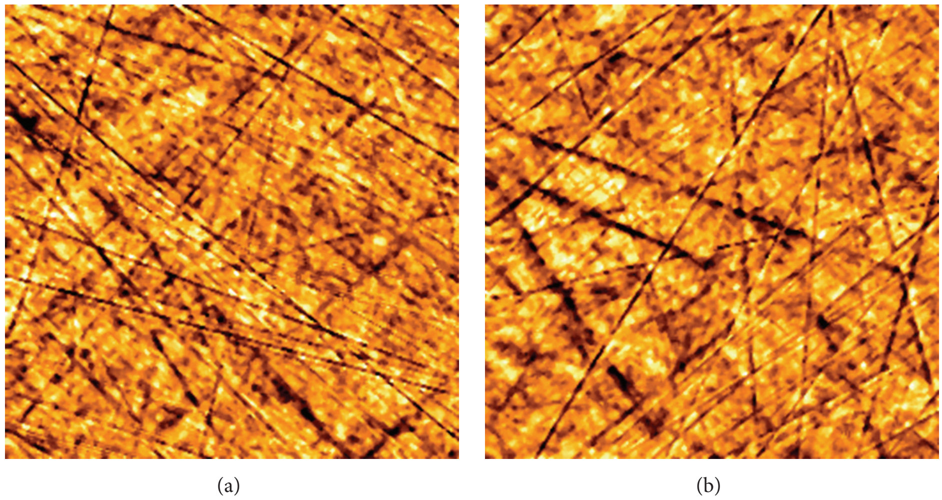


FIGURE 5: 2D AFM surfaces images of coated sides scratches for 6.5 mm GB: (a) first side; (b) second side.

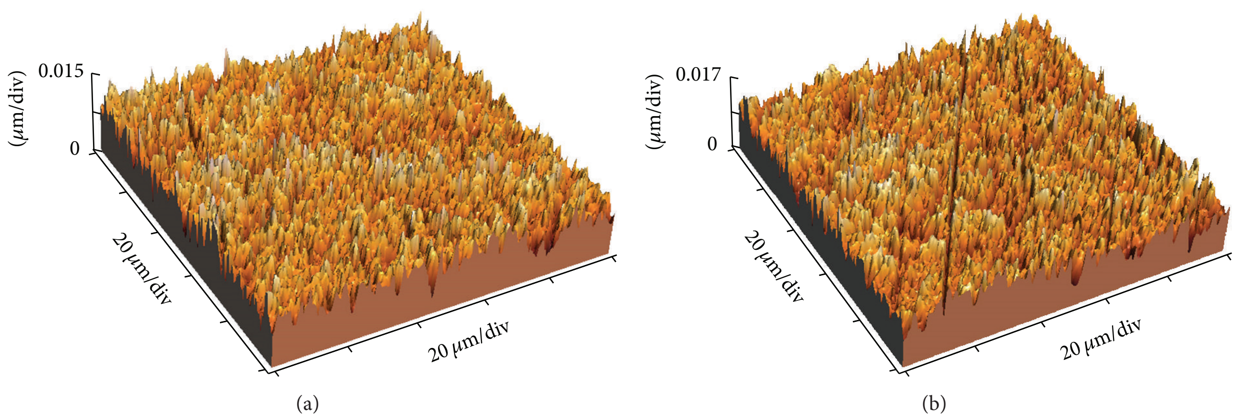


FIGURE 6: 3D AFM surface morphology of both sides of 6.5 mm GB: (a) first side; (b) second side.

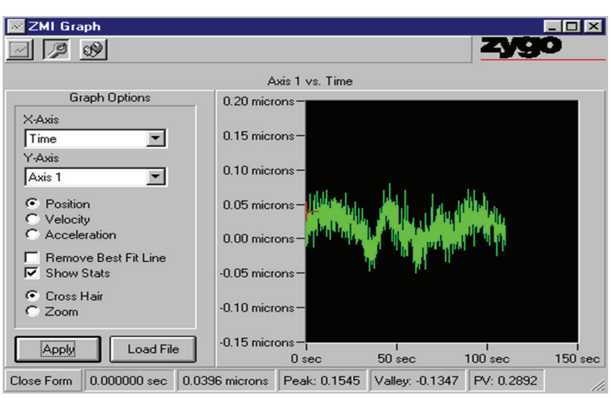
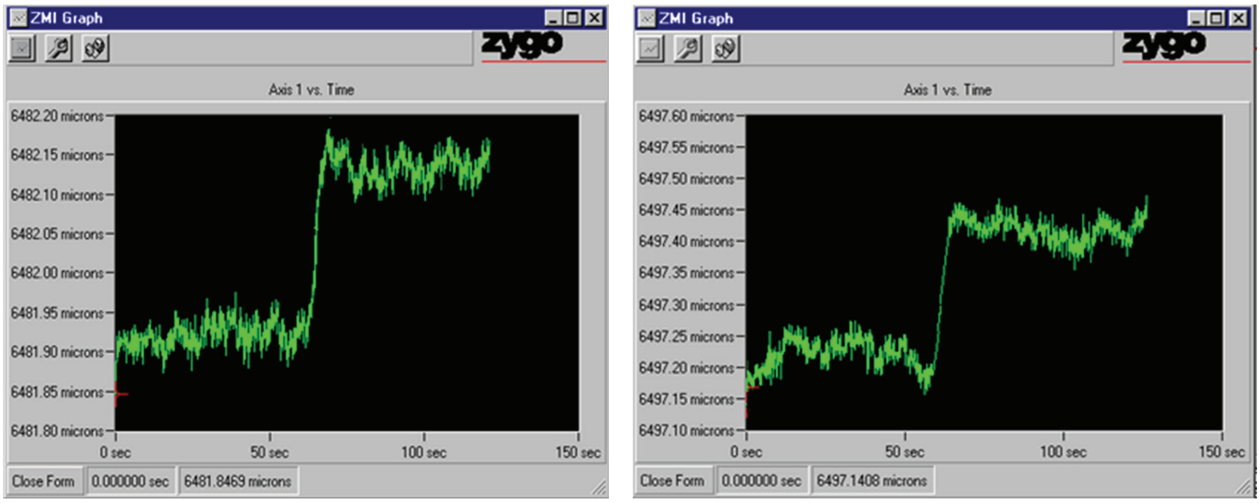


FIGURE 7: Typical measuring adjustment of the zero order using ZMI1000 interferometer.

a covering factor $K = 2$, providing a level of confidence of approximately 95%. All measurements were achieved at environmental temperature of $20 \pm 0.5^{\circ}$C in the NIS laboratory. For measurement using steel gauge blocks wrung on a steel base platen, the expansion coefficient will be equally sensitive to the relative uncertainty in the length measurements. The influences of environmental conditions are the same, as long as they are stable for measurements according to ISO 3650. Difference between left and right wringing: to measure the gauge blocks wrung to both the left and the right measurement surface and to report both these results and the mean. The standard deviation and the absolute maximum value of the differences between left and right wringing for steel gauge blocks is in the range of 40 nm.

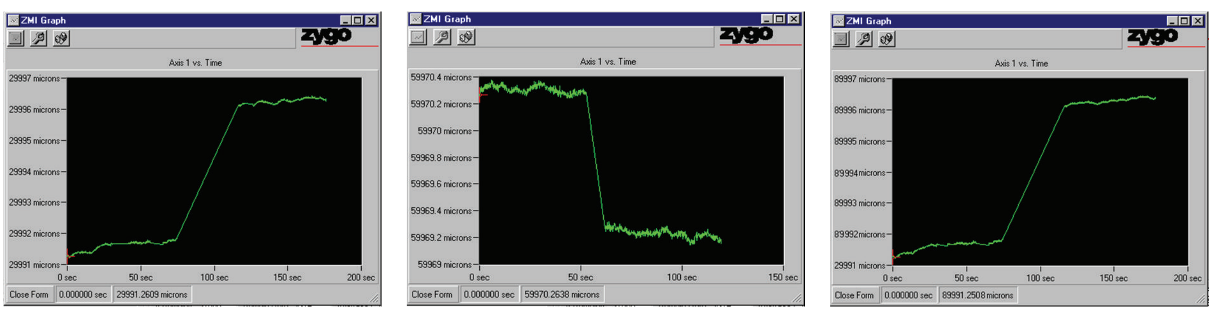
4. Measurement Results

Nine points novel protocol may be interpreted as a contour map for an advanced grade of gauge blocks. The value of flatness, surfaces texture profiles, or checking for defects on both ends is precisely required before each end surface had to be wrung onto a platen. Since the employed interferometer can investigate the surfaces of both GB ends. An equality points on the GB surface indicates surface co-planarity; inequality points may indicate to refuse the wringing process



(a) (b)

FIGURE 8: Deviation of measured positions on two edges of 6.5 mm GB surface: (a) SD_1; (b) SD_2.



(a) (b) (c)

FIGURE 9: Measurement positions of 30, 60, and 90 mm of GBs surfaces (SD_1 and SD_2).

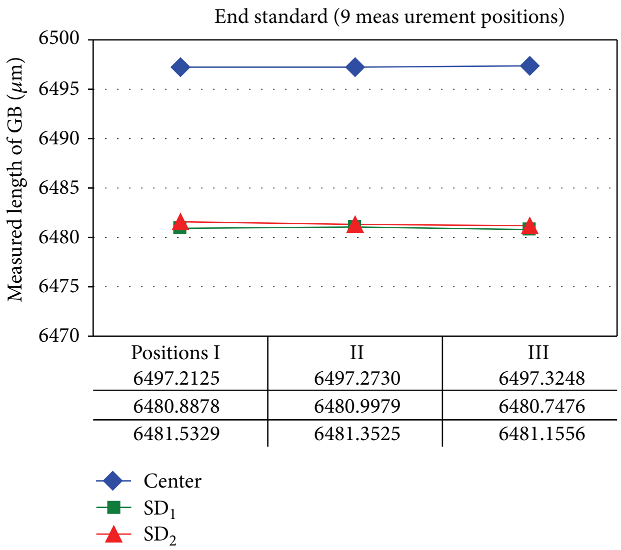
in order to avoid more costly damages. After right wringing is achieved, the upper face (unwrung face) flatness is measured at many positions, in addition to the other measuring parameters (parallelism and corresponding length) of gauge blocks. This process is then repeated for the other surface at same conditions. Parallelism between faces of gauge blocks using this novel protocol is easier and more accurate over all the two opposite points upon the two opposite GB surfaces. The knowledge of reference GB flatness, thickness, and parallelism of a specific grade allows unambiguously relating the measurement volume of one profiler with respect to the other. We can then verify and characterize their flatness, parallelism, and length. Figures 8 and 9 demonstrate the measurements at many different positions upon two edges of gauge block surface. The given data informed us about the differences, peaks, and valleys on gauge block surface.

The information is summarized and then employed to obtain an estimated uncertainty in the GB calibration. The average variation from nominal length of an employed gauge blocks for upper measuring surface wringing is −45 nm and for lower measuring surface wringing is +67 nm. Figures 8 and 9 could assure why all research work or international comparisons for NMIs laboratories working in this area are always mentioned to the "central length" of gauge blocks.

In Figure 10, it is straightforward to relate the texture measurement to the process marks. A swift calculation reveals that R_{av}, the average roughness, value is simply $PV/2$. PV is the peak-to-valley height of measured signal. As seen in (6), it is the mean of all obtained values within the assessment length. It may give a subjective judgment on an end standard quality specification according to ISO [1, 8]:

$$R_{av} = \sum_{n=1}^{9} \left(\frac{P_n V_n}{2} \right). \tag{6}$$

In high precision engineering measurements at NMIs, errors in optical paths due to geometrical form of surface imperfections of measuring surfaces of end standards have to be estimated accurately using AFM technique. These could be flatness and parallelism errors or even errors of form. As shown in Figure 9, this characterization is not so straightforward as it looks at first sight as been shown in Figure 3.



Positions I	II	III
6497.2125	6497.2730	6497.3248
6480.8878	6480.9979	6480.7476
6481.5329	6481.3525	6481.1556

FIGURE 10: Nine measurement positions on the center and the two edges of 6.5 mm GB surface.

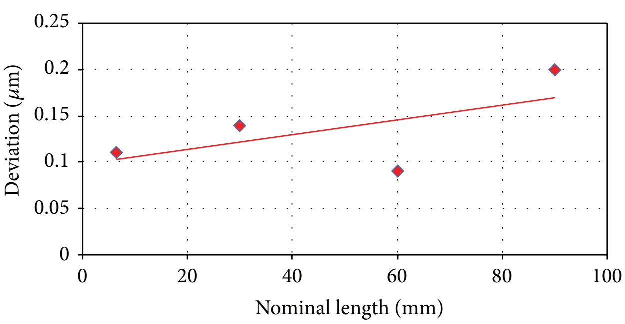


FIGURE 11: The deviation for different GBs length measurements with the same protocol.

Eventually, the experiment result clearly shows that the measurement method is proven to be capable of predicting the GB surface characterization beside length measurement errors.

5. Uncertainty Analysis

The novel protocol that has been designed for evaluating uncertainties of critical influence quantities (geometrical imperfection and wringing process, $U(L_g + L_w)$) may give end standard complete indication in more detail. Indeed, the experimental measurements for the concerned parameters of end standards agree with ISO 3650. The relative uncertainty due to instrument, laser, electronics, and interferometer polarization mixing is 7.15 nm [13]. Using interferometry, gauge blocks lengths could be measured to accuracy of an order of 40 nm for blocks that are 90 mm long (short GB range) [14, 15]. Applying uncertainties of an individual set, the maximum uncertainty likely to incur when using a grade 0 of graded GBs, the 1st set is $U(L_g+L_w) = 0.132\,\mu$m, the 2nd set 0.164 μm, and the 3rd 0.202 μm set, respectively. Figure 11 presents the deviation errors in the length measurement of selected GBs.

6. Conclusion

This work has been designed amid accurately determining the impacts of geometrical form of surface imperfections of gauge blocks grade 0 and its resultant wringing gab in calibrations of end standards using an appropriate novel measurement strategy. Individual and grouped wrung gauge blocks were calibrated in many sets of experiments. Results clearly illustrated that geometrical imperfections of measuring surfaces and wringing process of GBs have the largest relative error in dimensional metrology. The AFM images represent the true error range with great magnification due to surface imperfection within the range of 0.015–0.017 μm. The end standard surface imperfection profile is considered in an uncertainty estimation. The result analysis indicates an estimated uncertainty $U(L_g + L_w)$ within range from $\pm 0.132\,\mu$m to $\pm 0.202\,\mu$m for sets of experiments at standard conditions. Moreover, the authors emphasize, to be precise and verify standard uncertainty within the tolerance limits of sub-microns for contact and noncontact length metrology, they are mainly just taking into consideration the measured length at GBs faces centers.

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