Long-term stability analysis and its relationship with the steel structure of gauge blocks from several manufacturers

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Abstract: Gauge blocks are one of the most widespread measurement standards (etalons) in dimensional metrology laboratories. Among all its properties, it is worth highlighting the importance of dimensional stability. This property allows to classify these measuring instruments in quality grades. Although the gauge blocks should be dimensionally stable, it can be observed that there is a drift that can be observed when the calibration history is revised. In this document, authors present a statistical method for the estimation of the dimensional stability of gauge blocks using the calibration history of samples from the main manufacturers. In addition, all the samples have been subjected to metallographic analysis to evaluate the structure.

Keywords: Gauge block, Dimensional stability, Uncertainty, Microstructure.

1. Introduction

Gauge blocks are the most important and widespread measurement standards (etalons) across the industry and dimensional metrology laboratories [1-3]. This is because its extreme simplicity and accuracy have not changed appreciably in the last century. However, the requirements of greater accuracy for industrial applications have forced the continuous evolution of calibration methods for these etalons.

These material measuring standards are defined in ISO 3650:1998 as “material measure of rectangular section, made of wear-resistant material, with one pair of planar, mutually parallel measuring faces, which can be wrung to the measuring faces of other gauge blocks to make composite assemblies, or to similarly finished surfaces of auxiliary plates for length measurements”.

As it is possible to see in figure 1, the geometry of each gauge block can be characterized by the following characteristics [4]:

- Nominal length ($l_n$). This is considered at reference conditions of 20 °C and 1 atm.
- Central length ($l_c$).
- Deviations from Central length ($f_o$ and $f_u$).
- Deviation of the length at any point from nominal length ($r$).
- Deviation from flatness ($f_d$).
• Variation in length \((v)\), that it is the difference between the maximum \((l_{\text{max}})\) and the minimum \((l_{\text{min}})\) lengths and the sum of \(f_o\) and \(f_u\).

![Image of Gauge block and its main characteristics]

**Figure 1.** Scheme of a Gauge block and its main characteristics.

Commercial sets of gauge blocks include a lot of specimens with \(l_n\) from 0.5 mm to 100 mm. If it is needed a gauge block with \(l_n\) not included in the set, ISO 3650:1998 contemplates the possibility of adhering two gauge blocks due to molecular forces in a process known as wringing. There are two morphologies for gauge blocks depending on its \(l_n\) [4]:

![Images of Gauge blocks with different lengths]

**Figure 2.** (a) Gauge blocks with \(l_n \leq 6\) mm. (b) Gauge blocks with \(l_n \geq 6\) mm.

Each gauge block has two parallel surfaces where the measurements are carried and one surface where the information of the gauge block is engraved. This information uses to be the nominal length of the specimen and the manufacturer logo. In figure 2, the measuring faces, and the area destined to engrave the information are marked in grey and orange, respectively. Note that for gauge blocks with \(l_n \leq 6\) mm the marking area is contained in one of the measuring faces due to lack of space. Besides, gauge blocks are measured in this position.

In sections 7 and 8 of reference [4], metrological requirements and calibration procedures for gauge blocks depending on the calibration grade are collected. According to these sections, there are two ways to make the calibration of gauge blocks:

• Interferometry: preferably for gauge blocks with calibration grade K.
• Comparison: where the difference of its central length from that of a reference gauge block is measured by comparison in a mechanical gauge block comparator.
According to reference [4], gauge blocks should be made of wear-resistant materials with a Vickers hardness greater than 800 HV 0.5. This includes high-grade steel, hard alloys, ceramics, and others [3]. In this document, the authors focus on hardened steel gauge blocks because they are widely used [5].

Dimensional stability is a key requirement for these measuring instruments:

| Grade | Max. permissible change in length per year |
|-------|-------------------------------------------|
| K     | ±(0.2 \( \mu m \) + 0.25 \( \cdot 10^{-6} \cdot L_h \)) |
| 0     | ±(0.05 \( \mu m \) + 0.5 \( \cdot 10^{-6} \cdot L_h \)) |

This characteristic is very hard to reach because no material is stable. To reach these values, steel parts have traditionally been manufactured using 52100 steel (according to ASTM A295 standard and its equivalents) and during the manufacturing process, these parts are hardened, tempered, and annealed, before giving the specimens the final dimensions [3]. An annealed steel is expected to be at equilibrium [5] but it has been observed that there are still changes in its dimensions. The instability is produced by the transformation of the residual austenite that is left at the end of the manufacturing process to martensite [6]. This change in the microstructure implies a dimensional change because the retained austenite has a Face-Centred Cubic structure (CFC) and the martensite a Body-Centred Tetragonal structure (BCT).

In figure 3, it is possible to observe that it exists a variation in the dimensions of the crystal cell. Considering that these steels have between 0.90 and 1.10 %C, the dimensions are:

- For austenite, the network parameter \( a \) is between 0.35946 and 0.36034 nm.
- For martensite, the network parameter \( b \) is between 0.29704 and 0.29936 nm and the network parameter \( c \) is between 0.28777 and 0.28803 nm.

Traditionally, manufacturers left the hardened and thermally treated steel bars for years under environmental conditions to let them stabilize dimensionally. Thanks to this, gauge blocks were dimensionally very stable. In this document, the authors will present a method to determine statistically [7] the dimensional stability, using samples with lengths under 100 millimeters, samples 100 millimeters.
long, and samples longer than 100 millimeters, to cover all the typical ranges of measurement. The calibration history of gauge blocks has also been measured from the main manufacturers: FRANK, CARY, KOBA, MITUTOYO, JOHANSSON, TESA, and HELIOS. Besides, a metallurgical study has been made.

2. A statistical estimation of the dimensional stability of gauge blocks

Using information from calibration records the dimensional stability of gauge blocks can be estimated. Usually, calibration records contain the following information:

- The central length $x$ of the gauge block.
- The expanded uncertainty $U(x)$ of the central length, usually estimated for a coverage probability of approximately 95% using a coverage factor $k = 2$.
- The date $t$ when the calibration was performed.
- The name of the calibration laboratory where the calibration was performed.

Therefore, for each calibration record $i$ we will have three parameters: $(x_i, U(x_i), t_i)$. If we assume that variation of length along time is nearly a linear function, we could try to estimate the central length $x$ at time $t$ using the following expression:

$$x(t) = a + b \cdot t$$  \hspace{1cm} (1)

Then, if we have $n$ calibration records ($i = 1, 2, \ldots, n$) we will have $n$ linear equations like these:

$$a + b \cdot t_i \approx x_i \hspace{0.5cm} i = 1, 2, \ldots, n$$  \hspace{1cm} (2)

Using matrix notation these equations can be rewritten in the following manner:

$$\bar{A} \cdot \bar{y} = \bar{x}$$  \hspace{1cm} (3)

where $\bar{A} = \begin{bmatrix} 1 & t_1 \\ 1 & t_2 \\ \vdots & \vdots \\ 1 & t_n \end{bmatrix}$, $\bar{y} = \begin{bmatrix} x_1 \\ x_2 \\ \vdots \\ x_n \end{bmatrix}$ and $\bar{x} = \begin{bmatrix} x_1 \\ x_2 \\ \vdots \\ x_n \end{bmatrix}$

This is a generalized least squares (GLS) regression problem [7]. The correlation between calibration results $x_i$ cannot be excluded because calibration is usually repeated at the same calibration laboratory over the years. When two calibration results $x_i, x_j$ have been provided by the same calibration laboratory, its corresponding correlation coefficient $r(x_i, x_j)$ is positive but usually, no more information is available. Therefore, the only information we have is that $0 < r(x_i, x_j) < 1$. In this situation, probably the best estimation for $r(x_i, x_j)$ is the central value of the previous interval i.e., $r(x_i, x_j) = 0.5$. In a GLS regression problem, it is necessary to estimate the covariance matrix of the vector $\bar{x}$, $\overline{C_x} = \text{cov}(\bar{x})$. Terms $c_{ij}$ of this covariance matrix are the covariances $c_{ij} = u(x_i, x_j)$ of calibration results $x_i, x_j$ that can be evaluated using the following expression:

$$u(x_i, x_j) = u(x_i) \cdot u(x_j) \cdot r(x_i, x_j), \text{ for } i \neq j$$  \hspace{1cm} (4)

$$u(x_i, x_j) = u^2(x_i), \text{ for } i = j$$  \hspace{1cm} (5)

where $u(x_i), u(x_j)$ are the standard uncertainties of calibration results $x_i, x_j$. They are calculated from expanded uncertainties as:

$$u(x_i) = \frac{U(x_i)}{k}$$  \hspace{1cm} (6)

When two calibration results $x_i, x_j$ have been provided different calibration laboratories, its corresponding correlation coefficient $r(x_i, x_j)$ is close to zero, because correlation between two
calibrations performed in two different laboratories should be small. In this situation, \( r(x_i, x_j) \) is supposed to be zero.

Once the covariance matrix \( \overline{C}_x = \text{cov}(\bar{x}) \) has been estimated, the initial GLS problem in equation (3) can be transformed into an Ordinary Least Squares (OLS) regression problem multiplying both members of the matrix equation by a weighing matrix \( \overline{W} \) obtained via the Cholesky decomposition of \( \overline{C}_x \):

\[
\overline{C}_x = \overline{L} \cdot \overline{W}^T
\]

where \( \overline{L} \) is a lower triangular matrix. The weighing matrix \( \overline{W} \) would be \( \overline{W} = \overline{L}^{-1} \). The new problem would be:

\[
\overline{A} \cdot \overline{y} = \overline{z}
\]

where \( \overline{A} = \overline{W} \cdot \overline{A} \) and \( \overline{z} = \overline{W} \cdot \bar{x} \). Now, it can be demonstrated that the covariance matrix of the new vector \( \overline{z} \) is the unity matrix and, therefore, the new problem in equation (8) is an OLS regression problem which solution is:

\[
\overline{y} = (\overline{A} \cdot \overline{A}^T)^{-1} \cdot (\overline{A}^T \cdot \overline{z})
\]

The covariance matrix \( \overline{C}_y = \text{cov}(\overline{y}) \) of the vector \( \overline{y} = [a, b]^T \) is

\[
\overline{C}_y = \text{cov}(\overline{y}) = (\overline{A} \cdot \overline{A}^T)^{-1}
\]

This covariance matrix is a \( 2 \times 2 \) matrix that could be rewritten as follow:

\[
\overline{C}_y = \text{cov}(\overline{y}) = \begin{bmatrix}
    u^2(a) & u(a)u(b) \cdot r(a, b) \\
    u(a)u(b) \cdot r(a, b) & u^2(b)
\end{bmatrix}
\]

where \( u(a) \), \( u(b) \) are the standard uncertainties of parameters \( a \), \( b \) and \( r(a, b) \) is correlation coefficient between both parameters.

Parameter \( b \) represents the variation of gauge block length over time, usually expressed in \( \mu m/\text{year} \). Parameter \( a \) represents the central length of the gauge block at time \( t = 0 \). Once we have the estimation of parameters \( a \) and \( b \), and their corresponding uncertainties, we could estimate the gauge block length \( x(t) \) at date \( t \) using the following expressions:

\[
x(t) = a + b \cdot t
\]

\[
U[x(t)] = k \cdot \sqrt{u^2(a) + [t \cdot u(b)]^2 + 2t \cdot u(a)u(b) \cdot r(a, b)}
\]

where \( U[x(t)] \) is the expanded uncertainty, estimated using a coverage factor \( k = 2 \), of the gauge block length \( x(t) \) at date \( t \).

At the Laboratorio de Metrología y Metrotecnia (Laboratory of Metrology and Metrotechnic, LMM) of the Technical University of Madrid, we use this technique to control the stability of our gauge blocks over time. In figure 4 we present the results we have obtained in three characteristics gauge blocks.

Figure 4(a) shows the evolution of the length of a 100 mm grade 0, steel gauge block presenting a high drift over nineteen years. The parameter \( b \) is \( b = (-0.097 \pm 0.004) \mu m/\text{year} \) for this gauge block. Figure 4(b) shows the evolution of the length of a 900 mm grade 0, steel gauge block presenting a typical drift over 25 years. The parameter \( b \) is \( b = (-0.045 \pm 0.018) \mu m/\text{year} \) for this gauge block. Figure 4(c) shows the evolution of the length of a 1000 mm grade 0, steel gauge block presenting no significant drift over 33 years. The parameter \( b \) is \( b = (+0.001 \pm 0.017) \mu m/\text{year} \) for this gauge block. The gauge block of figure 4(a) presents an annual negative drift, \(-0.097 \mu m/\text{year} \), two times higher than the maximum permissible drift, \( 0.045 \mu m/\text{year} \) for \( x = 100 \) mm, specified by ISO 3650. On the contrary, the gauge block of figure 4(b) presents an annual negative drift, \(-0.045 \mu m/\text{year} \), compatible with the maximum permissible drift, \( 0.25 \mu m/\text{year} \) for \( x = 900 \) mm, specified by ISO 3650. The gauge block of figure 4(c) presents an annual positive drift of only \( b = +0.001 \mu m/\text{year} \). This value is smaller than its corresponding expanded uncertainty \( U(b) = 0.017 \mu m/\text{year} \). In situations like this, figure 4(c),
the null hypothesis (the gauge block has no drift) can be accepted and we can discard the presence of drift in this gauge block. According to ISO 360, the maximum permissible drift for a grade 0 gauge block with nominal length $L = 1000\, mm$ is $0.27\, \mu m/\text{year}$.

3. Metallographic study of gauge blocks

Metallography is a powerful tool to gain insight into the structure of the materials. As quenched and tempered structures may vary over time –because of the diffusive nature of the latter treatment–, direct observation of the structure allows knowing whether the gauge blocks are properly treated. Most of the steels employed in the fabrication of gauge blocks are part of high-carbon alloyed steels. This sort of metal alloy exhibits a quenchable structure after which the structure turns out as martensite needles –typically, these steels are quenched from intercritical temperatures after a globulization stage, so the obtained structure is indeed softer than the eutectoid quenched structure–, whose brittleness and strength both excel. To get a tougher structure, with better mechanical properties, the tempering process breaks these martensite needles in a finely dispersed cloud of carbides that merge with the globules of martensite formed before quenching (figure 5). This last structure is typically not resolvable through optical microscopy, but its coalescence, if the tempering stage is too long, is distinguishable (figure 6).

Temper after quenching is required to reduce the brittleness of the martensite. In this case, the temper process must be long enough, as a diffusive process, to guarantee that the retained austenite does not spontaneously transform –so the structure would furtherly evolve and the dimensions of the gauge block...

Figure 4. (a) 100 mm steel gauge block presenting a very high drift over 19 years. (b) 900 mm steel gauge block presenting a typical drift over 25 years. (c) 1000 mm steel gauge block presenting no significant drift over 33 years.
would vary— but it cannot exceed the time of carbide coalescence, after which the homogeneity and dimensional stability sink.

Figure 5. Tempered martensite structure of a properly treated gauge block (100x).

Figure 6. Over-tempered martensite structure of a non-properly treated gauge block (100x); the globular carbides are spottable.

4. Conclusions
Dimensional stability is highly related to the material properties. Phase changes and internal tensions affect to the measurement and could also make the gauge block go out of range, increasing the uncertainty of the measurement.

In this document, authors present an statistical method for the estimation of the dimensional stability of gauge blocks using the calibration history of samples from the main manufacturers. In addition, it has been observed the metal structure of the samples. It can be concluded that the evolution of the dimensional stability of these gauge blocks is closely related to the tempering process. Depending on the conditions of this thermal processing, the structure of the gauge blocks can change during its service life. This way, statistical procedures can help calibration laboratories to estimate how long its calibration interval could be, how long a gauge block can be used and, approximately, when it should be withdrawn.

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