Gage Blocks

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UNITED STATES DEPARTMENT OF COMMERCE • Sinclair Weeks, *Secretary*
NATIONAL BUREAU OF STANDARDS • A. V. Astin, *Director*

Metrology of Gage Blocks

Proceedings of a Symposium on Gage Blocks
Held at NBS on August 11 and 12, 1955

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Foreword

A major function of the National Bureau of Standards as set forth in the Act of Congress, March 3, 1901 and amended by Congress in Public Law 619, 1950 is the development and maintenance of the national standards of measurement. As custodian of our national standard of length the Bureau is obligated to calibrate secondary standards of length for other Government agencies, State governments, and industry. By far the most widely used precise standards of length in mechanical industry are precision gage blocks which by virtue of their accuracy, range of sizes, and relatively low cost have made precise standards of length available to even the smallest units of industry. Probably more than any other single development, the availability of such precise standards has made possible the mass production of interchangeable industrial components of the vast array of mechanical devices which have so greatly enhanced our standard of living in this century.

There exists a need to meet even more adequately some of the more critical requirements in the manufacture of industrial components. The Symposium on Gage Blocks was held to permit the exchange of ideas between the National Bureau of Standards and manufacturers and users of gage blocks in the hope that it might be possible to develop better techniques for their manufacture and use.

A. V. Astin, *Director*,
National Bureau of Standards.

Preface

The Symposium on Gage Blocks was held at the National Bureau of Standards on August 11 and 12, 1955 under the auspices of the Engineering Metrology Section of the Optics and Metrology Division.

Two sessions, at which fifteen papers were presented, were held. About ninety people attended the sessions.

Three papers dealt with the metallurgical and physical properties of gage block materials, with particular reference to dimensional stability. Another paper considered the characteristics of gage-block measuring surfaces, such as average roughness, depth of individual scratches, and condition of edges.

The present state of the art of applying light waves as standards of length is such that optical interference methods have attained supremacy in the accurate determination of length of contact length standards such as gage blocks. Accordingly, six papers dealt with the application of interferometry to gage blocks, conditions affecting the accuracy of interferometric measurements, and the precision and accuracy attained in recent comparative length measurements by different laboratories. Two other papers were on recent improved interferometer designs.

The four concluding papers, as well as two formal discussions and an informal discussion period, were concerned with the development of commercial and government standards and specifications for gage blocks. Consideration was given to procedures for the surveillance of gage blocks after they have been in use.

Irvin H. Fullmer, *Chief*,
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Contents

1. Precise Interferometric Measurement of Gage Blocks

By E. Engelhard [1]

The purpose of this report is to give a survey of the work of the Physikalisch-Technische Bundesanstalt (PTB) and the former Physikalisch-Technische Reichsanstalt (PTR) concerning length measurements based on light waves, and some suggestions on how to avoid errors which, according to our experiences, occasionally occur with this technique.

I shall start with a brief historical introduction. Length measurement by light waves was started in Germany by Kösters [2] nearly 40 years ago, but it should be remembered that Michelson, in his famous determination of the length of the meter with wavelengths of the red cadmium line, ingeniously anticipated the most important elements of practical length measurement by means of light waves.

Now, more than 60 years later, the most precise length measurements are made by means of light waves, although the meter and the yard, strictly speaking, are defined by a metal bar. This can be done by virtue of a resolution of the Seventh General Conference for Weights and Measures in 1927 stating the relation between the wavelength of the red cadmium line and the meter prototype.

The special significance of the light-wave technique for length measurement is founded on the well-known principal features of a light-wave scale, its indestructible and unchangeable character and its natural, very fine and accurate graduation. The most decisive attribute is that everyone, particularly the engineer, can make use of it as a practical standard of length. Thus the great progress in manufacturing modern industrial gage blocks would have been impossible without the technique of length measurement by light waves.

In order to explain the essential features of the technique of length measurement by means of light waves, reference is made to figure 1 which illustrates a very simple, well-known apparatus which was designed by Kösters more than 30 years ago and manufactured by Carl Zeiss. This instrument is generally used in Germany for measurement of gage blocks up to about 100 mm in length. This apparatus includes a monochromator having a collimator consisting of the slit C and the lens O, which makes light from C parallel. The dispersion prism Pr separates the light into beams of different wavelengths which are focused by the lens O_2, on the slit B, after reflection from several mirrors, Pl, S_1, P, and S_2. This apparatus provides a light-wave scale for the measurement of gage blocks in the following manner: The parallel monochromatic beams coming from Pr pass through the beam-dividing glass plate Pl to the mirrors S_2 and P,

[1] Physikalisch-Technische Bundesanstalt, Braunschweig, Germany.

[2] W. Kösters, Prüfung von Johansson-Endmassen mit Lichtinterferenz. Feinmechanik (Präzision) 1, 2–5, 1920; 39–41, 1922.

which represent the measuring surfaces of a gage block. Light is also partially reflected from Pl to the mirror S_1. An observer looking through the slit B sees the image of the gage block PS_2 superimposed on the image of mirror S_1. The mirror S_1 is imaged at R between the two parallel measuring surfaces of the gage block PS_2. If PS_2 is somewhat inclined with respect to S_1 by the screws below the plate P, two wedges are formed, one built up by S_2 and R and the other

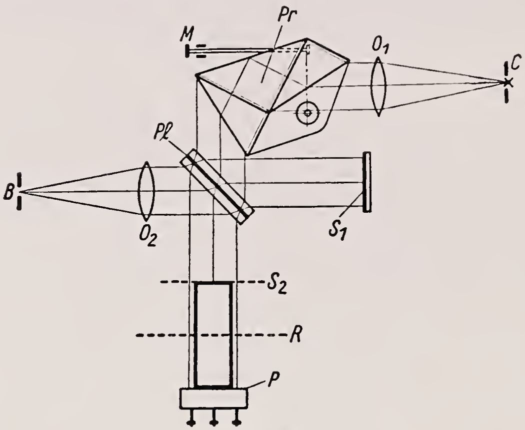

FIGURE 1.

by P and R. In this manner the length of the gage block PS_2 is divided into the thicknesses of two wedges.

If monochromatic light is incident on such a wedge, the well-known interference fringes of equal thickness, so-called because every fringe represents points of the same thickness, are observed. At the apex of such an interference wedge is a fringe of the order 0, the next fringe of the order 1 indicates a thickness of $\lambda/2$, the fringe of the order 2 marks the thickness $2\lambda/2$ and so on, λ representing the wave-

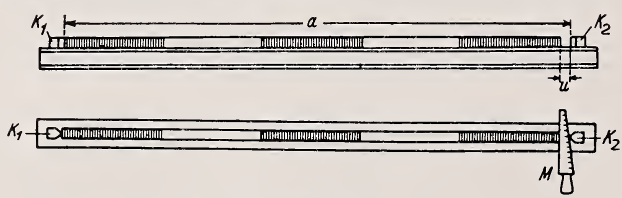

FIGURE 2.

length of the light wave. In general, the fringe of the order n corresponds to a thickness of $n\lambda/2$: The interference wedge resembles very closely the common measuring wedge used in ordinary length measurement for the determination of distances as shown in figure 2. This figure demonstrates the measurement of a surveyor's pole. The distance u between the fixed contact K_2 and the end of the pole is indicated as shown in figure 2 by a wedge graduated with lines on one face. Such a wedge is a very simple instrument for obtaining amplification in length measurement. If the amplification which depends on the angle of the wedge, is, for instance, 1: 10, a graduation in millimeters allows one to read a tenth directly and to estimate a hundredth millimeter. In the same manner the interference wedge enables us to measure distances, but its graduation is much finer, the discrimination being half a wavelength, i. e., approximately 0.25 μ (0.00001 in.). Its amplification is much higher, in the same degree as the graduation is finer. Its graduation lines, unfortunately, are not numbered, which causes some complications.

The field seen by the observer viewing through the slit of this gage-block interferometer is as shown in figure 3. One observes two interference wedges side by side, established as pointed out by the images of the measuring surfaces of the gage block and the reference mirror. If the interference fringes were numbered like the graduation lines on the common measuring wedge, then the numbers as indicated by each wedge would need only to be added. The fraction between the two sets of fringes should, of course, be included. As the fringes are not numbered, it becomes necessary to determine the order of the fringes. To overcome this difficulty in practice two operations

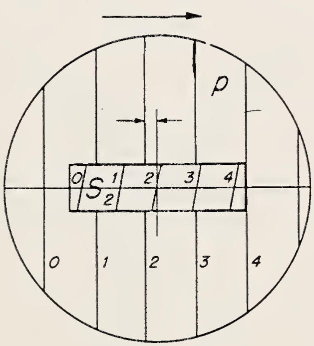

FIGURE 3.

are usually performed. First, a preliminary determination of an approximate value of the length in question is made by comparing the gage block with a known length standard, for instance, by means of mechanical equipment. Therefrom one obtains a probable value of the order within the accuracy of the mechanical comparison of gages, i. e., within a few units of the order of interference. Second, a determination is made of the fractional orders observed with different wavelengths and therefrom the exact value of the order is found by the method of coincidences. Because the latter procedure is somewhat complicated, present practice at the PTB is, in general, to increase the accuracy of the preliminary determination of length of a gage block to such a degree, that the order of interference is known with certainty by the approximate value only.

The method used to reach the necessary accuracy in determining approximate values of the gage blocks is based on interference in white light. In light-wave measurement white light plays a special part by indicating in a striking manner the zero order by means of the so-called achromatic fringe. Thus, the interference fringes in white light are very well adapted to the measurement of the small differences in length which occur in the comparison of gage blocks of equal nominal length.

An essential detail of the apparatus we use for comparing gage blocks by means of interference in white light is the double prism designed by Kösters (fig. 4).

Figure 4 shows the cross section of this double prism as an equilateral triangle ABC. The double prism is cut into two completely symmetrical prisms of 30°, ABD and ACD, which are cemented together with oil along the semimirrored surface AD. A beam incident normally on the surface AB from the left is divided into two beams of equal intensity at the partially coated surface AD. Both partial beams leave the prism after total internal reflection on the surfaces AB and AC in a direction perpendicular to the base surface BC. Suppose a mirror F_1 F_2 is adjusted nearly perpendicular to the beams. Then both beams are reflected by the mirror F_1 F_2 and sent back to the prism. After another total reflection on AB and AC, respectively, one beam is transmitted through and the other reflected by the semimirrored surface AD, both reaching the observer's eye on the right.

In principle, the prism represents a system of well-adjusted plane mirrors AD, AB, and AC imaging the point J_1 on the point J_2 or

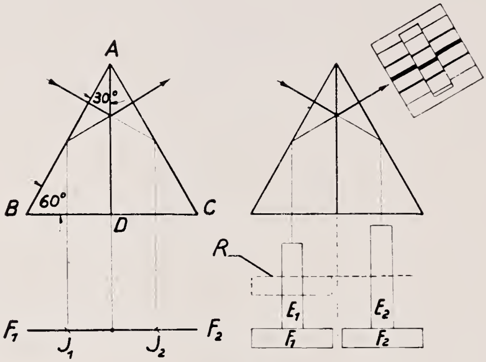

FIGURE 4.

vice versa. Therefore, if two nearly equal gage blocks, wrung to the surfaces F_1 and F_2, are slightly inclined one to the other as shown on the right, the prism forms two interference wedges by superimposing the images of corresponding surfaces of the gage blocks and the two projecting lower surfaces F_1 F_2. If the difference in length of the gage blocks is small enough, interference fringes are visible in white light, the achromatic fringe indicating the zero order or zero thickness of each wedge. Thus, the displacement of the achromatic fringes on both interference wedges corresponds to the length difference of the gage blocks. If one of the two gage blocks, for instance E_1, is replaced by a mirror, as shown in figure 4, the other gage block may be measured in monochromatic light in the usual manner. The prism forms an image of the mirror between the parallel surfaces of the gage block E_2 and thus, as pointed out before, divides the length of E_2 into the thicknesses of two wedges if the mirror is slightly inclined to the surfaces of the gage block. It makes no difference whether the inclination between the images of the reference mirror and the gage block faces is obtained by inclining the mirror or the gage block or by inclining one-half of the double prism with respect to the other half.

Figure 5 represents an apparatus used at the PTB for the comparison of gage blocks by means of the double prism. The two gage blocks to be compared are wrung on a single plate, the interference wedge being permanently adjusted by inclining the halves of the double prism. A collimator on the right makes beams of white light parallel. The fringes are observed in the usual manner through a slit on the left. The shift of the fringes, i. e., the difference in length of the gage blocks, is very precisely determined by means of an achromatic glass compensator indicating directly the difference in thousandths of a micron (0.04 μin.). The accuracy in comparing gage blocks with this apparatus is at least $\pm 0.01\ \mu$ (0.4 μin.). This accuracy is high enough for exact determination of the order of interference. Therefore, in measuring absolutely the length of the gage block in question by means of monochromatic light it is sufficient to determine the fraction in one color only, for example, in cadmium red, which is done by means of the glass compensator after removing the known gage block. In this way, very accurate absolute values

FIGURE 5.

for gage blocks up to 100 mm (4 in.) in length are obtained in a short time with an accuracy of the order $\pm 0.01\ \mu$ (0.4 μin.).

When longer gage blocks are measured by this method difficulty arises because of the effect of air. Until now, it has not been mentioned in this paper that the wavelength of light depends on the conditions of the atmosphere. Our primary length standard is the wavelength of the red cadmium line which is defined in dry air of 15° C and 760 mm Hg. Therefore, all length measurements by means of light waves usually are reduced to standard conditions by calculated corrections based upon the value of the refraction of air. This requires an accurate measurement of the temperature, barometric pressure, and moisture content of the ambient air. In general, this cannot be done with high accuracy and, therefore, the uncertainty of the corrections due to the refraction of air is somewhat high for gage blocks much over 100 mm (4 in.) in length.

For this reason Kösters designed an apparatus for the measurement of gage blocks up to 1 m in length, with which it is possible to eliminate the influence of air completely. This apparatus is used in the PTB for the most precise measurements of industrial gage blocks, the highest possible accuracy being about $\pm 0.01\ \mu$/m. The simplest method of eliminating the influence of air is to make the measurements in vacuum. But it is not feasible to place the blocks in a vacuum, because they would become longer as the atmospheric pressure was removed and corrections depending on the elasticity of the gage blocks would be necessary. Therefore, the effect of the air is eliminated in the method introduced by Kösters by determining it experimentally using a vacuum chamber for this purpose.

Figure 6 represents the scheme of the PTB apparatus for light-wave measurement of gage blocks up to 1–m length. An essential feature of this apparatus is once more the use of a double prism, forming an image of the reference mirror R between the surfaces M of the gage block E, and dividing the length of the gage block into two wedges. Viewed through the slit B two interference wedges, formed by the faces of the gage block and the reference mirror, are seen if monochromatic light is used for illumination. Another essential feature of this

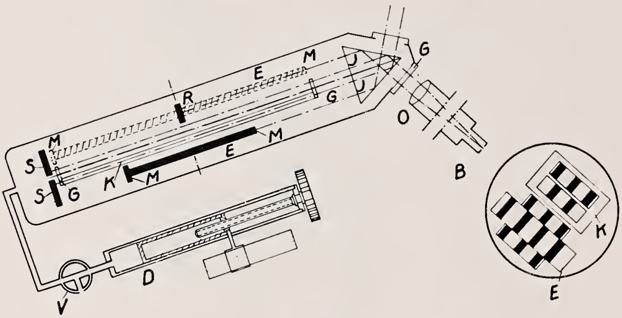

FIGURE 6.

B, Viewing aperture; D, piston and cylinder; E, gage block; G, glass plate; J, double prism; K, vacuum chamber; M, measuring surface; O, objective lens; R, reference flat; S, mirrors; V, valve.

apparatus is the use of a vacuum chamber for the elimination of the refraction of air. The vacuum chamber in its simplest form is an iron tube of rectangular cross section, 1 m in length, closed at both ends with plane-parallel glass plates so that it can be evacuated with a small high-vacuum pump. If this chamber is removed, the double prism images both mirrors S, one on the other, and if one mirror is inclined with respect to the other an interference wedge of nearly zero thickness arises. Introduction of the chamber into one beam, but with the end plates extending into the other beam does not modify the wedge in any manner unless it is evacuated. If it is evacuated, light in the chamber travels faster and the wavelengths become longer. Assume the wavelength in air is λ and in vacuum λ_0, the index of refraction of the air n is then defined by $n = \lambda_0/\lambda$. Then the number of wavelengths for light passing to and fro in the chamber of 1–m length is $1: \lambda_0/2$ or $2/\lambda_0$ if the chamber is evacuated, and $2/\lambda = 2/\lambda_0\, n$ if not, the difference between the unevacuated and the evacuated chamber being $2\ (n-1)/\lambda_0$.

When the chamber is evacuated an observer looking through the slit B has no idea that the wavelength in the vacuum chamber is changed, so he has the impression that the thickness of the wedge formed by the mirrors S has changed across the field covered by the evacuated part of the chamber, the change in the order of interference being equal to $2(n-1)/\lambda_0$. Consequently, an observer has a view as illustrated in the inset of figure 6. In addition to the two wedges corresponding to the gage block length in air on the left, at E, there are two wedges referring to the chamber, one wedge representing the unchanged thickness in air, being zero or nearly zero as given by the position of the mirrors S, and another wedge representing the thickness of the same wedge apparently changed by evacuating the chamber. If the fringes in both wedges were numbered, then the difference of the orders equal to $2(n-1)/\lambda_0$ could be immediately read from the wedges. Remember that the order of interference for a gage block of 1-m length in air is $z=2/\lambda$ or $z=2n/\lambda_0$ and that the order for the same gage block in vacuum is $z_0=2/\lambda_0$. Therefore, if the order $2(n-1)/\lambda_0$ as given by the chamber is deducted from the order of interference $2n/\lambda_0$, corresponding to the gage block in air, the order of interference corresponding to the gage in vacuum z_0 is obtained by the equation

$$\frac{2}{\lambda_0}n-\frac{2}{\lambda_0}(n-1)=\frac{2}{\lambda_0}=z_0.$$

Thus, the order of interference for a gage block of 1-m length in vacuum is obtained, without putting the gage block in vacuum, by deducting the order of interference indicated by the vacuum chamber from the order indicated by the gage block in air.

If the length of the gage block is not 1 m, but, let us say, 500 mm, the order indicated by the chamber of 1-m length must be reduced by dividing it by two.

In practice it is not feasible to measure gage blocks over 700 mm in length by this procedure. Measurement of blocks from 700 mm to 1,000 mm (1 m) is made in two steps, the first step being the measurement of a 500 mm gage block and the second step being the measurement of the difference in the lengths of the 500 mm and the longer gage block.

To simplify the method for the elimination of the air refraction the whole interference arrangement is fitted in a box which may be closed. The enclosure is connected to a piston D, which allows the volume of the sealed box to be varied. The piston can be moved to and fro in a cylinder by means of a spindle. Thus, the density of the air in the enclosure and hence the wavelength of light, which depends on the density of air, can be altered by compression or expansion, and the excess fraction or the fractional fringe displacement observed on the gage block can be adjusted to zero.

A scale is attached to the piston. In order to obtain the order of fringes referring to the length of the gage block in vacuum, a number that is read on the scale is deducted from the number of fringes corresponding to the length of the gage block in air, this last number being an integer because the fraction is adjusted to zero. So the decimal complement of the fraction read on the scale represents directly the fraction for the gage block in vacuum.

The graduation of the scale on the piston could in principle be obtained in the following manner: the chamber is filled with air and then slowly evacuated; hereby the number of the passing fringes in cadmium red is counted. This gives some number, let us say 843.92. After sealing the enclosure, the air contained therein is compressed by the piston until a whole number of fringes in the chamber is observed, the fraction in the field of the chamber being zero. This must be the 844th fringe. Then the position of the index on the scale is marked 844 and the piston is moved until the 845th or the 843d fringe is observed, and so on. The same method can be applied to cadmium green, blue, and other colors. In practice the scale is calculated, but it should be kept in mind that no known values of the refraction are necessary.

The scale does not cover the full range of wavelengths from vacuum to ambient conditions but only the range of wavelengths corresponding to the barometric pressure and temperature likely to be encountered in the measurement of gage blocks. With the valve, V, open there obviously is no relation between the scale reading and the difference in the number of wavelengths per meter in vacuum and for ambient conditions. The method of alining the scale is as follows:

The gage block to be measured is placed in the enclosure. The enclosure is then filled with dried air at ambient atmospheric pressure. After temperature equilibrium of the equipment has been reached the ambient barometric pressure B and temperature t are approximately determined. If, for example, the barometric pressure is 749.7 mm and the temperature 20.1° C, an assumed number of cadmium red fringes may be computed from the formula

$$z=z_{(760\text{ mm }20^\circ\text{ C})}\frac{1+\alpha 20}{1+\alpha t}\,\frac{B}{760},$$

where $\alpha=0.00367$ and $z_{(760\text{ mm }20^\circ\text{ C})}\approx 843.9/\text{m}$.

Substituting the assumed values of B and t in this formula, $z=832.2$.

The valve is opened for a short time immediately after determining z so that the chamber and the cylinder are open to the outside air. The piston is moved so that the scale for cadmium red reads 832.2. The valve is then turned so that the piston and enclosure are connected and both closed to the outside air.

The dispersion prism is adjusted for cadmium red and the fringe system associated with the vacuum chamber is adjusted horizontal by rotation of the double prisms by means of a hydraulic fine adjustment. The piston is moved in one direction or the other until a whole order is indicated for the vacuum chamber. By moving the scale in the appropriate direction the index is alined with number 832.00 or 833.00.

Changing to cadmium green the piston is moved so that a whole order is indicated in the vacuum chamber pattern. In this position the index should coincide with a whole number on the green scale such as 1062.00. If this is conspicuously not the case, the scale is moved one order right or left in cadmium red and the fringe pattern for cadmium green again checked for coincidence. The index should also align with whole numbers, for example, 1129.00, 830.00, and 952.00, respectively, on the cadmium blue, krypton red, and krypton yellow-green scales when the fringe patterns are brought into coincidence. Then the index, for any position of the piston, indicates the correct number of fringes corresponding to an air column 1 m long.

If the enclosure is subsequently opened, the position of the scale is incorrect and must be readjusted.

Measurement of a long gage block, 500 mm for example, is made in the following manner:

After the gage block with a steel flat wrung to one end has been inserted in the enclosure and the equipment has come to temperature equilibrium, the scale is adjusted as previously described. The temperature of the block is then measured. The dispersion prism is set for krypton red and the fringe pattern of the gage block is appropriately oriented with a hydraulic fine adjustment. The piston is advanced until the fringe pattern formed by the reference mirror and the gage block coincide. The reading of the index on the krypton red scale is noted. A similar reading is made using krypton yellow-green. The temperature of the gage block is read a second time. The values of the index on the scale are multiplied by 0.50000 for a 500-mm block. The decimal complements of the vacuum fractions are converted to units of length. With the aid of a table of nominal excess fractions for krypton red and yellow-green the nearest coincidence is found. The value obtained with the krypton yellow-green

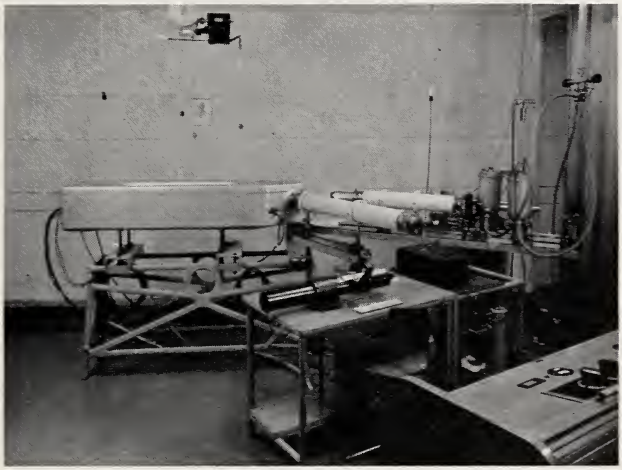

FIGURE 7.

is used as the length of the gage block because of the superior quality of this line.

It should be noted that the measurement of barometric pressure and air temperature for the alinement of the scale in no way signifies that the index of air must be accurately known as these data serve only to give an approximate index of refraction.

Figure 7 is a view of the complete equipment of the PTB for the measurement of gage blocks up to 1 m by means of wavelengths in vacuum. The thick-walled, airtight, aluminium enclosure covered with cork for thermal insulation is seen on the left. On the observer's table, in the middle ground, the piston is mounted, the scale on the piston being read by means of an eyepiece. A telescope of long focal length with an autocollimating eyepiece is needed for the observation of the fringes. On the right, in the background, the lamp houses for the lamps and a collimator with a powerful dispersion prism system are positioned. A small high-vacuum pump to evacuate the vacuum chamber is located at the side of the observer's table.

Figure 8 shows the opened chamber. The double prism is located at the left; the vacuum chamber is located along the middle axis of the trough; the reference mirrors for the chamber are on the right; a 500-mm block with an auxiliary steel plate wrung to it is on the side of the chamber; and the reference mirror for the measurement of the gage block is on the other side. All necessary adjustments are made from the outside by hydraulic controls.

Figure 9 is a view of the scale on the piston with the index indicating the fringes referring to the refraction of air. There are five graduated scales corresponding to five colors.

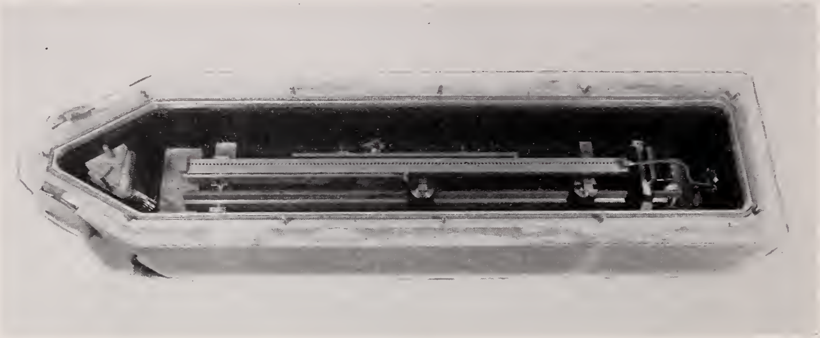

Figure 8.

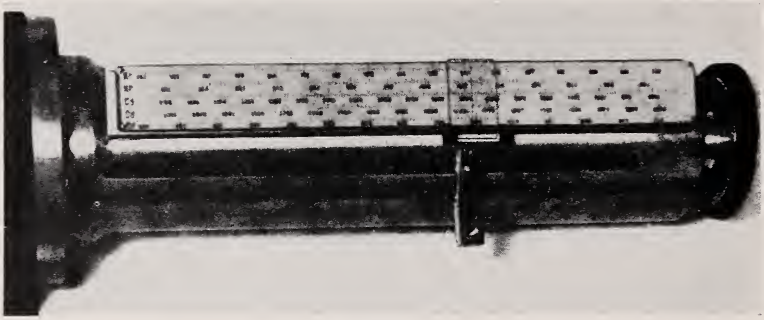

Figure 9.

This apparatus was designed by Kösters more than 20 years ago. It is unique at present but a new instrument, taking into account the experiences of the past 20 years, is now under construction at Carl Zeiss in Western Germany. It will be available in about 2 years. This apparatus will presumably play an important part in the future, because it makes possible the measurement of gage blocks to a very high accuracy by means of wavelengths in vacuum. This will be essential in the future, as the primary standard of length will probably be a wavelength of light in vacuum.

Another instrument designed by Kösters, quite similar in principle, but especially designed for the measurement of gage blocks up to 100 mm was built by Zeiss. Several of these instruments were completed at the end of the war but were dismantled by the Russians. This apparatus is now under construction in Germany and it is expected that it will become the most suitable equipment for the measurement of industrial gage blocks up to 100 mm, especially for the use of gage-block manufacturers.

The maximum accuracy required for the apparatus described in the foregoing is of the order $\pm 0.01\ \mu$ (0.4 μin.). Naturally, this implies that all uncertainties must be reduced to a minimum. The degree of uncertainty in the measurements made by laboratories of a number of countries is illustrated by an international comparison of gage blocks organizied by the BIPM (International Bureau for Weights and Measures) some time ago. The differences among the results of several official institutions and the BIPM were found to be about $\pm 0.05\ \mu$ (2 μin.). Inquiring into the reasons for these differences which considerably exceed the accuracy possible using the wavelength measurement technique, one finds repeatedly the same sources of error.

The most common error is due to the uncertainty in the measurement of temperature. The thermal coefficient of steel commonly used

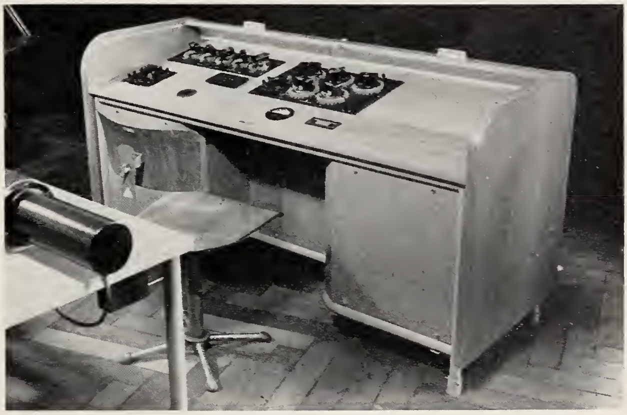

FIGURE 10.

for gage blocks, is about 10μ/m/deg C. This means the uncertainty in the measurement of temperature should be less than ± 0.01 deg if the required accuracy in length is $\pm 0.01\ \mu$ for a gage block 100 mm long. To place a mercury thermometer near the gage block is quite inadequate in this case. According to our experiences, the simplest and best method to obtain higher accuracy in measuring temperature by means of Hg-thermometers is to place a large metal block near the apparatus, the thermometer being placed in a bore of the metal block and the difference of temperature between the metal block and the gage block being determined by thermocouples. Naturally, the thermometers must be calibrated from time to time. Temperature measurements accurate to ± 0.02 deg C can be obtained in this manner. This corresponds to $\pm 0.02\ \mu$ for 100 mm or 0.2 μ for 1-m length. If higher precision is required, a platinum-resistance thermometer is used at the PTB, the difference in temperature between the platinum-resistance thermometer and gage block being determined by one or more thermocouples. Equipment for electrical measurement of temperature by means of a platinum-resistance thermometer is shown in figure 10. An electrical potentiometer, used to measure the electromotive forces of the platinum-resistance thermometer and the thermocouples, is shown in the center of the table. A galvanometer of high sensitivity is mounted inside the table. From time to time, i. e., several times a year and at least before every important length measurement, the platinum-resistance thermometer is checked in the usual manner by determining the triple-point of water. The uncertainty in determining this temperature usually is not greater than ± 0.0005 deg C. For a single measurement near 20 deg C the uncertainty is about ± 0.002 deg C and thus the mean value for two or more single values is accurate to nearly ± 0.001 deg C, which corresponds to an error in length of ± 0.01 μ/m.

Next to temperature the refraction of air is the most important source of error in length measurements based on light-waves. A method has previously been described to avoid this error by elimination of the refraction of air. If that is not feasible, an accurate barometer which has been checked under all conditions and calibrated periodically should be used. An error in barometric pressure of ± 0.2 mm Hg corresponds to an uncertainty in length of nearly ± 0.05 μ/m.

Other common sources of error originate in the properties of the interference wedge generally used for length measurement by light waves. Such an error arises from the inevitable inclination of the interference wedges and is equivalent to the well-known inclination error in length measurement. Inclination errors arise in length measurement, for example, if two gage blocks or two scales being compared are inclined relative to each other. In these cases the result of the length measurement is $L \cos \varphi$ instead of L, L being the real length, φ being the angle of inclination. If φ is very small, $L \cos \varphi$ is nearly equal to $L[1-(\varphi^2/2)]$, the error in length due to inclination being $-L(\varphi^2/2)$. This is the well-known second order inclination error which also arises in measuring length by interference wedges. The condition for elimination of the inclination error consequently is $\varphi=0$, meaning in practice that the observer's slit must be so adjusted that one looks exactly perpendicularily at the interference wedge. This is commonly done by means of an autocollimating eyepiece, which is quite essential for such apparatus. If the observer's slit deviates by the distance r from the normal direction, φ becomes equal to r/f, f being the focal length of the objective lens (see fig. 6). The inclination error, therefore, is $(-Lr^2)/(2f^2)$. Assume r to be 1 mm and f about 400 mm, then the error for a 100-mm gage block would be $-100/2\times 160{,}000$ or nearly equal to -0.3 μ (1.2 μin.). This indicates that the interference wedge or, in practice, the gage block surface must be exactly adjusted perpendicular to the light beams.

Strictly speaking this adjustment cannot be exactly accomplished for all beams reaching the observer's eye. Due to the finite size of the observer's slit there are also visible beams reflected in directions making an angle φ with the perpendicular beam. Thus most beams, except the central beam perpendicularly incident, give rise to an inclination error $-L$ $(\varphi^2/2)$ and by superposition of all beams of different inclinations coming through the observer's slit a lack of sharpness of the fringes results, increasing to such a degree that the fringes may disappear entirely if large slits are used. In addition a general shift of the fringes or an error in length occurs. It is very easy to calculate that this error for a circular slit is given by the expression:

$$e=-L\frac{D^2}{16f^2},$$

L being the length of gage block being measured, D the diameter of the circular slit, and f the focal length of the objective lens. For a rectangular slit, the error is given by

$$e=-L\frac{b^2+h^2}{24f^2},$$

b and h being the breadth and the height, respectively, of the rectangular slit. To compensate for this error, a plus correction of the same amount must be made. This correction is often neglected, but assuming the breadth and the height of a rectangular slit to be 2 and 0.5 mm, respectively, and the focal length 400 mm, the correction would be

$$-e=+L\frac{0.5^2+2^2}{24\times 400^2}\sim +L\times 10^{-6},$$

hence the correction in measuring a gage block of about 100 mm is nearly +0.1 μ (4 μ in.). Therefore, a slit as small as possible should be used not only to avoid errors due to fringe shift but also to avoid loss of fringe sharpness. A circular slit 0.5 mm in diameter should be sufficient as the correction for this slit does not exceed about +0.01 μ for a 100-mm gage block when a focal length of 400 mm is used.

Another error may arise when measuring gage blocks by light waves in consequence of the definition of the length of a gage block. According to a recommendation of the ISA (International Standards Association) the length of a gage block is defined by the distance of one surface of the gage block from the surface of an auxiliary plate wrung to the other surface of the gage block, the plate having the same surface finish as the gage block. Corrections must be made if these conditions are not fulfilled. Occasionally gage blocks made of steel are wrung to plates of glass or quartz in order to judge, by viewing through the plates, whether the gage blocks are wrung completely. With glass or quartz plates errors arise due to the difference of the phase change of light. If light waves are reflected from a surface, they suffer a change in phase as if the plane of reflection were not identical with the mechanical surface. There is a difference in the optical properties of glass or quartz and steel, the first two being insulators and the last an electrical conductor. From optics it is well known that the phase change on insulators is π and on metals $\pi-\epsilon$, π corresponding to $\lambda/2$ in phase or $\lambda/4$ if interpreted in terms of the length of a gage block. Therefore, $\pi-\epsilon$, being the phase change on a metal such as steel, corresponds to a length of $\lambda(1-\epsilon/\pi)/4$, ϵ being a material constant, depending in general on the color. Hence it is easy to see that gage blocks measured by light waves seem to be too short by $\lambda\epsilon/4\pi$ when wrung on an insulating plate such as glass or quartz. At the PTB we have determined this value in different ways and have found it to be very nearly −0.018 μ for all colors.

If we measure a gage block wrung to glass or quartz we use a correction of $+0.018\ \mu$ ($0.7\ \mu$in.).

A further correction related to the surface quality, i. e., to the roughness, is applied at the PTB to all measurements of gage blocks by light waves. Assume the value of roughness for the surface of the gage block to be ρ_1, and for the surface of the auxiliary plane wrung to the gage block ρ_2, the error in length would be $-(\rho_1-\rho_2)$ and a correction by $+(\rho_1-\rho_2)$ would be necessary. Naturally the value of roughness ρ cannot be any of the usual units of roughness, for example, root mean square. We have determined the values in question in different ways, for example, in the following manner (fig. 11). Assume three gage blocks of different roughness are

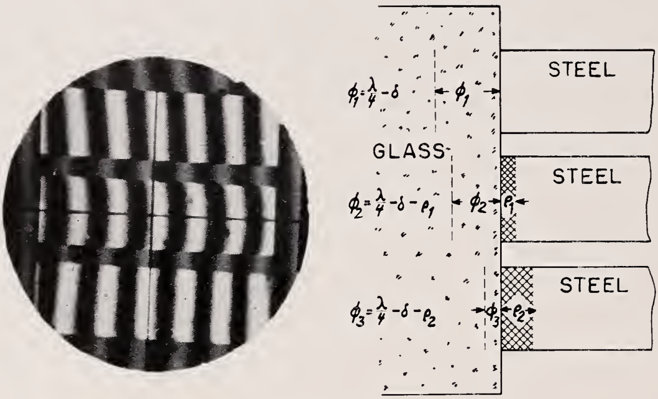

FIGURE 11.

wrung on a glass plate and an interference wedge is formed by the glass surface to which the gage blocks are wrung and a virtual image of a suitably located real mirror. This can be done by means of a Kösters interferometer, the only difference between this arrangement and an ordinary gage block measurement being that the gage block surface wrung to the plate is viewed through the plate. On the left of figure 11 the field of view to be observed in this case is shown. The upper field on the left represents a gage block surface of the highest possible finish; the shift of the fringes on the gage block surface relative to the fringes on the plate corresponds to the phase change on a steel surface of only $\psi_1 = \lambda/4 - \delta$. The middle field and the lower field refer to gage block surfaces of roughness ρ_1, and ρ_2, respectively. The fringes on the steel surfaces are shifted to the left by ρ_1 and ρ_2 with respect to the position in the upper field. Hence, the values for ρ_1 and ρ_2 can be easily determined.

If many gage blocks are to be measured, it is not practical to determine the roughness in this way. Therefore, we have developed a method for the determination of the roughness correction by measurement of the light scattered by the gage block surfaces. The design of the apparatus used for this purpose is shown by figure 12. The apparatus consists mainly of an Ulbrichts' sphere which is commonly used for measurement of light flux. From an objective lens a slightly convergent flux of white light is transmitted into the sphere through a hole. Light is reflected from the surface of a gage block placed in another small circular hole of the sphere. Specularly reflected light leaves the sphere by a third hole. Scattered light R_d is integrated by the Ulbrichts' sphere and measured by means of a photoelectric cell. If the hole at the bottom is closed by a flap, the total amount of

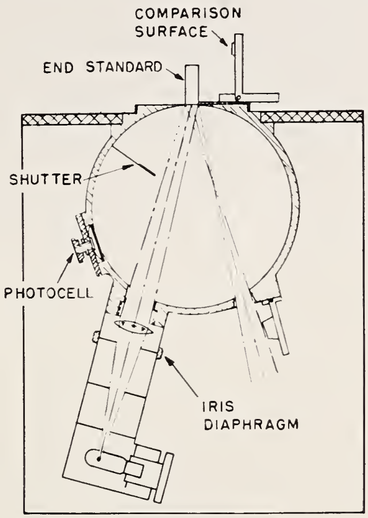

FIGURE 12.

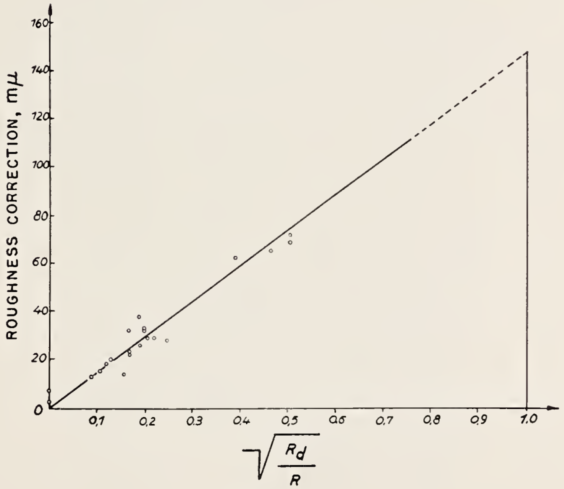

FIGURE 13.

reflected light R, both specularly reflected and scattered light, is indicated by the photoelectric cell. In this manner we measured a number of gage block surfaces. The roughness corrections for the same surfaces were determined by interference measurements. In comparing the results we found a simple relationship between the reflection measurements and the values of roughness (fig. 13). The abscissa represents the values $\sqrt{R_d/R}$, R_d being the scattered and

R the total reflected light as measured by the Ulbrichts' sphere. The ordinate represents the values of roughness in millimicrons as determined by interference. The curve indicates that there seems to be a linear relationship with the deviations from linearity being less than about 10mμ. Thus, it seems possible to determine the roughness corrections by measurement of the ratio of light scattered to that specularly reflected from the gage-block surfaces. The surfaces of every gage block measured by means of light waves are checked in this manner, the roughness correction being read off directly from the scale of a galvanometer indicating the photoelectric current. Thus, we get corrections due to roughness in a very short time. The total range of the observed roughness correction is, in practice, nearly 0.1 μ (4μin.). Even for the same manufacturer a range of 0.05 μ is found in some cases. This indicates that corrections for roughness are very essential, if an accuracy in length measurement approaching ± 0.01 μ is required.

Having discussed errors associated with external influences such as temperature and the conditions of air and with the optical conditions such as inclination, aperture correction, phase change, and roughness, we still need to consider the part played by the lamps which are essential to the formation of light-wave scales as represented by interference wedges. The question is, in what degree or in what manner are light-wave scales influenced by the characteristics of the lamps? At the PTB a great deal of the metrological work is concerned with this task, but time will not permit a discussion of the details.

Nearly 80 years after Michelson started his famous investigations of light-wave scales, spectroscopists and metrologists have reached an understanding of certain deficiencies of light-wave scales.

There are two essential characteristics to be considered. First, there is an immense number of wavelengths obtained from lamps because they are produced by an aggregate of atoms, each being in motion relative to the observer and each interacting with the others.

Second, the materials—gases or vapors—which are electrically excited in the lamps, are, in general, not homogeneous with regard to nuclear structure. Most of the materials used for light emission in lamps are mixtures of isotopes, the light-waves being modified by their different nuclear structures.

Therefore the following conditions for establishing light-wave scales of highest accuracy are desired:

First, low temperature and high mass of the light emitting atoms to meet the requirement that the atoms be as nearly at rest as possible.

Second, low pressure of the gas or vapor in the lamps and absence of external electric or magnetic fields, to meet the requirement that the emitting atoms be uninfluenced by secondary disturbances.

Third, the use of gases or vapors consisting of a single isotope of even mass only, in order to reduce errors of subdivision.

In the United States a lamp filled with mercury isotope 198 and excited by high-frequency voltage has been developed which fulfills these conditions very well. At the PTB we have designed a Geissler hot cathode type of lamp filled with krypton isotope 84 or 86 (fig. 14). The lamp is cooled with liquid air to the triple point of nitrogen, i. e., 63° K. For this purpose we use an airtight metal container. Figure 15 shows the container with the cover to which the lamp is fastened. A Dewar vessel is placed in the container. After having closed the container with the cover and having filled the Dewar vessel with liquid air (fig. 16) the container is connected to a vacuum pump to lower the pressure of the liquid air in the Dewar vessel (fig. 17). The triple point of nitrogen is reached in this manner in a short time. At

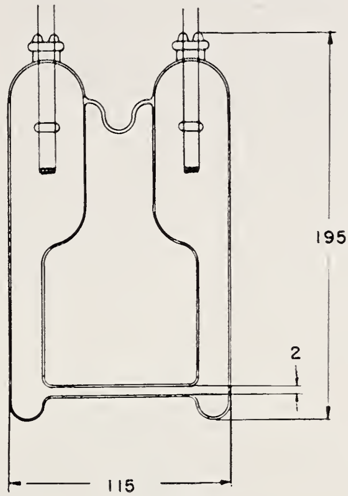

FIGURE 14.

FIGURE 15.

this point the vapor pressure of krypton, frozen at about 120° K, is only a few hundredths of a millimeter. Thus, very low krypton pressure is reached. The lamp can be filled with any pressure desired, the krypton pressure being determined by the temperature of liquid air only. According to our experiences it is possible to obtain light wave scales of incontestable exactness of subdivision with this lamp.

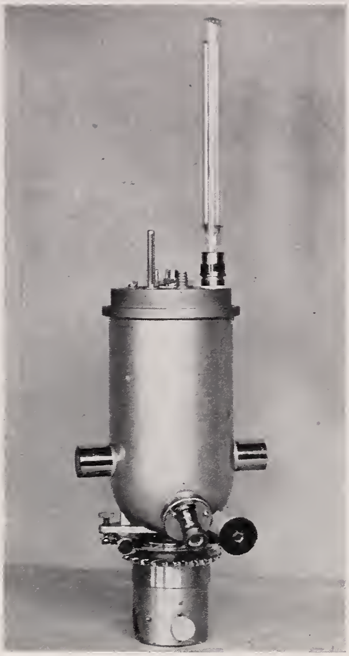

FIGURE 16.

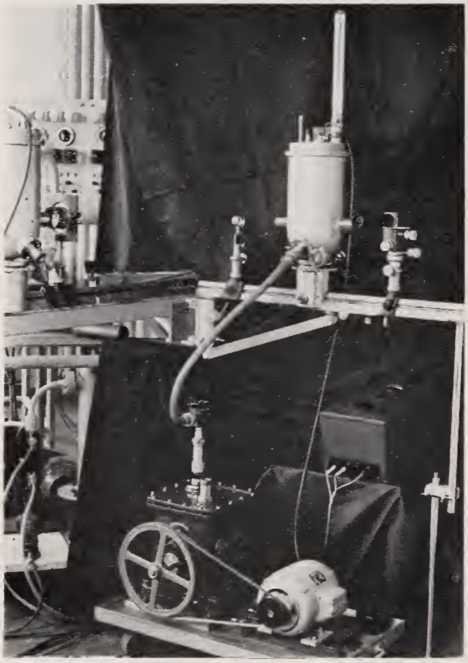

FIGURE 17.

The longest scale to be realized is nearly 800 mm including more than 2,000,000 graduation lines. The uncertainty of length at any point of the scale is less than $\pm 0.01\ \mu/\text{m}$.

The necessity of using lamps filled with isotopes of even mass requires the production of pure isotopes in adequate quantities. In the case of mercury-198 this is done by bombarding gold-197 with neutrons. Krypton isotopes can be separated by thermodiffusion as was done by Clusius and Dickel. A great deal of our work at the PTB during the last year was spent in building a thermodiffusion column for producing Kr-84. Thermodiffusion occurs between a hot and a cold plate positioned face to face, having a mixture of heavy

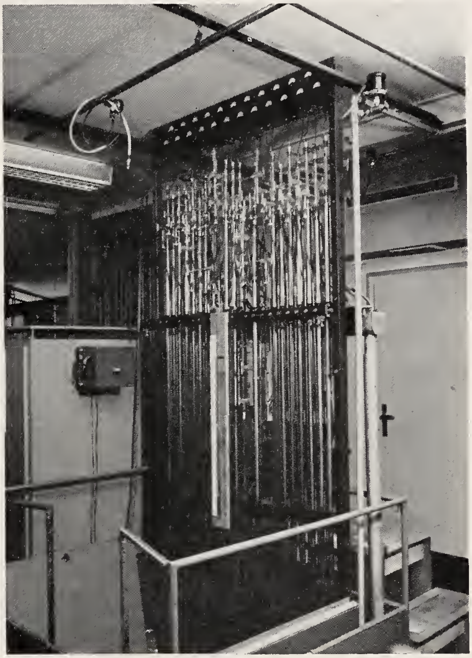

FIGURE 18.

and light particles between them. Heavy particles then diffuse to the cold plate and light particles to the hot. Clusius modified this arrangement by putting an electrically heated wire on the axis of a vertical tube of about 10-mm internal diameter and several meters length. This tube is filled with gas, krypton for example, and cooled externally with water. Thermodiffusion then takes place between the hot surface of the electrically heated wire and the water-cooled wall of the tube. Near the wire there is an upward flow of the heated gas, whereas near the wall the gas flows downward. Thus, due to the combined effects of diffusion flow and convection flow the lighter atoms are carried inward and upward and the heavier ones, conversely, outward and downward. Naturally the tube must be long to get complete separation of isotopes. The upper part of the equipment we have assembled for the separation of Kr isotopes is shown in figure 18. This column has an effective length of 72 m and consists of 23 single tubes made from copper, each 6 m long, which are connected together by circulating systems consisting of tubes of small diameter, one link of each system being heated so that a convection flow arises in the system conveying material from the upper end of one tube to the lower end of the next tube. This equipment can produce about 1 liter of Kr-84 with a concentration of more than 99 percent in 6 months. This is sufficient to fill several thousand lamps.

By utilizing pure isotopes in the production of lamps, the light-wave technique of length measurement now seems to have reached the highest possible perfection. Undoubtedly, light-wave scales as realized by means of isotope lamps are much more precise than the old-fashioned meter prototype which is the legal standard of length. It seems to be the intention of most of the industrial countries to relegate the meter prototype to the museum and to replace it by a light-wave scale which is limited in accuracy only by the laws of nature. Whether or not we succeed in doing that in the near future, light waves emitted by atoms will be more and more the actual length standards of industry. It is very instructive to follow the development of length units during the history of mankind. In prehistoric times the limbs of the human body were the common length units. After the creation of state authorities these units were superseded by arbitrary units symbolizing the sovereign power. These predominated in principle many thousand years. It is noteworthy that the rise of new ideas regarding a return to a natural length unit in the eighteenth century coincides with the abolition of dynastic power and with the creation of new public authorities. It is very attractive from the mental point of view that the meter is a child of the French Revolution, in its original state being connected to the globe, allegorizing on the one hand the universal political ideas of that period and demonstrating on the other hand the high level of geodesy in the eighteenth century. Revolution was followed by restoration of dynastical power, and curiously enough the meter was degraded at the same time to an arbitrary unit, lingering in this antiquated form until now. So the units of every epoch seem to be characteristic, to a certain degree, of the spirit of the age. Now we seem to stand at the beginning of a new era, the age of democracy and the age of the atom. Doesn't it seem to be a matter of course that we shall abolish the autocratic meter prototype by designating a new length unit, one that can be used anywhere in a real democratic manner and that we take our measures from the atom so significant to our century?

2. Calibration of Gauge Blocks in Canada

By K. M. Baird [1]

I should like to describe briefly the methods and equipment that are used at the National Research Laboratories of Canada for the calibration of end standards for industry. Although the basic principles of our methods are the same as used elsewhere, the way in which they are applied is, of course, governed by our particular needs in Canada and by the functions of our laboratory. Therefore, I shall first say something of these in order to indicate why our procedures are not quite the same as those used elsewhere.

There are two main reasons why our procedures differ somewhat from those of the national laboratories of larger industrial countries: In the first place industry in Canada is generally on a smaller scale and less highly developed than in countries like the United States or Great Britain. Consequently, the number of gauges that are calibrated is not large, about 1,000 a year at present, and we do not have to be equipped for testing in large quantities.

In the second place, the National Research Laboratories have not been called upon to do routine testing to the extent that other national laboratories have. Although its Applied Physics Division has among its responsibilities the maintenance of Canada's national units of measurements, the main emphasis is on their fundamental aspect, and the provision of reference standards on which routine tests can be based. The main work of the Division is concerned with research investigations likely to be helpful to the development of Canada's resources and industry.

The work of the Interferometry Section, which has charge of the unit of length insofar as it involves wavelengths, consists mostly of research concerning techniques of measurement, new sources of radiations useful for interferometry and investigation and measurement of wavelengths proposed as the new standard of length. The section also calibrates end gauges for industry but in general these are to be used as reference standards; it is not often required to make tests as to conformity to any particular specifications.

Because of these two reasons our procedures are suited to relatively small numbers of tests under the supervision of people who are also engaged in research, and our equipment is designed from the point of view of versatility rather than ordinary quantity testing.

End gauges are all measured by absolute calibration against wavelengths of light. Comparisons with steel reference standards are made only in exceptional cases.

Gauges up to 100 mm, or 4 in., in length are measured in the interferometer shown in figure 1. This was designed and built in the laboratory. It is of the Fizeau type and is somewhat similar in optical

[1] National Research Council, Ottawa, Canada.

construction to the interferometer in use at the British National Physical Laboratory. Light from a suitable source is collimated by a lens at the left end of the tube, T; it then passes through a dispersing prism in the rectangular box, M, and is reflected down onto the quartz reference flat and the gauge, G, which is wrung down onto another quartz flat. Light is returned through the dispersing system and collimator lens to the eyepiece, E, through which the interference fringes are viewed.

A general view of the interferometer in use is shown in figure 2. It is mounted in a room in which the temperature is controlled at 20° C to within ±0.1 deg C. A mercury-198 source can be seen at

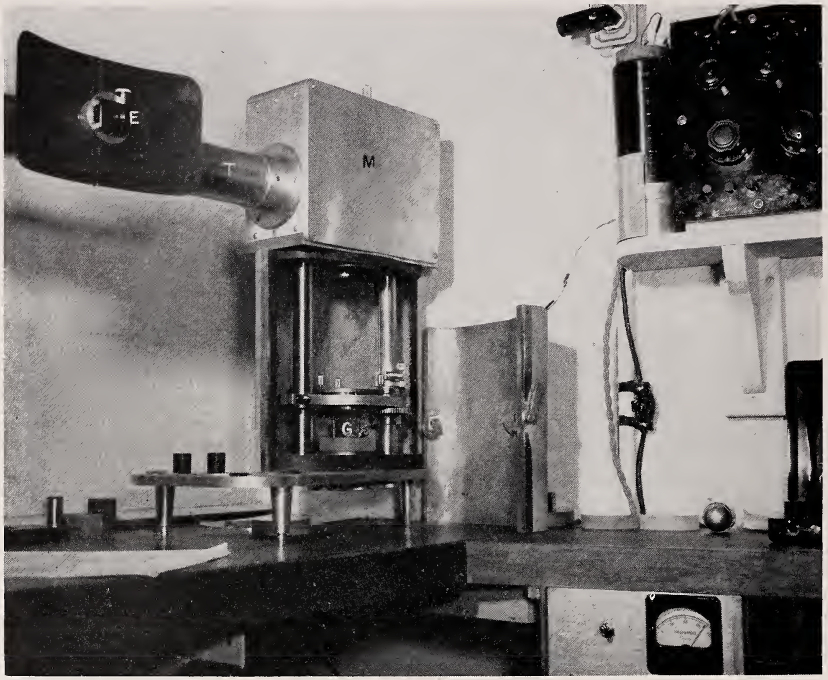

FIGURE 1. *Fizeau-type interferometer.*

the left; this has now been replaced by an arrangement whereby several alternative sources, including Hg^{198} and cadmium can be conveniently interchanged. A potentiometer bridge seen at the right is for the measurement of the temperature of the gauge by means of thermocouples, one junction of which is clipped to the gauge, the other placed in an ice bath. Temperature measurements are considered accurate to ±0.025 deg C.

The procedure in the measurement of a set of gauges is as follows:

Gauges are wrung onto several quartz flats, two to a flat, and set on the bench to come to temperature equilibrium. One flat at a time, with its gauges, is placed in the interferometer whose cover is closed; further time is allowed for final temperature equilibrium. During this time the observer calculates from his observations the length of the gauge measured just previously and wrings up a new pair of gauges to replace those just measured.

Observations are made of the fractional part of the order of interference for four colors of the cadmium spectrum with gauges less than 1-in., or 25-mm, length and of the Hg^{198} spectrum for longer gauges up to 4-in., or 100-mm, length. The length of a gauge at the center of its face is determined from these values by the use of prepared tables.

Corrections to the observed length are made as follows:

The gauge length at 20.0° C is calculated from the observed deviation from this temperature; it is assumed that the coefficient of dilatation of the gauge is the same as for a typical steel from which the gauge is made. Because the temperature is controlled to within

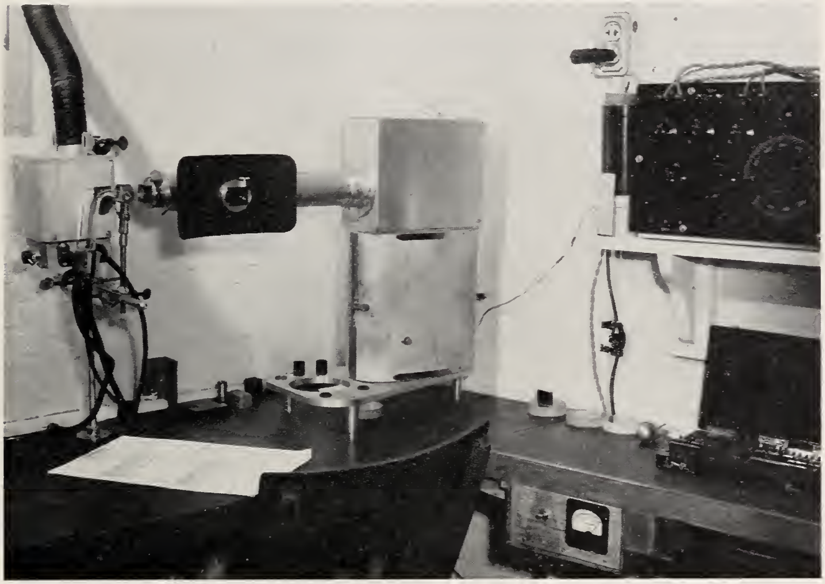

FIGURE 2. *General view of interferometer, light source, and potentiometer bridge.*

0.1° C of 20.0° C no significant error occurs. The dilatation of other materials is measured.

The corrections due to the refractive index of air are made by the assumption that it is the same as for normal air at the temperature, pressure and relative humidity at which the observations are made. The pressure is read on a sensitive barometer, the temperature is assumed to be the same as the gauge and the relative humidity 35 percent. Tests have been made occasionally by means of a sensitive refractometer and have shown that no significant error results from this cause.

The phase change on the surface of the block is determined by comparing the observed optical length of a wrung combination of about five blocks, taken at random from a set, with the sum of their optical lengths. From the difference is obtained a correction which is applied to the observed optical lengths of all the gauges in the set to give their physical lengths.

With this procedure a single observer is able to make an absolute calibration of about 20 gauges per day.

Standards longer than 4 in., or 100 mm, and up to 40 in., or 1 m, in length are measured on the larger interferometer shown in figure 3. This was also designed and built at the National Research Laboratories. It is of the Michelson type and normally has a cover for temperature stability which is not shown in the illustration. This interferometer was designed with emphasis on applicability to other research work and not for routine calibration in quantity.

Light from suitable sources which are mounted behind the monochromator, M, is passed through the monochromator and reflected into the collimator, C, to the beam splitter, S, from which one beam

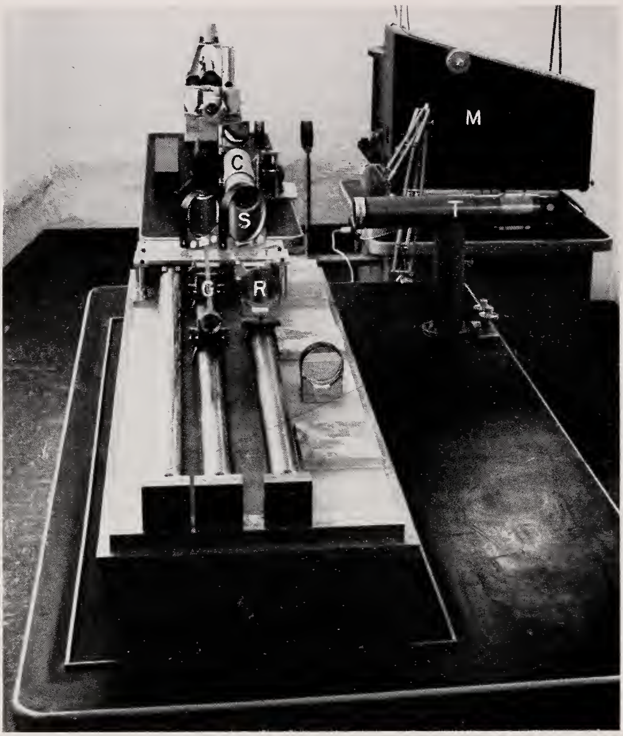

Figure 3. *Michelson-type interferometer for long lengths.*

goes to the reference mirror, R, the other onto the gauge, G, which has a flat wrung to its rear gauging surface. Interference fringes formed on recombination of the beams at S are observed through the telescope, T. Leveling is done hydraulically by means of the control knobs under the telescope.

Gauges up to 20 in., or ½ m, in length are calibrated in one step by comparison with seven wavelengths emitted by a Kr isotope lamp operated at the temperature of the triple point of nitrogen. Longer gauges are calibrated by measuring the difference between their lengths and those of shorter gauges. Gauges of 12 in. and less can also be checked against the wavelengths of Hg^{198}. Both these single isotope sources are made at the National Research Laboratories where investigations are being made as to their suitability for length standards.

Corrections to the observed gauge lengths are made in a similar way to that described for the gauges of 4-in. length and under.

Incidentally, the apparatus that can be seen in the background of figure 3 is a new instrument under development for the calibration of line standards or scales directly in terms of wavelengths of light.

In conclusion I shall say a few words about our accuracy of measurement. In our routine measurements on good gauges we guarantee an accuracy of plus or minus two millionths of an inch for gauges of 1 in. or less (or the equivalent in metric gauges) and plus or minus two parts per million for longer gauges. We feel that this limit is mostly imposed by the nature of the gauges. We do not contract to measure to a lower accuracy (in any case it is generally not any easier) but sometimes quote a lower accuracy on the lengths reported where the gauge quality makes the higher accuracy of no significance. It is possible to measure any given length to much better accuracy than the above, but we do not feel that one is justified in giving to any higher accuracy a general statement as to the length of a steel block which may be used in any number of ways, e. g., in a wrung combination, between points of a comparator, for optical comparison, etc.

If asked, we would calibrate a set to higher accuracy in special cases but then would wish to know how the gauge was to be used and would state the length that was significant for this purpose. A statement, in a general way, as to the length of a steel block to plus or minus tenths of millionths of an inch has not much more significance with present steel gauges than has the length of, say, a piece of rubber given to an accuracy of thousandths of an inch.

3. Use of Light Waves for Controlling the Accuracy of Block Gauges

By F. H. Rolt [1]

Gentlemen:

I feel it a distinct honor to have been invited to offer you a lecture today on the "Use of Light Waves for Controlling the Accuracy of Block Gauges." Unfortunately, I cannot deliver this lecture to you in person, but Mr. E. J. Schneider [2] has kindly offered to present it in my place.

As you all know, the manufacture of block gauges calls for the very highest degree of mechanical precision on the following features:

(1) The working faces must be flat to obtain the necessary degree of adhesion when the gauges are wrung together.

(2) This flatness must include a very high degree of surface finish of the faces.

(3) The faces must be parallel to each other to ensure equality of size at all positions between the faces.

(4) The actual size of a gauge, represented by the distance between its faces, must agree with its nominal size to within a very small tolerance.

To minimize burring in use, a further requirement is that there must be no sharp edges round the faces; beveling is not sufficient; the edges must be very carefully rounded off.

Now, the flatness and reflectivity of the faces of block gauges lend themselves admirably to the application of the principles of optical interference as a means of controlling the accuracy of these gauges to all the above requirements. As you know, the use of optical interference provides, in a sense, a series of finely divided scales of natural origin, the divisions of which are spaced perfectly regularly and at intervals that are known very precisely both in inches and millimeters. The divisions of these scales are approximately 0.00001 inch apart, and as they can be subdivided without difficulty into tenths it is possible, with them, to achieve an accuracy of one millionth of an inch in the examination of block gauges.

Various types of instruments based on the use of optical interference have been designed from time to time over the last 30 to 40 years for inspecting block gauges, and it is proposed in the short time I have available to offer you some general account of a few typical instruments of these types without entering too deeply into the detail of their construction.

Monochromatic Light

Interferometers in general make use of what is known as monochromatic light, that is light of a specific color or wavelength. Monochromatic light can be produced from a number of different sources

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[2] Engis Equipment Co., Chicago, Ill.

in the form of electrical discharge lamps, the most familiar of which contain either cadmium, mercury-isotope 198 or krypton. These particular lamps have the property of producing a number of very pure monochromatic radiations, the wavelengths of which have been determined very accurately in various laboratories throughout the world.

Optical Interference

The phenomenon of optical interference has, of course, been known for a very long time. It is the term applied to the combined effect of two rays of monochromatic light of the same wavelength which, emanating from a single source, are reunited after being separated and made to travel over paths of different lengths.

As you all know, a very simple case of optical interference can be observed with an optical flat supported over a plane reflecting surface

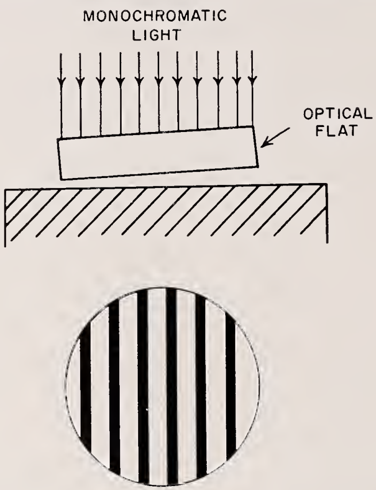

FIGURE 1. *Interference fringes formed between a flat reflecting surface and a slightly inclined optical flat.*

so as to enclose a slightly tapered air gap, as in figure 1. When illuminated normally by a parallel beam of monochromatic light, such a system is found to be traversed by a series of bright and dark fringes that are straight, equispaced, and parallel to the line of intersection of the two plane surfaces, as shown in the lower diagram.

This very simple optical system is the basis of all the interferometers used for testing the accuracy of block gauges as regards the flatness, parallelism, and surface finish of their faces, and for measuring actual size. For the purpose of all these tests the faces of the gauges are used as the lower reflecting surface of the system, and a series of straight bands or fringes, as they are called, is formed between the gauge face and that of a suitably disposed optical flat in a parallel beam of monochromatic light.

Tests for Flatness and Parallelism of Block Gauge Faces

A schematic diagram of an interferometer set up at the N.P.L. at Teddington in 1921 for inspecting the flatness and parallelism of the faces of block gauges is shown in figure 2. In this instrument the source of illumination is a mercury vapor lamp and a green filter is used in order to separate its strong green monochromatic radiation. The light from this lamp, after being concentrated on a pinhole, is rendered parallel by means of a collimating lens and illuminates the gauge that is wrung down on to a baseplate. Fringes are formed on the upper surface of the gauge and on the baseplate by means of an

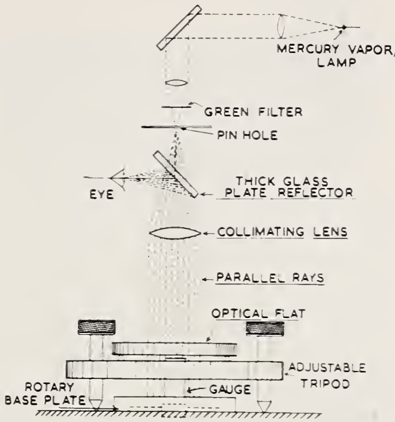

FIGURE 2. *Diagrammatic optical arrangement of N. P. L. interferometer for checking flatness and parallelism.*

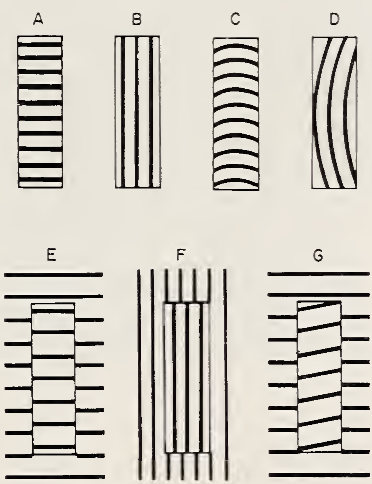

FIGURE 3. *Types of interference fringes formed on surfaces of gauges and baseplate.*

optical flat that is supported just above the upper surface of the gauge. If the surface of the gauge is perfectly flat the fringes will be quite straight and equispaced, as shown at A or B in figure 3. If the gauge face is not flat, even by only a microinch, it is revealed by a corresponding bowing of the fringes, as at C or D. The actual error in flatness of a gauge surface can readily be estimated from the amount of curvature of the fringes in terms of their spacing which represents a scale of approximately 0.00001 inch.

The parallelism between the two gauge surfaces is examined by noting the degree of parallelism between the two sets of fringes, one formed on the upper surface of the gauge and the other on the surrounding surface of the baseplate to which the gauge is wrung. Diagrams E and F in figure 3 represent cases of gauges with truly parallel surfaces. Diagram G, on the other hand, is what would be seen in the case of a gauge that has a transverse lack of parallelism

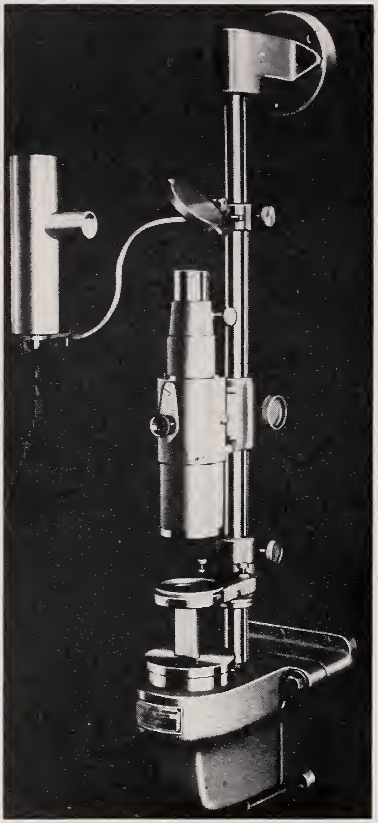

Figure 4. *N. P. L. type interferometer for inspecting flatness and parallelism of gauge faces.*

between its faces amounting to about a third of a fringe, that is approximately 3 microinches.

The N.P.L. type of interferometer for carrying out such tests on the flatness and parallelism of gauge faces has been made for several years jointly by Coventry Gauge & Tool Co. Ltd. and Hilger & Watts Ltd. A photograph of one of these instruments is shown in figure 4.

Tests for Surface Finish

When one carefully examines the fringes formed on the surface of an ordinary block gauge in an interferometer of the type just referred to, it will be seen that their edges are not perfectly straight. They present a very finely serrated appearance and this serration can be used as a criterion of the surface finish of the gauge under examination.

The type of instrument used for examining the surface finish of block gauges is known as an interference microscope. Generally speaking these instruments employ much the same optical system as in the flatness interferometer, but in order to see the serrated effect more clearly the fringes are viewed through a microscope.

The first interference microscope was designed by the Russian scientist Linnik. In the latest development of the Linnik instrument, Carl Zeiss provides three degrees of microscope magnification of 80, 200, and 480 times. In this instrument the optical flat is not placed directly above the surface to be tested but is replaced by a reference mirror situated to one side of the optical axis of the instrument, as in the well-known Michelson type of interferometer. The light source

FIGURE 5. *Hilger and Watts microinterferometer for measuring surface finish.*

is a thallium lamp, from which the strong green radiations are practically monochromatic. Figure 5 shows a similar type of microinterferometer which has recently been produced by Messrs. Hilger & Watts Ltd. of London. A special feature of this instrument is that the reference mirror has 3 sections with reflecting powers of 4, 50, and 90 percent. Any one of these sections can be brought into play to match the particular reflectivity of the surface to be tested, and the most distinct fringes thereby obtained.

Small objects to be examined are placed on the table as shown. This is provided with micrometer and tilting arrangements in two directions at right angles. The whole of the upper part of the instrument can be turned through 180° so as to project over the back of the base for viewing large objects resting on any convenient rigid support.

Two examples of photographs taken with this particular make of instrument in mercury green light at a magnification of 360 times are shown in figure 6. The one at A is of a ground steel surface, the

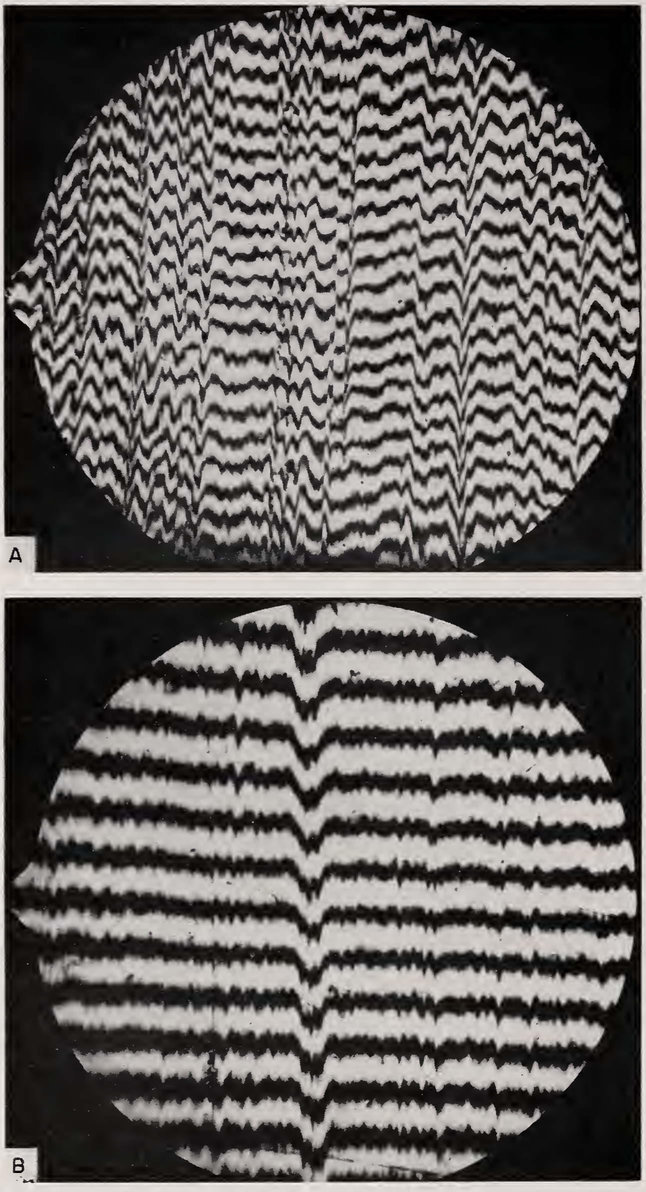

FIGURE 6. *Microinterferograms of ground steel surface A and lapped steel surface B.*

roughness of which, judging from the irregularities of the fringes, amounts to 2 or 3 fringe spaces, that is 20 to 30 microinches. The lapped steel surface at B is much smoother; the irregularities of its surface do not in general exceed a quarter of a fringe space, that is 2–3 microinches. Towards the center, however, there is a vertical scratch about 5 microinches deep.

In addition to this microinterferometer, Messrs. Hilger & Watts have constructed a simple attachment for fitting to the objective of their engineer's microscope. This instrument is shown in figure 7. The microscope works at a magnification of 120 times and a small camera is provided to enable the fringes to be photographed if desired.

I think it would be of interest to mention to you a comparison which was made at the N. P. L. a few years ago between "Talysurf" records of the surface of certain block gauges and photographs of fringes formed in a microinterferometer on the same gauges. To facilitate the comparison, the photographs were arranged to show the same horizontal and vertical magnifications as the Talysurf records. These two entirely different methods of delineating the irregularities over precisely the same areas of the surfaces examined

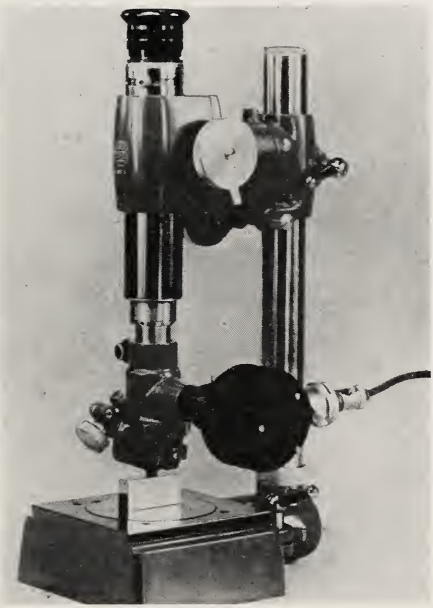

FIGURE 7. *Hilger and Watts surface finish microscope set on gauge block.*

showed truly remarkable agreement. The relative positions of the individual scratches were exactly the same and their depths agreed to appreciably less than a single microinch.

Microinterferometers can also be used with advantage for examining the smoothness of the rounding off of the edges of the faces of block gauges. Unless proper care is used in the process of rounding off these edges the peripheries of the faces are likely to be left in a rather ragged condition. This in practice leads to the setting up of minute burrs and the detaching of tiny fragments of metal from the edges, both of which can cause scratching of the faces when the gauges are wrung together.

Microinterferograms of the surfaces and edges of two block gauges taken in a Hilger microinterferometer are shown in figure 8. The one marked A shows the effect of carelessly chamfering the edge of the gauge in grinding. Photograph B in contrast is taken from a gauge, the edges of which have been carefully rounded off by fine stoning.

Measurement of Size of Block Gauges

I need hardly stress the importance of accuracy of size in block gauges. This applies particularly to reference sets of these gauges used in laboratories and standards rooms of factories as a basis for the calibration of other sets that are used for ordinary inspection and workshop use. Given good gauges, that is, gauges having faces that are accurately flat and parallel and of high quality surface finish, it is possible with modern interferometers to determine their size to an accuracy of one millionth of an inch, or even less in the case of the shorter gauges.

Block gauges are ordinarily made up to sizes of 4 in., or 100 mm, but interferometry can be applied to the measurement of much longer gauges, even up to ½ or 1 m in length.

In using such interferometers particular care has to be taken with regard to temperature as this, of course, has an important influence on the length of the gauge. The density of the atmosphere also influences the lengths of monochromatic radiations, so that in all interferometry work of the highest order, observations have to be recorded of the pressure, temperature and humidity of the air and the necessary corrections made for these factors in order to determine the true value of the wavelengths at the time of measurement.

Quite early, work on the application of interferometry to the measurement of block gauges was carried out at the Bureau International, Paris, and the National Bureau of Standards, Washington. It was subsequently pursued by the N. P. L. and Messrs. Adam Hilger Ltd. in England, and by Dr. Kösters and Messrs. Carl Zeiss in Germany. As a result of all this work several types of gauge measuring interferometers have been designed and made available commercially. I now propose to refer to some of the more recent designs of these instruments.

N. P. L. Gauge Interferometer

Figure 9 is a diagram of the optical arrangement of the gauge interferometer which was set up at the N. P. L. some 25 years ago. Basically this optical system is very similar to that of the N. P. L. flatness interferometer. The most important difference is the introduction of the dispersion prism, CD, which enables the various monochromatic radiations emanating from the source, S1, to be directed on to the gauge, G, through the optical flat, F.

As in the case of the flatness testing instrument, the gauge to be measured is wrung on to the lapped surface of a baseplate, B, and it is interesting to point out that the measured length of a gauge under such conditions is equivalent to what is known as its "practical length", that is the material length of the gauge plus one wringing film.

Figure 10 shows a diagram of the interference fringe systems formed on the upper surface of the gauge and the surrounding surface of the baseplate. With a good gauge these two sets of fringes are both

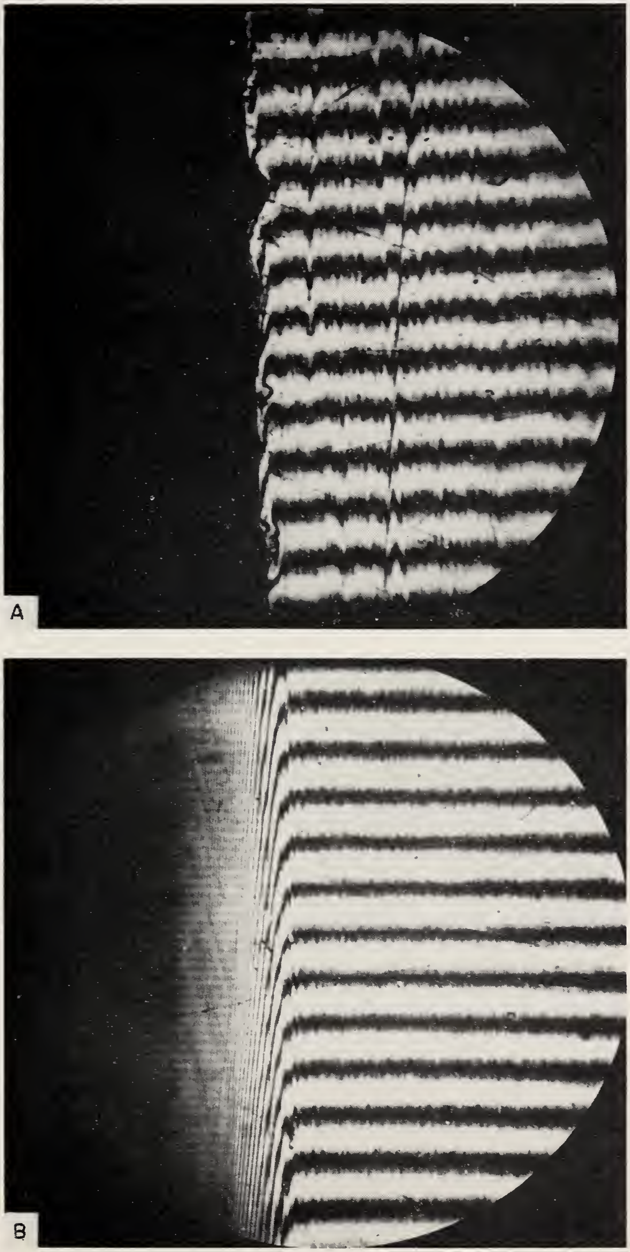

FIGURE 8. *Microinterferograms of surfaces and edges of gauge blocks.*

straight, equispaced and parallel to each other, but they are not necessarily in line with each other. In the diagram, the fringes on the gauge are offset with reference to those on the baseplate by a fraction a/b of a fringe space.

I do not think it is necessary for me to spend time describing to you all the details of the method of measurement, but essentially the measurement resolves itself into a measurement of the fractional

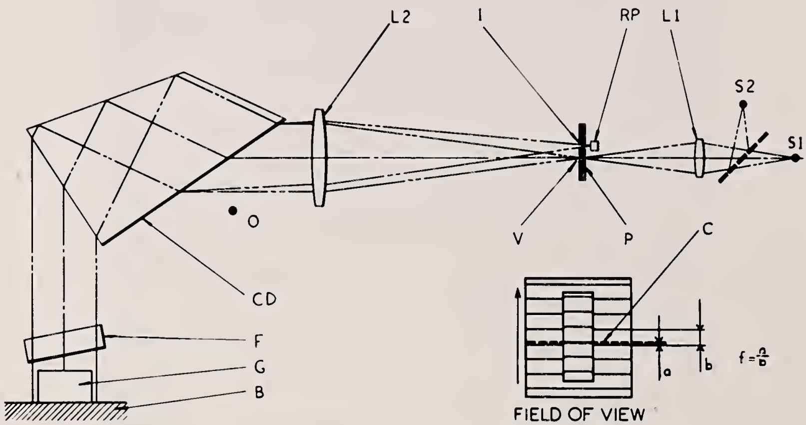

FIGURE 9. *Optical system of N. P. L. gauge interferometer.*

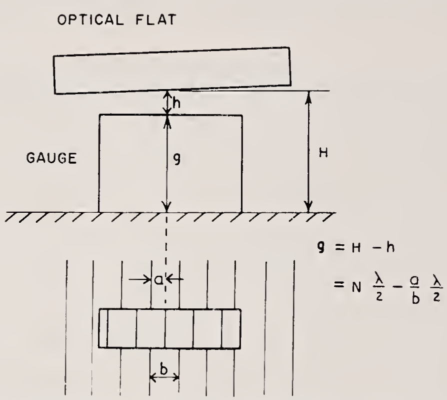

FIGURE 10. *Diagram of system of interference fringes formed on surface of gauge block and surrounding baseplate.*

displacement a/b for a series of monochromatic radiations on each particular gauge that has to be measured. From the measurement of these fractional displacements it is possible, by what is known as a method of coincidence, to determine the error of the gauge from its nominal length. Computed tables or a slide rule are commonly used to assist in this computation work.

The task of measuring a whole set of slip gauges by interferometry becomes very protracted if the gauges have to be dealt with one by one. It was for that reason that the N. P. L., when designing their gauge interferometer, arranged that the gauges could be wrung down in batches of 18 round the periphery of a rotatable baseplate.

This baseplate is so arranged that each of the gauges can be brought in turn under the optical flat and observations carried out upon it. A batch of 18 gauges can be dealt with and the results fully computed within about an hour.

The instrument is provided with a spare baseplate which can be loaded with a second batch of 18 gauges, and kept within the case of the instrument, so as to obtain thermal stability during the measurements of the first batch.

This N. P. L. type of gauge interferometer is now being made by Messrs. Hilger & Watts Ltd. of London, and a photograph of this commercially made instrument is shown in figure 11. Various constructional improvements have been embodied in this instrument which is fitted with two sources of monochromatic light, a cadmium and a mercury-198 discharge tube. This enables a choice to be made of the purest and the strongest radiations from these two sources.

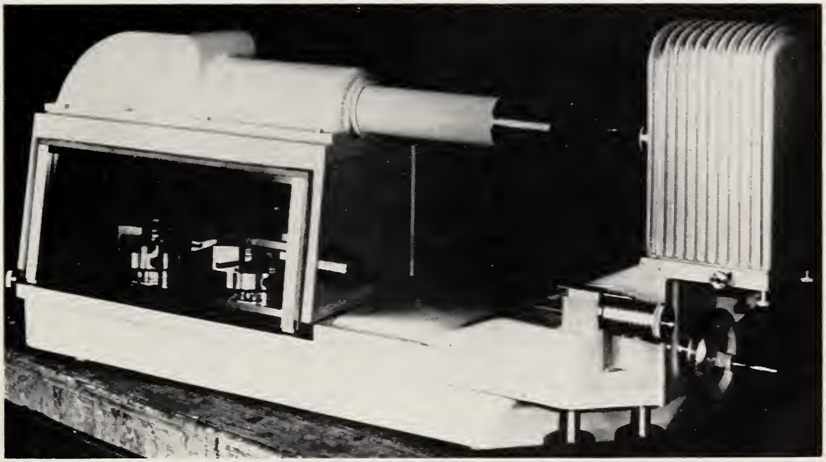

FIGURE 11. *N. P. L. type gauge interferometer built by Hilger and Watts, Ltd.*

Incidentally it may be mentioned that this interferometer can be used not only for measuring the lengths of gauges but also for viewing the flatness and parallelism of their faces. It should be noted that the instrument calls for no special supports for the gauges or for adjustments of their position for orientation. It can be used for measuring gauges of square or circular section, as well as those of the usual rectangular form.

Using the steel baseplates provided with the instrument, no difficulty need arise due to differences in phase change when measuring carbide or chromium-plated gauges. A short auxiliary gauge of steel or other material is first measured alone; this is followed by measurement of the gauge with the auxiliary gauge wrung on to its upper face, the differences between these two measurements giving the length of the gauge irrespective of the material of which it is made.

Hilger Double-Ended Gauge Interferometer

The optical principle of another type of Hilger interferometer, which was introduced about 1930, is shown diagrammatically in figure 12. It will be noted that in contrast with the N. P. L. instrument, this interferometer is based on optical reflections made simultaneously at both ends of the gauges to be compared and not at one end only. The system of measurement is not so simple as in the N. P. L. instrument. It ordinarily involves the use of white light as well as monochromatic light. It can be used for comparing the

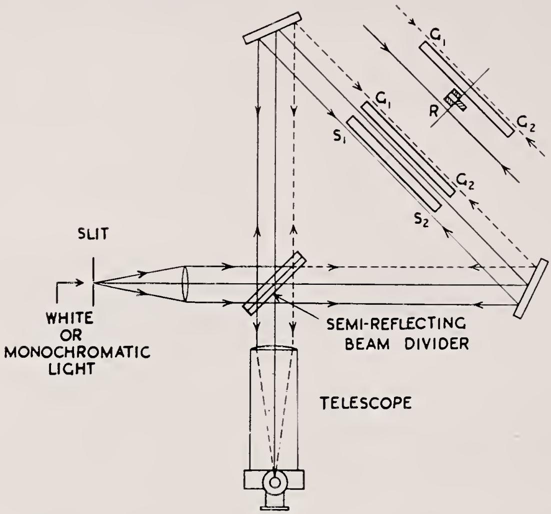

Figure 12. *Diagram of optical arrangement of Hilger double-ended gauge interferometer.*

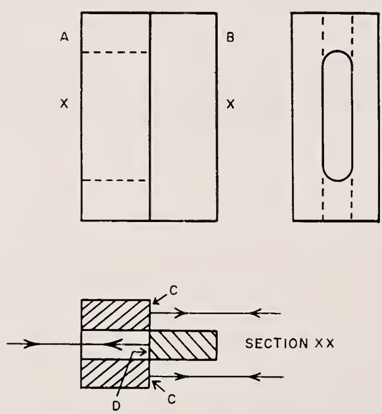

Figure 13. *Reference gauge, of zero length, used in Hilger double-ended gauge interferometer.*

lengths of two gauges S_1, S_2 and G_1, G_2 placed side by side between the two mirrors as shown. The same system is used when one wishes to determine the absolute length of a single gauge G_1, G_2. In that case one uses a reference gauge, R, as indicated in the figure, which in a sense has no material length. The construction of this reference gauge is shown diagrammetrically in figure 13. It will be noted that the two reflecting surfaces of this gauge, C and D, face in opposite directions as in an ordinary length gauge, but the distance between these two faces is only that of a wringing film.

Kösters' Interferometer

Let me now turn to some of the gauge interferometers which have been designed in Germany during the last 25 years or so.

The earlier types of these instruments were designed by Dr. Kösters and were constructed by Messrs. Carl Zeiss. The diagrammatic optical arrangement of Dr. Kösters' first gauge interferometer is shown in figure 14. As in the case of the N. P. L. instrument, the gauge to be measured is wrung vertically on to a steel or quartz baseplate. The optical system is based on that of the well-known Michelson interferometer. Interference takes place between the beams reflected from the reference mirror on the right and the surfaces of the gauge and of the baseplate, respectively. The instrument is so adjusted that the image of the reference mirror in the semitransparent, diagonally-placed beam divider is situated at about the midlength

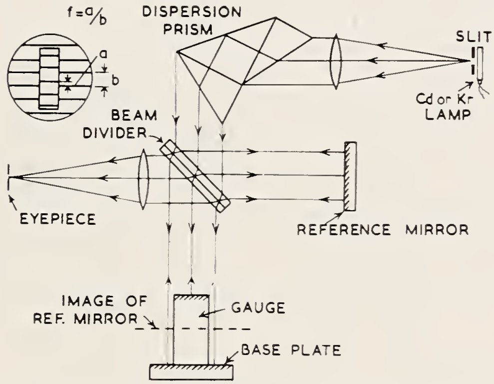

FIGURE 14. *Diagram of optical arrangement of Zeiss-Kösters gauge interferometer, vertical type.*

of the gauge. The path differences between the two interfering beams is thus approximately half the length of the gauge. With this instrument therefore it is possible to measure gauges of twice the length as compared with the N. P. L. type of gauge interferometer.

The basis of measurement in this Kösters' interferometer is somewhat similar to that used in the N. P. L. instrument, inasmuch as observations are made on the fractional displacement of the fringes formed on the upper surface of the gauge and on the baseplate, as shown in the inset diagram of figure 14.

The source of illumination in the Kösters' interferometer is either a cadmium or krypton lamp.

It may be interesting to mention that, by modifications to the Zeiss design of Kösters' interferometer, the N. P. L. has found it possible to measure gauges as long as 20 in. in this type of instrument. When dealing with such long gauges, however, it is preferable to arrange them horizontally rather than vertically. This was done in another design of interferometer by Dr. Kösters, with which he was able to measure gauges up to as much as 1 m in length.

It is interesting to note that Dr. Kösters used this horizontal type of interferometer in his determination of the relationship between wavelengths of light and the meter length. He first measured a gauge 500 mm long, and then the difference between this gauge and one having a length of 1 m. This provided him with sufficient information to determine the length of the meter gauge, and this in turn was compared with the length of a meter line standard, the value of which was known in terms of the prototype meter.

Shortly before the war, Dr. Kösters designed yet another type of gauge interferometer for measuring block gauges up to 200 mm in length. This interferometer was so arranged that it would accommodate six gauges at a time. Three of these instruments are said to have been constructed by Messrs. Carl Zeiss during the war, but

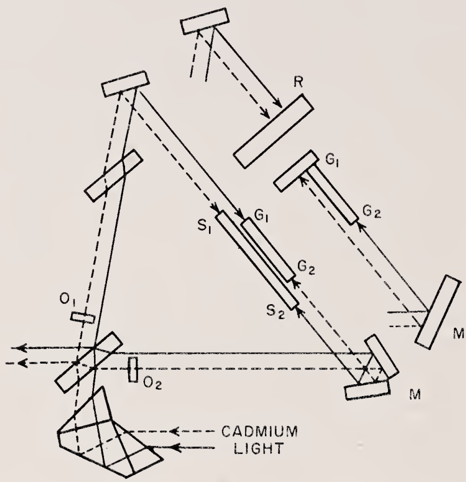

FIGURE 15. *Diagram of optical arrangement of Zeiss gauge interferometer, horizontal type.*

the only additional information that can be found about them is that they were dismantled in 1945.

Zeiss Gauge Interferometer

The latest form of block gauge interferometer made by Messrs. Carl Zeiss of Oberkochen in Western Germany was introduced about 3 years ago. Like the Hilger double-ended instrument it was designed for measuring block gauges by comparison one with another, or absolutely. From the diagrammatic optical arrangement of the Zeiss gauge interferometer shown in figure 15, it will be noted that the optical scheme of this instrument is rather similar to that of the Hilger double-ended interferometer. It possesses, however, one original feature in the form of inclinable optical plates O_1 and O_2 which are interposed in the paths of the interfering beams. By rotation of these plates it is possible to bring the two sets of interference fringes into exact coincidence and thus obtain a measure of their fractional displacement, instead of having to estimate it as in the case of the N. P. L. and Hilger instruments. In this Zeiss interferometer it is possible to measure a gauge by comparing its length with that of another gauge of known length, or alternatively a gauge can be measured absolutely by wringing a small baseplate on to one of its ends, as shown towards the top right-hand corner of figure 15.

If three gauges of nominally the same length or of different lengths are available, it is possible to determine their individual absolute lengths by a scheme devised by Messrs. Zeiss. The differences between two of these gauges wrung together and the third gauge are measured in all possible arrangements, and from the three differences thus obtained it is a simple matter to determine the individual lengths of the gauges.

It was mentioned earlier that when carrying out any interferometric measurements of gauges it is necessary to take readings of the pressure, temperature, and humidity of the air during the measurements. Messrs. Zeiss have suggested an alternative scheme for taking account of the variation in the density of the air, by providing with their instrument two quartz end gauges, one 20 mm and the other 70 mm in length, the difference between these two gauges being known under standard conditions. By comparing this true difference with that measured during any set of measurements on any other gauge, it is possible to arrive directly at the correction that should be applied to the standard wavelengths to suit the particular set of measurements concerned.

Accuracy and Adaptability of Gauge Interferometers

I have already mentioned that with suitable care it is possible to use gauge interferometers for measuring lengths of gauges to an accuracy of the order of one millionth of an inch. When measuring to such an accuracy, variations in the type and quality of finish of the surfaces of gauges can produce corresponding variations in phase change in light reflected from their surfaces. I mentioned earlier how this variation in phase change can be avoided by the use of an auxiliary gauge.

As you know, in ordinary sets of block gauges quite a fair proportion of the gauges are relatively thin, and although the faces of these thin gauges may be parallel to each other, the gauges themselves in the free state are often bent to quite an appreciable amount. To measure such thin gauges by reflection from both their faces then becomes very difficult owing to the distortion of the interference fringes that they produce.

4. Achromatic Interferometer for Gage Block Comparison

By T. R. Young [1]

The Optics and Metrology Division of the National Bureau of Standards has recently become concerned with the problem of extending the precision of measurement of length to 0.1 microinch per inch. The Engineering Metrology Section of the Division has been assigned the task of making measurements to this precision on end-blocks of the primary-echelon category. The factors that must be considered in an absolute measurement to such precision indicate that, at the present technological level, this measurement will be a laboratory endeavor requiring considerable time, control, and instrumentation. Fulfillment of these requirements may be justified in the measurement of primary standards; however, for the measurement of the much greater number of lower-echelon gage blocks existing in this industrial age, each gage block cannot be the subject of a laboratory investigation. Therefore, inherent to the problem of extending the precision of absolute measurement of gage-block standards is the problem of measuring lower-echelon gage blocks practically and with a precision making use of the new ultraprecision of the gage-block standard.

The precise measurement of lower-echelon gage blocks will undoubtedly be achieved by comparison with primary gage blocks. For this reason, a group at the Bureau consisting of Irvine C. Gardner, James B. Saunders, Edgar Robinson, and the author has, for the past year, been concerned with the design and development of an achromatic interference comparator. Although the principle of the achromatic compensator was originally conceived by Wilhelm Kösters and Paul Lampe [2] and later applied to a gage-block comparator, it is believed to be relatively unknown in this country and commercially unavailable. This paper will be concerned with the embodiment of the Kösters achromatic wedge system in a mechanical mounting temporary in nature but sufficiently precise to enable the possibilities of the wedge system to be thoroughly explored. A final form of the instrument remains to be designed, and it will be necessary on this instrument to incorporate adequate temperature control and to provide for the rapid inspection of gages. The specific prism system used in this instrument was designed by J. B. Saunders from glasses that he selected as specially suitable when combined to match the dispersion of air. E. L. Robinson made the optical components, which had to conform very precisely to the design if the system was to function in an adequate manner. Mr. Saunders devised special interferometric tests to control the optical components.

[1] National Bureau of Standards, Washington.
[2] W. Kösters and P. Lampe, German Patent No. 577377 (1929); Werkstattstechnik u. Werksleiter 23, 527 (1938).

Figure 1 shows the essential parts of the present instrument. Achromatic lens B (fig. 1) collimates white light, e. g., tungsten illumination, emitted from point source A. This light is transmitted by a double prism, C, in two parallel beams, as shown by the two typical rays of each collimated bundle. The double prism consists of two 30-, 60-, 90-degree prisms having rectangular faces. These are joined together as shown, using a very thin layer of oil or optical cement after one of the interfacing surfaces has been provided with an evaporated film of a density to provide equal intensities to the reflected and transmitted beams. The compensation necessary for white-light interference is achieved by making the prisms identical in size, using glass having the same index of refraction, taking care in

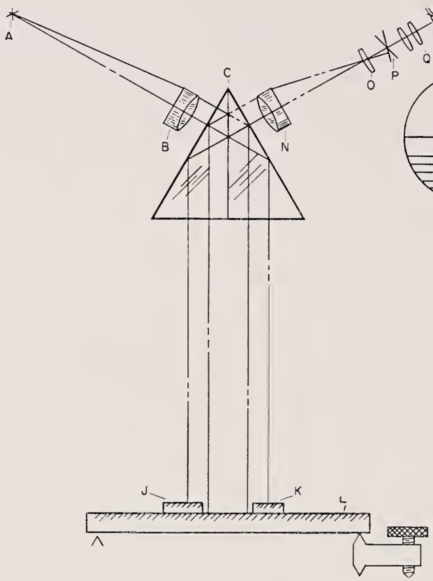

FIGURE 1.

the orientation of the prisms during the joining process and keeping the layer of cement or oil extremely thin.

After the two beams are transmitted by the double prism they are reflected normally from the measuring surfaces of the two gage blocks, J and K, and also from the surface of an auxiliary plate, L, to which the gage blocks are wrung. After reflection, the two beams return over their previous paths and are recombined at the dividing surface of the double prism, C. After recombination, part of each beam is transmitted through the collecting system of lenses N and O and a part is returned to source A. The collecting system of lenses images the surfaces of the gage blocks, as well as the surface of the auxiliary plate, L, in the plane of the cross hair, P. If the gage blocks are positioned properly in each beam, the images of the gage-block surfaces will be superimposed. A slight tilt of auxiliary plate L about an axis perpendicular to the plane of the drawing will cause two interference patterns to be formed, one between the images of auxiliary plate L as formed by the two beams, and the other between the two images of the gage-block surfaces. Viewed with an eyepiece, Q, the field may appear as shown in R. Each of the two fringe patterns will be a typical white-light pattern consisting of a small number of multicolored fringes. If the gage blocks are equal in length, the interference pattern formed by the images of their measuring surfaces will be identical to the pattern formed by the images of the common surface, L, and the fringes appearing within the outline of the gage blocks will be alined, color for color, with the fringes appearing from the auxiliary plate. If the two gage blocks are unequal in length, the two fringe patterns will be displaced from each other. If the inequality in length of the gage blocks were limited to such degree that both fringe patterns appeared simultaneously in the field, an observer still could not determine the difference in length directly from the

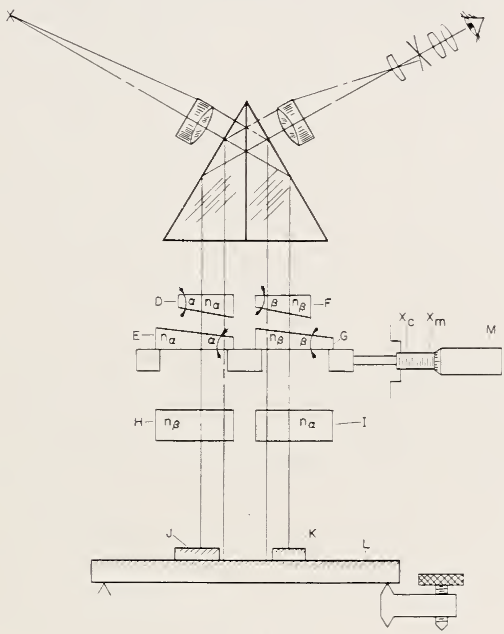

FIGURE 2.

displacement of the fringe patterns, even though he might recognize identical orders of interference in each pattern. Unlike the monochromatic fringe, no unit of length can be attached to an order of white-light interference, this being the resultant of interferences formed by a multitude of different wavelengths. Therefore, when using this interferometer, the observer does not follow the usual procedure of measuring the displacement of one fringe pattern with respect to the other. He measures instead, the movement required of an optical wedge system to compensate the optical-path difference arising when comparing gage blocks of unequal length. The form of this wedge system is shown in figure 2. For illustrative purposes, each wedge has been rotated 90 degrees to the right from its operating position. This also applies to the direction of thrust of the micrometer screw.

Wedges D and F, circular in form, match, respectively, rectangular wedges E and G in both wedge angle and index of refraction. When properly alined, these wedges form effective plane parallel plates in each arm of the interferometer. Once alined, wedges D and F are fixed in position. Wedges E and G are positioned on a movable stage driven by the micrometer head, M. In this manner, a plane parallel plate of variable thickness is introduced in each beam. The tangents of the wedge angles determine the change of thickness per unit distance of advance of the micrometer screw. The wedge angle and the index of refraction, α and η_α, differ from β and η_β, so that a differential change in the optical paths of the two arms is initiated by advance of the micrometer screw. The wedge angles are chosen in the design to provide a convenient relationship between the differential change of optical path and the advance of the screw. The wedge angles of this interferometer were chosen to provide a differential change in optical path per 0.001-inch advance of the wedges equal to that which would occur if one of the gage blocks were changed in length by 0.2 microinch. Therefore, the calibration constant K for the screw was designed to be 2.000×10^{-4}; i. e., a magnification of 5,000.

A differential wedge system with glasses in each arm differing in index of refraction is used because calibration constant K must be kept nearly invariant for the range of visible wavelengths emitted by the white-light source. In general, complete invariance cannot be attained in attempting to compensate a change of thickness of air by a change of thickness of glass. The use of a wedge system in only one arm of the interferometer would require for invariance a glass matching the dispersion of air. A glass even remotely approaching this dispersion does not exist, so an attempt is made to obtain approximate invariance by using two different glasses in a differential wedge system. Using this approach to the problem, the degree to which the designer can approach invariance depends upon his selection of the glass combination. When calibration constant K varies with wavelength a progressive deterioration of the fringe occurs as one attempts to compensate for increasing differences in air path; the closer the calibration constant is held to invariance, the lower is the rate of deterioration of the fringes. The effect of this deterioration can be observed as a shift of the black, zero-order fringe. This shift must be restricted to an undetectable amount because the black fringe is alined with the cross hair in the measurement procedure. Thus, a small rate of deterioration permits compensation for a greater range of air path difference and so permits comparison of gage blocks having greater differences in length. For this reason the range of the comparator depends to a large extent on the designer's choice of glasses. He has at his disposal a large number of possible glass combinations. If the design is to be obtained with a minimum of time and labor, he must, early in the design procedure, select from this large number a combination offering a good range. A method of easily determining a good combination of glasses has been devised, but as it involves a rather detailed description, it is not given in this paper.

To complete the requirements of this interferometer, plane parallel plates, H and I (fig. 2), are used. Each has an index of refraction identical to that of the wedges in the opposing beams. Each has a thickness equal to that of the wedge combination in the opposing beam when that wedge combination is of such thickness as to compensate for a zero path difference in air. Their purpose is to compensate for the glass of the wedges in the opposing beam. This compensation is necessary to retain the white light fringe condition.

A description of the alinement of the optical elements follows: The alinement of this instrument is particularly important in that the balance of the wedge system specified by the design must be achieved. Furthermore, the mechanical movements necessary for the various optical elements are implied in this description.

1. Starting with the instrument as shown in figure 1, the observer replaces the white light source with a monochromatic source so that aperture A emits light of wavelength λ. He uses for J and K two gage blocks differing in parallelism by several fringes as measured along the surfaces of the gage blocks. These gage blocks need not have the same nominal length. One tilts auxiliary plate L about an axis perpendicular to the plane of the drawing until a single broad fringe forms the auxiliary plate pattern. Several fringes will appear in the gage-block pattern.

2. One places wedges D and E in position, as shown in figure 2, and rotates wedge D about its optical axis until a single broad fringe again appears in the auxiliary plate pattern. This insures that wedges D and E function as a parallel plate.

3. One determines the effective angle of wedge E in relation to the direction of thrust of the micrometer screw by counting the number of gage-block fringes passing the cross hair for a given advance of the micrometer screw. The effective angle of wedge E is given by

$$\tan \alpha = \frac{\lambda}{2(n-1)} \frac{\Delta N}{\Delta x},$$

where λ is the wavelength of monochromatic light in standard air, n is the relative index of refraction of the wedge for wavelength λ, and ΔN is the number of fringes passing the cross hair for an advance Δx of the micrometer screw. If the effective wedge is not that specified by the design, wedge E is rotated a small amount and procedures 2 and 3 are repeated.

4. Compensating plate I is placed in position. Monochromatic light is replaced with white light. The auxiliary-plate pattern should still consist of a single broad fringe. If a colored interference order is observed, or if no interference order is observed, the micrometer screw is advanced until the black interference order forms the auxiliary plate pattern. The reading on the micrometer scale, x_c, is the compensated position for zero air path difference. It is convenient here to have a micrometer scale adjustment so that the reading x_c can be positioned at a convenient place on the scale.

5. Wedges F and G and compensating plate H are placed in position. With the micrometer set at x_c, G is translated by means independent of the micrometer screw until fringes in the auxiliary-plate pattern are observed. Wedge F is rotated until a single fringe forms the wringing-plate pattern. Then the translation of wedge G is continued until a black fringe is observed. This procedure insures that wedges F and G function as a parallel plate and are also compensated at the position x_c of the micrometer scale. Notice that in procedures 1 through 5 no change in the tilt of auxiliary plate L is to be allowed. If a drift does occur, it can be corrected at appropriate times in the procedure.

6. The micrometer screw is advanced to the midpoint of its scale, x_m. If x_m differs from x_c, the wedge system is then in a position to compensate for a difference in air path, the amount depending upon

the calibration constant of the screw. This air-path difference is accomplished by tilting auxiliary plate L about an axis perpendicular to the plane of the drawing in figure 2. The plate is tilted until the black fringe is alined with the cross hair. A number of fringes are now observed in the auxiliary-plate pattern. The fringe width will depend upon the magnitude of $x_m - x_c$ and the calibration constant of the screw. This can be explained by noting that when the auxiliary plate is tilted the position of zero air-path difference immediately moves to the intersection of the plane of symmetry of the prism and the plane of the auxiliary plate. When the micrometer is advanced from x_c to x_m, plate L must be tilted so that the difference in height between positions conjugate to the cross hair must be equal to $(x_m - x_c)K$. Then the black fringe will be alined with the cross hair. Thus, the angle of tilt is determined and the magnitude of this tilt determines the fringe width. If it is found that the fringe width is inconvenient for use, the position of x_c on the scale should be changed. This may be accomplished by the use of the micrometer-scale adjustment mentioned in procedure 4.

7. The calibration constant, K, of the micrometer screw must still be determined. White light is replaced with monochromatic light of wavelength λ. Auxiliary plate L is tilted so that one broad fringe forms the auxiliary-plate pattern. One can then determine the calibration constant of the screw by counting the number of fringes in the gage-block pattern that pass the cross hair for a given advance of the micrometer screw. One can determine the calibration constant by the equation

$$K = \frac{\lambda}{2} \frac{\Delta N}{\Delta x},$$

where λ is the wavelength of the monochromatic source for standard air conditions, and ΔN is the number of gage-block fringes passing the cross hair for an advance Δx of the micrometer screw. If it is found that K is different than that specified by the design, the calibration constant may be changed by rotation of wedge G. If this is done, wedge F is rotated until a single broad fringe again forms the wringing-plate pattern.

8. If desired, one can check the lack of invariance of K with wavelength by determining K for various wavelengths. The alinement is then completed by replacing the monochromatic source with a white-light source.

An alinement procedure, such as that mentioned above, is only necessary when the instrument is first assembled or when a reassembly is required. It is to be stressed that it is not a part of the measurement procedure.

The instrument on display at this symposium has a micrometer head with a range of 1 inch. Scale divisions can be read directly to 0.001 inch. The calibration constant varies with wavelength as follows:

$$K_{656.3} = 0.0001998$$

$$K_{589.2} = 0.0002000$$

$$K_{486.1} = 0.0001999$$

$$K_{434.0} = 0.0001998.$$

The subscripts refer to the wavelength in millimicrons. The calibration constant assumed for the instrument is 2.000×10^{-4} as the maximum sensitivity of the eye is at 555 $m\mu$. Using the full range of the instrument (1 in.), a maximum systematic error of 0.2 microinch is involved. As the effective calibration constant is undoubtedly between $K_{486.1}$ and $K_{589.2}$, gage blocks differing in length by as much as 0.0002 inch can be compared with error less than 0.2 microinch. To match this potential precision the micrometer screw must measure the advance of the wedge system more accurately than 0.001 in. per inch. In addition, if a precision exceeding 0.2 microinch is to be obtained in comparing steel gage blocks, the temperature of the gage blocks should be held equal to within 0.01 deg C. per inch of gage-block length. Furthermore, if the measuring surfaces of the gage blocks differ in surface finish a correction for phase change must be applied to achieve this precision. In addition to providing a simplified measuring technique and a large range, this achromatic compensating system provides a precision suitable for exacting laboratory measurements.

The convenient place on the scale for the reading x_c for this instrument was found to be 0.2500 inch. Placing x_m at 0.5000 or 0.0000 on the scale the wedge system is at a position to compensate a difference in height of 50 microinches. Tilting the auxiliary plate an amount to aline the black, zero-order fringe with the cross hair results in approximately six fringes in the field. This provides a fringe width convenient for alinement. With x_m at 0.0000 the whole range of the instrument (0.0002 in.) can be used. Placing x_m at 0.5000 on the scale, the instrument has a range of ±0.0001 inch.

To show the simplicity of the measuring technique when using this instrument, the measuring procedure is given. Assume that the lengths of two gage blocks with equal surface finishes are L_1 and L_2 and that unbeknown to the operator $L_1=L_2+95.4$ microinches.

1. The gage blocks are wrung to the auxiliary plate with the spacing between them such as to cause their images to superimpose in the center of the field of the instrument, as shown in figure 1.

2. After a time interval for temperature equilibrium, the micrometer screw is advanced to a reading of 0.5000.

3. The auxiliary plate is tilted about an axis perpendicular to the drawing in figure 2 until the black fringe of the auxiliary plate pattern is alined with the cross hair. As these fringes will always be parallel with the cross hair and perpendicular to the long dimension of the gage-block image, no other tilting adjustment is required.

4. The micrometer screw is advanced until the black fringe of the gage-block pattern is alined with the cross hair. A reading is taken of the scale. This may be either 0.9770 or 0.0230, depending upon which arm contains the gage block of length L_1. In this interferometer it is known from the design that movement of the wedge platform to the right (fig. 2) increases the optical path, and that the left arm is increased at a greater rate than the right arm. Therefore, if the reading is 0.9770, the longer gage block, L_1, is in the left arm and

$$L_1=L_2+0.0002000(0.9770-0.5000)$$

$$L_1=L_2+95.4 \text{ microinches.}$$

To conclude the description of the component parts and the operational procedure, it may be well to consider some of the advantages possessed by this instrument. While some of those listed below are common to other methods of interference comparison, it has other advantages that make it unique as an interference comparator. It is believed that these advantages make it necessary seriously to consider this interferometer as a practical comparator:

1. No measuring pressure is exerted on the gage-block surfaces.
2. It has good precision combined with an adequate range.
3. No prior knowledge of the difference in length of the gage blocks is required to avoid misinterpretation of the interference order.
4. The measuring procedure is relatively simple, and the need for training of the operator is kept to a minimum. No estimation of fringe fractions is involved.
5. The air paths and gage blocks are in close proximity at the time of measurement.
6. The parts are stable and, with the exception of the light source and the auxiliary plate, should last for years without replacement or maintenance.
7. Once assembled, the instrument does not require special monochromatic light sources.
8. Effects of vibration are reduced as the interferometer is sensitive only to vibrations tending to tilt the auxiliary plate with respect to the prism about an axis perpendicular to the plane of the drawing in figure 2.
9. The interferometer can accommodate a turret-type auxiliary plate for convenient comparison of more than one pair of gage blocks.
10. Although time does not permit discussion here, it is possible to measure absolute lengths with this interferometer by replacing the white-light source with a monochromatic source.

5. A High-Sensitivity Interferometer for Measurement of Phase Shift and Other Applications

By J. B. Saunders [1]

An interferometer arrangement is described that permits greater sensitivity than has previously been available. Its principal application is the measurement of thin films and also absolute phase shifts at reflection. With highly reflective surfaces, such as fresh silver, as many as fifty reflections may be used and, in such case, one order of interference will correspond to approximately one hundredth part of a wavelength of the light used. A method for applying this interferometer to the measurement of phase shift of light from metallic surfaces and for the comparison of gage blocks is described.

1. Introduction

The accuracy of measurement attainable in interferometry is limited by the inability of the operator to duplicate settings on the centers of the interference fringes. The principles of multiple reflections introduced by Fabry and Perot,[2] and further developed by Tolansky,[3] reduce the error of fringe readings by reducing the width of the fringes relative to their separations. However, asymmetry of the curve for light distribution about a minimum (center of narrow dark fringes) increases the difficulty of locating the minimum or darkest point.

This paper describes another method of multiple reflections that reduces the error in results due to error of reading the fringe fractions. Its applications are limited to small order differences and to small changes in order. Some of these applications are as follows: (1) Comparison of gage blocks, (2) variations of index of refraction in transparent fluids and solids, (3) thermal expansion, (4) thicknesses of thin films, and (5) the electromagnetic phase shift of light when reflected at a boundary. Numbers one and five of the above mentioned applications are of vital importance in the measurement of gage blocks. The phase shift (5) varies with wave length, with roughness or finish of surface, and from metal to metal.

The discussion of this paper is primarily directed to the measurement of phase shifts of light vectors at reflection. This involves measurements of wringing films (separation of gage block and the base plate to which it is wrung), surface-finish effects, and measurement of small differences between gage blocks. Because these quantities are often of the same order of magnitude as the errors in determination of fringe fractions, errors in the reading of fringes are very important.

2. Phase Shift of Light at Reflection

When light is propagated by transmission through any medium the phase change of the electric vector is uniform, continuous, and con-

[1] National Bureau of Standards, Washington.
[2] Ch. Fabry and A. Perot, Ann chim. phys. 22, 564 (1901).
[3] S. Tolansky, Multiple-beam interferometry of surface films (Oxford, Clarendon Press, 1948).

stant with time. If we represent time, measured from the time of emission, by T (fig. 1, A) the phase, β, of the vibrating light vector is proportional to T. That is, $\beta = kT$, where k is a constant of proportionality. If at some later time, T_1, (fig. 1, B) the light is incident upon the polished surface of a dielectric, the light beam is divided

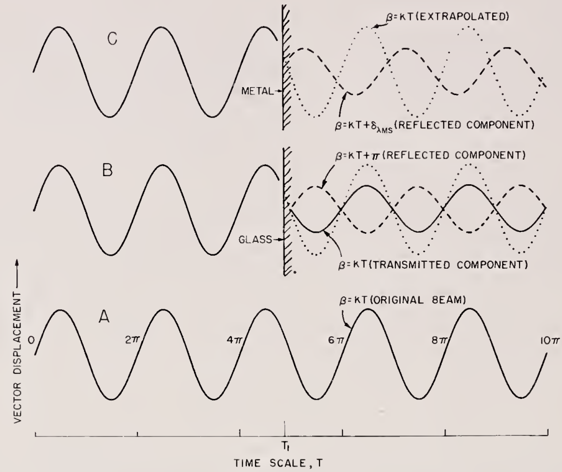

FIGURE 1. *Change in phase of light vectors with time, and at boundaries.*

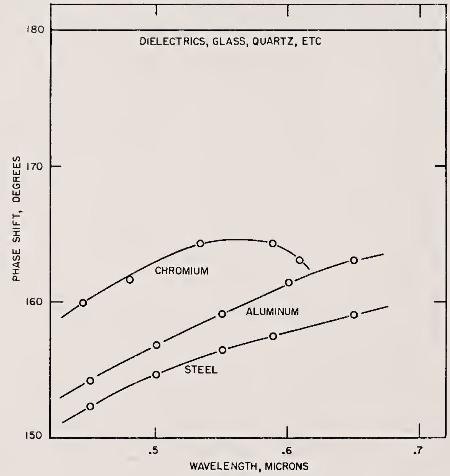

FIGURE 2. *Change in phase of light vectors at reflection from metals and dielectrics.*

into a reflected and a transmitted component. The phase of the transmitted component remains proportional to time T. The reflected component suffers a large increase in rate of phase change that lasts for a very short time during the reflection, in the neighborhood of T_1. The directions of the component beams are not shown in figure 1. No geometrical directions are indicated. The abscissas represent time, and the ordinates represent amplitudes of the vector displacements. The differential phase change between the transmitted and reflected components, for dielectrics, is precisely π radians for all wavelengths of light. The phase shift for metals ($\delta_{\lambda_{ms}}$ in fig. 1, C) is always less than π radians.

If the face of the reflecting surface has scratches, sleek marks, pits, etc., the quantity T_1 differs for different parts of a wave front, assumed parallel to the surface. This introduces a spread in values of the phase, β, for the reflected component beam. The observed phase will be some form of an average. However, as scratches, sleek marks, and pits do not affect the position of the measured geometrical surface, the phase change resulting from them is properly considered as due to the finish of the surface.

A graph, showing variations in phase shift, δ, at reflection with wavelengths, λ, for several materials, is given in figure 2. The change in β for steel between wavelengths $\lambda=0.4471\ \mu$ (helium violet) and $\lambda=0.7065\ \mu$ (helium red) is approximately 7.9° or more than one-fiftieth (0.022) of an order of interference. When measuring a 1-mm gage block, this change in order equals that caused by a change in atmospheric pressure of 15 mm of mercury, or to that caused by a change of 0.4° C in the temperature of the gage block.

3. Methods of Measurements

Several interference methods of measuring the phase of light at reflection have been used. In making such measurements with most methods the thickness of the "wringing film", the effects of surface roughness, and small differences in gage blocks require consideration. The quantities being measured in all of these methods are so small that other errors of measurement prevent the attainment of high accuracy in the results. The arrangement described herein increases the magnitudes of the fringe shift and related effects, relative to other errors, by using multiple reflections from the samples.

Consider two plane reflecting surfaces, M_1 and M_2 (fig. 3), that are adjusted to form a small angle α between them. If mirror M_1 receives a collimated beam of light, incident at an angle φ that is greater than α, the beam will be reflected back and forth between the mirrors. The angle of incidence decreases by an amount α at each successive reflection. At the Nth reflection it is $[\varphi-(N-1)\alpha]$. If φ is adjusted to equal an integral multiple of α, the beam eventually becomes normal to one surface; after which the angle becomes negative, increasing in the negative direction until it becomes $-\varphi$; after which the beam returns along the incident path.

If N equals the total number of reflections and the angle of last incidence is equal to the negative of the 1st incidence, then $\varphi-(N-1)\alpha=-\varphi$, or

$$2\varphi=(N-1)\alpha. \tag{1}$$

The light appears to be reflected from M_3, which is an image of M_1, if $(N-1)/2$ is even, and is an image of M_2 if $(N-1)/2$ is odd. In the interferometer arrangement, to be described here, surface M_3 represents an end mirror and receives, normally, one of the component beams that produce interference.

In order to arrange the elements properly, it is important to know the magnitudes of the following defined quantities, shown in figure 3:

A is the normal aperture; B and $(A+B)$ are the distances from the vertex of α to the points where the two limiting rays become normal to a reflector; C is the distance traveled by one limiting beam between the first and normal incidence; L_1 and L_2 are the lengths of surfaces used on M_1 and M_2, respectively; D and S are the distances indicated

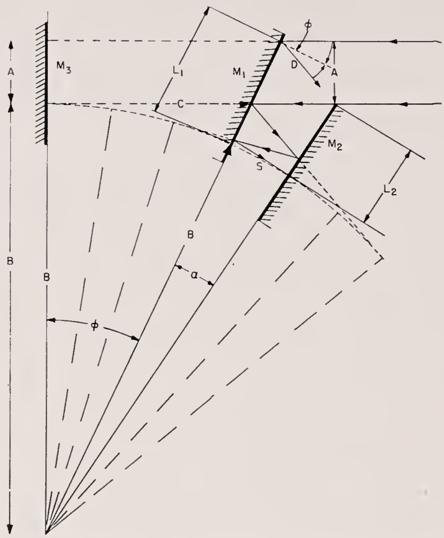

FIGURE 3. *Geometry of "increased-sensitivity interferometer".*

in figure 3. By applying the laws of trigonometry, one obtains the following formulas:

$$
\begin{aligned}
&A=D\sin 2\varphi \\
&(B+L_1)\sin\alpha=D\cos(\varphi-\alpha) \\
&(B+L_1)\cos\varphi=A+B \\
&(B+L_2)\cos(\varphi+\alpha)=B \\
&C=B\tan\varphi \\
&S=B\tan\alpha.
\end{aligned}
\tag{2}
$$

These six equations contain seven unknowns (assuming N, α and, in consequence of eq (1), φ known). By assigning a value to any one, the remaining six unknowns can be evaluated.

Some of these quantities will be limited by available instrumentation. The values of L_1 and L_2 cannot exceed the lengths of the faces of the gage blocks when measurements of gage blocks are to be made. The value of N will be limited by the intensity of the available light source and the reflectances of the surfaces. The author prefers to choose N as large as practical and to adjust A to a maximum, consistent with limitations upon other quantities. When measuring phase shifts at reflection the angle of incidence is restricted also, as phase shifts vary with the angle of incidence.

Figure 4 is a plot of phase shift, δ, for steel against φ, the angle of incidence. Curves are shown for light polarized parallel and perpendicular to the plane of incidence. These values were computed from Minor's [4] determination of optical constants and electromagnetic theory. It is seen that δ_{S20} (the value of δ_S at 20° incidence) differs from δ_{S0} by 1.3° for light polarized perpendicular to the plane of incidence. Similarly, $\delta_{P0}-\delta_{P20}=1.4°$ and $\delta_{S20}-\delta_{P20}=2.7°$, which corresponds to only 0.0075 fringe. The quantity $(\delta_S-\delta_P)$ represents a spread in phase shift caused by the coexistence of two superimposed sets of fringes that are not quite in phase with each other. The total spread is the summation, $\Sigma(\delta_S-\delta_P)$, for all reflections from the samples. If 7 reflections are used, there will be 2 reflections at 20° incidence, 2 reflections at 13⅓° incidence, 2 at 6⅔°, and 1 at 0° or normal. The

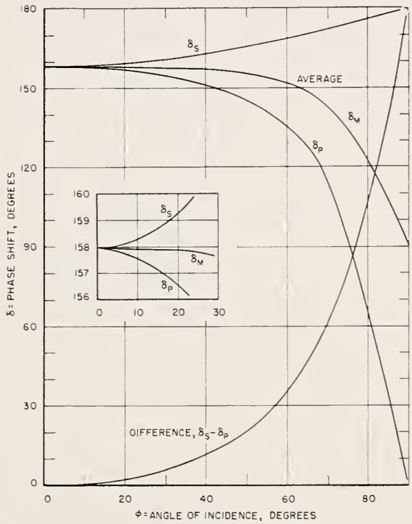

FIGURE 4. *Variation of phase shift at reflection with angle of incidence.*

The subscripts S, P, and M refer, respectively, to light polarized normal to the plane of incidence, parallel to the plane of incidence, and to the average or unpolarized light.

total spread is found to be 3.76°; or the change in the order of interference at any point due to changing from light that is polarized in the plane of incidence to light polarized normal to it is approximately 0.01 of a fringe. The observed fringe position, with unpolarized light, is the average. Figure 4 shows that δ_M remains very nearly constant for values of φ less than 20°. Consequently, no appreciable error is introduced by the change of phase with angle of incidence, provided φ does not exceed 20°.

The number of reflections, N, is obtained by direct observation of images of a small light source. Figure 5 shows the array of images of a light at L, seen by looking into mirror M_1. The subscript, v, of any image I_v represents the number of reflections from the two mirrors.

4. Measurement of Phase Shift at Reflection

One method of measuring phase shifts at reflection from metal gage blocks will be described. A wedge of small angle, α, and appropriate thickness is made with high-quality surfaces (see fig. 6, A).

[4] R. S. Minor, Ann. phys. **10**, 581 (1903).

Three holes are cut through the wedge, as shown in figure 6, B. A high-reflectance plane mirror, M_2, is contacted to the upper surface of the wedge, and three gage blocks are contacted to the lower face of the wedge; each block covering one of the three holes in the wedge. This places the three upper surfaces of the three gage blocks coplanar, if the wringing films are equal. We shall assume equality of the wringing films. This condition is practically attained if the blocks are "optically contacted" to the wedge.

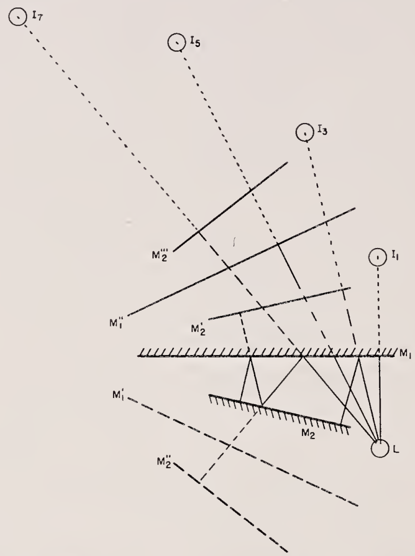

FIGURE 5. *Multiple imagery from multiple reflection of light between two mirrors.*

The subscripts of I represent the number of reflections suffered by light that produces the corresponding images.

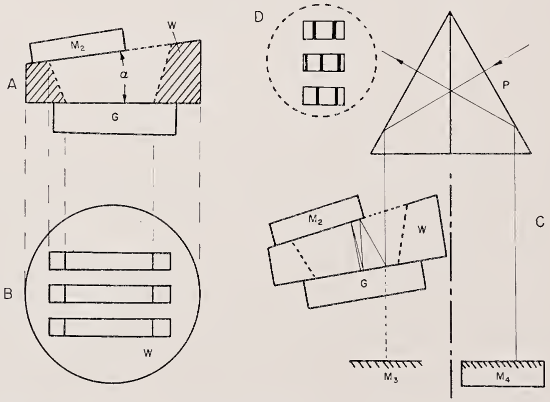

FIGURE 6. *Arrangement of an interferometer for measurement of phase shift of light at reflection.*

W is a wedge, M_2 a plane, high reflectance mirror, M_3 an image of M_2, M_4 an end mirror, G a gage block, α the angle between gage blocks and mirror M_2. B is a top view of W. C is a side view of a Kösters double prism interferometer. D shows the relative shifts of fringes that arise from differences in phase shift at reflection.

If this combination is introduced into one arm of an interferometer, as is shown in figure 6, C, interference may be obtained. The fringes (fig. 6, D) produced by interference of the two component beams, over the area of the unobstructed part of the beam that is reflected from the gage blocks and mirror M_2 combination, will form a single set of straight fringes if the phase shifts at reflection from the three gage blocks are equal. However, if one of the gage blocks is made of quartz (or glass) and is uncoated, its phase shift will differ from that of the metal gage blocks. There will be a shift in the fringe pattern, as is indicated in figure 6, D, which is a measure of the difference in phase shift at reflection between a dielectric and the metal surface of the gage block. If the light has suffered N reflections from the gage blocks, the magnitude of the fringe shift will be N times that for one reflection. If the metal blocks are of steel and the surface of one of them is a high quality optical surface, free from finish marks, (hereafter designated "the standard") the phase difference between it and the quartz will be approximately 22 degrees. The relative displacement of the observed fringe pattern will, accordingly, be 22 N degrees. If it is assumed that $N=10$, 22 N will equal 220 degrees, or 0.6 fringe—a quantity that may be measured 10 times as accurately as other methods of measuring phase shifts permit.

After having measured the phase shift of the standard metal surface, the phase-shift difference between it and a sample gage block (indicated here by the second metal gage block) is similarly measured. The purpose of using a standard is to obtain a higher reflectance and better observation conditions than are obtainable with the relatively low reflectances possible with uncoated quartz or glass. After having calibrated the standard surface, the quartz block may be replaced with sample surfaces to be measured. The particular arrangement shown in figure 6 permits two specimens to be tested simultaneously. Obviously the method permits an increase in the number that can be mounted together for simultaneous tests.

A more elegant arrangement is obtained by rotating the wedge of figure 6, C, 90 degrees from the position shown and adjusting the lateral position until the images of the specimen and standard coincide—eliminating mirror M_4 completely. The absolute order of interference, determined with polychromatic (white) light, is then a measure of the difference in phase.

5. Comparison of Gage Blocks

Another application of the above principle of multiple reflections is that of comparing gage blocks with standards. For this interferometer, the two gage blocks (a standard and the unknown to be tested) are wrung onto a baseplate in the conventional manner (see fig. 7). Mirror M_2 is adjusted to form a small wedge between it and the tops of the two gage blocks. If the top surfaces of the gage blocks are similar and the wringing films assumed equal, the observed relative shift in the fringe pattern is a measure of the difference in thickness of the two gage blocks.

In order to correlate observed orders of interference with differences in thickness of gage blocks, the top surfaces of the two blocks and that of mirror M_2 are projected to the vertices of the wedges between them (see fig. 8). Since, in general the gage blocks are not perfect parallels, their upper surfaces will usually produce different angles with the surface of mirror M_2, in figure 7. Also, these angles usually differ from the angles between the baseplate and mirror M_2. The details of the mathematics are too extensive to be included here. However, if we define d as the difference in thickness of the two blocks at the point of first incidence, ϵ the angle between their faces (difference in wedge angles), γ the observed angle between the two interfering beams, F the observed order of interference, h the maximum separation between mirror M_2 and the gage blocks, measured

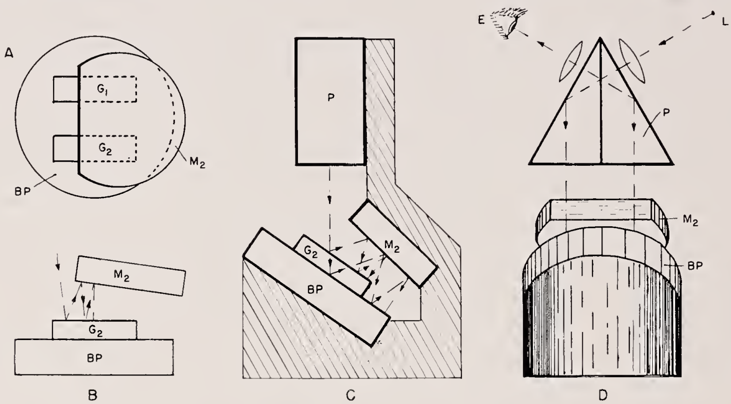

Figure 7. *Plan of interferometer for comparison of gage blocks.*

G_1, G_2 are gage blocks (standard and sample); BP is the baseplate to which the blocks are wrung; M_2, a plane high reflectance mirror; P a Kösters double prism beam divider. A and B are, respectively, a top and a side view of the combination of the mirror, baseplate and gage block. C and D are two horizontal side views of the entire interferometer, at right angles to each other.

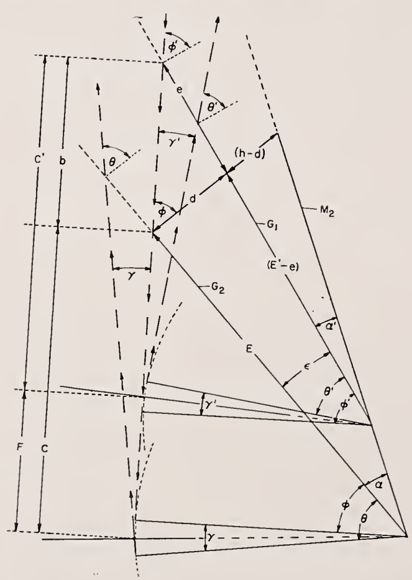

Figure 8. *Geometrical diagram of optics of "increased-sensitivity interferometer."*

The working equations for the interferometer are derived from this figure. Distances and angles are indicated. The lines marked M_2, G_1, and G_2 correspond to mirror M_2 and the gage blocks indicated in figure 7.

from the edge of M_2 adjacent to the aperture, ϕ the angle of first incidence of the beam on the gage blocks, and α the angle between the gage blocks and mirror M_2; then

$$d=\frac{F \sin \alpha}{\sin (\phi+\alpha)}+\frac{h\gamma \cos \alpha}{(\phi+\alpha) \sin (\phi+\alpha)} (\alpha \cot \alpha \sin \phi-\phi \cos \phi) \tag{3}$$

and

$$\epsilon=\frac{\alpha\gamma}{\phi+\alpha}. \tag{4}$$

The second term in eq (3) vanishes when γ becomes zero. This condition is satisfied when measuring thicknesses of evaporated films that are uniform in thickness, and when the two gage blocks have equal wedges that are properly oriented with respect to M_2. Because α is usually small, the coefficient of γ in eq (3) will always be comparable in value to that of the coefficient of F. If one-tenth of a fringe error in F is considered insignificant and γ is of this order of magnitude, then the second term of eq (3) becomes negligible. In any case, γ may be measured as precisely as F. Consequently, the principles of this instrument also afford a precision method for testing and measuring the parallelism of surfaces.

An interferometer of the above description is under construction. Measurement of phase shifts at reflection is contemplated for a first application.

6. An Improved Angle Interferometer

R. E. Sugg [1]

1. Introduction

The relation that length gages bear to the precise measurement of angles is apparent when the use of gage blocks with sine bars is considered. All the opportunities for error inherent in stacked blocks are present in this method of angle measurement and also in the use of angle blocks. In addition, observational errors may be greater than incurred in length measurement.

Our experience, substantiated by others [2] has been that claims made for the accuracy of angle blocks to ±1 sec of arc and for dividing heads and rotary tables to ±2 to 5 sec are often excessive. In order to use these media for measurement or positioning in the tolerance range of 1 to 5 sec, a means of calibration is required with an inherent accuracy to an order of magnitude greater (i. e., ±0.1 sec). This is an exceedingly small quantity, being approximately 1/13,000,000 part of a circle, and may be visualized as the angle subtended by the edge of a sheet of writing paper at 500 ft. At the edge of a 4-in.-diameter circle this amounts to less than a millionth of an inch, and, as usual when dealing in microinches, the use of an interferometer is indicated.

An interferometer for angle measurement was developed by T. J. O'Donnell, several years ago.[3] A similar instrument was constructed by Moore Special Tool Company for use in calibrating the precision rotary tables they manufacture. The instrument to be described is a modification of these designs to achieve freedom from error due to variations in ambient conditions, to assure ease of use, and to provide simplification in manufacture.

2. Principle of the Angle Interferometer

So far as we know, the use of interferometers for the direct measurement of angles has not been published, and a description is in order. It may be seen from figure 1 that the instrument is basically a Michelson interferometer in which the reflecting mirror in one of the light paths is replaced with two mirrors, one above the other on a rotary table, and inclined to each other at the angle desired for measuring or indexing. In order to set this angle to the required accuracy, the following steps are to be followed:

1 With the table set on zero and the mirrors set to the approximate angle, the mirrors are rotated until the required fringe pattern appears from either the upper or lower mirror.

[1] E. I. du Pont de Nemours & Co., Wilmington, Del.

[2] C. F. Bruce and W. A. F. Cuninghame, Measurement of angle by interferometry, Australian J. Appl. Sci. 1, 243 (1950).

[3] T. J. O'Donnell, The angle step plate interferometer (Physical Sciences Development Shops, Univ. Chicago, Oct. 27 and 28, 1952) (unpublished).

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2. The table is then rotated the exact angle of the mirrors until the fringe pattern appears from the second mirror.

3. The mirrors are then rotated counter to the table rotation until the pattern appears from the first mirror.

4. Repetition of the above steps is continued until the table has been rotated 360° or some multiple of 360°, plus or minus the amount of error in the mirror angle multiplied by the number of steps taken.

5. Compensation for the error may be made by resetting the mirrors or by arithmetic elimination.

It is apparent that the angle interferometer is, therefore, merely an ultrasensitive circle divider. Its accuracy is largely dependent upon the number of steps taken during the process of error determination. Accuracy is also dependent upon the magnitude of temperature variations during the setting and measuring cycle, sensitivity of

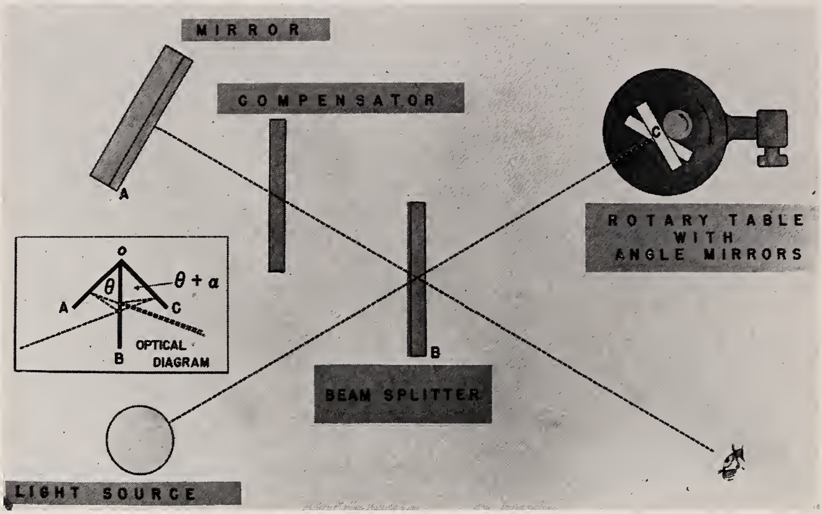

FIGURE 1. *Diagram of the angle interferometer.*

components to temperature variations, and to the optical resolution. The effects of temperature changes are essentially the same as those encountered in any gaging work, but the effects of resolution as determined by the aperture of the system, or effective mirror size, do need explanation.

Referring to figure 1, the back mirror, A, and the beam splitter, B, make an angle θ, which is matched as closely as possible in setting rotatable mirror C. The residual error, α, which is always indetectable, is determined by the length *OC*, which is the width of rotatable mirror seen in reflection from the various mirror surfaces. This arises from the fact that fringe deviation can only be accurately estimated to about two-tenths of the spacing and, as a second of arc is 4.85×10^{-6} radians, simple geometry determines that if *OC* is 1 in., α will be about ± 0.443 sec when the green line of mercury is used as a light source. α may be reduced to ± 0.1 sec by making the length of the rotatable mirror about 5 in. and the size of the other glass parts comparable. Of course, sensitivity may also be increased by a more precise method of determining fringe location than by visual observation of monochromatic fringes, but this complicates the system and will not be discussed now.

3. Design and Construction Details

Figure 2 shows the angle interferometer set up for use. In order to minimize temperature effects, all metal parts are made of Invar, heat treated to provide nominally a zero coefficient of expansion.[4] Not entirely relying upon the attainment of a zero coefficient, however, the apparatus for holding, adjusting, and rotating the angle mirrors has been made with as few parts, as compact, and as symmetrical as possible. This is the real heart of the instrument, since a shift of a few millionths of an inch in some parts during use could introduce an error greater than the accuracy attempted in measuring or indexing.

As previously indicated, the width of the angle mirrors is 5 in. The back mirror and the plates are 6 in. in diameter with all mirrors made of fused quartz and the interferometer plates of selected crown

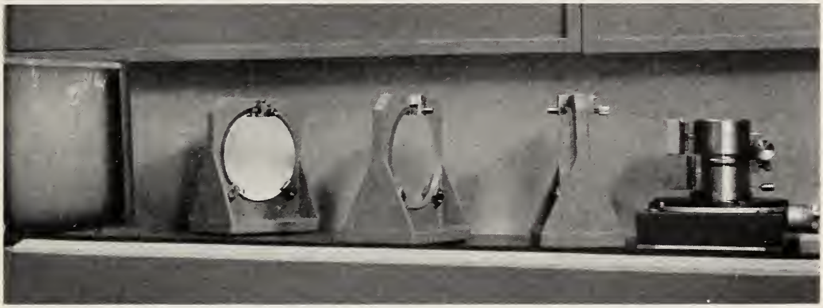

FIGURE 2. *Angle interferometer set up for use.*

The light source appears at the left with the angle mirrors and rotary mechanism at the right.

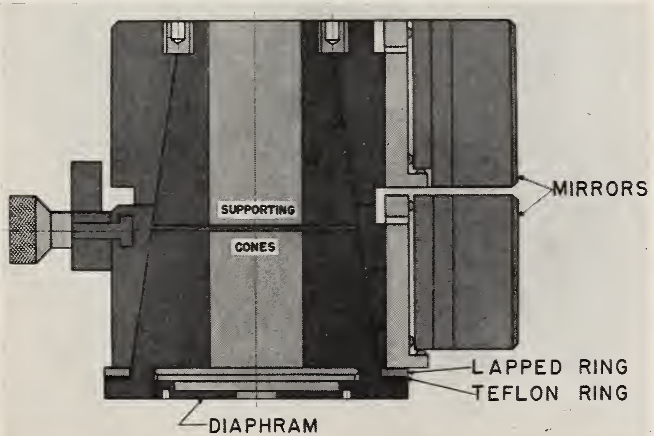

FIGURE 3. *Cross section of angle mirror assembly.*

The equipment for fine adjustments is not shown.

[4] B. S. Lement, B. L. Averbach, and Morris Cohen, The dimensional behavior of Invar, Trans. Am Soc. Metals, 43, 1072 (1951).

glass. Flatness and parallelism were held to tolerances better than $\frac{1}{20}$ wavelength.

A cross section of the angle mirror assembly is shown in figure 3. Provision is made for fastening the unit to the rotary table through a diaphragm to prevent any distortion of critical parts. The carrier for the bottom mirror rests principally upon a thin Teflon ring (0.002 in. thick) and partly upon the lower cone. The upper cone, attached to the lower carrier, provides a similar seating arrangement for the upper mirror carrier. The cones are plated with 0.001 in. thick porous chromium of the channel type. Before assembly, watch oil was applied to the chrome and then wiped as dry as possible.

Proper weight distribution between cone and base was achieved by lapping the Invar ring, shown above the Teflon, until smooth rotation without any tendency for "stick-slip" action was achieved with absolute positioning of the mirrors. Use of the full mirror width is achieved by mounting the mirrors with spring clips inserted in grooves cut into their edges near their back surfaces. This also minimizes distortion from mounting and from changes conceivably occurring in the metal parts.

4. Results and Conclusions

The instrument has just been completed and checked, but has not yet been placed in service for measuring, calibration, or indexing. An interesting feature is that it is essentially self-checking—by necessity, because no other standard is sufficiently accurate; and by nature,

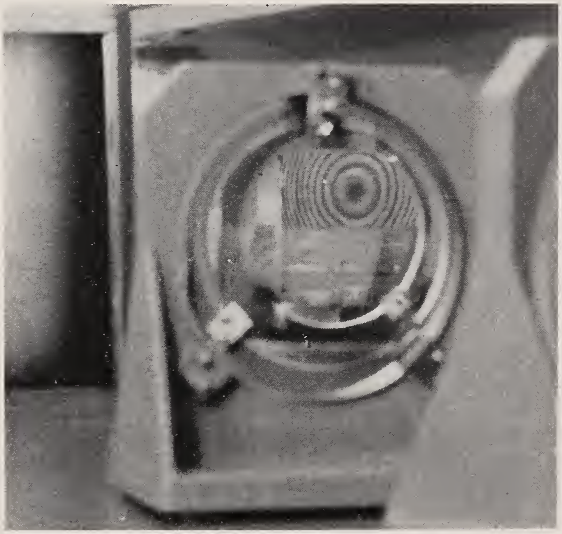

FIGURE 4. *Fringe pattern as seen when the top mirror is in position.*

because deviations of 0.1 sec may be detected by a suitable number of steps in closing the circle over a multiple of 360°.

The fringe pattern as seen by the eye is shown in figure 4. Zero position of the mirrors is determined when no change in the fringes occurs as the eye is moved to sweep the center of the pattern from one edge of the mirror to the other. A deviation of one second is shown by two fringes appearing or disappearing in the center, with other deviations showing proportional changes.

Stability of the instrument was checked by setting the mirrors to zero angle (within ± 0.1 sec.). No change could be noted over a 2-hr period, which might be a normal usage time for determining a setting and making a measurement. Over a week end no change could be detected in the position between the angle mirrors, but a drift of 2 sec occurred in the unit as a whole. This was probably in the bed on which the instrument was mounted or in the rotary table. No attempt was made to control the temperature closely, and variations of 50 deg F or more have been deliberately introduced by directing a stream of hot air on one side of the angle mirror assembly without noticeable effect.

It is expected that the angle interferometer will find widest use in the calibration of rotary tables and checking of angle blocks. However, it should also be suitable for direct measurement of many precise machined parts, and it is expected that under some conditions it may be usable for direct indexing in precision machining operations.

Without the previous development work done by T. J. O'Donnell, Physical Sciences Development Shops, University of Chicago, the design and construction of our instrument could not have been undertaken. We are indebted to him and to Fred C. Victory of the Moore Special Tool Company, Bridgeport, Conn., for the construction details of their interferometers and for valuable suggestions which led to our design.

L. C. Eichner of L. C. Eichner Instruments, Clifton, N. J., contributed greatly to the design and constructed the mechanical components. Peter Lenart, Jr., Ferson Optical Company, Ocean Springs, Miss., did an excellent job in grinding the plates and mirrors to tolerances more exacting than the normal requirement for an interferometer.

7. Effect of Unstable Thermal Conditions During the Testing of Long Gage Blocks

By J. C. Moody [1]

Metrologists generally agree that a principal source of error in the making of precision measurements is the variation in temperature between the piece to be measured and the measuring reference. Factors such as vibration, lack of cleanliness, and crowded working conditions also contribute to the measuring errors, but fortunately these can be easily understood and controlled. Temperature problems are not equally simple.

Uncontrolled heat transfer by convection, conduction, and radiation directly affects the temperature of everything in the measuring area. These are fundamental factors, and metrologists at the top measuring echelon—the National Bureau of Standards—consider them all in their efforts to reach the sixth decimal place by means of interferometry.

But what of the industrial laboratory where long gage blocks are tested against masters certified by the Bureau to ± 0.000001 inch per inch of length? The thermal factors so carefully considered by the Bureau also affect the accuracy of work done in industrial laboratories. However, it is both impractical and unnecessary for such laboratories to carry their work to the same degree of closeness as is needed by the Bureau.

The studies described here were undertaken by Sandia Corporation primarily in an effort to standardize a simplified but reliable procedure for the testing of long gage blocks. The principal variables affecting this operation are temperature, geometric shape of the subjects, the relative location of the master and sample during the thermal-equilibrium period, the length of the thermal-equilibrium period, and the finish and color of the surfaces. It was assumed at the outset that if a quantitative measure of the length caused by these variables could be clearly established, industrial gage laboratories could use this information to increase their accuracy in measuring long gage blocks.

A light-colored, 20-in. Hoke gage block that had been certified by the National Bureau of Standards to be 20.000040 in. long was selected as the master for this test; a darker-colored, 20-in. working Hoke gage block was selected as the sample. A 24-in. comparator equipped with a 10,000$\times$ magnification milliammeter box with a full scale of 0.0005 in., each graduation 0.00001 in., was the measuring device used. An accurate temperature recorder completed the required equipment.

The first step was to determine the difference in length between the master and sample. Since the temperature of the measuring room remained constant within ½ deg F during the 12 hr immediately preceding the start of the work day, the nearest approach to thermal equilib-

[1] Physical and Electrical Standards Department, Sandia Corp., Albuqerque, N. Mex.

rium occurred just at the beginning of each work day. To take advantage of this fact, the test pieces were set up for calibration in the afternoon and readings taken at the start of the work day. These preliminary tests were repeated daily for a week and showed that the sample was 0.000030 in. longer than the master.

During the first day after this preliminary calibration had been completed, the temperature in the measuring room was erratically cycled through an extreme temperature variation of 6 deg F. The master and the sample were spaced 5 ft apart on the work bench between tests, and readings were taken at intervals of approximately one hour throughout the day. Under these extremely unfavorable conditions, a maximum deviation of −0.00007 in. from the established value of the sample was obtained.

The identical procedure was repeated the next day except that the temperature was controlled to a gradual rise of 3 deg F from 7:30 A. M. to 4:30 P. M. In spite of this greatly reduced temperature variation, the maximum deviation of −0.00007 in. from the established value was again recorded.

In an effort to determine the cause for this behavior, on the following day the relative positions of the master and sample between tests were reversed. . The temperature was again controlled to a gradual rise of 3 deg F during the day. This time a maximum deviation of +0.00010 in. from the established value was recorded. The fact that the deviation in this test was in the opposite direction from that found the previous day indicated that thermal conditions differed between the two areas 5 ft apart in which the subjects were kept between the tests. This indication was confirmed by velometer tests which showed the air velocity in the one area to be greater by a factor of 5 than that in the other area.

For the fourth test, the temperature was again allowed to increase 3 deg F during the day, but this time the subjects were stored immediately adjacent to each other in that area of the bench where the air currents were negligible. For the first 4 hr the established difference of +0.00003 in. was read on each hourly test. But the reading taken at 1 P. M. showed a difference of +0.00006 in., indicating a change of +0.00003 in. from the established value. This change remained constant throughout the rest of the day.

Those results indicated that the conditions allowed to prevail during this test were not adequate to insure minimum measuring error. But two interesting questions were raised by the test: First, why was the change in length preceded by a lag of 4 to 5 hr? Second, why did the change occur so abruptly and then stabilize?

A review of the results obtained to this point suggested that the effect of the difference in color between the sample and the master on the magnitude of over-all error was considerable. In an attempt to evaluate this effect, another test was undertaken. The temperature control unit of the measuring room was allowed to function normally so that the room temperature was held at 68 to 68.5° F.

Both gage blocks were set up on the base of the measuring machine and were left there throughout the test so as to minimize the necessary handling. With all the lights left on in the measuring room, a gradual growth of 0.00001 in. in the sample was observed. When the overhead lighting was reduced, the size of the deviation diminished accordingly. Apparently this effect was a result of the difference in reflectance values between the darker colored sample and the lighter maste

More radiant heat was being absorbed by the darker subject, causing it to expand more than did the lighter. Here then is a culprit easily overlooked—radiant heat from overhead lights.

To bring these experiments to a conclusion, one more test was necessary. The conditions of the previous test were duplicated except that all lights were turned off except one small unit in the corner which gave only the minimum light needed to read the instruments. Under these conditions, the results of the hourly tests were consistent. The

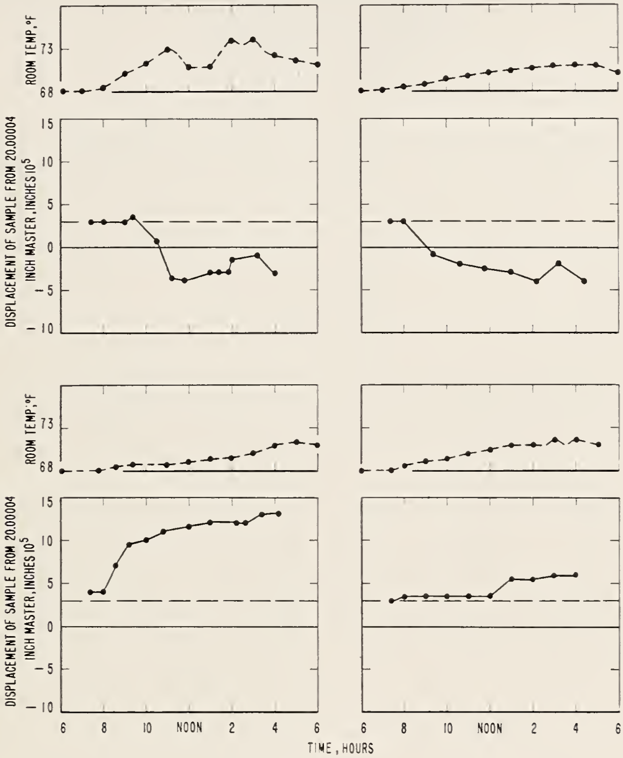

Figure 1.

length of the sample remained 0.00003 in. greater than that of the master.

On the basis of this series of tests, a technique for the testing of long gage blocks was established. This technique requires: (1) that the master and sample be allowed to stabilize thermally in an area where the thermal conditions are uniform; (2) that the subjects be placed on the comparator at least 1 hr before calibration; (3) that the temperature in the measuring area be held stable within ½ deg F; (4) that the subjects be protected from direct illumination; (5) that the master and sample be of the same geometric shape; and (6) that the measuring area be carefully studied for possible thermal instability due to air currents and due to radiation from the walls or from other heat emitting sources in the measuring room.

A practical test was conducted the following week. The master and the sample were taken out of storage, thoroughly cleaned, and left on the work bench for 24 hr to stabilize. The next morning the lights were reduced to a bare minimum and the gage blocks set up on the comparator base. A reading was taken 1 hr later. The sample measured 0.00003 in. longer than the master, the exact difference established at the outset of these experiments.

8. Secular Length Changes of Gage Blocks During Twenty-five Years

By Walter B. Emerson [1]

Secular changes in length during twenty-five years were determined for nineteen steel end gage blocks of known composition and heat treatment. Although the composition and heat treatment of all gage blocks were reportedly the same, some of the blocks appear stabilized after an initial decrease in length, whereas others continue to increase either at uniform or reduced rates.

The material commonly used for gage blocks is hardened steel, but if this material is not stabilized by proper heat treatment, large secular changes in the gages may occur. Changes in length of steel blocks subjected to various heat treatments have previously been observed over relatively short periods, but to my knowledge no accelerated aging test has been devised that can definitely be correlated with changes that may take place in a gage block under normal conditions over a long period. Changes that have occurred in NBS gage blocks during 25 years may therefore be of interest and possibly of value.

A series of four 1-in., two 2-in., three 4-in., two 50-mm, and two 100-mm AA quality Johansson steel gage blocks (set 1010) of known composition and heat treatment [2] was purchased in 1929. These were selected by C. E. Johansson for excellence of planeness, parallelism, and surface finish. Their lengths were determined upon receipt and at irregular intervals thereafter. In addition to these gage blocks, four 1-in., one 2-in., and one 4-in. Johansson blocks of probably the same composition and heat treatment were obtained in 1927 (set 410). Data on these are included in this report.

Absolute lengths of the gage blocks were determined by the interferometric method described by Peters and Boyd.[3] This is essentially a modification of the Fabry-Perot method, using the gage blocks as separators for the interferometer plates. The four 1-in. blocks obtained in 1927 (set 410) were calibrated by this method and then sent to the National Physical Laboratory, Physikalisch-Technische Reichsanstalt, and the Bureau International des Poids et Mesures to determine the uniformity of interferential calibrations. Measurements of the individual laboratories differed from the mean by 0 to 1 μin. Excellence of agreement of the international laboratories was further confirmed by calibrations of decimeter end gages in 1935. These gages were made of fused quartz to minimize the effect of temperature. The comparisons gave the same lengths to an average deviation of 0.016 μ (1 part in 6 million) and to a probable deviation much less.

Gage blocks of the same material and surface finish, and of the

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[1] National Bureau of Standards, Washington.

[2] Confidential data furnished by Edward C. E. Johansson.

[3] C. G. Peters and H. S. Boyd, Interference methods for standardizing and testing precision gage blocks, BS Sci. Pap. 17, 677 (1922) S436.

same approximate length may be accurately compared by the more rapid Fizeau method (see footnote 3).

Lengths here reported are based upon combinations of the two methods. Absolute lengths of a few of the gage blocks were determined by the Fabry-Perot method. Lengths of the other gage blocks were then obtained by comparison with these. This procedure may involve an error of perhaps 1 to 2 μin. in some gage blocks, as for example when a 4-in. gage block is determined by comparison with a combination of two 2-in. gage blocks, the length of one of the 2-in. gage blocks having been determined by the Fabry-Perot method.

Another factor to consider is wear resulting from wringing. Rolt [4] has shown that lengths decreased 2 μin. by 200 wringings for gage blocks with surface finish comparable to these and thereafter remained constant. Practically all change results from the first 50 wringings. It is considered probable that most of the wear of the NBS gage blocks took place within 5 years after the initial measurements.

Figures 1, 2, 3, and 4 give differences from nominal lengths during a period of approximately 25 years for the set 410 and the set 1010 gage blocks.

Figure 1 shows increases in length ranging from 3 to 21 μin. for set 410 (1 in.) gage blocks. The rate of increase appears to be maintained after 25 years. Any wear of the gage blocks during the first few years is masked by the tendency of the gage blocks to increase in length. Set 1010 (1 in.) gage blocks Nos. 1, 2, and 3 show a small initial decrease in length and then remain quite constant. Number 4 increased 12 μin. and was still increasing but at a less rapid rate after 25 years.

The 2-in. gage blocks, Nos. 1 (set 1010) and 2 (set 410), (fig. 2), showed a decrease of 4 μin. after 7 years and then remained constant or possibly increased slightly, whereas No. 3 (set 1010) increased for 25 years, although at a less rapid rate since 1942. The 1951 value for this gage is somewhat questionable as it was obtained from comparisons that involved errors of wringing that could increase the determined length 1 to 2 μin., whereas the 1955 value is based upon direct absolute determinations.

All 4-in. gage blocks (fig. 3) grew at fairly constant but different rates for the individual gages from 1929 to date, and give no indication of leveling off.

The 100- and 50-mm gage blocks (set 1010) (fig. 4) decreased 0.160 μ (6 to 7 μin.) from 1929 to 1936 and thereafter remained constant. This initial decrease in length appears greater than would be expected from wear only.

At the suggestion of E. S. Rowland and his associates, at The Timken Roller Bearing Company, two gage blocks (2 in. No. 1 and 1 in. No. 1, set 1010) that appear to be stabilized and two (2 in. No. 3 and 1 in. No. 4 set 1010) that appear to be increasing in length were sent to their laboratory in 1955 for determinations of retained austenite and residual stress.[5] The results of their findings were presented at the Symposium and are given in this Circular.

[4] F. H. Rolt, Gages and fine measurements, vol. 1, p. 169, 170, and 171, (Macmillan and Co. Ltd., 1929).

[5] Determination of retained austenite required that an area approximately ¾ x ¾ in. be etched on one side of the gage blocks. Etching appears to have changed the direction and magnitude of the slope of the gage-block surfaces. Measurements at the Bureau indicated that previous to etching, the length of the gage blocks at the etched side was slightly greater than that at the opposite side. After etching, the length at the etched side was the lesser. The observed changes in differences of length at the two sides of the gage-blocks before and after etching were: 2 in. No. 3, 15 μin.; 2 in. No. 1, 7 μin.; 1 in. No. 4 set 1010, 18 μin.; 1 in. No. 1 set 1010, 8 μin. The differences were greater for gage blocks that were changing in length than for those that appear to be stabilized.

The length changes observed in the present gage blocks are small in comparison with several other gage blocks measured. Unfortunately the composition and stabilization procedures for the latter are not known.

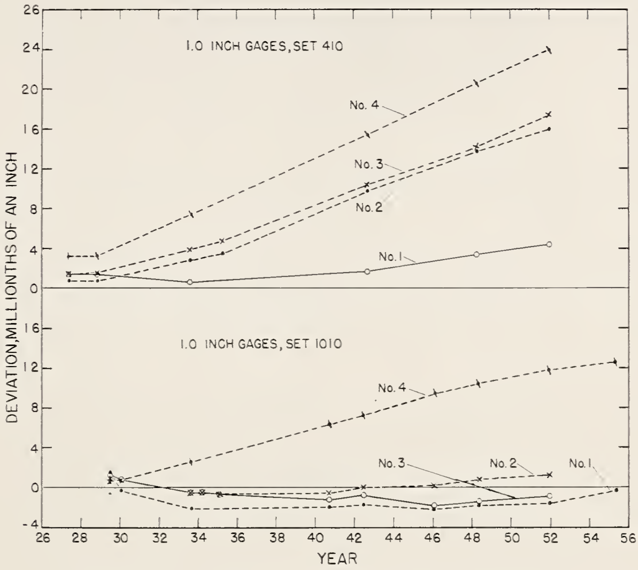


Figure 1. *Length changes of 1-inch gage blocks.*

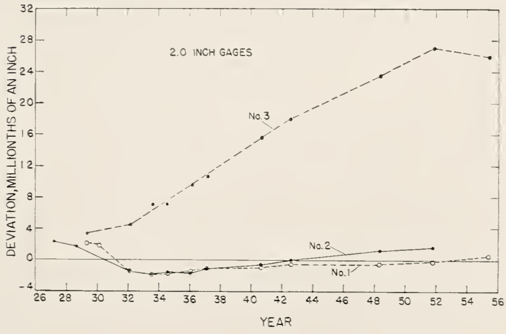


Figure 2. *Length changes of 2-inch gage blocks.*

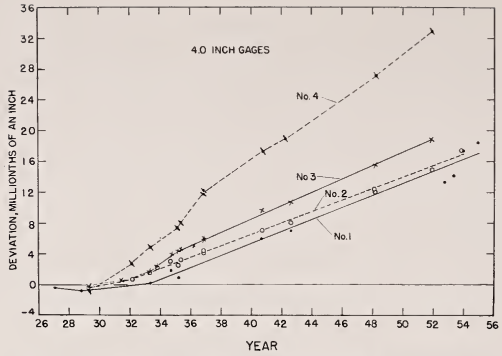


FIGURE 3. *Length changes of 4-inch gage blocks.*

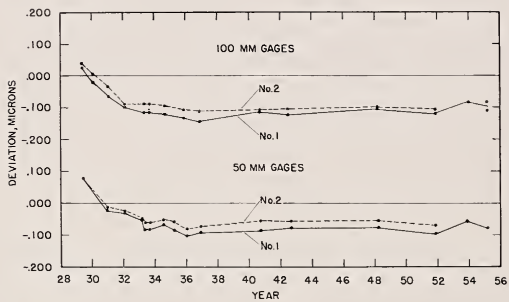


FIGURE 4. *Length changes of 100- and 50-millimeter gage blocks.*

9. Retained Austenite and Residual Stress Measurements on Certain Gage Blocks

By A. L. Christensen [1]

The Timken Roller Bearing Company laboratory was given the opportunity of examining four gage blocks whose length changes have been carefully followed for the past 25 years or so. Two of the gages are nominally 2 in. in length and two, 1 in. One each of the two different sized gages has remained remarkably stable in length during this period of time, whereas the other two have grown uniformly in length in an amount totalling approximately 13 μin./in. The blocks were prepared from 1.3-percent-carbon steel at the Ford Motor Company in 1929.

It was the purpose of this examination to determine if there were residual stress differences or variations in retained austenite contents in the blocks that possibly could account for their rather marked difference in growth behavior. Retained austenite is an unstable nonequilibrium phase in hard steels, with a propensity to transform to martensite with an accompanying increase in volume. Relaxation of residual stress may also cause distortion of the steel samples, and in this connection it is of interest to note that martensite is normally considered to be strain nucleated, and, hence, any plastic flow that might occur has the double effect of stress relaxation and austenite transformation. In other words, transformation of austenite may alter the stress pattern, and relaxation of the stress pattern may in turn influence the austenite to martensite transformation.

The measurements of residual stress and retained austenite in these gage blocks were made by the use of X-ray diffraction techniques, and they are described briefly before presenting the results.

The measurement of stress by X-ray is, as in other techniques, a measurement of strain and not stress (fig. 1). The interplanar distance, d, of a selected family of crystalline planes in the phase under study is used as an internal indicator of strain present, and in the two-exposure method illustrated here is determined at two or more ψ angular orientations of those planes to the direction in which it is desired to measure the stress. The angles normally used are 0° and 45°, or 0° and 60°.

These d values may then be equated to the stress by means of a theoretically derived expression, one form of which is shown in figure 2, or by means of a simple constant of proportionality, usually called the stress constant. In the derivation of this expression it is assumed that the value of E, Young's modulus, and ν, Poisson's constant, remains independent of the orientation of the lattice planes to the direction of stress, or that the material is isotropic. However, if the

[1] The Timken Roller Bearing Co., Canton, Ohio.

stress constant is experimentally ascertained, lack of isotropy does not impair the usefulness of the method.

There is, on the other hand, a problem that exists in the measurement of stress in hard steels, which is not ordinarily present. We note in figure 3, that whereas the diffraction lines are well defined as a whole, they are broad and possess ill-defined peaks, which make

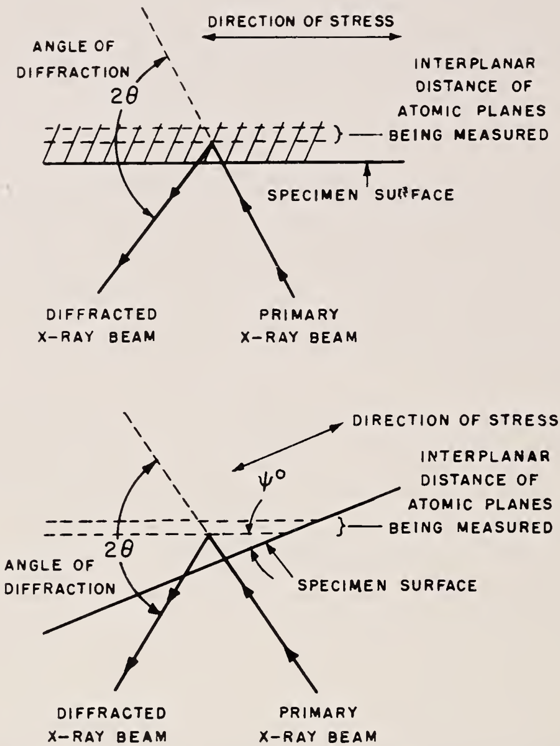
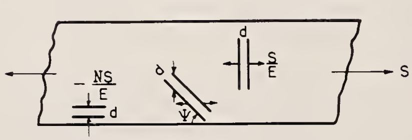


FIGURE 1. *Orientation of measured lattice planes to direction of stress.*

$$d_\Psi = \left[\frac{(1+N)}{E} d_0 S\right] \mathrm{SIN}^2 \Psi + d_0 \left(1 - \frac{NS}{E}\right)$$

OR $d_\Psi = C\ \mathrm{SIN}^2\Psi + B$



$$S = \left(\frac{d_\Psi - d_\perp}{d_\perp}\right)\left(\frac{E}{1+N}\right)\frac{1}{\mathrm{SIN}^2\Psi}$$

OR $S = K\Delta d$

FIGURE 2. *Expression for relation of residual stress to interplanar distance.*

it difficult to determine their positions with sufficient precision for adequate stress measurement. Fortunately, in stress measurement, we are not concerned with absolute line positions but only in the relative line position obtained at each ψ angle used. Thus, we may take advantage of the fact that the line sides are linear over a fair range and extrapolate them to their peaks for their relative positions. But one complication yet remains. A change in line symmetry is observed as the sample is shifted from one ψ angle to another, and

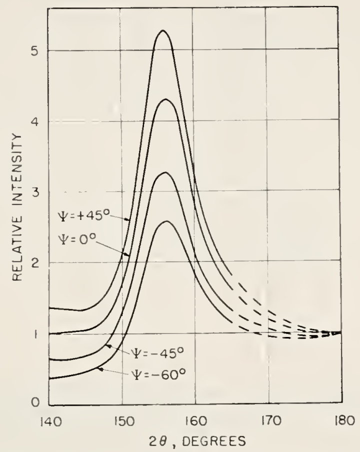


FIGURE 3. *Variation of line shape with angle ψ.*

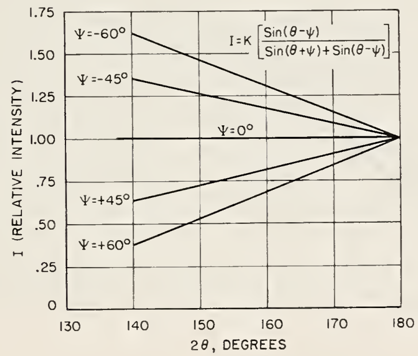


FIGURE 4. *Absorption effect.*

this variation in symmetry is sufficient to cause an appreciable error in the measured line position.

Analysis of the cause for this change in line symmetry discloses that the X-ray beam absorption within the sample results in the diffracted X-ray intensity becoming a function of the diffraction angle 2θ (fig. 4), and that this function is different for each ψ angle. Consequently, suitable corrections may be applied to the intensity readings obtained and an accuracy of 2 or 3 thousand pounds per square inch in stress measurement can be achieved.

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The measurement of retained austenite is far simpler than the measurement of stress (fig. 5). The integrated intensity or total area under a line diffracted from the austenite phase is determined and compared to an area under a line from the ferrite or martensite phase. The ratio of these two areas multiplied by a suitable constant gives the percentage of austenite present. It is evident that determining the true line intensities necessitates subtracting out the

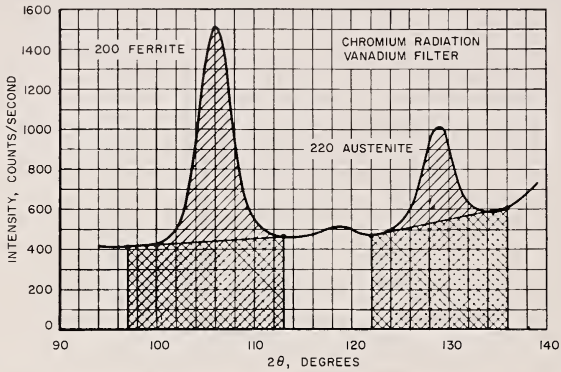

FIGURE 5. *Retained austenite measurement.*

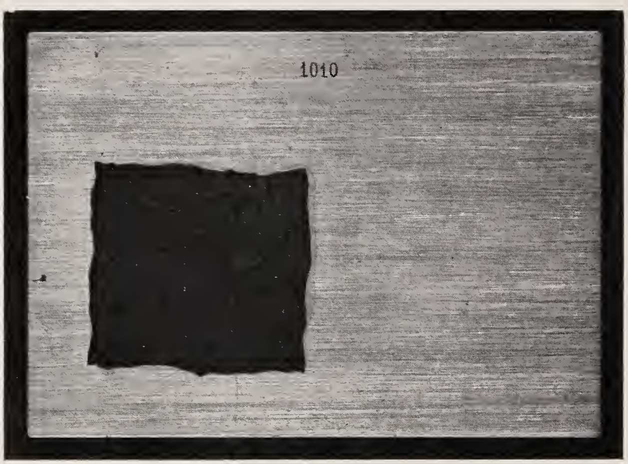

FIGURE 6. *Two-inch gage block No. 1010.*

background, and it is equally obvious that the background level cannot always be accurately established. Hence, ordinarily one uses as many lines of both the austenitic and ferritic phases as possible to average out this uncertainty. However, in the measurements made on these blocks, only the two lines illustrated here were used. Therefore, we hesitate to claim an absolute accuracy greater than plus or minus 10 percent of the austenite present, although on a relative basis the results are very much better than this.

Figure 6 is a photograph of one of the 2-in. blocks examined. The black area is the area in which the measurements were taken and is the result of etching approximately four thousandths stock from the surface to get below the effects of grinding. The etching was done in a solution of 5 percent nitric acid, 95 percent water, at room temperature.

Measurements of stress were made, before and after the stock removal, in the direction of the grinding and also transverse to this direction. Although it has been commonly believed that grinding induces tensile stresses, experience at Timken has indicated that good grinding practice invariably introduces compressive stresses of the order to 100,000 lb/in.^{2} in the direction of grinding and somewhat higher transverse to this direction. These grinding stresses normally do not penetrate more than 0.004 in. deep.

It is observed in table 1 that our expectations of the residual stresses in the as-ground surfaces were borne out. However, 0.004-in. stock removal was insufficient to remove the effect of grinding—at least in the 1-in. blocks—because through-hardened pieces of this size and geometry ought to be slightly in tension on the surface. Time did not permit examination of the stress condition at greater depths. Nevertheless, we believe the results indicate first that the grinding of the 1-in. blocks was somewhat different from the grinding of the 2-in. blocks, and second, that there is no significant stress variation between the two blocks that remained stable and the two that grew approximately 13 μin./in.

TABLE 1. *Stress measurements*

Block	Nominal length	Approximate change in length	Surface stress (as-received)		Stress (0.004-in. stock removed)	
			Longitudinal	Transverse	Longitudinal	Transverse
	in.	*μin./in.*	*lb./in.^{2}*	*lb./in.^{2}*	*lb./in.^{2}*	*lb./in.^{2}*
2–B4–2	1	<−1	−143, 000	−191, 000	−25, 000	−4, 000
4–B4–2	1	+13	−152, 000	−203, 000	−20, 000	−6, 000
2–B1–6	2	<+1	−136, 000	−199, 000	−5, 000	−2, 000
1–B1–5	2	+13	−141, 000	−203, 000	+1, 000	+4, 000

TABLE 2. *Retained austenite measurements*

Block	Nominal length	Approximate change in length	Surface austenite (as-received)	Austenite (0.004-in. stock removed)
	in.	*μin./in.*	%	%
2–B4–2	1	<−1	8. 6 to 8. 7	10. 1 to 10. 9
4–B4–2	1	+13	9. 3 to 9. 5	14. 0 to 14. 0
2–B1–6	2	<+1	6. 7 to 7. 1	10. 3 to 10. 4
1–B1–5	2	+13	13. 7 to 13. 9	18. 8 to 19. 8

The retained-austenite measurements, however, are considered significant. It is observed in table 2 that at a depth of 0.004 in., the retained-austenite contents of the two blocks that increased 13 μin./in. are appreciably higher than in the other two blocks. Those measurements taken on the as-ground surface do not indicate this marked difference in the instance of the 1-in. blocks, but this fact is unimportant because grinding causes transformation of the austenite.

These data are obviously superficial and fragmentary but lead one to speculate that the difference in growth behavior was caused largely by variation in retained austenite, and had all blocks been treated to reduce the retained austenite below 10 percent, they would have all remained fairly stable and behaved pretty much alike.

10. Dimensional Instability in Gage Blocks

By Frederick C. Victory[1]

With the increasing accent on higher accuracy in gage-block measurement, both comparative and absolute, in terms of wavelengths of light by means of interferometry, it seems inconsistent that more effective steps have not been introduced to insure the permanence of such accuracy. Indeed, transient accuracy can be, and often is, more dangerous than known and acknowledged errors in gage blocks.

Physically measurable errors in geometry, poor surface finish, and deviation from nominal size can be allowed for in the use of gage blocks. The more subtle, and frequently greater errors resulting from permanent dimensional instability present a hazard of unsuspected dimensional change in blocks, after measurement and certification.

Hardened steel, in addition to its well-ordered obedience to the laws of thermal expansion, is subject to erratic and entirely unrelated dimensional variations of considerable magnitude. These changes can be either shrinkage or growth and may occur under the following conditions:

1. A slow, progressive change, continuing for months or years, which may start immediately after hardening or at any time thereafter.
2. An instantaneous and complete change at any time after hardening.
3. A reversal of direction of change at any time after hardening.

It is well recognized that a variety of unstable constituents may be produced during the hardening cycle of steel, depending upon the analysis and the temperature : time relationship. Some of these constituents are transitory, and are not normally carried down to room temperature, except in unstable condition. Other constituents are considered end products of the reaction and are, in themselves, unstable.

The entire problem of dimensional instability may be resolved in terms of the crystalline structure of these constituents as affected by the atomic rearrangement within them. Recent research[2] on the problem has revealed by dilatometric and X-ray diffraction examination that transition phases during the cycle result in shifts in atomic arrangement within the structure and are attended by volumetric changes in the steel.

The two offending constituents in hardened steel are austenite retained at room temperature after quenching and untempered, or tetragonal, martensite.

At this point consider the reaction of steel to the hardening cycle, for example, an oil-hardening steel of the low-alloy type.

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[1] Moore Special Tool Co., Bridgeport, Conn.
[2] The physics of metals, Frederick Seitz (McGraw-Hill Book Co., New York, N. Y., 1943).

Upon being heated from room temperature, at which it exists in the annealed state as a spheroidized structure, the steel obeys the laws of thermal expansion until a so-called critical temperature is reached. At this point the steel undergoes a marked change in crystalline structure, entering what is known as the gamma phase, the product being austenite. This transformation is evidenced by several observable phenomena, the one pertinent to the discussion being decrease in atomic volume, or shrinkage. To restate this, austenite is less voluminous than the structure from which it is formed [3] (see fig. 1).

On the cooling side of the cycle, the behavior of the steel is, to a great extent, governed by the rate of cooling. If allowed to cool slowly the steel reexpands to its normal volume for that temperature, at a point somewhat below the temperature that marked its original transformation. In this case the resulting product will be pearlite. Continued cooling to room temperature will restore its volume to that before treatment.

But if cooling is sufficiently rapid, as in the case of a quench, reexpansion at the secondary critical temperature (an isothermal reaction) is avoided, and austenite is carried down to a much lower temperature. At this point (approximately 400° F) a direct transformation from austenite to martensite begins and continues until room temperature is reached or cooling is otherwise interrupted. This austenite-martensite reaction is, again, a result of atomic displacement within the crystalline structure, and is accompanied by an increase in volume (see fig. 1) to an extent exceeding that to which steel owes its hardness characteristic, and in this stage, it is unstable.

In the untempered stage, martensite has a tetragonal crystalline structure, which tends to transform, over a period of time, to a stable cubic structure of appreciably smaller volume. This accounts for the shrinkage phenomenon in hardened steels that have been inadequately or improperly tempered.

Theoretically the tempering cycle specified for most low-alloy steels carries this reaction through to a reasonable degree of completion, rendering the steel relatively immune to this form of instability, and restoring it to its original volume at room temperature. Low-temperature tempering and too short a time at heat, which occur accidentally or in an attempt to attain maximum hardness, will result in something less than complete conversion and stability.

From the standpoints of maximum hardness and stability, it would be highly desirable to have the austenite to martensite transformation continue to completion. Unfortunately this is almost never the case. Because of variations in temperature and effectiveness of the quench, and a degree of reluctance on the part of the austenite to transform, a percentage of the unstable austenite with its smaller crystalline structure is carried down to room temperature. Here it can exist only precariously, and if not triggered into a sudden transformation by some form of shock, will gradually decompose into bainite; in either case with a resulting increase in volume which causes dimensional growth in the steel.

This retained austenite may vary from 2 to 35 percent, or more, depending on the specific analysis of the steel and conditions obtaining during the hardening cycle. The gravity of the problem becomes

[3] B. S. Lemen, B. L. Averback, and M. Cohen, The dimensional stability of steel, Part IV—Tool steels, Trans. Am. Soc. Metals **41** 1061 (1949).

apparent when one learns (see footnote 3) that conversion of less than 1 percent of the steel's volume will result in a growth of 0.0001 in. per inch of length.

At this point it may be noted that hardened steel almost inevitably contains two unstable constituents affecting it dimensionally in opposing directions, and to varying degrees, depending on proportion and the presence of any external triggering stimulus such as physical or thermal shock. Occasionally, and by chance, they may establish, between themselves, a precarious equilibrium, or the predominant one will control the direction of change for a time until stabilized or exhausted.

At this point it might be appropriate to consider the practical consequence of such instability in gage blocks by citing specific case—examples:

Case A

Specimen: A class "A," 4-in. gage block.

Conditions: Used for somewhat less than 1 year in a temperature-controlled room as a master block for reference.

Observation: At the end of a year comparison showed a suspected growth of 0.00004 in., verified by the National Bureau of Standards. The manufacturer replaced this block on a no-charge basis.

Conclusion: The growth could only have resulted from the decomposition of unstable, retained austenite. Whether or not a significant percentage still remained was not determined.

Case B

Specimen: An 18-in. gage, measured and certified by the National Bureau of Standards.

Observation: At the end of 2 years storage in a temperature controlled room this gage was flown to England for measurement by the National Physical Laboratory, where it was certified as being 0.0002 in. longer than before, after conversion from English to American inches had been taken into account. Naturally this brought up a question as to the validity of the new length determination. Subsequent measurement by the National Bureau of Standards confirmed the fact that the gage had, indeed, grown slightly over two ten-thousandths inch. Whether or not this was an isothermal reaction, i. e., at room temperature, or had been the result of the low temperature (−45° F) encountered in the baggage compartment of the aircraft could not be determined.

Conclusion: Frequent periodic measurements of this gage clearly showed that it is still continuing to grow and is useless as a master.

Case C

Specimen: An 81-piece class B set of gage blocks, of which not more than a half a dozen blocks were ever used during a period of 2 years.

Observation: Casual comparisons against master blocks indicated that a few of the blocks were undersize. The entire set was returned to the manufacturer for measurement and certification. The resulting certificate proved to be a rather amazing and revealing document. Each block was short by many times the tolerance for that class of block, in nearly a direct proportion to its size. This value ranged from 0.000034 in. for a 0.50-in. block to 0.000596 in. for a 3-in. block.

Conclusion: Because the original certification of this set and the subsequent certification revealing the error were both made by the manufacturer, it is impossible to state which of two possible conditions might fit the case. Either the entire set of blocks (assumed to be representative) had shrunk as a result of the isothermal conversion of untempered, tetragonal martensite, or the masters with which they had been compared had grown an equal amount as a result of decomposed austenite. It is somewhat more likely that the former explanation is the more valid.

Although a number of additional examples could be cited, they would merely be repetitious and contribute nothing new to the discussion. More to the point would be a brief consideration as to what may be done to cope with this serious problem.

The subject of stabilizing hardened steel is highly controversial and in many cases is regarded as a closely guarded secret. For a time, subzero treatment was considered most effective. Manufacturers of commercial refrigerating equipment and their disciples proposed this as the panacea for all stabilizing problems. Unfortunately the answer is not that simple.

Although it is true that subzero treatment, as an immediate continuation of the initial quench, is capable of converting a large percentage of retained austenite to martensite, there are certain practical limitations to this method.

The thermal shock of being reduced to −150° F is very likely to produce fractures and cracks in the steel. As a result a tempering operation is introduced between the quench and the subzero treatment, with the unfortunate result of rendering the latter largely ineffective. In this case the austenite becomes sufficiently stabilized to resist conversion by low temperature but will still decompose isothermally.

An additional source of trouble results from this method. The conversion product of austenite under subzero conditions is tetragonal, unstable martinsite, previously cited as being responsible for the shrinkage sometimes noted in gage blocks. It is a reasonable assumption that this sort of cycle was responsible for the shrinkage noted in the 81-block set previously discussed. At best, the subzero cycle can only be expected to affect one of the two unstable constituents found in hardened steel.

Conversely, ordinary tempering at the temperature: time ratio recommended by steel manufacturers can be expected only partially to effect conversion of the other unstable constituent. Unfortunately, these two treatments are largely incompatible in combination.

Recent research at several of our leading technical institutes has revealed that a somewhat unorthodox tempering cycle provides an effective method of simultaneously coping with both undesirable constituents.

Although it is not the purpose of this discussion to recommend specific cycles for each type of steel, one example will serve to illustrate the point. In the case of an oil-hardening steel of the analysis 0.90 C, 1.70 Mn, and 0.25 Si, the conventional treatment would be to quench from 1,420° to 1,440° F and draw for 1 hour at 350° F. This would result in a commercially acceptable structure for ordinary tool work, but not for gage blocks.

If, however, the austenitizing temperature is carefully controlled at the low side of the range, say 1,425° F, ±5 deg F (no small problem in itself), a smaller percentage of austenite will be carried down to room temperature than otherwise would be the case. Then, with a draw of 400° to 410° F continued for 18 hours, the remaining austenite is completely converted to stable bainite, and the tetragonal martensite is simultaneously converted to stable cubic martensite. The resulting structure, although its hardness is about three points lower than maximum for this analysis on the Rockwell C scale, will be entirely stable dimensionally.

Potential stability or instability can be determined within varying degrees of accuracy by several methods, destructive and nondestruc-

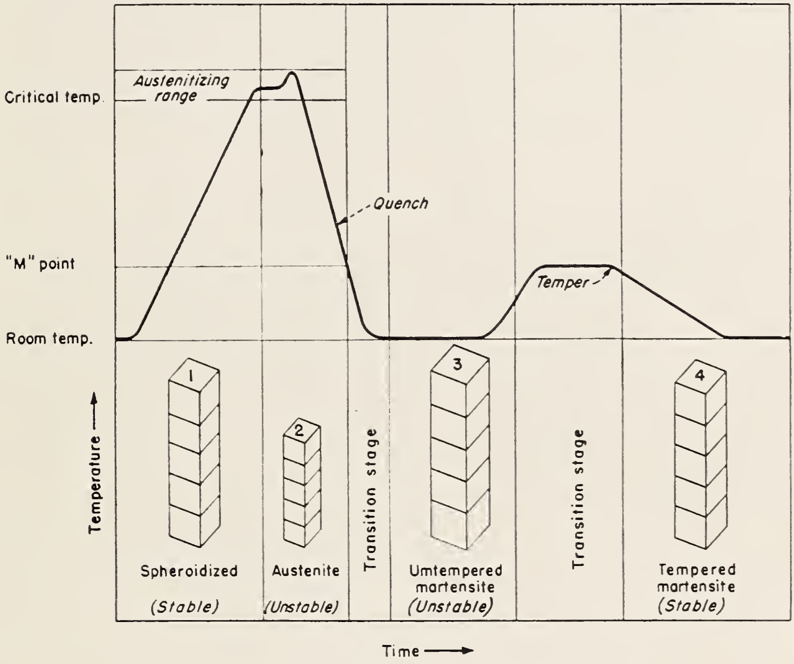

FIGURE 1.

Volume changes occur in steel, according to the content of various crystalline structures. Here is shown the situation resulting from a theoretically ideal hardening cycle. Structures 1 and 4 are stable and equal in size (chart not drawn to scale).

tive. At one time it was the practice of the National Bureau of Standards to determine this dilatometrically by boiling the specimen at 212° F for 24 hours and remeasuring. If no change in length occurred, the gage was assumed to be stable. The writer's experience indicates that this cycle is inadequate and inconclusive. The minimum temperature at which one can be certain of the effective conversion of semistabilized austenite is 390° F for most oil-hardening steels, consequently a more realistic and revealing test would be to subject the specimen to a 4-hour cycle in an oil bath at 400° to 410° F and then redetermine the length. The X-ray diffraction examination method is capable of determining the amount of retained austenite within about 0.5-percent accuracy. Surface examination with a microscope reveals much as to the crystalline structure but seems to be less accurate than either of the previous methods. One additional method seems to offer much promise, both as to the accuracy of result and economy of use. It is based on the ability to measure electronically the differences in magnetic permeability of the specimens as affected by varying percentages of austenite and untempered martensite. The method involves comparison against standard specimens of known values.

In conclusion, it might be said that industry, in its faith and reliance on the gage block as a practical and convenient standard of linear measurement, needs and deserves a practical assurance of the permanence of its accuracy, disregarding the factor of wear.

11. Surface Characteristics of Gage Blocks

By A. G. Strang[1]

The primary function of a gage block is to provide an accurate standard of length. Its accuracy, singly or in combination, is governed essentially by the planeness, parallelism, and microfinish of the surfaces. The contact surfaces must also be free from large pits, deep scratches, excessive porosity, and burrs. The quality of the surface microfinish largely governs the ability of the gage blocks to wring together, the resistance to wear, and to some extent the accuracy of length measurement by both mechanical and interferometric methods.

With the improved methods of manufacturing and grading of abrasive particles and with the wide variety of abrasives and suspending lubricants on the market, gage block manufacturers now have a simpler job in selecting suitable materials which will give them the desired surface finish. Obviously the better wringing surfaces are those that approach a true plane.

Gage blocks, to wring well, must be free from fuzz or burrs, which project above the true plane. Scratches below the plane are of secondary importance. We know that careful stoning of gage blocks frequently improves the wringing tremendously because it wears off the microscopic burrs. This is necessary on many new blocks if they are to be wrung to a clean quartz surface. Furthermore, gage blocks with excessive fuzz will decrease in length rapidly until several microinches of fractured metal are worn off.

There is still considerable difficulty in accurately rating comparatively smooth surfaces, especially the finish encountered on gage blocks. The tracer-type surface analyzer[2] used at the Bureau produces a graph, or chart, of the surface and also indicates the arithmetical average deviation from the mean plane, that is, the plane where all the peaks are leveled off to fill in the valleys. The arithmetical average deviation of the surface irregularities is defined as the average value, in microinches, of the departure of the profile from a meanline or centerline, whether above or below it, throughout the traversing length. In other words, it is the sum of all the areas enclosed between the profile and the meanline, divided by the traversing length, and is expressed by the formula

$$Y=\frac{1}{l}\int_{x=0}^{x=l} |y|dx,$$

where Y is the arithmetical average deviation, or height, and l is the length of surface traversed.

[1] National Bureau of Standards, Washington.

[2] American Standard B46.1, Surface roughness, waviness, and lay, American Society of Mechanical Engineers, New York, N. Y. (1955).

In Europe, this deviation is called centerline-average. To prevent confusion in this paper between arithmetical average, abbreviated AA, and Grade AA gage blocks, I have chosen to use centerline-average, abbreviated C. L. A. The centerline-average values are not too reliable for these fine finishes. In order to get the best meter reading or chart, the stylus must never trace over the same path.

The diamond stylus is a four-sided 90° pyramid truncated to 0.0001-in. width at the end. Measurements indicate that the end is rounded to approximately a 0.0001-in. radius, and therefore, this stylus can reach to the bottom of nearly all of the scratches on gage blocks.

The average width of the scratches on AA gage blocks varies from [3] 20 μin. on mirror-finished gage blocks to 80 μin. on the rougher finishes. A graph should show the true peak to valley depths of the narrow scratches but seldom does. However, it is usually possible to see a definite difference between gage blocks of different roughness. With a load of 0.1g on the tracing point, it is possible that inertia and/or friction in the pivot assembly of the tracer may prevent the point from faithfully following all the irregularities of a surface at the speed of traverse which is usually used. By reducing the tracing speed from 0.0025 in. to 0.0005 in. per second, it is possible to produce a chart which more faithfully records the profile of the scratches. By adding a correction for indentation of the diamond point into the peaks, a more reliable peak-to-valley distance is obtained.

The following figures illustrate gage-block surfaces having good and bad characteristics. The selection of gage blocks was made from sets produced by the world's leading manufacturers. Some illustrations are not characteristic of the product of the manufacturer but in most cases they are.

Figure 1 shows interference micrographs of AA steel gage blocks. The bands on the blocks are interference fringes produced by the predominant green spectrum line of thallium. The half-wavelength is 10.7 μin. Fringe displacements are proportional to elevations of surface irregularities. For example, a fringe displacement of ½ fringe downward would indicate a scratch or hole 5.3 μin. deep. Each of the photomicrographs covers an area 5.4 mils in width and 7.1 mils in length. This group of pictures shows extremes in the surface roughness of AA steel gage blocks. Note that there is a wide variation in the surface roughness of the products of different manufacturers.

Figure 2 shows interference micrographs of grade A steel gage blocks manufactured by the same four companies but note the difference in finishes. The gage block of manufacturer 1 is much rougher than the AA grade gage block in figure 1, which indicates that this manufacturer produces AA gage blocks rather than selects them from the factory run. The finish on the A grade gage block, produced by manufacturer 2, is about the same as for the AA gage block shown in figure 1 whereas the finish on the A grade gage block of manufacturer 4 is better than that on the AA gage block.

Graphs of the preceding eight gage blocks, where the trace of the surface analyzer traverses a distance of approximately 150 mils, are shown in figure 3. The coordinate spacing corresponds to 2 μin. in the vertical direction and 2 mils in the horizontal direction. Here we have

[3] One microinch, abbreviated 1 μin., equals 0.000001 in.

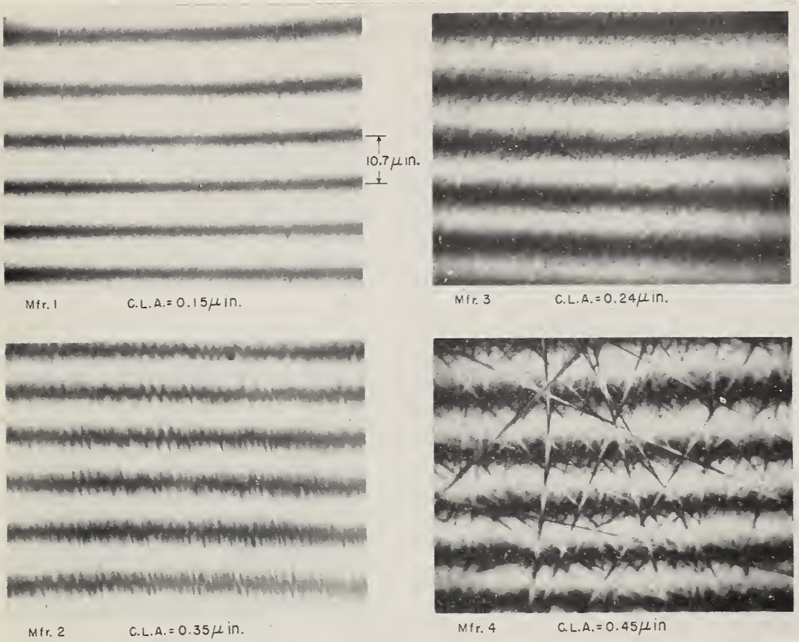

FIGURE 1. *Microfinish on grade AA steel gage blocks.*

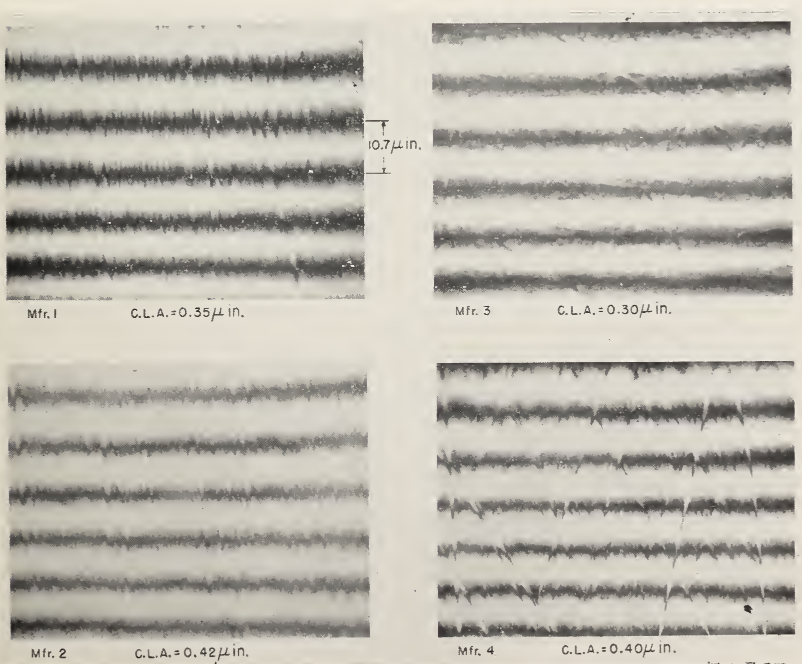

FIGURE 2. *Microfinish on grade A steel gage blocks.*

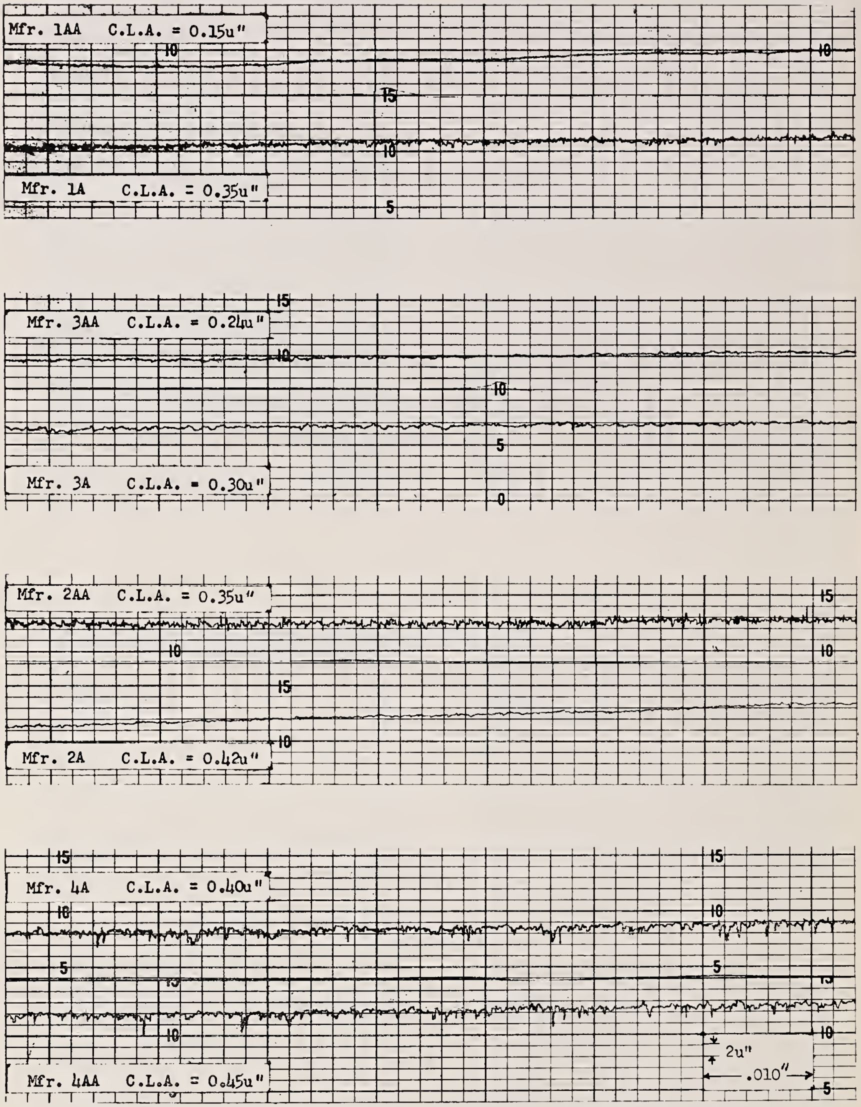

FIGURE 3. *Graph of microfinish on grade A and AA steel gage blocks.*

examples of apparently conflicting data. The charts do not indicate the narrow deep scratches but they show that there is a definite difference between the finishes. In chart 1AA of figure 3, the mirror finish shows a simple wavy surface with no scratches because the stylus indentation of 0.8 μin. is nearly equal to the depth of the scratches which average 1 μin. In chart 1A, the predominant depth is 2.5 μin. In chart 3AA, the predominant depth of scratch is 1.7 μin. and in 3A, 2 μin. For the AA gage block, produced by manufacturer 2, the C. L. A. value is less, the chart is rougher, and the predominant scratch depth is greater than for the A gage block. The scratch width is slightly wider on the AA gage block and, therefore, the tracer picked up greater depths and produced a rougher chart. The predominant depth of

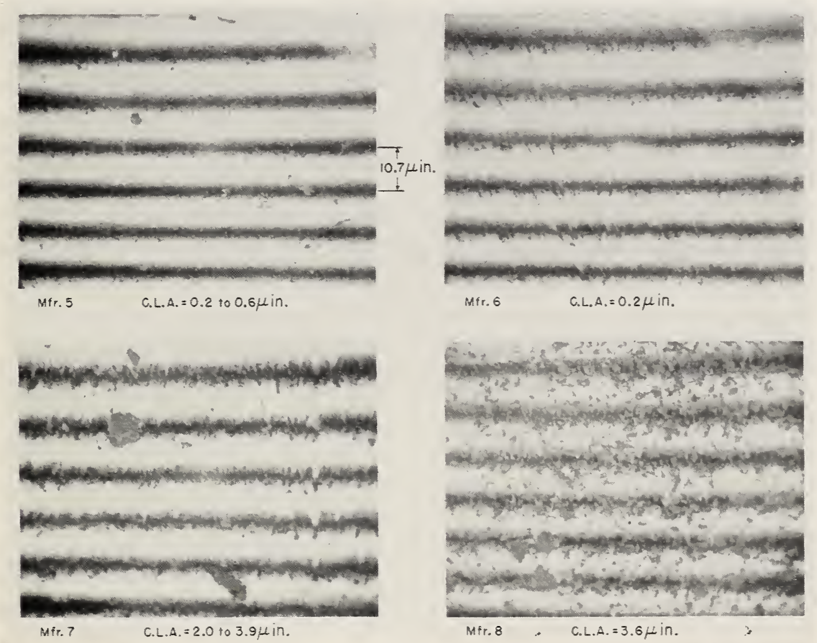

FIGURE 4. *Microfinish on grade A and AA tungsten carbide gage blocks.*

scratches on gage block 4AA is 4.0 μin. and only 1.5 μin. on the 4A gage block, but their centerline-average values only differ by 0.05 μin. Due to the random lapping, the tracer can often travel a short distance along the scratches and thus record a more accurate depth.

The microfinishes on tungsten carbide gage blocks are illustrated in figure 4. The scratch depth on all carbide gage blocks is very shallow (seldom over 2 μin.) and there is very little fuzz. This accounts for their good wringing characteristics. The major problem is defective carbide having excessive voids. The large void in the block of manufacturer 7 is about 0.0007 in. in diameter.

The corresponding charts in figure 5 indicate the size (both width and depth) of the voids. On the gage block of manufacturer 7 there is a hole .0008 in. in diameter and over 27 μin. deep. Surface imperfections give large and varied readings of C. L. A. which do not repre-

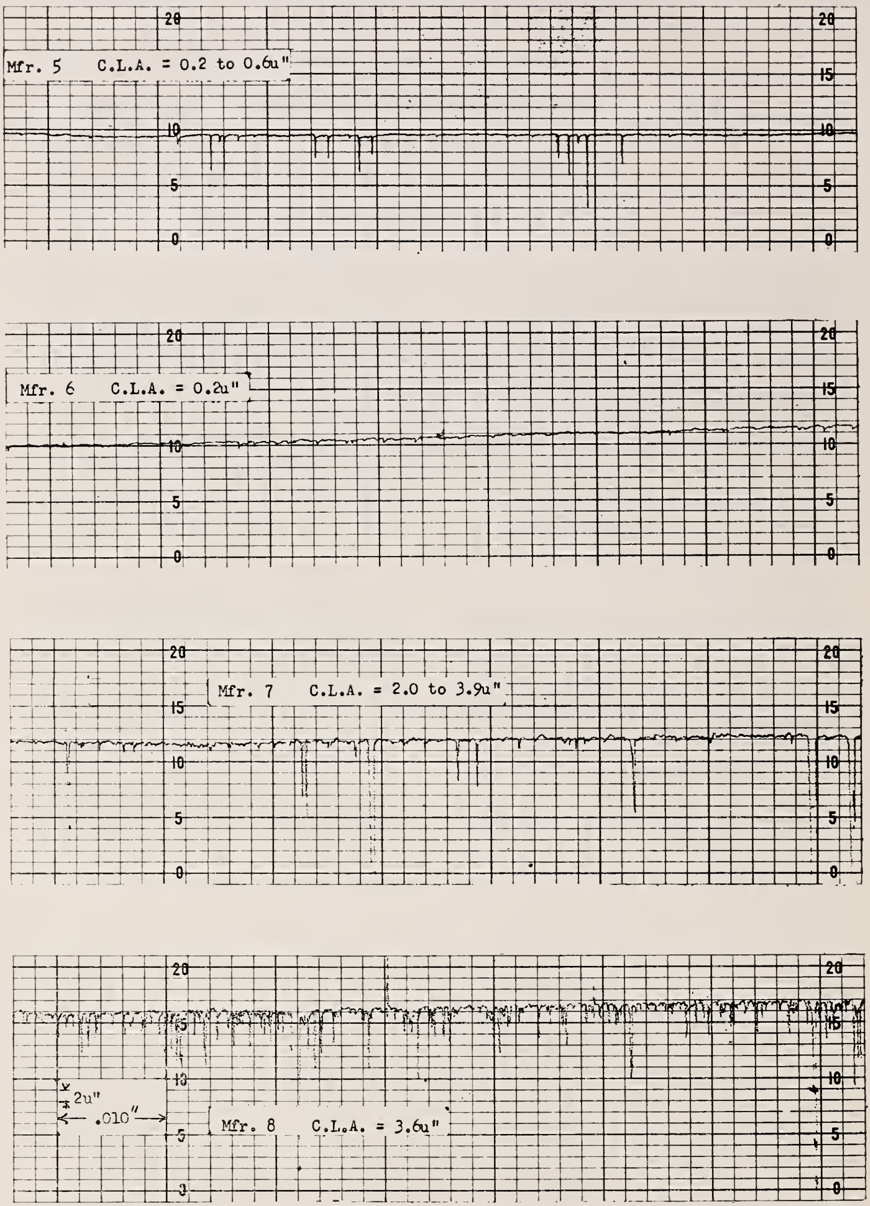

FIGURE 5. *Graph of microfinish on grade A and AA tungsten carbide gage blocks.*

sent the real surface roughness. Care should be exercised in using porous carbide gage blocks for accurate gaging with a mechanical indicator as it is possible for a contact point having a small radius to partially penetrate such holes.

Surface finishes on chromium-plated gage blocks are shown in figure 6. Chromium-plated gage blocks are popular for their wear characteristics and corrosion resistance but unpopular where good wringing is an important factor. The gage block of manufacturer 10 shows why some chrome-plated gage blocks fail to wring well. The wringing surface is a series of hills and valleys of irregular heights. When the surface roughness is reduced as shown in the interference

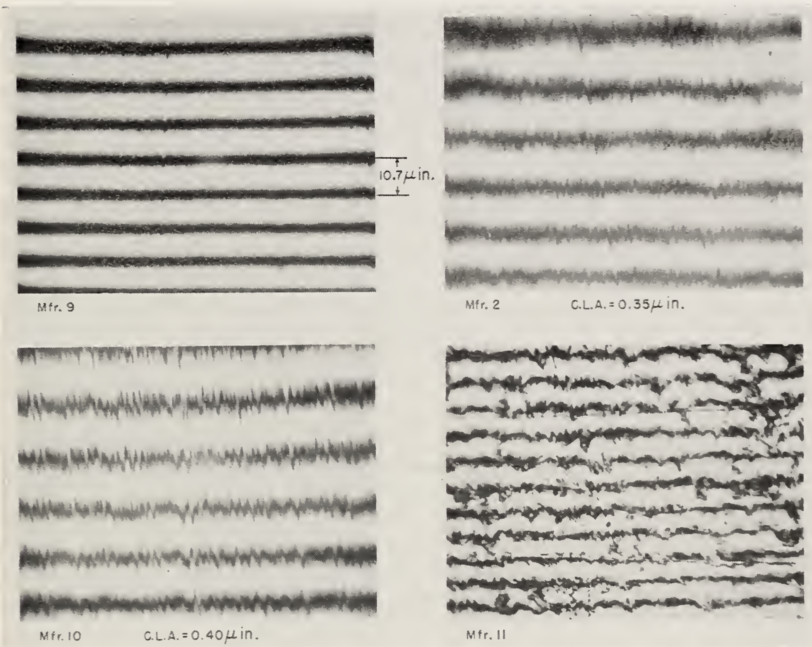

FIGURE 6. *Microfinish on grade A and AA chromium-plated gage blocks.*

micrographs of the gage blocks of manufacturers 9 and 2, and the surface is plane, these gage blocks wring very well.

Objectionable gaging surfaces are illustrated in figures 7 and 8. The steel surfaces of the gage blocks of manufacturers 12 and 13 are not satisfactory. The first surface has excessive pits for steel, and the second shows oxidation caused by excessive surface temperature during the final lapping operation. A micrograph of a fresh steel surface has a bright background with clean, well-defined dark lines or abrasive scratches. Figure 7 (manufacturer 14) shows a chromium carbide AA gage block with a large pit (size 5.4 by 2.5 mils) in the surface. The hole is 38 μin. deep. Smaller pits (1 mil in diameter) are often found. Figure 7 (manufacturer 8) shows a very porous surface such as is found on some tungsten carbide gage blocks. Figure 8 (manufacturer 2) illustrates a crazed chrome-plated surface probably caused by high surface stresses. Figure 8 (manufacturer 11) illustrates

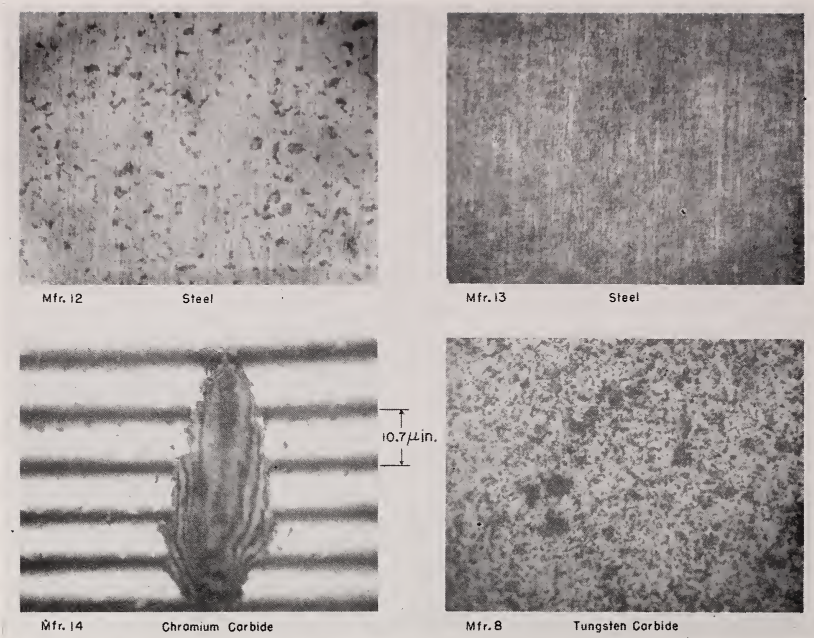

FIGURE 7. *Surface characteristics on gage blocks.*

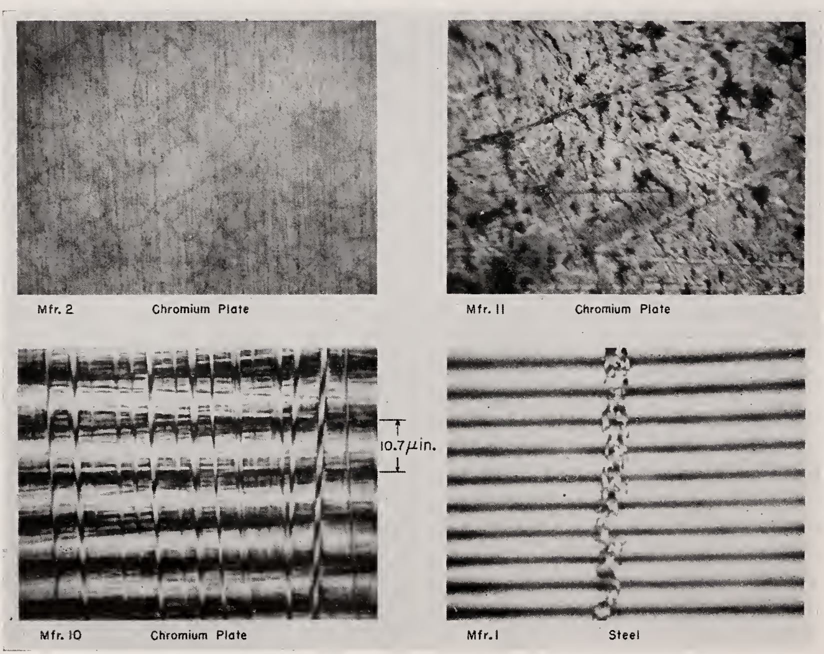

FIGURE 8. *Surface characteristics on gage blocks.*

a poorly bonded chrome-plate. Figure 8 (manufacturer 10) indicates that fairly large abrasive particles were lodged in this rough chromium surface because the tracer shoes of a surface indicator dislodged them and caused the large scratches. The striated fringe pattern is caused by the rough surface finish which has a predominant scratch depth of 6 μin. The blemish on the mirror finished steel gage block shown in figure 8 (manufacturer 1) was produced when the skid of a surface analyzer traversed the surface. The torn surface is 7 μin. deep in places. Similar damage was not produced on rougher finished gage blocks.

The ease with which many mirror finished surfaces can be scratched leads us to believe that the hardness of a very thin layer, perhaps

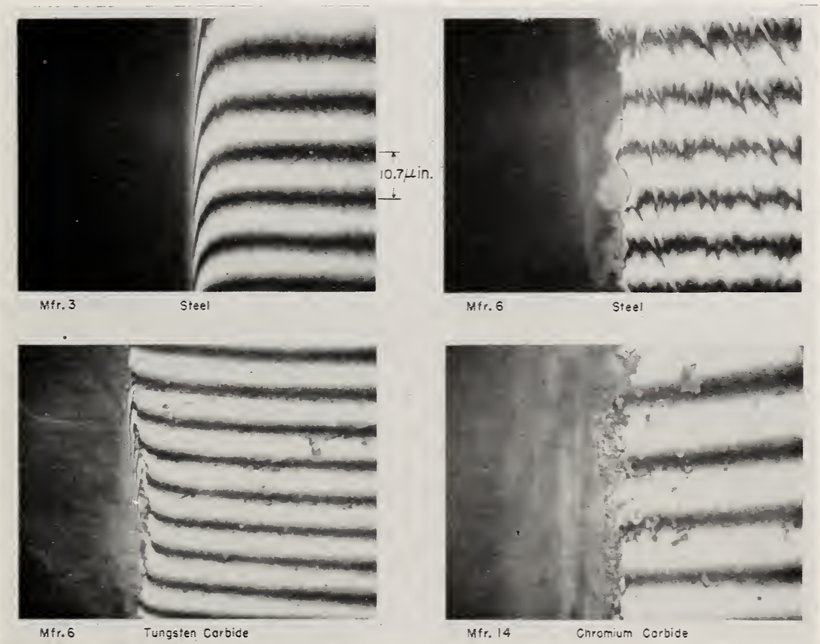

FIGURE 9. *Edge conditions on grade AA gage blocks.*

3 to 7 μin. deep, is appreciably less than in the rest of the gage block. We think that some annealing of a steel surface with a decrease in hardness may occur during a lapping operation as the surface approaches a mirror finish.

Figure 9 shows the variety of edge conditions found on AA gage blocks. The gage block of manufacturer 3 illustrates the ideal contour of an edge. This type of edge will not scratch another gage block when blocks are wrung together. Grinding a beveled or radius edge will not produce this smooth edge but stoning will. The edge on the tungsten carbide gage block has a burr raised 11 μin. above the gaging surface; thus the surface will not wring to another gage block surface. This type of edge has been found on other manufacturers' steel and carbide gage blocks. The chromium carbide gage block has a fractured and crumbly edge.

It is believed that ragged edges are the greatest source of potential damage to gage block surfaces. Sometimes small pieces of metal break off the edges and get between the wringing surfaces. Many cases were found where scratches on gage blocks start at a ragged portion of an edge. Furthermore, it is extremely easy to produce a

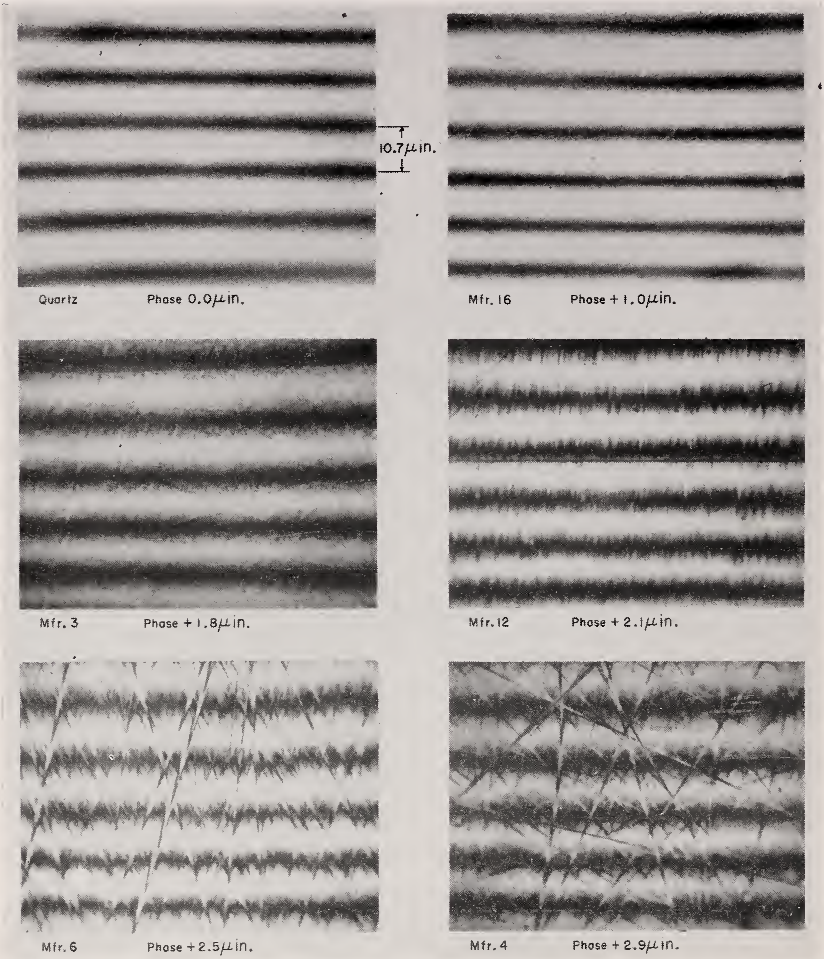

FIGURE 10. *Comparison of surface roughness and phase change correction on quartz and steel gage blocks.*

burr on an edge of this type. It is hardly more than necessary to touch such an edge against a hard surface to produce a burr. The burr may be only a few microinches high but it generally cannot be entirely removed by stoning and usually adversely affects the wringing quality of the gage blocks.

Previous speakers have discussed phase change correction. This correction is necessary because light appears to penetrate a metallic surface to a slight extent before it is reflected. The effect is partly due to the theoretical electromagnetic phase change which occurs when light is reflected from a material which is a conductor of electricity and partly due to the effect of surface roughness. The phase change at reflection from a nonconductor such as glass or quartz conventionally is considered to be zero. The phase correction for a highly polished steel surface is +0.8 μin. When a surface is not perfectly smooth, a further correction is necessary to compensate for the penetration of the light into the irregularities. This correction increases in proportion to the surface roughness and varies from less than 0.5 to over 2.0 μin. The true phase correction (+0.8 μin. for steel) and the correction for surface roughness are usually summed together as the phase correction. The interference micrographs in figure 10 compare the surface roughness on gage blocks with total measured phase change correction. The table below summarizes the data.

Mfr. number	Composition	Measured phase change correction	Predominant scratch depth	Centerline—average height
		μin.	μin.	μin.
--	Quartz	0.0	<1.0	0.05
16	Steel	+1.0	<1.0	.07
3		+1.8	1.7	.24
12		+2.1	2.2	.28
6		+2.5	3.0	.35
4		+2.9	4.0	.45

It is interesting to note that the sum of one half of the predominant scratch depth on steel and the theoretical phase change correction for steel (+0.8 μin.) are in close agreement with the measured phase change correction. In most sets of gage blocks, it is possible to find a 1 μin. spread in phase change correction, therefore, it is essential that the manufacturer produce a very uniform surface finish on all AA gage blocks.

12. Questions and Suggestions With Regard to Gage Blocks

By Edvard Johansson [1]

The papers read yesterday and today have dealt with the scientific measurement of gage blocks. I feel that something should be said regarding the standardization of gage blocks from the standpoint of the manufacturers. I shall therefore deal more with standardization and questions of interest in the mutual work on gage blocks of the national laboratories and the manufacturers of precision gages. Thanks to very close mutual work with leading scientists of different national standards laboratories, we have today an almost perfect length standard in the gage block.

Many new ideas and suggestions regarding improvement of gage blocks come almost every day. New materials, new shapes, and new types of accessories are a few of these. We can find, in addition to the ordinary rectangular type, cylindrical, square (with and without center hole), heavy duty, and even triangular-shaped gage blocks. No wonder then, that the scientists responsible for the measurement of these gage blocks would like to standardize only a few conveniently-shaped types of gage blocks.

The first combination set of gage blocks was used at the Royal Rifle Factory in the town of Eskilstuna, Sweden. This set is now in the possession of the C. E. Johansson Co. in the same town and these are real heavy-duty blocks. Such gage blocks are therefore not a recent development. They were soon found to be too heavy and were superseded by a lighter type, the conventional rectangular type gage block. Later, during the first world war, the round type was developed here at the National Bureau of Standards. Experience in the use of gage blocks during the past 60 years has shown that there is no real need for gage blocks having shapes other than the conventional rectangular and square types.

The mutual work of the national laboratories in creating and adopting a common international standard for gage blocks will be of great value to both manufacturer and user. In this work the main question is the standardization of the tolerances for the length, the flatness, and the parallelism of the gage blocks. The tolerances must be specified so that they include the accuracy to which the national laboratories are able to determine the length in question. Regardless of the accuracy claimed by any gage-block manufacturer for his product, the length of a gage block cannot be known more accurately than the uncertainty in the measurement specified by the laboratory that calibrates the block.

The first tolerances system for gage blocks was made symmetrical and progressive to assure that a combination of gage blocks would

[1] C. E. Johansson Gage Co., Dearborn, Mich.

not exceed the tolerance limits for a solid gage of the same nominal size. Later on, a nonsymmetrical tolerance system was used to some extent. This was to permit greater wear and extend the life of the gage blocks. The British standard, by way of example, stipulates for the inspection grade a tolerance of $+7$ and -3 μin. The tolerance for the work shop grade is $+10$ and -5 μin. for gage blocks up to 1 in. in length. If a 1-in. combination is made up with two gage blocks from the inspection set and these two gage blocks are made with the allowable wear tolerance $+7$ μin., we find that the length of this combination is outside the allowable maximum tolerance limit of $+10$ μin. for a single 1-in. gage block of the work shop grade. Thus the inspection grade has actually become less accurate than the work shop grade. The application of such a nonsymmetrical tolerance system to gage blocks causes confusion as to the grade of accuracy. When a plus tolerance from 2 to 3 times the minus tolerance is specified, most of the gage blocks in a set will be oversize. With respect to the calibration and reference grades having symmetrical tolerances, the plus tolerance blocks will, in effect, represent a new and larger measuring unit. Nothing is more confusing than these nonsymmetrical tolerances, especially in consideration of the work on the unification of the two existing inch sysems, the American and the British inch.

More than 25 years ago the first step was taken to unite the two existing inch systems into one international inch system. The basic length of this system is almost exactly midway between the American and the British inch systems. For industrial purposes this international inch was adopted in 1933 by the American Standards Association and some years later was also adopted in England. The international inch has not yet been accepted legally in either country, and the progress of the work toward unification of the two very closely related inch systems seems to be very slow, even after 25 years of consideration.

I take this opportunity to express myself in the interest of my company and many other manufacturers of precision gages, and request that the National Bureau of Standards and the National Physical Laboratory of England do everything possible to expedite the adoption of a common definition of the inch. A common inch system would certainly be unanimously recognized in other countries.

In the definition of the length of a gage block a reference point on the measuring surface is specified. This reference point is differently defined in different specifications. Users of gage blocks as well as manufacturers usually specify the length at the center of the measuring surface on rectangular gages. The certified deviations from nominal length in a certificate of calibration should, therefore, refer to the center of the measuring surface of rectangular gage blocks and, on square gages, to a point midway between the edge of the center hole and the edge of the side bearing the nominal size marking. It would be less confusing for users and manufacturers of gage blocks if the center and midway points on the measuring surfaces were accepted as standard reference points for the length.

With regard to the material used in the manufacture of gage blocks, I shall discuss only chromium plate. It is essential that a very hard type of the chromium plating be applied, and that it be deposited on the hardened steel in such a manner as to insure against chipping and peeling in normal use. Chipping and peeling may occur if the chromium plate is too thin although otherwise meeting all requirements. This may happen when the plunger of a measuring device is brought in contact with the chromium plated surface in a conventional manner. The tip of the plunger penetrates the surface of the gage block to some extent, the amount depending partly on the elasticity of the material of which the gage block is made. When this occurs brittle chrome may crack. If the deposit is too thin, sliding of the gage block under the plunger may tear the chrome film. A minimum thickness of the chromium deposit is therefore essential to support the plunger without cracking the chromium film. An investigation of this matter would be of interest and a recommendation should be included in specifications with regard to the minimum thickness of the chromium deposit. It would be of interest to know if any one here has had any experience with regard to a required minimum thickness of the plating.

A specification for gage blocks should include a requirement that all reports of the calibration of gage blocks specifically state the accuracy of the reported values. Certificates list the deviation from the nominal length of a gage block in microinches, but the accuracy to which the calibration was made is usually not stated. If, by the way of example, a 1-in. gage block of "A" grade is certified to be 1 in. plus 4 μin. and the accuracy of the calibration is plus or minus 3 μin., the 1 in. gage block may be any value between 7 and 1 μin. longer than the nominal length. In the former case the error in the length of the gage block is outside the permissible limit for a grade "A" block. From the manufacturer's standpoint it is necessary that a certificate issued by a national laboratory state the accuracy of the calibration.

When gage blocks are measured by interferometric methods, either absolutely or by comparison, the calibration certificates should list the correction factors that have been used for parallax and for the change of phase. The latter, to a large extent, depends upon the surface finish of the two surfaces involved. A manufacturer of gage blocks who uses interferometric methods needs to know the correction factors that have been applied.

Regarding the squareness of the measuring surfaces to the sides, it is desirable that a common international standard be adopted. The German requirements in DIN 861 are acceptable whereas the British requirements in British Standard 888; 1950 are unnecessarily restrictive.

Considering the very close tolerances that prevail nowadays, it is essential that the manufacturers of gage blocks work very closely with the national laboratories, especially with regard to the performance of gage blocks, and this meeting, at the invitation of the National Bureau of Standards, is a step in the right direction. I hope that such meetings can be held more frequently in the future in order to create a better and closer understanding between the manufacturers and the users of gage blocks on one hand and the national laboratories on the other.

13. Gage-Block Surveillance

By M. S. Hoskins [1]

In the calibration and surveillance of over 1,000 sets of gage blocks used by 23 military organizations and many manufacturing contractors over the past several years, it is apparent that there are definite needs for the clarification of certain misconceptions and for constructive suggestions for improving the surveillance, care, and proper use of gage blocks in the laboratory and shop. At Sheffield we need and demand the best in gage-block surveillance for the two hundred and some sets in use throughout our own plants and for the sets that we calibrate for our wide variety of industrial customers. With the increasing demands for higher precision in industrial dimensional standards, and with continually improved methods of calibrating gage blocks, the proper handling of blocks in use must be controlled more thoroughly; first, to insure the accuracy needed for certifying the smaller tolerances, and second, to insure the practicality of recalibration, which, of course, becomes exceedingly more difficult as the blocks are more used and abused.

My analysis is intended to be constructive and not a reflection upon any user of gage blocks, and all of my remarks pertain to the used block. I will say at the start that there has been considerably better thinking in the last few years, especially in the realm of better gage-block inspection procedures, and there is a decided trend to what I like to call "laboratory affection" for this precision instrument known as the gage block. However, I feel that there is an area for greater precision appreciation, and so I should like to point out more specifically some misconceptions and poor usage practices that sometimes occur.

One of the longest standing beliefs, and the one that causes probably more inaccuracies in measurement than any other, is the belief that once a set of blocks is purchased, it is perfect and will remain perfect forever. This, of course, is not true, even if the set has never been used, because of possible dimensional instability. Before joining the Sheffield organization, I checked badly worn sets that had been in use for as long as 15 years with no calibration whatsoever. However, the user of one of these sets would not believe that his set was far out of specifications until he was actually shown. His comment of "Oh, but those are precision gage blocks" was answered and corrected by mine, which was simply, "No, they *were* precision gage blocks." A rather unique—or at least I hope it is unique—condition occurred in one of the old uncalibrated sets. Evidently, three of the blocks from this set had been lost, and substituted in their places were three pieces of steel stock carefully etched with nominal size and more or less lapped. A rough mechanical measurement of size found them to be

[1] Eli Whitney Metrology Laboratory, The Sheffield Corp., Dayton, Ohio.

about 0.003 in. undersize and quite out of parallel. Despite my being convinced that they were merely to hide the empty spaces, I found that these pieces were actually being used with the other blocks in the set. These old uncalibrated sets and homemade blocks are fortunately in a minority. However, many, many sets have been inspected that were worn far beyond all practical use for which they were intended. This was mainly the result of neglecting to have the sets recalibrated periodically under a schedule based on amount of use of the blocks and the accuracy required to do the job.

Even after calibration and recalibration requirements are understood, it is occasionally difficult to make some inspectors and others understand that the calibration report is to be used. The smaller the tolerance, the more important the report of size. One extreme case of such neglect was that of the probably well-intentioned but inexperienced foreman of a group of final inspectors who, after he received current calibration reports for all of the sets in his department, carefully put the reports in a nice, clean folder and locked them up in his desk drawer so they wouldn't get dirty. The locked-up report is, of course, more unusual than the occasional inspector who only consults the calibration report when he is expressly warned of the errors caused by inaccuracies of his block combinations. The calibration report should be kept in plain sight in the work area.

Another misconception occurs often enough to be mentioned, that is, that "gage blocks is gage blocks." Occasionally, the use of identical buildups from several sets cannot be avoided; then it is important to avoid putting the blocks back into the wrong cases. Inspection discipline should prohibit this negligence, and having all of the blocks marked with individual identification or serial numbers, helps to avoid such confusion.

After a department recognizes the merit in having its gage blocks periodically calibrated, and even when the inspector intelligently uses his calibration report, problems still remain. Gage blocks may be used as parallels or shims in fancy set-ups, or the blocks may be clamped down to a surface plate or angle plate with C-clamps to make sure they stay put. These special uses were explained to me when I started to investigate why some blocks had objectionable terraces and circular scratches on them. Most of the other markings, nicks, scratches, and burrs—of which there were an amazing number—naturally came from dropping, wiping the blocks on dirty rags and paper, laying the gaging surfaces down on a gritty, dirty workbench, and from using the blocks on freshly lapped material without first carefully cleaning it. Rust and acid stains came from finger prints being allowed to remain on the blocks and from eating salted peanuts or fruit while working with the blocks. One other easily recognizable marring of the block comes from using the gage blocks to set snap gages without using wear blocks. The aforementioned damages are not necessary and should be thoroughly eliminated from the work methods and procedures.

A final point to be made is that the proper wringing of two or more gage blocks together is an art which must not be neglected. The gage blocks should be wrung together only when they are clean and no single block has burrs of *any* amount that will scratch or mar the surface of any other block. Then the blocks are to be wrung, not forced or pushed together. Briefly, an initial light, circular motion that will begin the wringing if the blocks are clean, and then adding very slight pressure into full engagement, is the correct way to wring blocks.

Referring to my previous statement about improvements in thinking, people are definitely bringing up to date their ideas as to the accuracy and importance of gage blocks. They have begun to ask more questions about what should be done and how to go about it. They have become more insistent that gage blocks be checked and have been quick to bring in individual blocks for certification when questions of dimensional accuracy have arisen with a contractor or government inspector. One man went a little too far in the improvement angle, I think—maybe not—maybe our inspection methods will go that far soon—but I had one request to explain just how we went about measuring the depth of germs on the gage blocks, as it was evident to this man that there were germs present. Through another man's misuse of the word 'contaminated,' he had been led to believe that this was done. At least he was aware that the gage blocks were subjected to high precision measurement. A check revealed that he was not trying to be humorous.

A program of calibration must provide different techniques of measurement for different qualities of blocks. A set of the highest accuracy possible, for use of the standards laboratory, would be designated a reference or referee set. The ideal situation would be to have no block in this set with a flatness or parallelism error greater than 0.000001 in. and with its size within 0.000002 or 0.000003 in. of nominal. The next quality would be a master set for the standards laboratory, whose accuracy is within 0.000002 in. for flatness and parallelism and whose size is within 0.000005 in. of nominal. The technique for measuring or calibrating these sets would be by the absolute method. The absolute method, of course, yields the highest accuracy in length measurement and is done by comparing the blocks with several wave lengths of light used as length standards and with corrections made for any difference from the norm of temperature, barometric pressure, vapor pressure, and acceleration of gravity. In our new Eli Whitney Metrology Laboratory at Sheffield we have the Kösters absolute interferometer and the Zeiss Opton interferometer to accomplish this type of measurement, and these facilities are continuously made available by Sheffield to private industries along with its other precision measuring equipment. For application of this method, it is essential that the flatness and parallelism errors of the block to be tested be no more than 0.000003 in., otherwise it would be a waste of time and money to try to measure blocks by this method. The larger the flatness and parallelism error, the greater the observational error, and soon the observational error may exceed the specified tolerance.

The best accuracy for the next group, which could be called a standard set for the gage laboratory, would be a limit of 0.000005 in. for flatness and parallelism errors and no more than 0.000007 in. deviation from nominal size. In all of these categories the deviation from nominal size is of less concern than flatness and parallelism errors. Size may deviate from nominal and not really affect the quality of the block at all. Following the standard set would be the working set for the inspection room for use on parts. This working set accuracy should be within 0.000010 in. for flatness, parallelism, and length. Both the standard and working sets could be measured by a careful and trained inspector applying the comparison method with a high magnification external comparator.

Allowing for important exceptions that may exist in any one plant, any blocks over the above tolerances or specifications, and not exceeding 0.000020 in. in flatness and parallelism errors, when provided with a deviation chart could be relegated to the shop as a shop set.

As to the handling of gage blocks, it should be the responsibility of every laboratory, inspection room, and shop foreman to educate every person using gage blocks in proper cleanliness habits, handling procedures, and wringing methods. Gage blocks are highly precise instruments and should be handled as such with no margin for error.

With regard to a recalibration schedule, a good rule of the thumb would possibly be:

Reference sets—recalibration every 6 months.

Master sets—every 3 months.

Standard or inspection sets—every 2 to 3 months.

Shop sets—every 9 months to 1 year—with the exception of those shop sets used in abrasive areas, for such sets would probably need very frequent reinspection.

A facility either within the home organization or on the outside, set up with the proper equipment and trained personnel to perform these difficult types of calibration should be provided, and a calibration schedule should be set up and followed.

I have pointed out many malpractices and have suggested a few methods to overcome the problems. Let me then, briefly, sum it all up. Gage blocks must be calibrated, and by a method indicated by their accuracy requirements. The accuracy requirements must be set up according to the use of the blocks and the amounts of the tolerances of the work. The calibration report must be used, and the report reevaluated as often as surveillance shows it to be necessary—a surveillance that checks use and abuse, wear and damage, and is cognizant of the tolerances being checked by these blocks.

Gages and measuring equipment for the dimensional control of modern mass production require constant surveillance to insure their continuous accuracy. Gage blocks occupy the keystone position in the precision structure that assures the dimensional conformity and interchangeability of parts that flow into the mass assembly of items that make our national economic abundance and the weapons of our national defense. Just as we accomplish the surveillance of the accuracy of our watches by periodic checks against radio time signals or authoritative clocks, so also does each gage or item of measuring equipment require periodic checking against accurately known standards. In the American production scene, gage blocks are found almost universally in use as the authoritative dimensional standards, from the tool room to the high level standards laboratories. Gage blocks are the vital surveillance tools in all echelons of precision dimensional control, and they must be subjected to rigid surveillance themselves to assure the effectiveness of all tools for precision dimensional inspection.

14. Concerning the Revision of the German Standard DIN 861, Parallel End Standards (Gage Blocks)

By E. Engelhard [1]

A new version of the German standard for gage blocks and their accessories became effective in Germany some months ago.

Specifications for gage blocks in Germany were first established in 1927. Since that time gage blocks have come much more into use, with the requirements today for accuracy on the one hand and for precision in manufacturing gage blocks on the other hand, being remarkably higher. Thus the former German specifications have not fully agreed with the actual situation for many years. About 1930 when the ISA system of tolerances for fits, with not less than 16 grades of fits having a minimum tolerance of 0.5 μ (0.00002 in.), was introduced in German industry, it became apparent that new finer specifications for gage blocks would soon be necessary. Objections to the introduction of the new system of fits made by gage manufacturers at that time could only be answered by promising new specifications for gage blocks with finer grades. The specification was prepared in 1931 but unfortunately was not available before this year due to difficulties during and after the war. As a new specification for gage blocks is also being prepared in this country, perhaps it may be timely to look at the specification now used in Germany and especially at some of the considerations on which it is based.

In the new version of the German standard, "gage blocks" DIN 861, three points are dealt with: (1) definitions, (2) shape of gage blocks, and (3) tolerances.

Concerning the first item the following statements are made in DIN 861: (1) The length at the center m (fig. 1), which requires no explanation, is defined as the perpendicular distance of the center of the gage block surface A from the plane surface of an auxiliary plate B made from the same material as the gage and wrung to the other gage block surface A′, the surface of the auxiliary plate B being of the same quality as the surface A. This version agrees fully with the definition of the length of a gage block that is accepted in all countries in accordance with an ISO recommendation. Note that this definition involves the thickness of a wringing film. This is important, in order to avoid complications when gage blocks are wrung together. (2) The error in the length at the center f_m is consequently defined by the difference between the length at the center and the nominal length, $f_m = m - l$. (3) The third definition of the standard concerns the length at any point of the surface of the gage block indicated by b (fig. 2). The length at any point of the gage block surface, in consequence of the definition of the length

[1] Physikalisch-Technische Bundesanstalt, Braunschweig, Germany.

at the center m, is defined as the vertical distance of any point on the gage block surface A from the plane surface of an auxiliary plate wrung to the other surface of the gage block under the conditions given by the definition of the length at the center; for example, b_1 and b_2 are the values of length for the points 1 and 2, respectively, of gage-block surface A. (4) The deviation f_b at any point of the gage-block surface is consequently defined by the difference between

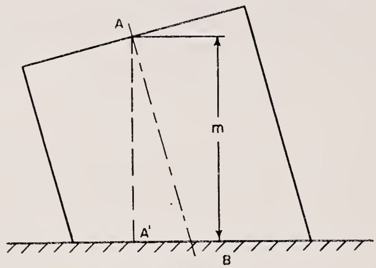

FIGURE 1.

the length at any point, b, and the length at the center, m, $f_b = b - m$. The geometrical conditions of the gage-block surface, including flatness and parallelism, are completely determined by the value of the deviation f_b at any point of the surface.

The preceding four definitions of length at the center, m, error of the center, f_m, length at any point of the surface, b, and deviation at any point on the surface from the length at the center, f_b, which are the most important dimensions of a gage block, were, in principle,

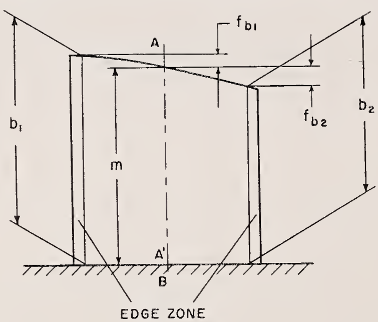

FIGURE 2.

specified in the former version of DIN 861. (5) A definition of obliquity (fig. 3) has been added in the new standard.
According to the new DIN 861, obliquity of gage blocks is defined by s, s being the deviation in perpendicularity of the side faces relative to *every* measuring surface. Therefore, for every side face, *two* values, s_1 and s_2, of the obliquity are taken into consideration, s_1 being the obliquity of one side face relative to the lower surface, s_2 the obliquity of the same side face relative to the upper measuring surface of the gage block. Altogether eight different values are possible for the four side faces of one gage block. Limitation of obliquity is necessary, otherwise combinations of gage blocks might not fit in the holders as specified by the standard. In order to determine obliquity it is recommended that the gage block in question be placed on a surface plate

with one side face set against a straightedge clamped to the plate surface. The location in a horizontal plane of this side face of the gage block should then be determined by a suitable method, for example, by a mechanical test indicator also fixed on the plate. The gage block is then replaced by a square and a reading of the test indicator made in the same manner, the difference of the two readings corresponding to s. (6) The next definition in DIN 861 concerns wringing. Wringing is undoubtedly one of the most essential features of a gage block, because it permits the formation of lengths in very fine increments. Therefore, in preparing a specification for gage blocks, it is recom-

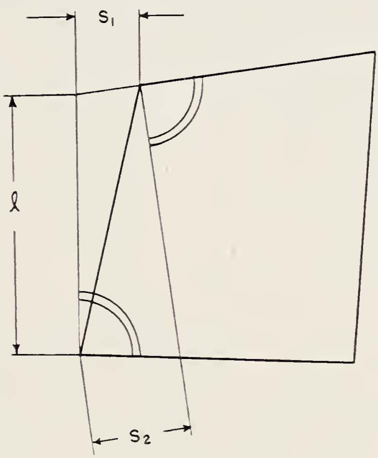

FIGURE 3.

mended that the requirements as to wringing be very exactly defined. DIN 861 explicitly states that the adhesion of surface must not be obtained by supplementary substances and that close, i. e., optical contact, as judged by means of an optical flat, must be obtained over the whole surface.

Part 1 of DIN 861 covers definitions. Part 2 covers the shape of gage blocks. First, it should be mentioned that only gage blocks made of steel, the coefficient of thermal expansion being (11.5 ± 1.5) 10^{-6} per deg C, and diamond pyramid hardness number not less than 800 kg/mm^2 are specified in the German gage-block standard. Furthermore, in this part of DIN 861, the nominal cross section for different lengths of gage blocks is stated. The cross section, in general, is rectangular, 9 mm in width and 20 and 30 mm in length for gage blocks up to 0.5 and 10 mm, respectively, and 9 mm in width and 35 mm in length for longer gage blocks. Gage blocks having other cross sections are allowed provided the area is the same as in the case of the rectangular section. However, gage blocks of other than rectangular section are quite unusual in Germany. A further stipulation of DIN 861 requires manufacturers to mark gage blocks with their trademark.

After defining or stating the nominal sizes for gage blocks in parts 1 and 2 of DIN 861, the essential tolerances are indicated in part 3 (fig. 4). This table represents the allowable values (1) for the errors in length at the center f_m, (2) for the deviation of length at any point of the surface f_b, and (3) for the obliquity s, all values expressed in microns (0.00004 in.), the reference temperature being, as usual, 20° C (68° F).

Nominal Size	Grade of Accuracy 0			Grade of Accuracy I			Grade of Accuracy II			Grade of Accuracy III		
mm	f_m	f_b	s	f_m	f_b	s	f_m	f_b	s	f_m	f_b	s
0.1	—	—	—	0,2	0,15	—	0,5	0,25	—	1,0	0,5	—
0,5	0,1	0,1	50	0,2	0,15	60	0,5	0,25	75	1,0	0,5	90
10	0,12	0,1	50	0,25	0,15	60	0,6	0,25	75	1,2	0,5	90
20	0,14	0,1	50	0,3	0,15	60	0,7	0,25	80	1,4	0,5	95
30	0,16	0,1	50	0,35	0,15	65	0,8	0,25	80	1,6	0,5	100
40	0,18	0,1	50	0,4	0,15	65	0,9	0,25	85	1,8	0,5	100
50	0,20	0,1	50	0,45	0,15	65	1,0	0,25	85	2,0	0,5	100
60	0,22	0,1	55	0,5	0,15	65	1,1	0,25	85	2,2	0,5	110
70	0,24	0,1	55	0,55	0,15	70	1,2	0,30	90	2,4	0,6	110
80	0,26	0,1	60	0,6	0,2	70	1,3	0,30	90	2,6	0,6	110
90	0,28	0,1	60	0,65	0,2	70	1,4	0,30	95	2,8	0,6	110
100	0,3	0,1	60	0,7	0,2	70	1,5	0,30	95	3	0,6	120
150	0,4	0,1	65	0,95	0,2	80	2,0	0,30	110	4	0,6	130
200	0,5	0,1	70	1,2	0,2	85	2,5	0,35	120	5	0,7	140
300	0,7	0,15	80	1,7	0,25	95	3,5	0,40	140	7	0,7	170
400	0,9	0,15	90	2,2	0,25	110	4,5	0,45	160	9	0,8	190
500	1,1	0,15	100	2,7	0,3	120	5,5	0,45	180	11	0,9	200
600	1,3	0,2	110	3,2	0,3	130	6,5	0,5	200	13	1,0	250
700	1,5	0,2	120	3,7	0,35	140	7,5	0,6	200	15	1,1	250
800	1,7	0,2	130	4,2	0,35	160	8,5	0,6	250	17	1,1	300
900	1,9	0,2	140	4,7	0,4	170	9,5	0,7	250	19	1,2	300
1000	2	0,25	150	5	0,4	180	10	0,7	300	20	1,3	350
1500	3	0,3	190	7,5	0,5	250	15	0,9	400	30	1,7	450
2000	4	0,4	250	10	0,7	300	20	1,1	500	40	2	600
3000	6	0,5	350	15	0,9	400	30	1,6	700	60	3	850
4000	8	0,65	450	20	1,1	550	40	2	900	80	4	1100

FIGURE 4.

The table covers a range in length from 0.1 mm up to 4,000 mm and four grades of accuracy 0, I, II, and III, the grades I and II being nearly the same as in the previous version of DIN 861. Two grades, a higher one, namely 0, and a lower one, namely III, have been added in the new version. Using the designations usually specified in this country, grade 0, I, and II correspond rather closely to AA, to A, and to B precision. There is no equivalent of grade III in this country. Take, for example, the tolerances for a gage block 100 mm, or nearly 4 in., in length. The allowable tolerances for the length at the center are, according to DIN 861:

	0	I	II	III
DIN 861	$\pm 0.3\ \mu$	$\pm 0.7\ \mu$	$\pm 1.5\ \mu$	$\pm 3\ \mu$
	±0.000012 in.	±0.000028 in.	±0.000060 in.	±0.000120 in.

and according to American classification

	AA	A	B
American standard	±0.000008 in.	±0.000016 in.	±0.000032 in.

The tolerances in length for every accuracy grade as stated by DIN 861, are nearly twice as large as for the preceding grade, the tolerances for grade I being twice as large as for grade 0, for grade II twice as large as for grade I, and so on. This classification of gage blocks in four grades, as stated in the German specifications, takes the usual organization of industrial measurement technique into account. According to the common use of gage blocks in industry, the four accuracy grades 0, I, II, and III could be designated in the same row—as is done in the British standard—as reference grade, calibration grade, inspection grade, and workshop grade, the latter being provided for use in workshops, the inspection grade for controlling gages used in the workshops, the calibration grade for calibration of inspection equipment, and finally the reference grade for the purposes of central metrology laboratories in official institutions or in large plants. The new classification of gage blocks in four grades, instead of in only two as in the previous edition of DIN 861, satisfies the requirements of gage manufacturers for more accurate gage blocks that arose from the higher requirements of the ISA system of tolerances. The introduction of the accuracy grade 0 takes the general improvement in manufacturing gages into account. For many years the situation in Germany was such that gage blocks of high quality were, in general, underrated with regard to quality because they were classed with gage blocks of much lower quality, the highest accuracy grade having been grade I until a short time ago.

With regard to the deviations in length at any point of the surface of the gage block, a comparison with the American specification is impossible without further consideration, because in this country separate requirements are listed for parallelism and flatness, whereas the German standard specifies only one value for the surface errors, this being the deviation in the length at any point of the surface f_b.

One might think that this method of specifying surface errors is not very convenient because it makes a difference whether a surface deviation, for example, of $\pm 0.6\ \mu$, as allowed for a 100-mm gage block in grade III, is due to lack of parallelism only, or whether it is due to lack of flatness only. In the first case, the surface could be of the highest quality with regard to planeness, whereas in the second case, the allowable deviation being due to lack of flatness only, would certainly result in a surface so distorted that it could not be wrung to another plane. The German standards committee discussed the question of whether it is preferable to state separately the tolerances for parallelism and flatness or to define only a single limit for surface errors. The final conclusion was that, in general, it is impossible to separate errors in parallelism and errors of flatness in practice, and therefore they should not be specified separately. Strictly speaking, parallelism is connected to the geometrical concept of plane surfaces and if surfaces are not plane, parallelism has no significance. Consider a gage-block surface with an error in flatness. A correct statement of the error in parallelism perhaps could be made in the following manner: A plane surface may be defined in such a manner that the summed squares of the deviations of each point of this surface from the real surface are a minimum. Parallelism consequently should be determined relative to this ideal plane. Naturally such a method is not practical. Therefore the German specification does not have separate requirements for parallelism and flatness but only the values of f_b, i. e., the values for the permissible deviations in length at any point on the surface with errors in parallelism and of flatness both included. But this does not mean that the surface of a gage block may have errors in flatness of the full amount of the allowable value for the surface deviations f_b, for example $\pm 0.6\ \mu$ for a 100-mm gage block as stated for the accuracy grade III, because it is explicitly stated in DIN 861, that the gage blocks have to satisfy the wringing requirement and this would be impossible if the error in flatness were larger than, let us say, a few tenths of a micron. Thus the decision that gage blocks must satisfy the conditions of wringing, in addition to the limitation on the values of f_b, represents, in reality, a sufficient restriction with regard to the surface errors, and has the advantage of being very easily recognized.

The situation is quite similar with regard to microflatness. The German specifications on gage blocks do not contain any exact information in this respect, in spite of the fact that it is more and more customary for block manufacturers to give information on the surface finish. DIN 861 requires only that the surface finish must be good enough to allow wringing of the gage blocks. There are two reasons for doing so: First, it was felt by the German standards committee that it was too early to specify definite requirements for surface finish, the situation of this field being, in general, not yet clear enough. Second, there was no unanimity of opinion with regard to the degree of surface finish that would be most suitable in practice. The common opinion seems to be that the highest degree of finish should be sought in every case. But objections are often made that surfaces with a very high finish, in practice, are too easily damaged. Indeed, before the war gage blocks of very high quality, but with lower surface finish, were manufactured in Germany explicitly for this reason. In general, the most practical method of specifying surface finish seems to be a requirement as to wringing quality.

With regard to the allowable values of the obliquity, there is little of importance to say. As may be seen from figure 4, the values of s, in general, are rather low, for instance the highest allowable value of the obliquity s for a gage block 100 mm, or about 4 in., in length, for accuracy grade III, is 120 μ or nearly 0.1 mm. The highest possible value of 1,100 μ or more than 1 mm is allowed for a 4,000-mm gage block in grade III.

In general, the new version of DIN 861 contains only specifications, decisions, or statements that are absolutely necessary, no more and no less. In preparing the new standard consideration was given to the fact that gage block manufacturers must inspect their product for compliance with every requirement of the standard. That is of interest not only to gage-block manufacturers but also to the official institutions authorized to inspect gage blocks such as the PTB (Physico-Technical Institute of the Federal Republic) in Germany. The official inspection of gage blocks at the PTB is based entirely on the requirements of DIN 861. The pertinent certificates not only deal with the determined values for length or the other specified sizes of gage blocks but also state explicitly that the gage blocks satisfy the requirements of one of the accuracy grades of DIN 861. Gage blocks that do not fulfill the requirements of the standard are not certified. Thus, by means of DIN 861, not only manufacturing but also official inspection of gage blocks is regulated in Germany, this standard representing a generally acknowledged and commonly used criterion in judging the quality of gage blocks. Naturally no one in Germany is of the opinion that the present specification for gage blocks is perfect, but it is hoped that the present version will satisfy all essential requirements for 10 or 20 years, in spite of the fact that desires for still higher accuracy and specific requirements concerning the surface finish have already been expressed.

15. Proposed Federal Specification for Gage Blocks, Attachments, and Accessories

By I. H. Fullmer[1]

[The draft specification, which is now available as Federal Specification GGG–G–15 from the Business Service Center, General Services Administration, had been previously distributed to those in attendance. The following is a condensed record of Mr. Fullmer's comments on the specification.]

This is a purchase specification for the Federal government. To give you a little of the background and history of it: We have for a long time felt that there ought to be a Federal specification for gage blocks, but as you are well aware, there are so many controversial features to such a specification that it never was undertaken until the Navy Bureau of Ships was given responsibility for the purchase of items of this kind for the entire Department of Defense. A large part of the work that is represented in this document was done by W. V. Hurley of the Bureau of Ships, who is here in the audience. We commented at length on the first draft, which was submitted to NBS, and since then we have been working closely together on formulating the specification.

The scope is that the specification is applicable to precision gage blocks in either the English or metric systems for uses as follows: (1) Laboratory standards for calibrating other gage blocks, (2) laboratory standards for the inspection of other types of gages, (3) inspection gages in tool shop projects, and (4) work gages for laying out and setting up work with high accuracy for machining operations.

The classification covers three shapes: Rectangular, square with center hole, and square without center hole. There are the usual recognized grades of accuracy: AA, A, and B.

Materials specified are steel, chrome-plated steel, and carbides—chromium carbide, tungsten carbide, and other carbides.

In tables I and II are given the sizes of blocks that are generally recognized as standard in the industry. There is an advantage in stipulating these, as the listing will prevent to some extent the specification of odd-size blocks, which present a special problem in measurement. Then is listed a series of sets of blocks, that is, the sizes that go into any given set. There are seven generally recognized sets of blocks stipulated, based on a survey of government requirements made by Mr. Hurley.

You have heard the discussion of the German standard for blocks and you were furnished translations of the German standard. There is also available a British standard for gage blocks, the latest revision being in 1950.

Referring to paragraph 3.4.3 and the requirement that the case shall be marked with the manufacturers' name or trademark, the

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British have this additional requirement: "If the sizes of the gages, as engraved upon them, are not visible when the gages are in their respective compartments, each size shall be marked in the case, immediately adjacent to the appropriate compartment". That is really quite general practice, but it might be well to stipulate it in our specification.

Next, paragraph 3.5.3.1, Surface defects: "Wringing and gaging surfaces shall be free from all burrs, however slight, sharp corners, and other defects which may affect accuracy or serviceability. The edges of wringing surfaces shall be smoothly rounded (not sharp nor beveled) and free from ragged grind marks. The porosity of carbide gage blocks shall be such that no pit on a wringing surface shall exceed 0.001 inch in diameter, width, or length." The British specification definitely specifies that a rounding of the edge shall be equivalent to a radius of 0.015 in. Whether or not it is desirable to stipulate a definite radius for that rounding, I am not certain. It seems to me it would be a rather difficult specification to enforce.

In our next paragraph, 3.5.3.2, Parallelism, flatness, and surface finish: "Gage blocks, attachments, and accessories shall have their wringing surfaces flat, parallel with each other, and smooth within the tolerances specified in table III. For sizes of blocks less than 0.100 inch the tolerances for flatness and parallelism are applicable when the block is wrung to an optical flat. Wringing surfaces of grade AA gage blocks, which are concave from the middle to an edge to a depth exceeding 0.000002 inch shall be subject to rejection. (See 4.4.3.) The finish of gaging surfaces shall meet the requirements of table III when tested by means of a surface roughness analyzer of known accuracy. (See 4.3.1.)" We felt that the stipulation regarding concavity was necessary, particularly on the reference grade of blocks, because such blocks do not wring satisfactorily, and when the edge is turned up in that way one is liable to damage other blocks when wringing the gages. Our practice in this country, at least here at the Bureau, has been to check flatness of gages not wrung down if they are 0.1 in. in size or longer. The British practice is to wring them down up to 0.160 in. Our specification is considerably more rigid, then, in respect to flatness because it will not accept blocks that are warped. Of course, warped blocks again present a difficulty in wringing. When the blocks are thinner than 0.1 in. they often cannot be readily wrung down, and actually it is almost impossible to obtain a thin block that is not warped. The warping in general extends to about the 0.115 in. size, but from 0.1 to 0.115 in. the warping is not serious; the blocks generally wring down satisfactorily. They are usually within the tolerance specified for flatness.

Turning to table III we might examine the tolerances specified. These tolerances compare quite closely with those specified in the British standard, there being differences of one or two millionths inch in certain categories. With regard to surface finish specifications, I think we should consider that a requirement for wringability might serve as a substitute for flatness and surface finish requirements, as Dr. Engelhard pointed out this morning. However, our practice is well established along the lines laid down and seems to be working satisfactorily. In any case, I think that a wringability test is an important test to make because it uncovers a variety of defects.

Referring to the last column of table III and the referenced footnote, which states that "all scratches shall not exceed the depth specified except that random scratches not exceeding twice the specified depth may occur at intervals of 0.001 in. or greater": the interval of 0.001 in. represents about one-half of the diameter of the field seen in a microinterferometer. A series of scratches, which are somewhat deeper than the average specified, can be tolerated if there are reasonable spaces separating them.

Table IV, tolerances on lengths of gage blocks, conforms with practice except that we have specified a biased bilateral tolerance, more plus tolerance than minus. As you heard this morning, there is some objection to specifying tolerances in that way. It is a matter of a choice of two evils. We tried balanced bilateral tolerances. If one were buying a B block with a tolerance of ± 0.000008 in. and then allowed 0.000003 in. observational error, one might get a block 0.000011 in. short, that is a block which is worn out before it is used. For that reason we have given a plus bias to the tolerances, and we feel that in general, the random sizes that we will get in a set of blocks will not all be excessively plus. Some will be minus and, in general, the combinations are not expected to be biased plus to any detrimental degree.

Referring to paragraph 3.5.3.3, Squareness of sides, we have specified a tolerance of 5 min. When the blocks are supported in a horizontal position, if the sides are appreciably out-of-square there may be difficulty. This tolerance of 5 min we found to be more or less representative of blocks which we check. The British specification is 0.001 in. over the length of the gage. In a 1-in. length that amounts to 3.5 min compared with our tolerance of 5 min. Specifying it as they do, the specification becomes more rigid as the length increases.

I call your attention to the fact that we do require that a manufacturer's certificate of inspection be furnished with each set. This is desirable because it assures that the set has been inspected properly. Also, for the person who inspects it for the government, a discrepancy would give an indication that perhaps the measurements of a given block should be repeated.

Under paragraph 3.4.2; "Cases shall be so designed that when the case is open the blocks, attachments, or accessories are readily removable, but when closed and fastened they shall be firmly held in place. The means of fastening the lid shall be of such strength and positive action that the lid will not open during shipment as the result of either breakage or opening of the fasteners. Unless otherwise specified in the invitations for bids, contract, or order the case dimensions shall be in conformance with manufacturer's standard practice." For some time sets of blocks that were shipped to the Bureau for calibration were often received in damaged condition, either because the clasps on the cases broke or they were not fastened securely.

We have stated a requirement for wringability of blocks under "Inspection", paragraph 4.3.2: "Either as a separate test, or in the course of testing the parallelism as required under 4.4 and 4.5, the wringing quality of all blocks shall be examined. When wringing or gaging surfaces are wiped clean with a dry cloth or chamois, not less than 95 percent of the surface shall wring down on a transparent (quartz or glass) optical flat, as indicated by the absence of color between the wrung surfaces when viewed in white light." We feel that the block should wring down over the entire surface, but we can tolerate a spot that does not, provided that the block is within the flatness tolerance.

In the inspection of blocks we feel that all AA and A blocks should be inspected, that is, the entire set of blocks. Most of this inspection will be performed by government laboratories other than the National Bureau of Standards. The Bureau is not at present in a position to undertake what we might term acceptance inspection of gage blocks. Our function is to provide calibrated masters where they are needed. Occasionally we have had the experience that a set has been shipped here by the manufacturer, and it has been stated that the agency ordering the set has required a certificate from the Bureau before the set is accepted. Usually that is done without the foreknowledge of the Bureau and is a practice that should be avoided. If the buying agency of the government wants an inspection by the Bureau, the agency should order it directly from the Bureau.

In the inspection of B blocks we have tried to set up what might be called a sampling plan. Grade B blocks do not require 100-percent inspection of the set. We have put in this stipulation that "the 2-, 3-, and 4-inch blocks shall be measured individually and a sample of 15 gage blocks shall be drawn at random from the set, of sizes to and including 1 inch. The length correction of each block shall be determined in accordance with 4.4.1. The set shall be regarded as conforming to the requirements of this specification for length if both: (a) All individual errors are within the interval −8.4 to +12.4 microinches, or this interval times the length in the case of the 2-, 3-, and 4-inch blocks; (b) after subtracting 2 microinches from each error for the blocks in the random sample and regarding these as whole numbers, the sum of their squares is less than 213."

This specification was worked out after we spent hours with members of the Mathematics Division and statistical experts from the Bureau of Ships. Mr. Marthens is going to present some charts later showing the basis of that specification.

In addition to this test of 15 blocks, we would require what is called a composite test. "A composite test involving length, parallelism, flatness, and wringing quality shall be made as follows: Nine groups of blocks shall be formed from a set, each group consisting of from 8 to 10 blocks each. The blocks of each group shall be wrung together and the combined length of each group measured. The set shall be regarded as conforming to the requirements of this specification if: (a) Each of the 9 groups has a correction of less than 28 microinches, or (b) 8 groups have corrections less than 28 microinches and the remaining group, having a correction larger than 28 microinches, has not more than one block outside of the tolerance for length when each block of that group is measured."

Another requirement in the specification which might be discussed further is that for hardness. It has been traditional in this country to require a hardness of Rockwell C65 on steel gage blocks as a minimum. As was brought out here in the discussion yesterday morning, blocks that are not quite so hard are more likely to be stable than blocks hardened to C65. Thus there is again a choice as to which is more tolerable, lesser hardness with greater stability or higher hardness and increased wear resistance with less stability.

16. Discussion

Discussion relating to papers Nos. 7 and 11

Question: Do you substitute the average depth for what is commonly known as a root mean square?

Mr. Strang: The trend in this country now is to eliminate the rms value. This has been accepted in most industries. Arithmetical average seems to be a simpler value to understand. We are using, and many European countries are using, what is called the center line average, or arithmetical average.

Mr. Haven: Arithmetical average has been officially adopted in this country, Mr. Curtis.

Mr. Strang: Theoretically there is about a 10 percent difference between the two values. Practically you usually obtain about the same value using instruments which indicate in rms or arithmetical average units.

Mr. Haven: Are there any other questions?

Dr. Gardner: I don't have a question but I wish to refer to Mr. Moody's paper. I enjoyed it very much. There was one thing he mentioned which I think should have been emphasized a bit more, perhaps. That is, that this radiant energy that heats these gages is not necessarily from light bulbs. A good bit of the radiant energy comes from material that is at such a relatively low temperature one can't see it at all. We were working, for instance, in a room that had one wall separating the room from the hall and one wall separating the room from the earth. The difference in temperature of these two walls gave a radiation effect which caused us quite a bit of trouble until we eliminated it by use of aluminum foil. Mr. Moody mentioned this effect but he talked so much more about lights that I wanted to emphasize that it isn't only the sources of visible radiation in the room that cause this heating effect.

Mr. Haven: I think that everyone who has worked in laboratories has found that lights do have an effect on gage standards. I am glad Dr. Gardner brought out the effects of other sources of radiant energy.

Question: From the standpoint of acceptance and inspection of blocks, would you care to indicate your preference for instrumentation, the tracer type instrument or microinterferometer or a combination?

Mr. Strang: I think that if a tracer type instrument with a slower tracing speed were available, I would prefer it. Average deviations from a mean line obtained with the microinterferometer are usually about twice the values obtained with a tracer type instrument. I think the center line average values shown in the slides are too low. If the tracer could move slowly, I believe it would give fairly good values. If it moves too fast, there is some loss in the indicated depth. With microinterferometers that are available now the scratch width won't show up unless you increase the magnification of the instrument or make enlargements. The charts obtained with a tracer type instrument are much easier to interpret than the fringe patterns of the microinterferometer.

QUESTION: How often would the tracer point have to be checked if it were used continuously?

MR. STRANG: We haven't worn a tracer point to any appreciable extent so I can't answer that question. From what we have heard they last a long time.

MR. A. W. YOUNG: I would like to point out two things. Someone here mentioned a tracer stylus of 30 microinches radius which wore very rapidly. We have checked tracer styli periodically and I haven't observed too much change in them. As far as the stylus entering at a slower speed, Dr. Rolt pointed out in his paper that they have made comparative tests on gage blocks and in that case what was done—I believe Eric Lindberg of General Motors Research has done some of the same work—was to slow up the motor drive by using a manual control. You can get a much slower manual drive which would allow the stylus to enter at a very slow speed. All that is required is a simple suction attachment.

MR. HAVEN: I think we have to recognize that the Talysurf is a general purpose instrument. The finish on gage blocks represents a rather extreme application and calls for special methods.

Are there any other questions? (None)

Discussion following papers Nos. 4 and 12

MR. HAVEN: Are there any questions?

QUESTION: I wonder if you could tell me the movement of the micrometer screw for the total two ten-thousandths of an inch range of this interferometer?

MR. T. R. YOUNG: The total travel is one inch.

QUESTION: One inch on the micrometer represents 2 ten-thousandths of an inch in the length of the gage?

MR. YOUNG: Yes.

QUESTION: Thank you.

MR. HAVEN: Are there other questions?

DR. GARDNER: Mr. Chairman, I have very much enjoyed the presentation of Mr. Johansson and agree with him on essentially all points. I think if the National Physical Laboratory and the National Bureau of Standards had the privilege of deciding between the American and British inches this matter would have been settled long since. Unfortunately, it is not so simple. I don't know what the British problem is but here we have to convince Congress that this change should be made. That isn't always the most direct method of procedure. The ASA standardization is admittedly sort of a stop-gap, but it is very surprising the respect some people have for these inches which we think are sort of outworn and outmoded. I would not want this assembly to go away believing that the failure to come to an agreement on these inches is an indication of the failure of scientific men or of the two national laboratories. It is purely a matter of legal complications which are much more than you would imagine.

Regarding the chromium plating, I believe the National Bureau of Standards, in another section, has developed a very ingenious instrument for measuring the thickness of chromium plating, particularly when it is applied to a substance such as steel. We can measure these chromium layers without mutilating them and without the slightest difficulty. I don't know whether we have reached an opinion here as to the most desirable thickness of chromium or not, but it can be readily measured once we have decided on the matter. I believe the Bureau certificates now give the measurement at the center of a gage block instead of at the edge. As to the accuracy and precision, we are constantly trying to improve both here. We have a rather extensive development program in progress and the instrument that you have seen today is one of our steps in progressing towards a more precise and accurate method of determining the length of gage blocks.

There is a committee in the Bureau that is considering this whole question of how to state accuracy and precision and what we should say, and I think before very long our reports will be perfectly adequate in that respect. It is not an easy problem. To make a definite statement of the precision of the measurement which we can stand by and to make a definite statement of the accuracy is not simple. In fact, it is impossible, but we can make statements that will be true perhaps 99 percent of the time.

Mr. Haven: Are there further comments or questions?

Voice: I don't think that the user should be expected to accept a grade A block that is in error by 7 millionths, because, as I understand it, Dr. Gardner just stated that the 3 millionths observational error is more or less in there to reduce controversies and that the size that is given for the block is usually more accurate. I am afraid that some of the manufacturers are taking advantage of the uncertainty in measurement. I never liked it and I don't think we should be expected to accept blocks that are in error by the tolerance plus the full amount of the uncertainty.

Mr. Fullmer: I might say that the practice of the Bureau has changed in recent years with regard to certification of blocks. During the war particularly, when acceptance of blocks by the government was based on our calibration, we actually listed the criteria for the various grades of blocks and applied the observational errors to the tolerance. We have discontinued that practice entirely. Our calibration reports now merely state the size of the block, the errors, etc. There is no judgment passed on the block as to whether it should be accepted or rejected by the users.