GALINDENT: THE REFERENCE METROLOGICAL SYSTEM
FOR THE VERIFICATION OF THE GEOMETRICAL CHARACTERISTICS
OF ROCKWELL AND VICKERS DIAMOND INDENTERS

A. Liguori – A. Germak – G. Gori – E. Messina

ABSTRACT
The paper describes the GALINDENT system that LTF – Galileo Hardness Testing Department, in co-operation with the Institute of Metrology "G. Colonnetti", has developed for the geometrical verification of Rockwell, Vickers diamond indenters, as prescribed by ISO Standards. This system consists of two instruments: an Interferometric Sine-Bar, for angular, straightness and flatness measures and a Rotary Table, for the verification of the spherical tip of Rockwell indenters. These two devices can be set up in one workstation, interfaced with the same computer for data analysis. A software package has been specifically developed to manage the entire system. The measurement test cycle is completely automated in order to ensure objective and reliable results. The operator interface, based on a graphic window menu in the Windows® environment, is extremely user friendly and it does not require any programming knowledge.

INTRODUCTION
Galindent is a computer-aided system, as shown in fig.1, for the geometrical characterisation of diamond indenters for Rockwell and Vickers hardness tests, as prescribed by ISO Standards [1,2,3,4]. Galindent consists of two workstations, sharing the same processing unit and software:

- an **Interferometric Sine Bar**, for the measurements of angles and other geometrical quantities on Vickers indenters as well as on the conical part of Rockwell indenters;
- a **Rotary Table**, for the characterisation of the spherical tip of Rockwell indenters.

Thanks to the user-friendly software, the operator is guided while carrying out each measurement, but is free to choose the sequence of the various phases (after the system is set up). A database manager included in the software itself, makes data retrieving quite easy and fast.

Fig. 1 – The Galindent system

Standard requirements for Rockwell Indenters
According to ISO standards, the following characteristics are to be verified in order to evaluate the conformity of this type of indenters:
  a) included angle of the diamond cone (α)
  b) angle between the axis of the diamond cone and the axis of the indenter holder (β)
  c) deviation from straightness of the generatrix line of the diamond cone (δ)
  d) radius of the spherical tip (R)
  e) deviation of the tip profile from the average spherical surface (ε)
The following tolerances are prescribed by ISO standards for the above mentioned quantities:

Characteristic	ISO: commercial indenter	ISO: standardising indenter
α	± 0,35°	± 0,10°
β	± 0,50°	± 0,30°
δ	0,002 mm/0,40 mm	0,0005 mm/0,40 mm
R each section:	± 0,015 mm	± 0,007 mm
R average:	± 0,010 mm	± 0,005 mm
ε	0,002 mm	0,001 mm

Standard requirements for Vickers Indenters

According to ISO standards, the following characteristics are to be verified in order to evaluate the conformity of this type of indenters:

a) angle between the opposite faces at the vertex of the diamond pyramid (α)
b) angle between the axis of diamond pyramid and axis of the indenter holder (β)
c) length of the line of junction between opposite faces (f)
d) permissible difference of the sectional planes of the square form (Φ)

The following tolerances are prescribed by ISO standards for the above mentioned quantities:

Characteristic		ISO: commercial indenter	ISO: standardising indenter
α		± 0,5°	± 0,1°
β		± 0,5°	± 0,3°
f	up to <HV 0.2	0,0005 mm	0,00025 mm
	HV 0.2 to <HV 5	0,0010 mm	0,0010 mm
f	HV 5 to HV 100	0,0020 mm	0,0010 mm
Φ			± 0,2°

INTERFEROMETRIC SINE BAR

Principle

The Sine Bar workstation is based on Mirau interferometry for the measurement of angles, flatness, straightness, etc.: a metallurgical microscope is equipped with DI objectives, where a light beam is split into two beams; one is directly reflected to the observer (either through the eyepieces or through a TV Camera), the other is directed to the observed field, which reflects it to the observer as well. The two split parts of the light beam will thus recompose and generate an interference pattern; in any point of the formed image, the phase – and therefore the luminance level - depends on the difference of the optical path run through by light: points whose differential optical path is equal to the light wavelength λ will have the same phase, i.e. the same light level. To be in such conditions, the two points must be placed in two planes, perpendicular to the optical axis of the microscope and whose distance is an integer multiple of λ/2. By this simple physical phenomenon it is possible to reconstruct the geometry of an observed surface through the analysis of the interference fringe pattern, which can be seen as a topographical map of the surface itself, where the fringes are the geometrical locus of points placed on the same plane normal to the optical axis. This principle is adopted in the sine bar workstation of Galindent (fig. 2) in order to place the indenter surface, or part of it, in conditions of normality to the optical axis which is fixed: the rotation to place the surface into this condition is measured to evaluate angles in the indenter geometry. Moreover, the analysis of the fringe pattern allows also to evaluate the flatness error on the pyramid faces of Vickers indenters, as well as straightness error on the cone generatrices of Rockwell indenters.
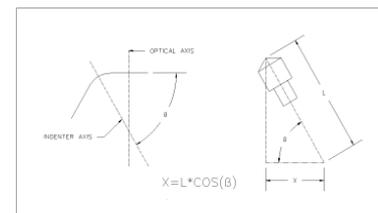
Fig. 2 – Sine Bar principle

Description

The instrument, as shown in fig. 3, is composed by:

- a metallographic microscope with universal epi-illuminator and 5-position nosepiece;
- colour-filter for observation in green light (wavelength ≅ 0,55 μm);
- 5x, 50x and 100x objectives for bright field observation;
- 10x and 20x objectives for double-beam (Mirau) interferometry;
- trinocular tube with two 10x eyepieces and C-mount camera adapter;
- a specially-designed sine-bar, with regulations on the 6 degrees of freedom to be mounted on

Fig. 3 – Interpherometric Sine Bar

the microscope stand in place of the traditional stage;
- a motorised linear transducer, 60 mm stroke, with computer interface;
- an encoder with a resolution of 1500 points.

Once the indenter is mounted on the sine-bar, the equipment allows to rotate the indenter around the axis of its holder, in 8 fixed position (45° interval); so it is possible to inspect 4 axial sectio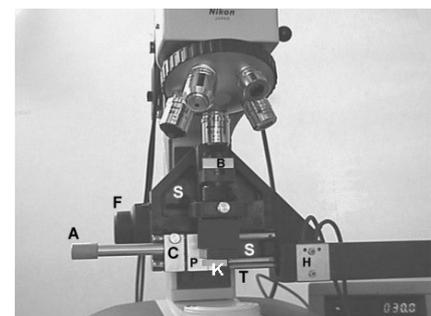ns of each indenter; further, it is possible to rotate the indenter on the plane defined by the optical axis of the microscope and the axis of the indenter holder in order to perform the correct position.

Fig 4 – Generatrix Straightness measurement

For Rockwell indenters, the generatrix line of the cone is brought perpendicular to the optical axis of the microscope by the evaluation of the shape of the interference fringe pattern observed: from the measure of the distance, it is possible to calculate, for each position, the inclination angle ω_i of the indenter. Once each ω_i value is known, the values of α and β angles are computed, by the application of trigonometry. Moreover, the straightness deviation ε of the generatrix is easily evaluated from the fringe pattern, fig 4. Qualitative evaluations of the blend between the cone and the spherical tip, as well as the detection of superficial defects of the diamond, are possible with the equipment.

For Vickers indenters, each face of the pyramid is positioned perpendicular to the optical axis in a similar way; thus, from the measurement of ω_i for the 4 faces, the value of α and β are computed by trigonometric calculations.

From the fringe pattern, on each face the flatness error Ω can be easily evaluated. The measurement of the offset f is possible by the observation with the 100X objective

The instrument is designed for 6,35 h5 mm diameter of the indenter shaft: different values are available as optional as well as for the length of the indenter.

It is well known that the ISO 6507-3 standard is not very clear and well defined about the verification of the pyramid indenter squareness: in particular, the Standard does not define which section, normal to the indenter axis, shall be verified or, in other words, at which distance from the indenter tip the squareness

Fig. 5 – Vickers indenter angle measurement (aligned fringe pattern)

error shall be evaluated. According to IMGC, we perform the squareness measurement as follows:

a) for each face of the pyramid, on the base of the fringe pattern obtained on the interferometric Microscope, the plane normal to the face and containing the indenter axis is identified; let *p1, p2, p3* and *p4* be the four planes thus identified.

b) the angles between the planes *p1, p2, p3* and *p4* are measured by an angle transducer mounted on the indenter axis. These angles, nominally equal to 90° each, are assumed as the angles of the quadrilateral section between the pyramid and a plane normal to its axis.

This solution has the advantage of taking into account the whole face geometry, fig. 5, rather than its section by an undefined plane, and is expected to give a more significant result for what the indenter behaviour is concerned. It has to be pointed out that, in the above described approach, the pyramid axis and the indenter holder axis are assumed to coincide, which is not exact; but, also considering the type of indenters for which this verification is required, the error due to this approximation is negligible in practice, since the misalignment is of a few tenths of degree.

Performances

The described equipment allows the geometrical verification of the diamond indenters according to the above mentioned standards, with the following performances:
- repeatability on α angle measurement: 0,03°;
- reproducibility on α angle measurement: 0,06°;
- accuracy of α angle measurement: 0,1°;
- accuracy of flatness measurement: 0,0003 rnm;
- accuracy of straightness deviation: 0,001 mm;

- estimation of offset (f) measurement: 0,00025 mm.

The testing time for the verification of each indenter is 10-15 minutes; the set-up time is about 10 minutes for each testing session.

ROTARY TABLE
Principle
In order to characterise the spherical tip of the Rockwell cone indenters, a rotary table is adopted to rotate the indenter around the centre of the nominal radius and detecting the displacement of the actual profile from the reference one by a linear transducer with a spherical probe. Repeating this operation in several axial sections of the indenter the full geometry of the tip can be reconstructed to give a global evaluation of the tip itself. The reference profile, corresponding to a sphere of nominal radius, is obtained by detecting a ruby sphere of 0,4 mm diameter: the table is adjusted to rotate around a vertical axis through the centre of this sphere, while the relevant profile is assumed as the "zero" for the indenter profile detection. Some design choices have been adopted to improve the system performance and accuracy:

- the table rotation is supported on air bearings, in order to achieve high stiffness of the table and virtually eliminate friction and therefore any related consequence, like non-uniform rotation, variation of the rotation axis due to lateral forces caused for example by stick-slip effect;
- the displacement transducer is placed in a horizontal plane, and its axis is in radial direction with respect to the nominal sphere; thus, the measuring direction is always normal to the nominal surface of the indenter, and therefore the uncertainty contribution due to the shape of the transducer probe (a sphere of much bigger radius than the tip radius), is minimised.

The theoretical principles which the table is based on are clearly exposed in [5].

Description
The "core" of the device is an air-bearing supported precision table, which holds a supporting device for the indenter to be verified. The support is capable of several adjusting movements, shown in Fig. 6. The indenter **I** is mounted on a holder **C** which allows indenter rotation around its own axis, so that different axial sections can be verified. Twelve sections, one every 15°, are identifiable by a graduated scale in the knob **C**, while the knob **D** can be used to block the rotation in the desired section. The micrometric screw **A** - **B** acts on a vertical stage which moves the whole indenter holder (and therefore the indenter itself) vertically, so that the transducer **M** can be put on the axial plane of the indenter. The knob **A** and **B** are for coarse and fine adjustment respectively. All these groups (i.e. indenter holder and vertical stage) are mounted on a cross-stage: one axis of this stage, moved by knobs **E** and **F** for coarse and fine adjustment respectively, is in radial direction; the other, moved by a similar micrometric screw (**N** and **P** for coarse and fine movement), moves the transversal stage, operating in tangential direction. The last two stages allow the operator to place the indenter in the correct position with respect to the rotation axis of the table. There are two more adjustment knobs on the rotary table, identified by the letters **G** and **H** in Fig. 5: they act on a stage which carries the transducer **M**, moving it along its axis. This adjustment is used during setup to zero-set the transducer value on a reference sphere of nominal radius. The last degree of freedom of the Rotary Table is its rotation movement, which is measured by a shaft encoder, directly mounted in the table base. The table rotation can be manual or automatic.

Performances
The performances of this device connected to a computer for data acquisition and processing are:

- resolution (along transducer axis):   0,0002 mm
- ε measurement uncertainty: 0,0005 mm
- R measurement uncertainty: 0,003 mm

Fig. 6 – The Rotary Table

SOFTWARE FOR DATA ACQUISITION AND EVALUATION
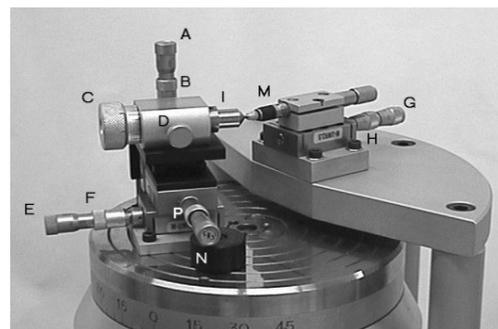The above mentioned performances for both the Sine Bar and the Rotary Table are achievable by the

availability of a data acquisition and processing system. A personal computer, based on a Pentium IV processor with suitable connected boards is the necessary processing system to complete the workstation. The Galindent package is provided for:

- data acquisition from the linear transducer and the encoder of the sine-bar equipment;
- calculation of angles from the measured quantities and statistical uncertainty evaluation;
- acquisition and digitisation of the TV-camera image of the fringe pattern, for computer aided measurement of the straightness deviation of the generatrix line of the diamond cone;
- acquisition and analog to digital conversion of the transducer output on the rotating table;
- graphic display of the detected profile (fig. 7 and 8);
- regression analysis on the transducer output for the calculation of radius and shape error;
- certificate print-out.

The Galindent package adopts a MS Access® database structure to save its working data, like users' information, measured data, indenter data, and so on; the reason for this is to give the users the possibility of accessing these data also with common software packages (like MS Access®, Excel® or Word®), normally available as office automation tools, for customised processing: it is therefore possible and quite easy to perform processing or reporting operations (like reporting, data analysis, Internet or Intranet data sharing, etc.) far besides the Galindent software possibilities. In other words, while the Galindent package is capable of a complete series of standard operations strictly connected to the Galindent system itself, its database structure is open to a virtually infinite range of possibilities in terms of customised processing, reporting, analysis, sharing, publishing. etc. towards the whole world of information technology.

VERIFICATION TESTS
Procedures
Due to the fact that the Galindent is a Primary Reference Metrological System, the following principles for its verification have being adopted.

With reference to the Rotary Table, after the session of set up, we have carried out a complete measurement of the Reference Ruby Sphere on twelve different axial sections. Then, we have performed measurements on several indenters. Then we have carried out again the control of the Reference Ruby Sphere on four different sections, in different days. Further, we have carried out a comparison with the IMGC indenter.

With reference to the Sine Bar and in particularly for the measure of the angle, we have performed a set of five measurements (three series on four sections, each measurement) on the same IMGC indenter without dismount. Then, we have repeated this control, but dismounting and re-mounting the indenter each time. Further, we have repeated three set of measures on the same indenter, but moving it (just a little angle of 1-2º) in its slot. Then, we have performed measurements on several different indenters both Rockwell and Vickers, carrying out informal comparisons with the similar System of our Sit Calibration Centre. With reference to the verification of the Rotary Table, we have obtained uncertainties of the R measurement lower then the announced performances: 1-2 µm against the 3 µm. The other performances have resulted complying with the values above described.
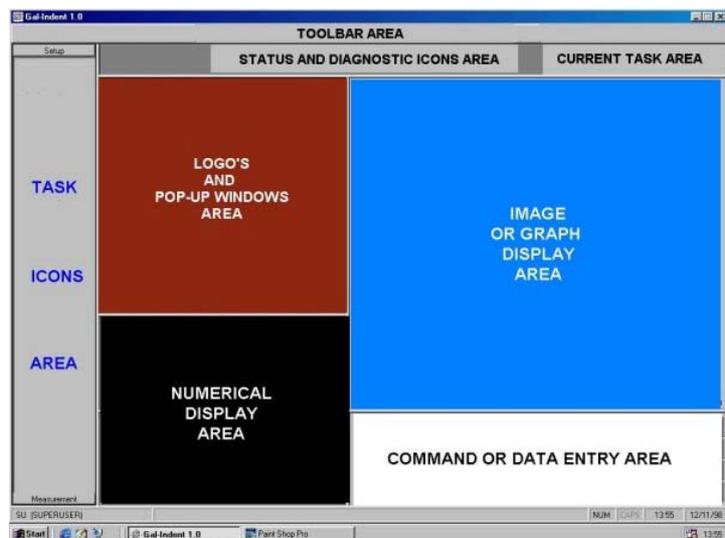

Fig. 7 Software package: Man-Machine Interface

With reference to the verification of the Sine Bar, we have obtained:

- repeatability of angle measurement: lower then 0,02°;
- reproducibility of angle measurement: 0,03°;
- the medium difference of the measure of the angle has been inferior to 0,1°. In particular, for the IMGC indenter, we have obtained a maximum difference of 0,03°.

All these results have been observed during the last three years on several systems that have already been operating successfully at the NPL Laboratory in London [6,7] and at the LTF's SIT Calibration Centre in Antegnate (Bergamo – Italy) [8]. Recently the new software and control has been implemented also in the IMGC measuring system.
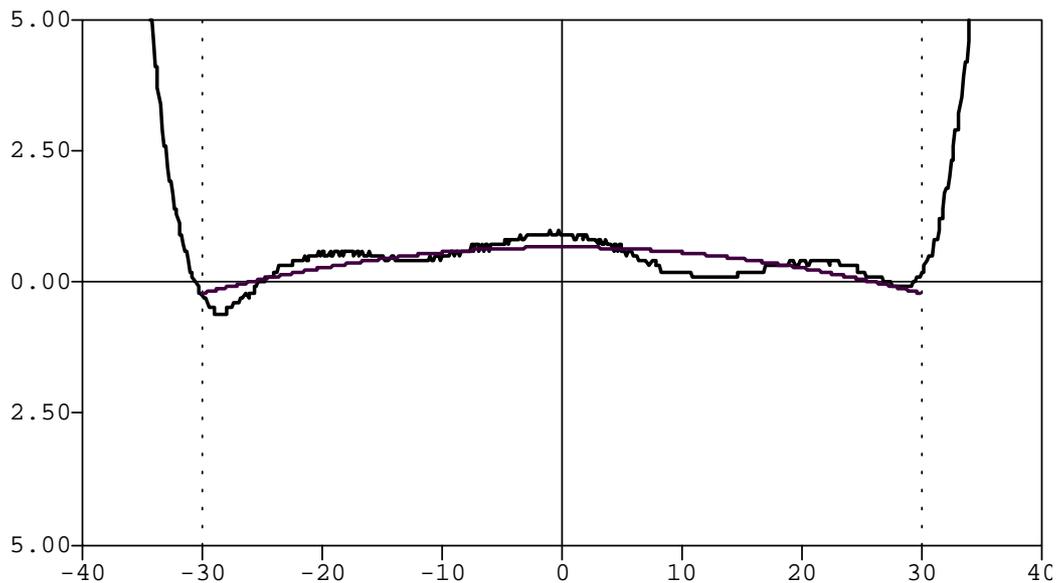
GENERATRIX: 135°-315°   Mean Radius: 194.1 µm

Fig. 8 – Software package

References

[1] ISO 6507-2:1997   Metallic materials -- Vickers hardness test -- Part 2: Verification of testing machines
[2] ISO 6507-3:1997   Metallic materials -- Vickers hardness test -- Part 3: Calibration of reference blocks
[3] ISO 6508-2:1999   Metallic materials -- Rockwell hardness test -- Part 2: Verification and calibration of testing machines (scales A, B, C, D, E, F, G, H, K, N, T)
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[5] G. Barbato and S. Desogus, Measurement of the spherical tip of Rockwell indenters, Journal of Testing and Evaluation, JTEVA, v. 16, No. 4, July 1988, p. 369-375.
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[8] F. Turotti, A. Liguori and G. Gori, LTF Spa contribution to the standardization of hardness measurements, HARDMEKO '98, Proceedings of International Symposium on Advances in Hardness Measurement, (Beijing, China 21-24 September 1998) p. 41-46.

Authors:
A. Liguori (LTF Spa – Strada Statale Soncinese 52, 24051 Antegnate, (BG), Italy)
A. Germak (CNR-IMGC – Strada delle Cacce 73, 10135 Torino, Italy)
G. Gori (Dimensioni – Via Salutati 3, 51100 Pistoia, Italy)
E. Messina (Via Cimarosa 2, 51100 Pistoia, Italy)