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EQUOTIP – REBOUND HARDNESS TESTING AFTER D. LEEB

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Abstract – Hardness tests have always been important to conclude on specific mechanical properties of materials in a fast and economic manner, i.e. in a (quasi) non destructive test. This paper has its focus on the most recent test method, the dynamic rebound hardness test method after D. Leeb. The EQUOTIP[1], Leeb's original instrument, is fully discussed and newest improvements are presented. So far, PROCEQ SA, Swiss manufacturer of the instruments, maintained and protected the constancy of the L-Value over the last 30 years. Recent round robin results show the way, where standardization work can be improved to hold the high level of reliability of the measuring base, the L-Value.

Keywords: EQUOTIP, Dynamic Hardness, Portable Hardness Testing

1. INTRODUCTION

Hardness tests are important means in materials research and industrial production as mechanical characteristics of materials are retrieved quickly and economically. For example, in industrial production specific material treatments (alloying, cold and hot working, heat treating …) have a strong influence on the final conditions of products and their mechanical properties. Hardness tests provide a convenient and reliable mean to optimize material properties or the production process and to quantify the defined specifications in a final quality control.

The term "hardness" may be defined as the ability of a material to resist permanent indentation or deformation when in contact with an indenter under load. Also the more general variant "Hardness is the response of a material to stressing by penetration exerted by a body harder than itself" is used, especially for dynamic hardness testing [1]. Generally, a hardness test consists of pressing an indenter of known geometry and mechanical properties under pre-defined conditions into the test material.

Different hardness test methods were developed and adopted in a big variety of test problems. The main concern is always to compare test results on an unequivocally base, an accepted reference scale. As hardness depends on the test method and the definition of the application parameters, hardness is not a fundamental (physical) property of materials. Thus, it is highly important of clearly defining the instrument and the test parameters. Several decades ago already first agreements and standards where developed on a local, regional level. Within the last decades also several improvements in standardization on a global level could be achieved.

Standardized hardness tests according to the static methods of Brinell, Vickers and Rockwell and to the dynamic method of Leeb, respectively, are the most frequently used. Each method allows for presentation of results in several, different scales like Rockwell C or B, HV5 or HV100. The scale definition depends on method and test parameters applied (indenter type and shape, test force application and quantity). Other hardness test methods conclude to these values indirectly by comparison measurements.

The classic, stationary hardness tests after Brinell, Vickers and Rockwell are well established. However, as soon as it was required to test very large pieces or pieces that are unwieldy to be tested in the usual types of testing machines no alternative was available. Testing parts of fixed structures, or testing under any conditions which require that the indentation force be applied in a direction other than vertical, made the search for portable solutions indispensable. Comparators working according to the UCI (ultrasonic contact impedance) test method or according to the Pin- and Tele-Brinell test method were used at first, but basically dynamic hardness testing showed its practical use due to fast and easy use and high accuracy [2-4]. The use of those portable hardness testers was initially limited to field tests where the test piece couldn't be brought to the testing instrument. However, meanwhile many different portable hardness testers proved there excellence even for laboratory use.

2. EQUOTIP

2.1. Leeb's invention

Dietmar Leeb studied in the early 70ties the different hardness test methods with main focus on portable solutions like the method of Baumann-Steinrück, Schmidt and Shore [5]. The most frequently used portable hardness testers where of dynamic type, where the test load is applied impulsively. The question arose, how can - without loss in measurement accuracy - the common hardness range be extended and the operation become more flexible, e.g. independent of test direction, faster, user independent and comfortable.

The genius result was the invention and successful production of the EQUOTIP in 1975 (Fig. 1), a dynamic hardness test method and instrument [6]. This method is also

[1] EQUOTIP is a registered trademark of PROCEQ SA.

known in connection with the inventors name as Leeb hardness test method or rebound hardness test after D. Leeb. The EQUOTIP is nowadays the most frequently used portable hardness tester. Users appreciate especially it's flexibility, ease of use and fast and accurate measurement over a long period of time. Due to it's usefulness – even in overhead position – and the sound measurements very frequently the whole series production is controlled by EQUOTIPs where now also the need for an automated tester has grown up.

Fig. 1. First two models of EQUOTIP hardness testers. Above: 1975 series; below: series of red hexagonal EQUOTIP, produced between 1978 and 1990 (courtesy PROCEQ SA, Switzerland).

2.2. The EQUOTIP principle

An impact device (Fig. 2) fires an impact body containing a permanent magnet and the very hard indenter sphere itself towards the surface of the test material. The velocity of the impact body is recorded in three main test phases;

i) the pre-impact phase, where the impact body is accelerated by spring force towards the surface of the test piece.
ii) the impact phase, where the impact body and the test piece are in contact. The hard indenter tip deforms the test material elastically and plastically and is deformed itself elastically. After the impact body is fully stopped, elastic recovery of the test material and the impact body takes place and causes the rebound of the impact body.
iii) the rebound phase, where the impact body leaves the test piece with residual energy, not consumed during the impact phase.

Leeb's genius idea was to measure the velocity of the impact body contact-free via the induction voltage generated by the moving magnet trough a defined induction coil mounted on the guide tube of the device. The induced voltage is directly proportional to the velocity of the magnet,

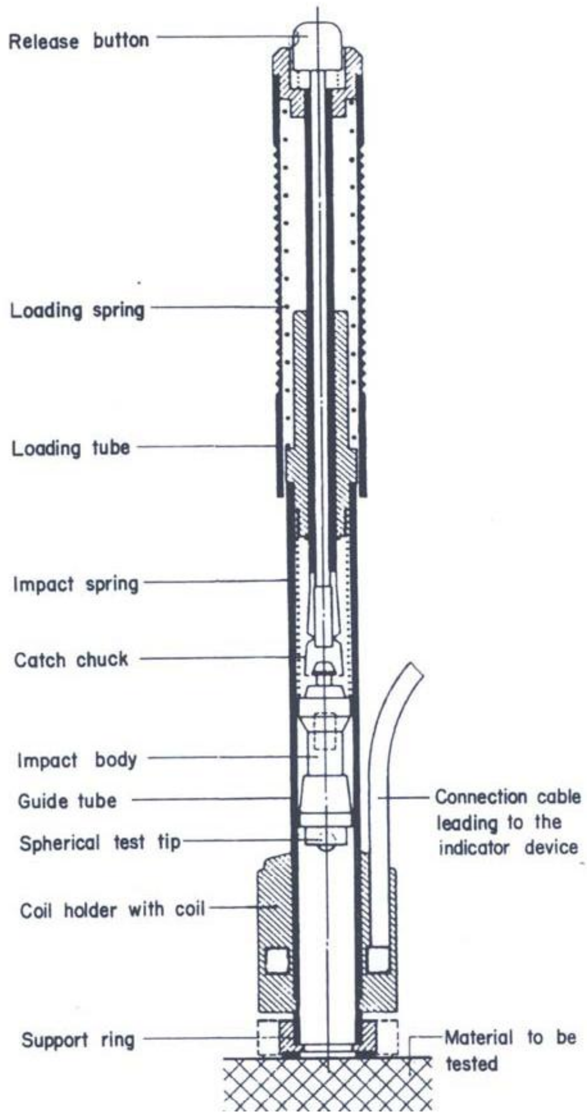

Fig. 2. Schematic view of the EQUOTIP impact device D.

thus, the impact body containing the magnet. The induced induction signal (Fig. 3) is recorded in an electronic indicator device and the peak induction voltages are further processed to give Leeb's hardness number, the L-value. The shape of the induction signal is unique for each device type.

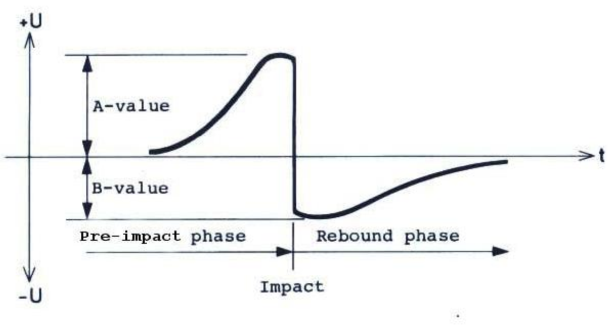

Fig. 3. Typical induction voltage signal generated by the permanent magnet inside the impact body during the main three test phases of an EQUOTIP hardness test.

2.3. The L-value

The L-value, also known as Leeb-number or Leeb-hardness (HL), is simply described as equal to the ratio of the rebound velocity v_r to the impact velocity v_i of the impact body, multiplied by 1000;

$$L = \frac{\hat{A}}{\hat{B}} \cdot 1000 \quad \propto \quad \frac{v_r}{v_i} \cdot 1000 . \qquad (1)$$

The peak induction voltages are proportional to the impact and rebound velocities and are measured at a defined position from the test surface.

A fully elastic rebound ($v_r = v_i$) would cause L = 1000, all energy is elastically recovered and no plastic deformation takes place. On the other hand L will be lowered with decreasing material hardness, where less resistance to plastic deformation is present and a lot of energy is consumed during the indentation. The measurement procedure also explains the naming of the EQUOTIP, where EQUO = Energy QUOtient.

The symbol for the hardness scale, L or HL, is followed by a suffix character, representing the type of impact device used for the test, e.g. LD, LS, LG, … . As in all hardness tests, the instruments and the key parameters influencing the hardness reading need to be defined within close tolerances. The main instrument parameters influencing the L-value are;

a) the impact energy
b) the impact body
c) the point of velocity measurement

The impact energy (kinetic energy of the impact body when impacting the surface of the test object) is determined by its mass m and its velocity v_i in the moment of the impact;

$$E_i = \frac{m\, v_i^2}{2} . \qquad (2)$$

However, even if absolute energy is kept constant, different combinations of mass and velocity would give a different response of the material tested and consequently a different L-value. Thus, both, mass and velocity need to be precisely defined. It was Leeb's intention to make gravity and friction effects on impact velocity as small as possible, thus, the flight path is kept as short as possible, the measurement point is close to the surface, spring force is used to accelerate the impact body and magnetic and eddy current influences are controlled.

The impact body is of paramount importance for the L-value. His specific characteristics result from the combination of the individual structural components;

- the material, form and shape of the indenter, e.g. the spherical diamond test tip of impact device E.
- the material, orientation and dimensions of the permanent magnet and its position in the impact body.
- the material, stiffness, form and dimension of the impact body as a whole.
- the way of combining these different elements with each other.

The complex interaction of all these parameters during the whole hardness test can be simply summarized in the term "overall elasticity" (OE). This accounts for the overall behaviour of the impact body as a whole during the impact. The main critical components are Young's-modulus of the individual parts, geometry and the interconnection of these parts. This explains also, why serious manufacturers don't offer questionable repair tools to allow for an uncontrolled indenter change.

The point of velocity measurement is determined by the position of the induction coil on the guide tube of the indicating device. At this point, the induction voltages are measured. In case of device type D this position is about 1 mm from the test surface, thus, in principle the velocity of the impact body is measured at a defined position from the test surface. If the measurement point is too near, the reproducibility of the measurement suffers, because the signal is often slightly disturbed shortly after the impact. On the other hand when the distance becomes too long then internal friction may alter the measurement of rebound speed v_r. Also the width of the measured signal curve plays a role, because it determines, how good the proportionality between minimum value B and rebound v_r velocity is.

In summary, the specified impact body represents by way of impact velocity, impact body mass and overall elasticity (v_i, m, OE) the penetration stressing and in form of the rebound velocity v_r the materials response to this penetration. Thus, all information on hardness is available and the L-value is a suitable and direct measure for materials hardness.

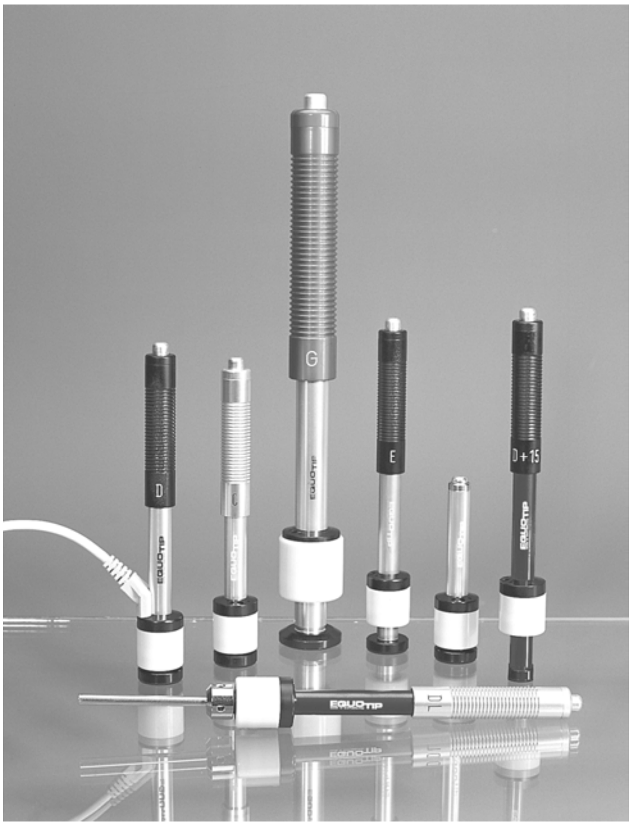

Fig. 4. Family of seven EQUOTIP impact devices (courtesy PROCEQ SA, Switzerland).

2.4. Different impact devices

Depending on application out of a whole family of impact devices (Fig. 4) can be selected.

i) Impact device D is the universal unit for most hardness measurements with a wide measuring range, testing components up to a maximum hardness of 68 HRC. It is recommended for steel and cast steel, cold work tool steel, stainless steel, cast iron (lamellar and nodular graphite), cast aluminum alloys, brass, bronze, wrought copper alloys (low alloyed).

ii) If high volume measurements are performed and the wear of impact body D is reached fast, the newly developed impact device S is recommended. Impact device S is has a 10times longer durability than impact device D and will most probably become the standard rebound hardness tester of the future. The same materials as with impact device D are tested but with slow wear of the impact body's test tip.

iii) Impact device E utilizes a synthetic diamond test tip (approx. 5000 HV), testing components up to a maximum hardness of 72 HRC. The same materials as standard D unit are tested but preferred at extended hardness range, i.e. above 800 LD (58 HRC, 690 HV). Applications for measurement are in the high end range, such as steel and cast steel, stainless steel, cold work tool steel with carbide inclusions and on rolls in the hardness range up to 1200 HV. Impact bodies show no fading even at high hardness levels compared to device D.

iv) Impact device DC is a short impact device with the same properties and applications as impact device D, testing components up to a maximum hardness of 68 HRC. It is suited for special applications in very confined spaces such as holes, cylinders, or measurements inside of assembled machines and constructions.

v) Impact device D+15 tests components up to a maximum hardness of 68 HRC and has the same range of applications like D/DC but utilizes a particularly slim front section, which allows hardness measurements in holes and grooves and on recessed surfaces by using an elongated impact body and a coil position elevated 15 mm (0.6 in.).

vi) Impact device DL tests components up to a maximum hardness of 68 HRC. The range of applications is the same as D+15, but has the special feature of a slimmer front section — 4 mm diameter × 50mm (0.16 × 2 in.) — for use in confined spaces and at the base of grooves, drill holes, and gears.

vii) Impact device G features increased impact energy (approx. 9× that of the standard impact device D), testing components up to a maximum hardness of 646 HB. Application is in the Brinell range on heavy coarse grained castings and forgings, steel and cast steel, cast iron (lamellar and nodular graphite), and cast aluminum. The increased diameter of the spherical test tip provides in addition a better averaging of the coarse grained microstructure. It requires less surface finish than impact device D for accurate readings.

viii) Impact device C uses reduced impact energy (about 25% of that for impact device D), testing components up to a maximum hardness of 70 HRC. Applications are surface hardened components (case hardened) and coatings with a min. layer thickness of 0.3 mm (0.01 in.), as well as walled or impact sensitive components (small measuring indentation). Measurements can be made on steel and cast steel, cold worked tool steel, and cast aluminium alloys. Better surface finish than impact device D is required.

To extend the application range of the EQUOTIP instruments also for small, light weight and thin materials, the use of a static hardness probe, developed also by Mr. Leeb according to the Rockwell method, is also possible. The probe R5, also known as EQUOSTAT, is fully compatible with the EQUOTIP indicating device (Fig. 5, upper image). Thus, EQUOTIP has become a complete portable hardness test system for all kinds of metals.

3. APPLICATIONS

3.1. Applications

The EQUOTIP is a very renowned test method in nearly all industries where metallic components are fabricated, heat treated, machined and maintained (see Fig. 5 for typical applications). Big, massive and thick test objects like heavy rolls, dyes and moulds, rails and tracks on tooling machines, cranes, pressure vessels, pipelines and motor blocks are classic applications.

The application range for small and thin test objects is accessible with the optional static probe R5 (Rockwell low load tester). The instrument is best suitable for all kinds of metals, even curved surfaces and hard to access test locations can be tested.

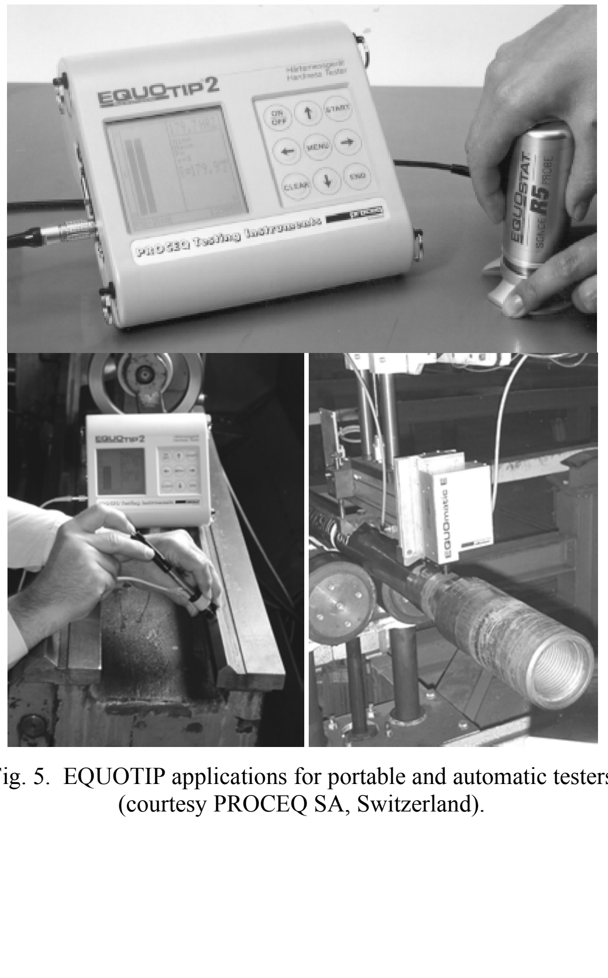

Fig. 5. EQUOTIP applications for portable and automatic testers (courtesy PROCEQ SA, Switzerland).

3.2. Requirements

Suitability of one of the EQUOTIP impact devices for a specific application depends on the following criteria;

- Material (grade, structure, physical properties)
- Mass and thickness of the test piece and support of the test location
- Surface properties (roughness, curvature, test area)
- Accessibility of the test location
- Indentation size

Generally it is recommended to perform the test on objects of sufficient mass and size properly supported and at rest. Care should be taken when preparing the surface finish as heat or cold working could change the surface hardness. Each hardness test is a localized test, thus, the result is valid for a determined zone only. In order to get a representative average for a test object, it is recommended to use statistic aids. Typically the mean value, the standard deviation and the scattering range of five to ten impacts is used to retrieve general test results.

4. INTERNATIONAL STANDARDIZATION WORK

4.1. EQUOTIP - reliability

The widespread acceptance to the industries of the EQUOTIP principle has led to it's standardization in 1996 (ASTM 956-96). Test procedure, instrument verification and calibration of reference material are described therein. Since that time, many companies started to produce variants similar to the original EQUOTIP. Recently, a round robin test has been started by the ASTM with the goal to confirm the EQUOTIP conversion curves. A wide hardness range is covered by using a set of standard reference plates, all calibrated in HB and HRC (Fig. 6).

Excellent agreement of the EQUOTIP conversion curve with the measured values on NIST traceable reference material is found. The variant, however, shows a constant offset of about 10 LD and consequently a remarkable discrepancy in the conversion chart. This highlights the fact, that dynamic hardness testers according to Leeb but of different origin than the EQUOTIP, can deviate considerably from the original defined hardness scale.

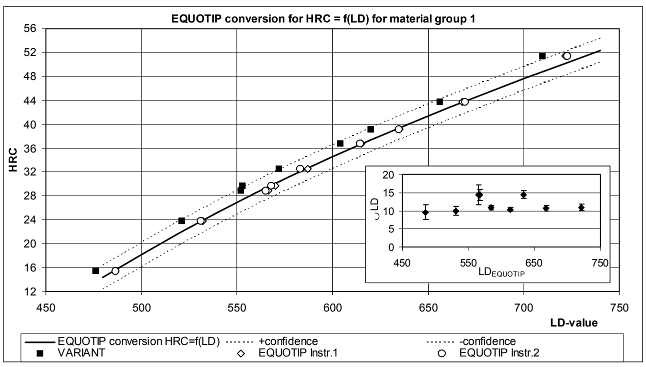

Fig. 6. First ASTM round robin results of Leeb hardness testers on NIST traceable reference material. The continuous line rapresents the common EQUOTIP conversion curve within confidence intervals. The small image inside the graph shows the deviation from the LD-values of the original EQUOTIP if a tester of different origin (variant) is used.

It is alarming to see, that instruments of different origin than the EQUOTIP may give considerable different results at discretion of the well defined Leeb Method. Quite often the measurements are good in the hardness range of standard reference blocks between 700 and 750 LD. But below and above this hardness level, deviations may be considerably larger (up to 40 LD). The results by such testers have to be considered insignificant and erroneous [7].

The EQUOTIP measurement base, the L-value, was maintained constant for the last 30 years by the developer and manufacturer. Some of the first instruments sold at the very beginning are still in use and the measured L-value is within the specified limits in perfect agreement with results of newly produced EQUOTIP instruments. Other manufactures, however, may use production criteria which have an influence on the original L-value as discussed above. There are also instruments available using a different method of velocity determination (triple coil technique). These instruments need to be calibrated to the original L-value as defined by the EQUOTIP instrument. The same holds as for conversion relations to static hardness values; the genuine instrument value is more accurate than any tuned value, especially, if the whole hardness range is considered.

4.2. EQUOTIP – conversions

At the very beginning of the EQUOTIP hardness test method, the new hardness number Leeb (HL, L-value) was not known and conversion had to be supplied into traditional hardness values like Brinell (HB), Rockwell (HR), Vickers (HV) or Shore (HS). As the users had already their experiences to assess production quality, they wanted to get familiar with the new number gradually. In the meantime more and more the genuine Leeb hardness value according to the EQUOTIP principle is accepted as decisive method to qualify production processes. It's significance and reliability for acceptance tests has been certified throughout many industries. Industry simply adopted the corresponding written specifications, thus, it was not necessary to change any working procedure and the relevant production control doesn't suffer from conversion scattering.

Conversion into other scales has to be considered with care in order to avoid problems related to changes in material properties, e.g. due to handling (stress induced hardening for instance). The "real" converted hardness value may divert from converted curves out of standard materials of similar grade. This effect is significant for all conversions between scales even for HB ↔ HR, HV ↔ HR, HRx ↔ HRy etc. (x, y different parameter defining unequivocally the corresponding scale).

As the way of material usage is different in different test methods and as each test has its own uncertainty, the correlation of two methods is always more affected regarding accuracy than in a specific test itself. In addition, such conversion curves are always material specific, thus depending on the material the correlation can be different. This holds especially for dynamic rebound hardness values, where the permanent deformation behaviour, the hardness, is basically determined by the elastic response of the material. Thus, the elastic properties, Young's modulus and the yield strength, of the material to test have a dominant effect on the test result. In Fig. 7 a simplified stress-strain diagram for two materials of equal yield strength R but different Young's-moduli, E_1 and E_2, illustrates the effect. The same amount of total deformation work W used to penetrate a defined indenter into the material causes different elastic (Wel) and plastic (Wpl) deformation. The material with higher E-modulus, E_1, will accumulate a significantly smaller part of the elastic energy and therefore release less residual energy when the testing body rebounds.

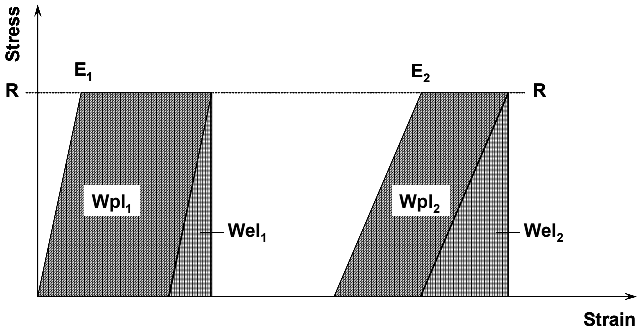

Fig. 7. Schematic view of a stress-strain curves from two materials with different Young's-modulus but same yield strength.

A correlation between L-value and static hardness is only possible for specific materials. However, it was found that the empirical assessed conversion curves are valid for a broad range of materials, grouped according their common elastic properties (e.g. 10-20% spread in Young's modulus). For example in Fig. 6, the EQUOTIP conversion curve HRC=f(LD) for material group 1 (unalloyed and low alloyed steel and cast steel in hot rolled or forged and thermally treated condition) was determined based on standard reference material (DIN Werkstoff No. 1.2842, i.e. AISI O2, DIN Werkstoff No. 1.0402, i.e. AISI 1020, DIN Werkstoff No. 1.0301, i.e. AISI 1010) traceable to the German national calibration standard at MPA Nordrhein-Westfalen, Dortmund, and confirmed on reference material (AISI 4140, i.e. DIN Werkstoff No. 1.7225) traceable to the American national calibration standard at NIST, Gaithersburg.

However, when conversions need to be made they should be done with discretion and under controlled conditions. Converted hardness values should be considered as informative estimation and not as acceptance values. The important exception is to have direct comparison of results between different hardness testing methods on the same material.

3.5. Calibration and Verification

In EQUOTIP hardness testing, the following distinction is made;

i) An EQUOTIP hardness tester is produced according stringent construction criteria and all parameters influencing the L-value are 100% controlled. At the end of the production chain, all instrument components (impact device, impact body, indicating device) are cross-checked (calibrated) against referenced components of the reference instrument. Thus, EQUOTIP components are fully interchangeable from instrument to instrument. The EQUOTIP reference instrument fulfils of course more stringent requirements than the series instrument and was maintained constant over all the time by the manufacturer of the EQUOTIP.

ii) The impact devices and impact bodies are designed in such a way, that a user cannot alter or "adjust" anything. This concept helped to guarantee over all the years the constant quality and absolute comparability of the L-value measured by an EQUOTIP instrument. However, the performance of the instrument can easily be checked (verified) using a calibrated reference material.

iii) Standard reference blocks are tested by a reference instrument, a calibration machine. The measured value is than marked on the reference block, this is called calibration. Calibration instruments need to conform to highest quality requirements. The requirements on the reference material are material, treatment, dimension, surface, magnetization and homogeneity over the whole test area. The calibrated reference blocks are used to indirectly check the performance of series produced hardness testers.
Once the reference block is consumed, i.e. the calibrated surface area is fully impacted; the functionality of the block can not be regained by grinding or any other means. The reason is that the required hardness uniformity over the whole surface area is very production sensitive and unique. Hardness uniformity and calibration values are not applicable to subsurface cross sectional areas.

The traceability back to national standards is an important instrument criterion, e.g. "NIST traceability" is a commonly found term in the USA. The meaning of it is that an instrument can be verified on reference material traceable to the corresponding national entity, e.g. the NIST. NIST has the primary hardness machine for the Rockwell C Scale and provides reference material calibrated with this machine. All Rockwell testers can be checked for conformity. Once the instrument conformity is given, this Rockwell tester, e.g. of an accredited laboratory, can calibrate secondary reference material. This procedure provides traceability back to the primary machine at NIST or at any other national entity, maintaining the national primary hardness test machine.

Hardness testers providing conversion curves to other hardness scales like the Rockwell C scale can by this way indirectly be checked for conformity with the national standard, even, if basically the conversion is verified. Note: each hardness number is a combination of several factors which can have a compensating influence on each other. Thus, it is generally recommended to verify an EQUOTIP frequently on the supplied reference test block (indirect verification). A direct verification by an authorised body should be performed periodically. If traceability to a national reference machine is requested, this can only be achieved by indirect verification of the EQUOTIP conversion curve. The international primary EQUOTIP hardness tester is protected and maintained since 1975 by the manufacturer of the EQUOTIP.

5. CONCLUSION

Different international associations and standardization bodies like the DIN (Germany) or the ASTM (USA) acknowledge the high testing quality of EQUOTIP and realize the widespread, common acceptance of it. However, to ensure the high reliability of the measurement base, more international, independent standardization work is needed. The L-base needs to be assured.

Regarding the future trends in dynamic hardness testing, the main efforts are made in providing more durable and flexible instruments, ready to communicate with standard documentation facilities.

Especially, fully automated testing in production lines is on demand. Promising solutions are provided by the automatic version of the EQUOTIP, the so called EQUOmatic (Fig. 5, bottom right). Interaction with common programmable logic control (PLC) centres makes a quick 100% control of components feasible.

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