Digital transformation applications in mechanical quantities – hardness measurements

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Abstract – **One of the most important and widely used testing method for extracting mechanical properties of material is the hardness test. It is mainly based on realizing a deformation on the material, measuring the geometric dimensions of the deformation and from that calculate the hardness value. Measurements are performed with imaging instruments like optical microscopes, mostly operated manually. However, new developments aim to determine the border of indentation, measure its diameter and diagonal length, save and mark the locations of the measured indents on the surface of the hardness reference block by making use of a fully automated indentation measurement system (IMS). This digitalization approach shifts hardness measurements from manual processes to using pixel-wise image processing and fully automated IMS, leading to increased precision, repeatability and speed and leading the way for further improvements by digital transformation.**

I. INTRODUCTION

Understanding of the critical mechanical properties of materials used in manufactured products, building, and infrastructure projects is essential for safety assurance, production cost control, and the creation of healthier, easier-to-use products. Such understanding relies on accurate, reliable, and consistent reference standards for material properties at the NMI level and the ability to trace measurements from the top-level standards to basic workshop tests through an unbroken chain of traceability.

Hardness testing is one of the most important material testing methods, with Brinell, Vickers and Knoop tests are among the most widely used testing methodologies. Hardness is quantified by measuring the size of an indentation made by a specified, controlled force with an indenter of known geometry. However, the accuracy of such measurements may vary significantly depending on influencing factors such as image magnification, handling by the user, the measuring instrument, and the software used. This leads to differences among NMIs and between NMIs and secondary or testing laboratories.

This difference is largely due to the absence of standard methods and clear specifications for the various indentation measuring systems in use by the many different laboratories. Also, each manufacturer is using his own specifications, settings and software. The need for a solution was highlighted by the 2005 CIPM Brinell pilot study (CCM.H-P3)[1], where large differences between participants' results were seen due to variations in imaging system parameters, e.g., numerical aperture (NA). Such variations become even more pronounced further down the measurement chain, where less advanced equipment is used without stringent control of influencing parameters.

To transcend this, automation has been a promising solution. Not only does it decrease human error and enhance reliability but also improve efficiency, repeatability and allows for the unification of systems throughout the traceability chain. Advances in digital technologies, including computer vision, are enabling new prospects for completely automated hardness measurement systems.

As part of the EPM project 22RPT01 TracInd BVK-H – Traceability for indentation measurements in Brinell-Vickers-Knoop hardness (TracInd-BVK-H) the underlying issues are addressed by both normative measures as well as digitalization and unification of the processes involved in hardness measurements. One of the aims of this project part is to determine the border of indentation, perform its diameter and diagonal length measurement, save the location of the measured indents on the surface of the

hardness reference block to be shared with the users for further measurements. This means currently manually operated measurement steps are replaced by computer vision, algorithm-based evaluation. This includes the fully automatic indentation measurements, the reporting the measurements results together with the indents location with coordinates in a fixed reference coordinate system using pixel-based image recognition resulting faster, more reliable measurements with reduced uncertainty.

Brinell, Vickers and Knoop indentation measurement methods are realized in different ways at the national metrology institutes (NMIs) as well as calibration and testing laboratories. In some applications there are manually measurement application while in some other there are some semi-automatic indentation measurements. In manual measurements the operator determines the border or the corner of indents based on personal preference and perception while in some applications the custom-made software is used for such application.

The possibility of realizing fully automatic indentation measurements, not only one single indentation but n indentations including both direction diameter/diagonal lengths, a kind of calibration of hardness reference block as a whole is investigated. For this, certain goals are set for the design and development of such a system.

The basis for the system developed during the TracInd BVK-H project is the semi-automatic IMS that was realized and used in the TÜBİTAK UME Hardness Laboratory[2].

A fully automatic IMS first and foremost require fully automated length measurements in two dimensions, so the indent can be measured without manipulation or any intervention by the operator. For this, the IMS must be capable to record its exact location above the indentation and the travel needed to reach the opposing side.

Next, the IMS should be capable to measure more than one indentation at once, again without operator intervention. For this, the IMS needs to know the exact location of the indents where it should look for them on the hardness reference block. For this, the IMS will be used to mark the locations in the block before their realization in the hardness standard machine. The coordinates of the location of indents will be saved and used in a later time to make the analyses of the indent. With these requirements a fully automated IMS can be realized.

II. CURRENT INDENTATION MEASUREMENT SYSTEMS AND THEIR LIMITATIONS

As mentioned, IMSs at the NMI level are either manual or semi-automatic. In both cases operator input is required to finish the measurements.

While in manual operation the full measurement is done by the operator, in the semi-automatic case automatization enables measurement in one direction of the Brinell, Vickers and Knoop indents, followed by a manual rotation of the indentation by 90° to make the second diameter or diagonal length measurement, necessitating the precise alignment of the diameter or the diagonal length to be measured in the same direction as the first measured one, which is a source of error.

There are few trials to start the measurement of one indentation in two directions and the possibility to measure more than one indentation by specifying the location of n indents manually by the operator after their realization, however no such system is currently in operation. Therefore, there are no practical information on how to implement full automation into an IMS.

Automation of measurements is seen as the means to overcome the issues plaguing current systems while also resulting in labour and cost reductions. Digitalization offers new possibilities to further and improve the measurement systems by automatization and computer vision.

For future developments it is extremely important to have an unanimously agreed upon set of parameters to be used by the IMSs in regards to contrast, optical resolution, aperture, luminance, edge definitions and more. In a first step, a fully automated optical measurement system was developed and implemented, greatly improving performance of the hardness measurement while removing operator error and increasing reliability and availability of the system.

The most significant problem during hardness testing, more precisely the measurement of the indentation, is the decision on where the border of the indentation begins.

Due to the test procedure, indentations in hardness tests are not sharp-edged. Instead, indentations merge into the undeformed surface slowly. Pile-up behaviour is observed when material is occasionally pushed out from the indentation, and at times material around the indent is pulled down with it (sink-in behaviour).

Both make the transition from the undeformed surface to the indentation even more complicated to define [3], [4].

Conventional hardness testing methods use optical systems, such as light microscopes, to determine indentation size.
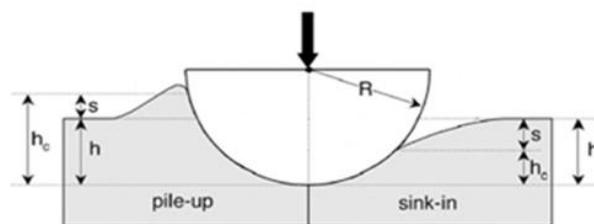

Figure 1: cross section of an indentation profile showing pile-up and sink-in behaviour [5]

The investigation of this behaviour is an important part of the project and its goal of unifying hardness measurement in the whole traceability chain, from NMI level down to the material testing laboratories.

76 indentations were produced and measured and characterized utilizing both conventional optical methods as well as state-of-the art methods like scanning tactile and laser confocal measuring systems to measure the 3D surface areas of indentations.

A 2D profile passing through the largest diameter of the indent is shown in Figure 2, along with the slope (in black) and the rate of change of slope (in red). The two valleys in the curve representing the rate of change suggested in [6], were used to determine the diameter of the indent. This value is treated as the reference value.
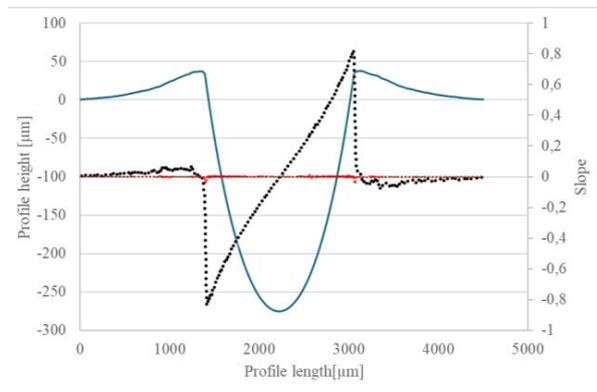

Figure 2: Cross section of the 75,26 HBW 2,5/187,5 indentation profile using the tactile measurement data for the calculation of slope angle and rate of change of the slope angle

Using these results of the investigation of the reference indentations, an analysis of the different measurement methods like scanning tactile and confocal laser versus standard optical measuring systems is conducted. This is highly relevant for the linking of higher-level laboratories and NMIs to the lower level testing laboratories which are almost always using standard optical measurement systems.

In the future with advances in image processing, AI and also a reduction in cost, many of the optical systems will change or be adopted to at least semi-automatic IMS. With this, the use of image processing and edge detection algorithms will increase significantly.

Since the definition of the indention borders will be based on the three-dimensional structure of the indent as shown in Figure 2, a close correlation of measurement data of both the advanced 3D measurement systems and the conventional 2D optical measurement systems is of utmost importance. Otherwise (and partly as still is common practice today), the data will have significant discrepancies and the uncertainty of measurement will increase unproportionable lower down the chain of traceability. This can partly be mitigated by the use of image processing and powerful edge detection algorithms.

Also, the use of advanced image processing systems on low-tech optical systems has a lot of potential for fast implementation and therefore increased speed of hardness measurement improvements. Since it is mostly software, many of the current manual systems can at least be retrofitted to semi-automatic IMS.

III. DEVELOPMENT OF A FULLY AUTOMATED IMS WITH AN INDENTATION MANAGEMENT SYSTEM AND MARKING TOOL

A complete Brinell, Vickers and Knoop scale capable IMS comprises two main components; hardware used for visualisation on the indentation, and a software that is used for realisation of the measurement itself.

As a starting point of development of the fully automatic IMS the currently available automatic indentation measurement systems for Brinell, Vickers and Knoop indentation measurements (either primary reference systems or calibration machines) were reviewed. Different types of design parameters such as electro-mechanical structure and custom-made software, different measurement algorithms and systems including auto-focus, auto-calibration of the system by making use of certified line scales and laser interferometer optic systems were investigated.

Although current systems allow for the (semi-)automated measurements of indentations, they are not connected to the hardness standard machines and require the operator to tell them where to look for the indentation to measure.

The design developed in this project aims to automate as possible in order to completely remove operator influence in both areas of measurement as best possible.

In the scope of the TracInd BVK-H project research [5] this is partially fixed with the introduction of an automatic marking system. The IMS will mark indentation locations on the hardness reference block beforehand, and save its locations. After producing the indentations, the reference block is placed back into the IMS for measurement, with the IMS already knowing where the indentations are located. While the process of indenting the blocks in the hardness standard machines still require an operator, the measurement of the indentations afterwards is speed up significantly. This system is only a first step towards further developments in regards to a fully digitalized measurement process.

As part of the automation, the system was equipped with the capability of marking the locations of indentations that are selected by the operator from the software of the IMS prior to realisation of indentations and later fully automatically measure the size of the realised indentations regardless its number, creating a real automatic indentation measurement capability. For this, revisions were made on

a four axis, motorized stage IMS present at the TÜBİTAK Hardness Laboratory for both mechanical components as well as software.

While hardness testing is considered non-destructive, it still cannot be replicated exactly in the same point as they plastically deform the measuring point. Also, indentations will push material away and therefore influence the immediate material around the indentation, effectively reducing the surface area available for testing. It is therefore necessary to use specially prepared hardness blocks in which the homogeneity of the surface hardness is sufficiently guaranteed so as to be able to highlight significant variations in hardness to be attributed to the variation of the test parameters and not to the variation in hardness of the material.

To deal with this, a mechanical part used to make a circular mark on the surface of the block was designed and adopted to the present system. With this part's help, the operator will place the hardness reference block on the plate of the IMS, and the region where the indentation measurements will be made will be adjusted by the operator and recorded by software developed in the project.

Since the indentation size and therefore the hardness measured is highly dependent on the surface condition of the block there are only limited options in order to mark the blocks. These options exclude any invasive markings like engraving or scratching since it will alter the surface itself, as well as laser engraving or etching since this will influence to hardness of the blocks surface layer. Therefore, non-invasive options needed to be considered. For the ease of use the marking with a waterproof pen was selected.

Different hardness blocks will have different indentation sizes, so the marking tool is designed to be used with different markers in different brush thicknesses in order to be able to mark different hardness reference blocks without abstracting too much area.

The IMS system marks the indentation location automatically (with the help of the four motorised stages). All directional movements of the table are precisely calibrated and recorded by laser interferometers. After the marking process is finished, the indentations will be realised in the traditional way with the hardness standard machines and the block will be placed as it was for marking the indents' places. The IMS performs measurements of the indentation within those circular marks with the help of image processing and edge detection in accordance with the definition of indentation.
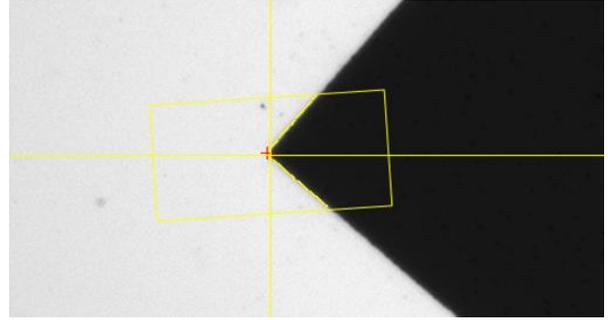

Figure 3: Determination of indentation corner with image processing used in the TÜBİTAK UME IMS

The revised software of the IMS currently available at TÜBİTAK UME Hardness Laboratory was improved with ability of autofocus, edge detection by image processing for circular shaped Brinell indents, determination of the corner of Vickers square and Knoop equilateral-shaped indentations, automatic measurement of one indentation for both diagonal and diameter measurement and extension of this measurement to the entire surface for a serial of *n* number of Brinell, Vickers and Knoop indentations whose coordinates were already recorded by the software during marking for indentations suitable for automated measurements. All these activities were implemented into the IMS available with an existing motorized stage with four-axis (X, Y, Z and rotation).

The improved edge detection algorithm is based on the detection of the gradient between bright and dark sections, where the bright area is the undeformed surface of the hardness reference block reflecting the lighting back up to the lens and photosensor, while the dark area is the deformed surface of the indent, where the light is reflected away from the photosensor.
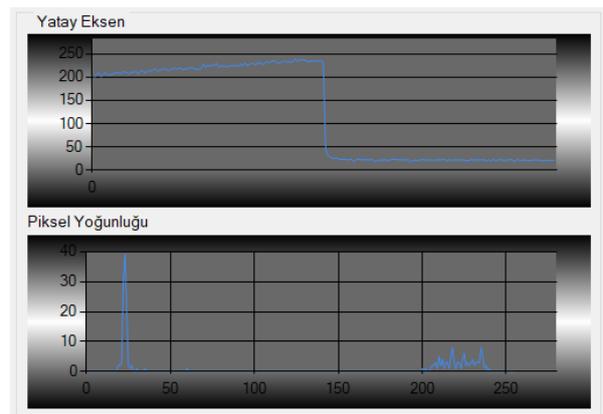

Figure 4: Graphical depiction of the edge detection algorithm: top: the change in brightness along the horizontal axis, bottom: the maximum change in brightness between pixels during the transition

The basic function of the algorithm can be seen in Figure 4. The top graph shows the change in brightness in the horizontal axis in the measurement area (yellow zone shown in Figure 3) with the value 255 being the brightest and 0 being the darkest spot. Where the brightness is dropping significantly, the transition zone of the undeformed surface into the indentation is assumed. Next, the algorithm scans the pixels in the drop zone for the maximum gradient between pixels, in order to determine the maximum rate of change of slope, as suggested in [6] and shown in Figure 2. This allows for the best possible approximation of the real indentation borders without actually using 3D measurement data. With this approach the uncertainty can be reduced to the size/length of the pixels analysed by the algorithm. The pixel-wise uncertainty is mostly given by the resolution of the sensor used (provided there is good enough lighting to saturate the pixels of the sensor used), as well as the magnification of the microscope itself. Insufficient magnification will lead to wider pixels and therefore reduced sharpness in the gradient of brightness, resulting in increased uncertainty of measurement. Also, if there is insufficient lighting, neighbouring pixels may "bleed" into each other, again reducing the sharpness of the image being processed. This highlight yet another problem with the use of automated edge detection algorithms: the algorithm can only work with the picture provided, and will therefore only be as good as the quality of the underlaying image.

This means, the settings selected for the microscope itself in regards to contrast, optical resolution, aperture, luminance, edge definitions and more are very important parts in all measurements. These have a direct influence on the measured length of the indentation and are currently not regulated in any of the relevant international standards and documents such as ISO 6506 [7], ISO 6507 [8], ISO 4545 series [9], etc. Each laboratory uses slightly different settings for their microscopes, so even if all systems would be operating with an algorithm on the same functional basis as described above, there would still be variations in measured hardness due to the incoherent settings on the IMS, especially the microscope part.

Therefore, the TracInd BVK-H project is studding these influences and determining their relations to the hardness value calculated for different surfaces, hardness scales and IMS used. Based on the results a set of unified parameters will be issued in order to be used with the IMS, providing the best possible results.

The fully upgraded system was tested from repeatability and reproducibility points of view and verified by making use of certified line scales. Examples of the function of the new, updated IMS can be seen in Figure 3. After full completion of the system verification and performance tests will be made with other partners' measurement systems and it will be verified from consistency and accuracy points of view. Measurements performed with different systems by the consortium members will be compared with automated measurements of the same indentations made at TÜBİTAK UME and a correlation between the indentation specifications and the accuracy of the automatic measurements and its correlation to the 3D data will be determined. The purpose is to identify the characteristics of indentations that are suitable for automated measurements.

For the possibility of not all indentations being suitable for automatic measurement due to contrast limits, optical resolution, illumination conditions, and indentation quality, the upgraded system will be used to study the effect of these parameters on recognition capabilities. This includes studying the interplay between optical system parameters, material properties, and software processing for autofocus and edge detection. The findings of those tests listed above will contribute to guidelines for manufacturers of future IMS in order to improve and unify measurements by the means of automation even further.

IV. PROJECTED OUTCOMES AND IMPACT ON FUTURE HARDNESS MEASUREMENTS

The implementation of the new IMS is a significant improvement on the old systems in multiple areas, as shown in the tests already performed.

The most obvious improvement is the elimination of user error by fully automating the measurement system. This allows for a lot faster, more reliable and fully reproducible indentation measurements. Human mind and decision making (e.g. on where the border of the indentation measured actually is) is subjective and can be easily influenced by different outside factors and personal preference, while a computer vision system will decide always 100% objectively according to its algorithm. This results in improved measurement uncertainty, increased repeatability and practically fully eliminated a major uncertainty factor: human/operator error.

Furthermore, marking by the IMS used to signal the operator where the indentation is to be made on the block helps with the realisation of the indentations, providing a well visible, consistent marking to follow.

The developed set of parameters as well as findings from the improvement of the TÜBİTAK UME IMS will be implemented directly into the new generation of IMS, ensuring more consistent measurements between the different laboratories.

Future improvements may include also fully automated indentation process by the hardness standard machine being connected to the IMS via a server, both being controlled by a centralized system. This will allow for fully automated processes and may also be used with the digital calibration certificates (DCC) in development at a current time by different research groups and metrology organisations.

At the highest metrology level for calibration of reference hardness blocks at NMIs and calibration certificates needs to include the measurement results currently available in traditional calibration certificates

such as the measured diameter or diagonal values and the calculated hardness values from the geometrical values. The DCCs should also include all relevant technical information regarding the traceability of the hardness machine, i.e. the force generation systems, time measurement system, and the indentation measurement system, and furthermore encompass the information about other relevant parameters such as microscope settings with contrast, optical resolution, aperture, luminance and the information about the edge detection algorithm.

The units of hardness cannot be represented directly in a DCC as a SI units according to D-SI guideline [10], but needs to be defined as a hybrid unit, specifying the test method, test load and the indenter geometry.

V. CONCLUSION

The full digitalisation of the TÜBİTAK UME IMS is a first step towards full connectivity between the IMS and the hardness standard machines, reducing measurement uncertainty and increasing reliability, while providing a basis for further development for the use in all levels of laboratories. Furthermore, important work is done in the area of correlating high-end 3D laser scanning measurement systems with the conventional 2D optical systems in use in the calibration- and testing laboratories around the world. This builds the basis for advanced image processing and edge detection algorithms, which can later be used to be implemented or retrofitted in these current optical systems, therefore marking a significant step towards the unification of hardness measurement and a decrease in measurement uncertainty all along the traceability chain.

This approach of unification by digitalisation will help to reduce the differences between different laboratories and NMIs, improving hardness metrology and measurement at a global scale.
The digital transformation of indentation measurement systems offers significant potential for redefining how laboratories collaborate, report and validate results. The integration of fully-automated systems with cloud-based platforms and DCCs could enable remote verification real-time quality monitoring-features especially valuable for international metrology networks.

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