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RESEARCH

Surface Roughness Effect on Microhardness Measurements

Raimonds Sirants[a,*], Janis Lungevics[a]

[a]*Institute of Mechanical and Biomedical Engineering, Faculty of Civil and Mechanical Engineering, Riga Technical University, Kipsalas 6B, Riga, Latvia.*

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* Corresponding author:

Raimonds Sirants
E-mail: Raimonds.Sirants@rtu.lv

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A B S T R A C T

Micro-Vickers hardness measurements are essential for evaluating micro-scale material hardness, providing insights into surface properties and material strength. However, many factors can influence the precision of hardness measurements. This study examines the influence of surface roughness on the results of micro-Vickers hardness measurements. A polished stainless steel gage block is used as a test sample. Sample surfaces are textured using different grit sandpapers. The surface texture was analysed using the 3D surface roughness measuring system. A test matrix with eight different test forces ranging from 0.01 to 0.5 kgf was used for micro-Vickers hardness measurements. The measurement results indicated that a small change in the surface roughness impacts the measurement results with a more significant effect when applied test forces are below 0.1 kgf. Obtained surface hardness values increase with surface roughness, accompanied by a rise in the standard deviation of the measurements.

1. INTRODUCTION

Micro-Vickers hardness measurement is a crucial technique for assessing the mechanical properties of materials, particularly when dealing with small-scale features or variations within a material [1,2]. This preference allows for detailed analysis of microstructural features, surface treatments, thin films, and component integrity, aiding industries like aerospace, automotive, and biomedical engineering in enhancing material performance and reliability [3].

Several factors can influence the accuracy of micro-Vickers hardness measurements. These factors relate to the material being tested, the testing equipment, the operator, and the interaction between these elements [2,4]. Surface texture, defined by features such as roughness, form, waviness, and surface flaws like scratches, introduces variability in microhardness tests by altering how the indenter interacts with the sample, especially as indentation depth decreases, making surface preparation essential [3]. The effect of surface roughness on measurement results has been studied more in nanoindentation and indentation hardness research where lower forces are applied. These studies show that surface roughness and other material irregularities significantly influence measurement accuracy [5-7]. Furthermore, several studies indicate a correlation between micro-Vickers hardness, indentation hardness, and nanoindentation results, particularly with steel samples [8-9].

Surface roughness can impact micro-Vickers hardness results in several ways [3,4,10]. High roughness levels may lead to uneven plastic deformation beneath the indenter, particularly at low loads where smaller indentations are more affected by surface asperities, leading to load distribution inconsistencies that affect hardness values [4,10]. Furthermore, the orientation of surface texture features, such as grooves from polishing or grinding, may introduce anisotropy into hardness measurements, causing the indentation to deform asymmetrically when aligned with these features [4,11-13].

The indentation size effect (ISE), where hardness appears to change with indentation size, is exacerbated by surface roughness, as smaller indentations are more likely to reflect local variations due to asperities rather than true bulk properties [2,14]. Optical distortions also become more problematic on rough surfaces, where shadows or reflections interfere with accurately measuring the indentation diagonals, especially under high magnification [2,10,15]. Also, rough surfaces can enhance elastic recovery around indentation edges, particularly in harder materials, as the irregular surface texture causes differential recovery that further distorts the indentation shape.

ISO Standard ISO 6507-1:2023 [15] addresses these surface roughness challenges, highlighting that rough surfaces can cause errors in indentation testing by creating irregular contact between the indenter and sample surface. This issue is particularly significant in microhardness testing, where smaller indentation imprints are more sensitive to surface irregularities. However, standards do not provide specific roughness values, emphasising the importance of sample preparation, particularly polishing [4,15].

Several studies have shown that surface roughness significantly impacts micro-Vickers hardness measurements, primarily due to difficulty accurately measuring the indentation diagonals on rough surfaces [4,10,11]. The accuracy of Vickers hardness (HV) depends on the precise measurement of indentation diagonals [16], with hardness calculated using the applied force (F) and the square of the average diagonal length. Even slight inaccuracies in diagonal measurements can result in substantial errors in calculated hardness values [11,14]. Furthermore, rough surfaces are more prone to contamination, which can alter the indenter's interaction with the material, adding another source of inconsistency [4].

The aim of this study is to examine the effects of surface 3D texture on the accuracy of micro-Vickers hardness measurements. Specifically, to determine how different surface roughness effects micro-Vickers hardness measurement results with varying load conditions.

2. MATERIALS AND METHODS

2.1 Sample preparation

A stainless steel (440C) gauge block was used as a test sample. The gauge block polished surface and one grinded side surface were examined for microhardness measurements (see Fig. 1). The polished surface was divided into four equal sections. One section remained untreated to preserve the original surface roughness. The remaining sections were scratched using 1500, 2000, and 3000 grit sandpapers.

Surface scratching was performed parallel to the shortest edge of the sample. Scratching with all sandpapers was performed with the same load (~9.81 N) and total abrasion distance (3 m).

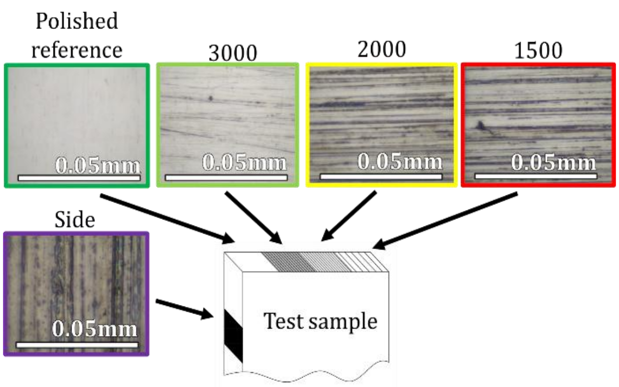

Fig. 1. Representation of used test sample accompanied by images of surfaces after treatment in 1000 times magnification. 1500, 2000, and 3000 represent the grit sizes of the sandpaper used for surface texturing.

2.2 Surface texture measurements

Sample surface roughness was analysed using the AVANT 3D surface roughness measuring system (Mitutoyo, Japan). This system had an S-3000 roughness detector module, a high-accuracy Y-axis table, and an auto-levelling table. The S-3000 roughness detector module included a 0.75 mN detector and a stylus 12AAC731 with a cone angle of 60° and a tip radius of 2 μm. The measurement results were postprocessed using MCube Map Ultimate 10.0 software.

2.3 Microhardness measurements

Microhardness measurements were conducted using a Micro-Vickers indenter HM220D (Mitutoyo, Japan). The microhardness testing machine was equipped with a CNC XY sample holding stage, which, combined with AVPACK 3.0 software, provided semi-automatic sample testing. All hardness indentations were measured with a 100x magnification lens to ensure the highest resolution.

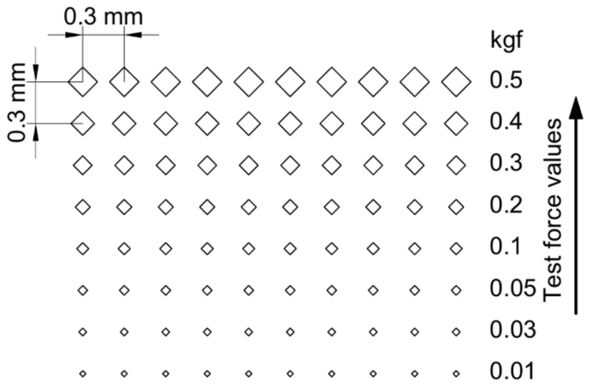

Fig. 2. Hardness test matrix. Ten measurements with eight different test forces were performed to analyse sample surface microhardness. Indentations were spaced 0.3 mm apart in X and Y directions.

A test matrix with eight different test forces ranging from 0.01 to 0.5 kgf (10 measurements for each test load) was used for microhardness measurements. Indentations were spaced 0.3 mm apart in both horizontal and vertical directions. The layout of the test matrix is illustrated in Figure 2. The matrix was applied twice for each surface with varying roughness, with the sample rotated by 90 degrees for the second measurement.

3. RESULTS AND DISCUSSIONS

3.1 Surface Texture Measurements

The surface texture parameters are summarised in Table 1. Surface arithmetic mean roughness (Ra) and arithmetic mean height of the surface (Sa) measurements were taken at 1x1mm surface area and calculated according to ISO 25178 standard. Ra values were calculated from 20 equally spaced profiles. The 3D area for each surface consisted of approximately 12 million points.

3D surface texture parameters, such as Sa, provide a more comprehensive and accurate surface representation, considering peaks and valleys across the entire surface area [17-18]. 2D parameters only consider a single line profile and may not accurately capture the complexity of the surface. This means 3D surface roughness parameters can be more accurate in describing surface quality than 2D parameters [4]. This also affects why the obtained Ra values differ from the Sa values.

Table 1. Sample surface texture parameters. Ra (Arithmetic Mean Roughness), Sa (Arithmetic Mean Height of the Surface), Sq (Root-mean-square height), Sdq (Root-mean-square gradient) and Sdr (Developed interfacial area ratio).

Surface texture parameter	Polished reference	3000	2000	1500	Grinded Side
Ra, nm	4.6 ±0.5	8.7±0.5	35.4±1.9	64.8±2.5	386±9.7
Sa, nm	5.4	9.1	35.4	64.4	385.9
Sq, nm	6.9	11.6	47.9	85.5	491
Sdq,	0.0061	0.0113	0.041	0.062	0.1689
Sdr, %	0.0019	0.0064	0.0844	0.193	1.369

Previous studies have demonstrated a strong correlation between microhardness values and the amplitude parameters Sa (arithmetic mean height) and Sq (root-mean-square height). Additionally, significant correlations have been observed with the hybrid parameters Sdr (developed interfacial area ratio) and Sdq (root-mean-square gradient) [4]. Consequently, these parameters were selected as key surface texture descriptors for characterizing the sample surfaces in this study.

3.2 Micro-Vickers hardness measurement results

Obtained micro-Vickers hardness measurement results can be seen in Figure 3. Each measurement point is calculated as the average of 20 measurements.

At lower applied forces below 0.1 kgf, surface roughness significantly affects the hardness values. Experimental results show that the rougher surface tends to show higher hardness and standard deviation values [19-20]. The effect decreases as the load increases. The error bars, representing the standard deviation, are larger at lower forces, particularly for rougher surfaces, indicating that rougher surfaces lead to greater variability in hardness measurements at lower loads [20-22].

In Figure 3, the side surface (Sa = 386 nm) shows the largest variability at lower forces, indicating less consistency in hardness measurements for this significantly rougher surface. Figure 3 also shows the impact of the indentation size effect (ISE), which refers to the phenomenon where the measured hardness of material changes with the size of the indentation. Ideally, Vickers hardness should be independent of the applied load. This effect is often observed in micro-Vickers hardness measurements, specifically at loads below 0.1kgf [1,3,20]. Several factors impact ISE, such as visual perception issues, material characteristics, and metal flow at indent edges [1,3]. From indentation images located on the sides of the graphic in Figure 3, the effect of surface texture is visible in determining indentation diagonals of the lowest test forces.

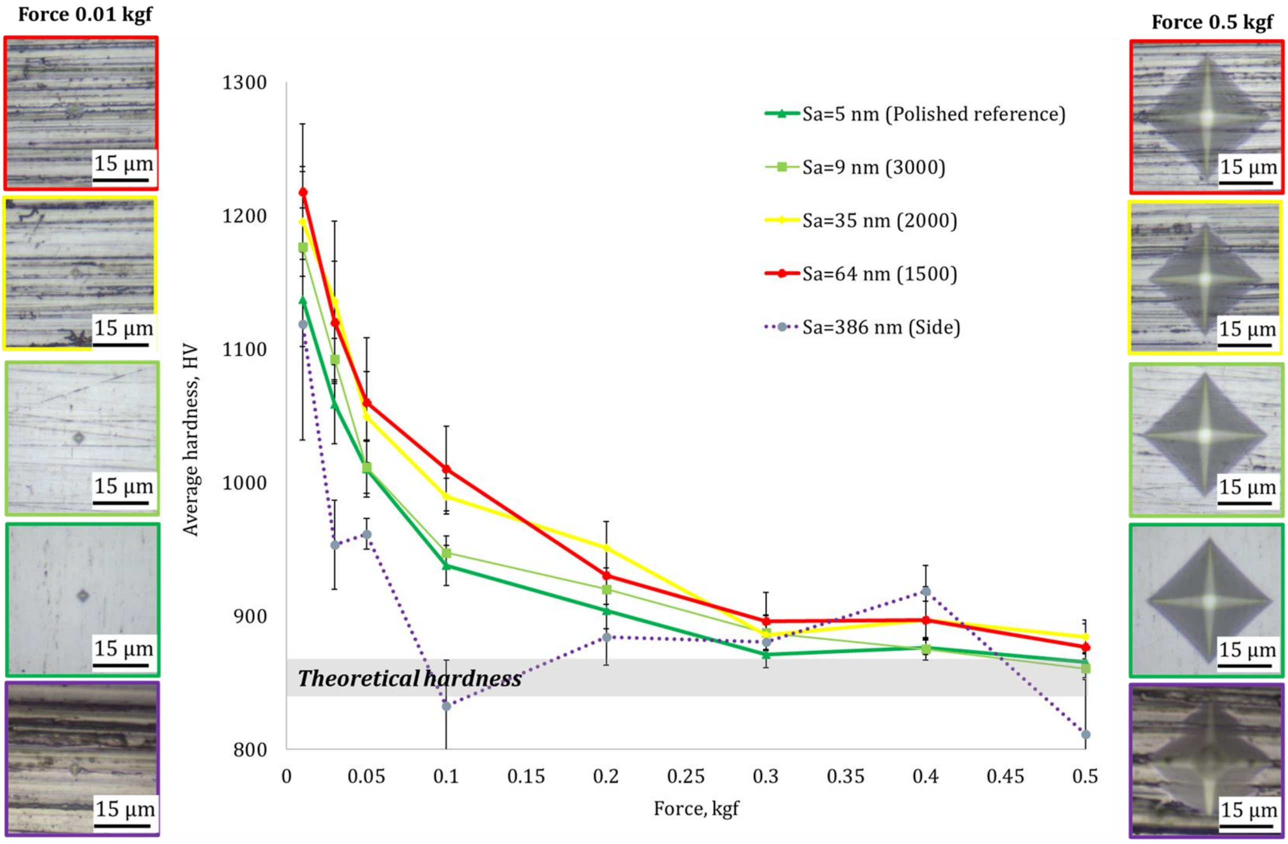

Fig. 3. Micro-Vickers hardness measurement results depending on the surface roughness and applied force. Different lines represent different sample surfaces. Solid lines represent the sample's polished surface, which was scratched with sandpaper, and dotted lines represent the side surface of the sample. Error bars represent the standard deviation of hardness measurements. Images of indentations at the maximum (0.5 kgf) and minimum (0.01 kgf) testing forces are shown on either side of the graph. The theoretical hardness value marked with a grey line of the sample (850±10HV) is calculated as the average value of the measurements at higher forces from 0.5 kgf to 2 kgf.

Figure 4 shows that surface roughness significantly affects the standard deviation of micro-Vickers hardness measurements, with rougher surfaces (Sa = 386 nm) leading to higher variability, especially at lower forces. As the applied force increases, the standard deviation decreases for all roughness levels, but smoother surfaces (Sa = 5 nm and 9 nm) consistently exhibit the least variability.

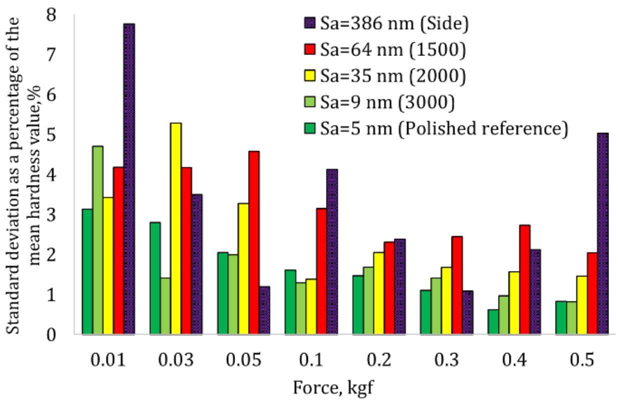

Fig. 4. Surface roughness influence on the standard deviation of micro-Vickers hardness measurements as a function of applied force (kgf). Each bar represents the standard deviation in percentage for different surface roughness levels (Sa) and applied forces. The standard deviation is shown as a percentage of the mean hardness value.

Intermediate roughness levels show moderate deviations, while the roughest surfaces maintain higher variability even at higher forces. Overall, the influence of roughness decreases with increasing force, but smoother surfaces consistently provide more reliable and precise hardness values across all force ranges [20].

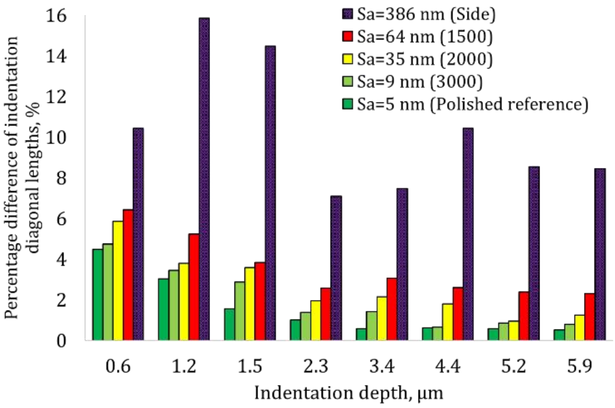

Fig. 5. Graph represents the percentage difference of indentation diagonal lengths as a function of average indentation depth (μm) for various surface roughness levels (Sa) across different sample surfaces.

Figure 5 shows that surfaces with higher roughness (Side, Sa=386 nm) consistently show significantly higher percentage differences in diagonal lengths, especially at smaller indentation depths. This suggests that surface roughness is dominant in measurement variability at lower forces. Surfaces with lower roughness (Sa=5 nm, Sa=9 nm) exhibit smaller percentage differences across all force levels, indicating more precise and consistent indentation measurements on smoother surfaces.

The percentage difference for all surfaces decreases as the indentation depth increases. However, rougher surfaces (Side, Sa=386 nm) still show greater variability than smoother surfaces, but the gap between rough and smooth surfaces decreases.

Figure 6 shows the change in micro-Vickers hardness value when 0.04 μm is subtracted from one diagonal, equal to moving the measurement line by one pixel. A ±0.04 μm variation in measured diagonal length significantly influences hardness values.

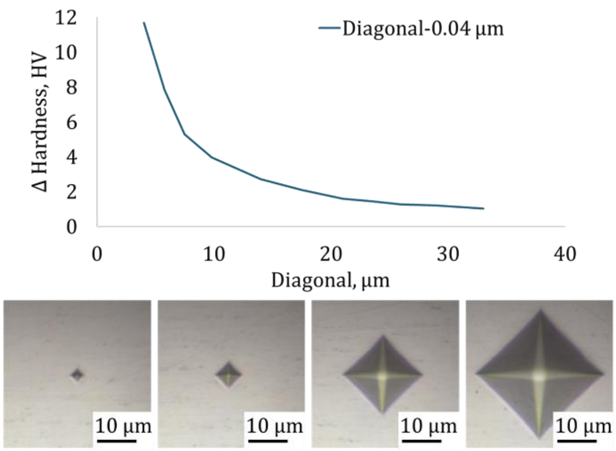

Fig. 6. Hardness variation by changing measurement line position by 1 pixel or 0.04 μm. For comparison, images of indentations on the polished sample surface are added at the bottom of the graph.

For determining the Vickers hardness of metallic and other inorganic coatings, the ISO 6507-1:2023 standard recommends that surface roughness (Ra) be less than 1/20th of the indentation depth to minimise roughness's impact on the hardness measurements' accuracy [4]. These recommendations are primarily intended for measuring coatings, but they will be used as a reference point for the bulk sample because, in existing standards for micro-Vickers, nothing is mentioned about sample roughness. It is only specified that the samples should have a surface that is as smooth as possible. Figure 7 demonstrates the used sample roughness values below the recommended Ra levels for hardness testing. However, variations in surface roughness still have a noticeable effect on the measured hardness values and standard deviation of measurements, especially when lower test forces than 0.1 kgf are used. Therefore, revising the recommended roughness value limits, especially at lower testing forces, would be necessary to obtain more accurate measurement results.

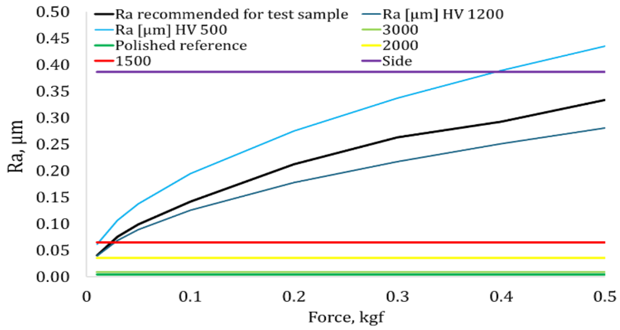

Fig. 7. ISO 6507-1:2023 standard recommended mean surface roughness (Ra) for tested samples depending on testing force compared with the sample surface roughness value.

Figure 8 shows that as the surface roughness increases, the surrounding texture becomes more pronounced, with visible peaks and valleys. This rougher texture likely contributes to indentation depth and shape variability, as the surrounding topography can influence material displacement during the indentation process. The smoother surfaces exhibit a more uniform profile around the indentation, suggesting a more consistent hardness measurement.

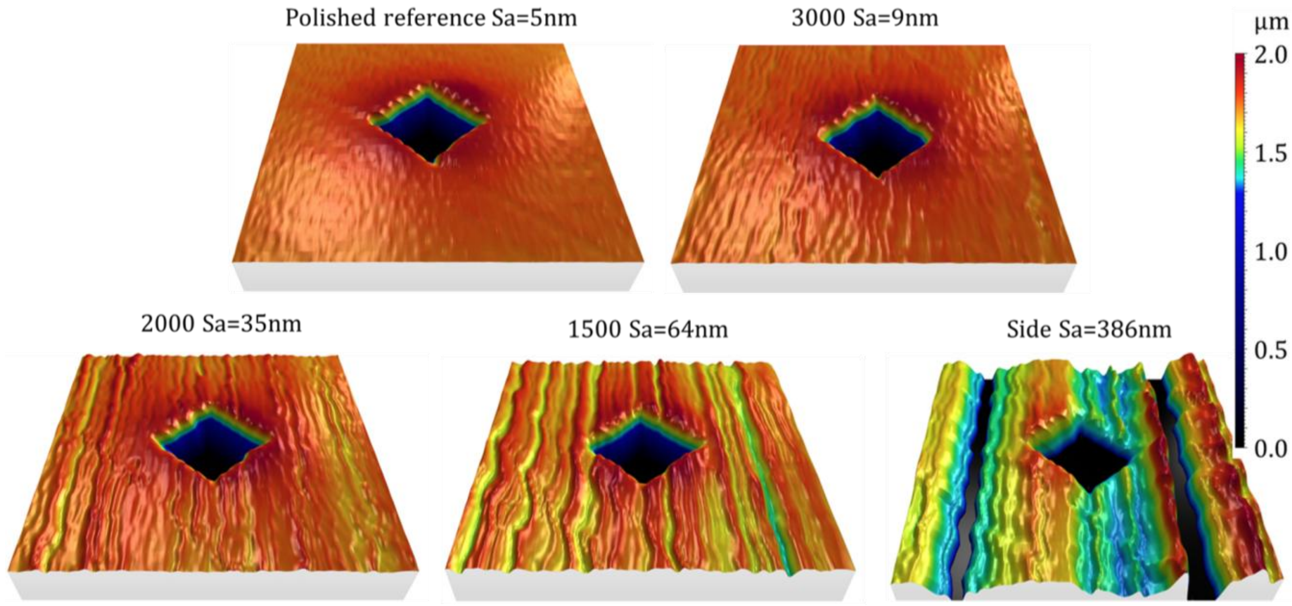

Fig. 8. Sample surface and indention (force 0.5kgf) 3D view. Extracted area dimensions X=80.1µm, Y=80µm.

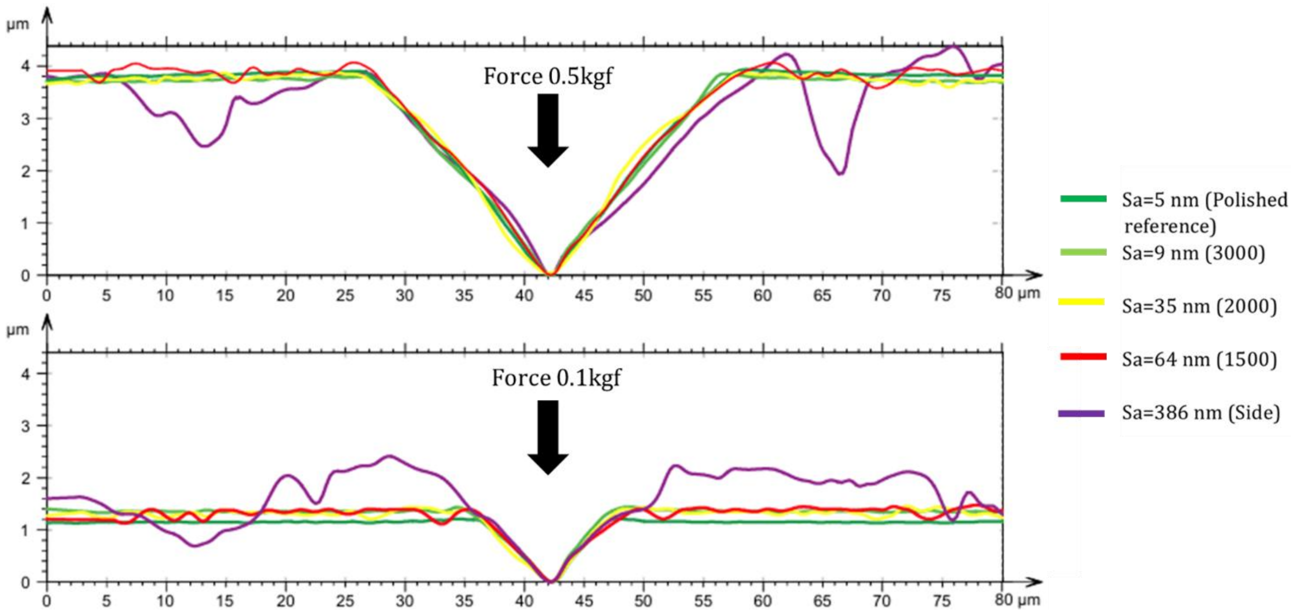

Fig. 9. Extracted profiles of indentation diagonals perpendicular to the scratching direction for different surface roughness values (Sa) under applied forces of 0.5 kgf and 0.1 kgf.

Figure 9 shows that if surface roughness increases, there is greater variability in height around the indentation. This variability is more pronounced at the higher force (0.5 kgf), where the rougher surfaces show significant deviations from the baseline. The polished and smoother surfaces (Sa = 5 nm and 9 nm) show relatively consistent profiles around the indentation, with minimal deviation.

The profiles exhibit shallower indentations for the lower applied force (0.1 kgf). However, the rougher surfaces still show more fluctuation in the surrounding surface, suggesting that roughness impacts the indentation profile even at lower forces. This figure highlights that higher surface roughness leads to greater inconsistency in indentation depth and surrounding profile, which can introduce variability in hardness measurements.

Future research in this study will aim to establish a more precise correlation between the recommended surface roughness parameters and indentation depth and test this relationship for different materials and types of surface treatment.

4. CONCLUSIONS

Surface roughness significantly impacts micro-Vickers hardness measurements:

- At lower applied forces (below 0.1 kgf), surface roughness significantly influences the measured hardness values. As the surface roughness increases, the measured hardness values tend to be higher. This trend is evident across different roughness levels. At lower applied forces (below 0.1 kgf), higher surface roughness leads to significantly higher standard deviation (up to 2.5 times for measurements at 0.01 kgf). The side surface, which has the highest roughness value (Sa = 386 nm), shows the greatest variability in hardness measurements at lower applied forces. This suggests hardness measurements are less reliable for significantly rough surfaces under low-load conditions. The factors influencing this are attributed to uneven contact between the indenter and the surface, distortion of the indentation geometry, and challenges in accurately defining indentation edges on rough surfaces.
- As the applied force increases above 0.1 kgf, the influence of surface roughness on hardness measurements decreases. The hardness values converge, and the variability (standard deviation) reduces, indicating that higher loads mitigate the effects of surface roughness on hardness measurements. As the applied load increases, the larger indentation size averages out surface irregularities, reducing the impact of roughness. This results in more consistent measurements, as the bulk properties of the material dominate over localized surface features. These findings underscore the importance of accounting for surface roughness, particularly under low-load testing conditions.
- The surface roughness values of the used samples are lower than the standard recommendations, but there is a visible effect on the measurement results. Therefore, revising the recommended roughness value limits, especially at lower testing forces, would be necessary to obtain more accurate measurement results.

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