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Effects of machine hammer peening on case-hardened 16MnCr5 gear analogue shafts

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Abstract. Gears are integral to many mechanical systems, including industrial machinery and automotive transmissions. Subject to significant mechanical and tribological stresses from rotational forces and torque transmission, gears often face challenges like surface wear and fatigue. Enhancing the durability and performance of gears is therefore vital, and this is where manufacturing processes such as Machine Hammer Peening (MHP) come into play. As an incremental forming process, MHP has the potential to substantially increase the mechanical and tribological load capacities of gears. The objective of this study is to assess how MHP can enhance the surface characteristics of case-hardened 16MnCr5 (1.7131) gear analogue shafts, focusing on the reduction of surface roughness and the increase in surface hardness. Such improvements contribute to improved wear resistance, which can significantly extend the lifespan of the gears, ensuring more reliable performance in demanding operational conditions.

Introduction

Machine Hammer Peening (MHP) is an advanced incremental material forming process, primary employed for the mechanical surface treatment of workpieces [1]. In MHP, a semi-spherical carbide hammer head delivers repetitive strikes to the workpiece, with high-frequency oscillations of a plunger driven by an actuator [2]. Such actions cause plastic deformation, modifying the microstructure of the surface boundary layer and potentially triggering local phase transformations. MHP effectively improves surface characteristics by inducing strain hardening and increasing hardness [3]. A key aspect of MHP is its ability to induce residual compressive stresses within the edge zone [4], which substantially strengthens the mechanical integrity of the material. Additionally, MHP reduces surface roughness, leading to improved frictional behavior of the treated surface. **Fig. 1(a)** shows a schematic illustration of the MHP tool, detailing key process parameters such as hammer frequency f, hammer head diameter d, stroke distance h, step over distance s, and impact angle β_i. **Fig. 1(b)** displays the MHP tool as it is mounted on a robot, highlighting the integration of advanced robotics to achieve precise positioning and control during the peening process.

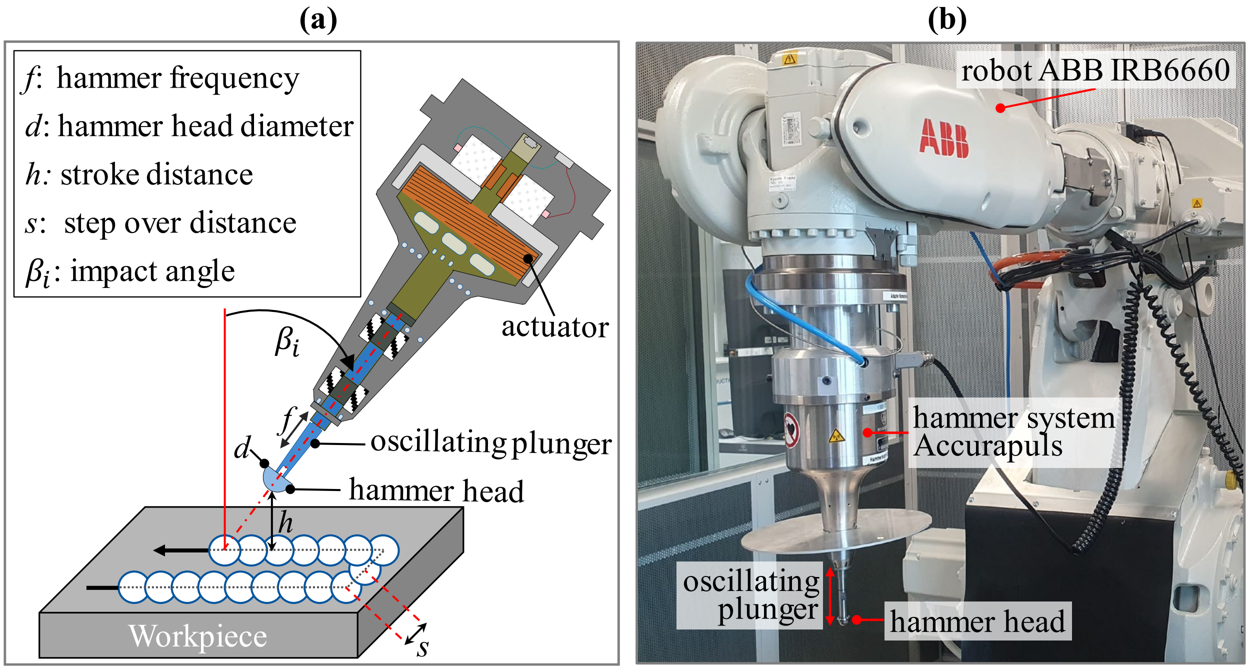

Fig. 1: (a) Schematic illustration of MHP tool with its key process parameters; (b) MHP system setup mounted on a robot.

As a precise edge zone machining technique, MHP introduces a high level of control in the creation of surfaces with uniform structures and reduced roughness [5]. This level of precision provides a notable advantage over conventional method of shot peening, which may not consistently produce uniform surfaces and often risks increasing surface roughness [1]. Moreover, compared to other surface treatment methods like laser shock peening (LSP), which can introduce unwanted thermal residual tensile stresses and melting edges that may lead to cracking [6], the cold forming process of MHP inherently avoids these detrimental effects. The unique benefits of MHP, alongside the advantages it shares with traditional techniques, make it a valuable process in the maintenance and enhancement of industrial components. This is especially relevant in gear systems, where the consistent surface finish and the prevention of crack initiation are of paramount importance [7].

Gears are vital components within various mechanical systems, facing significant mechanical and tribological stresses. These stresses often lead to surface wear and fatigue, adversely affecting both the durability and operational efficiency of gear systems [8]. Inducing residual compressive stresses in the edge zone is an established technique to reinforce fatigue strength and the durability of these components [9]. Research focused on the fatigue strength of 16MnCr5 materials under different residual stress scenarios revealed that the presence of residual compressive stresses, particularly in surface-near layers where cracks are prone to initiate, substantially extends component service life [10]. These insights affirm the effectiveness of MHP as an effective post-processing technique for case-hardened 16MnCr5 (1.7131) gears. By enhancing their service life and ensuring reliability, MHP proves to be an indispensable method, especially in applications that entail severe operating conditions.

To date, the application of MHP in machining case-hardened gears made of 16MnCr5 has been limited, with only foundational research exploring the relationship between the MHP process parameters and the resultant surface integrity, encompassing roughness, hardness, microstructure, and residual stresses. Building on the crucial insights from the preliminary research [11,12], which identified optimal MHP process parameters, this study delves into the effects of varied MHP strategies on enhancing the lifespan of gear analogue shaft specimens. The research is driven by two main objectives: first, to evaluate the impact of different hammering strategies, with an emphasis on the peening angles and directions, on the surface integrity of the gear analogue shafts; second, to establish a basis for the application of MHP to spur gears, necessitated by their complex geometry which requires non-orthogonal MHP approaches. This comprehensive investigation of diverse MHP strategies aims to provide a deeper understanding of the influence MHP on the mechanical properties of gears. The results of this study make a substantial contribution to the field of gear technology by not only establishing foundational methods for implementing MHP in gear manufacturing but also by assessing the service life of gears after MHP treatment. This approach ensures a holistic understanding of the effects of MHP, from process parameters to practical applications in enhancing gear longevity.

Experimental Setup

This study employs an experimental approach to investigate the effects of various angle settings and machining directions in MHP on the surface structure and edge zone properties of case-hardened 16MnCr5 gear analogue specimens. The specimens are produced through a comprehensive manufacturing process chain that includes pre-turning, stress-relief annealing, finishing turning, case hardening, and grinding. **Fig. 2(a)** shows a produced analogue specimen.

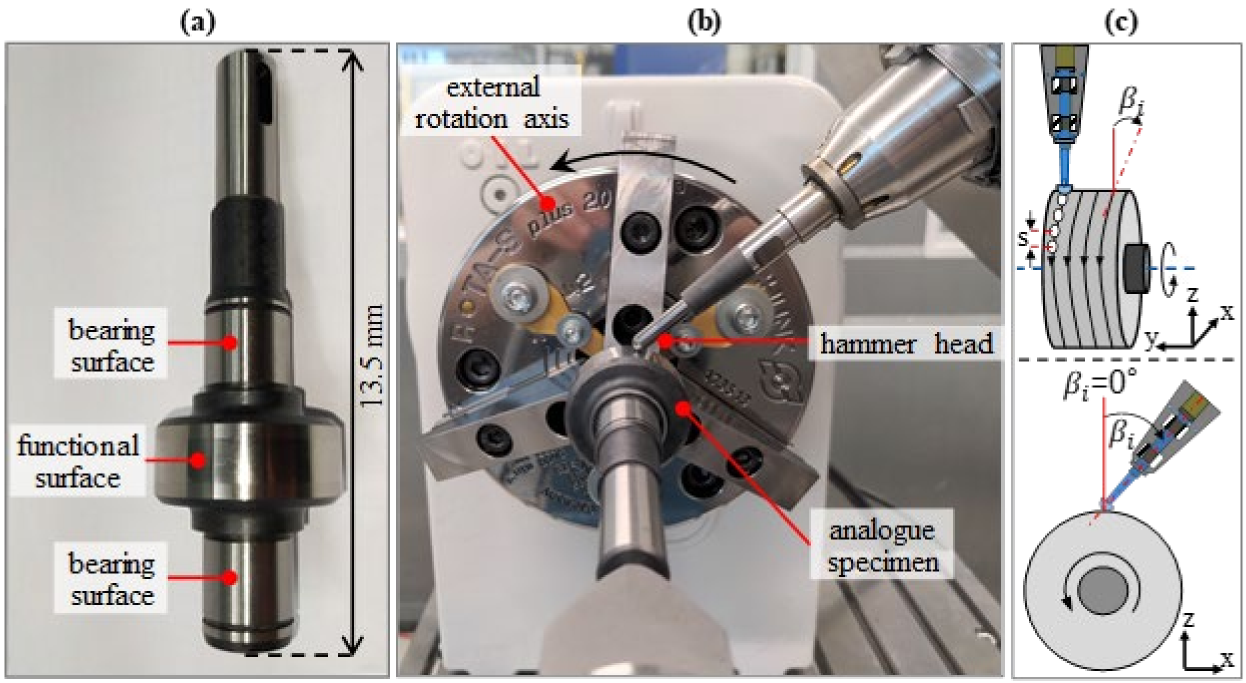

Fig. 2: (a) Case-hardened 16MnCr5 gear analogue shaft specimen; (b) Experimental test setup with external rotation axis; (c) Spiral-like machining strategy with MHP impact angle.

After manufacturing of the specimens, they are placed in the external rotation axis and subjected to MHP using the Accurapuls hammer system, as shown in **Fig. 2(b)**. Previous analyses have determined that a low stroke h in combination with a small step over distance s optimally enhances time strengths and reduces wear [12]. For this reason, h = 0.3 mm and s = 0.07 mm are selected as constant manipulated variables. Additionally, the hammer head diameter is set at 8 mm across all tests.

Guided by findings from a previous study, the selected MHP strategy for this research is a spiral-like pattern [13], as illustrated in **Fig. 2(c)**. This strategy is beneficial as it avoids the need for directional changes, thus preventing repeated peening on the same spot. Employing this spiral-like strategy, impact angles β_i are varied at 15°, 30°, and 45° to assess their effects. Furthermore, each angle is applied in both positive and negative directions to facilitate surface treatment in pushing and pulling modes. This methodology allows for the identification of the MHP strategy with the greatest potential for enhancement of the surface hardness and reducing the surface roughness of the gear analogue shafts. The final phase of this research entails a detailed investigation of the edge zone properties of the specimens. This analysis is conducted on specimens after grinding before any surface treatment, named as initial state, and after undergoing MHP using the different mentioned strategies. To increase the reliability of the results, three separate specimens are used for each of these conditions, as outlined in **Table 1**.

Table 1: Overview of the experimental strategies and number of test specimens.

Initial state		**Number of specimens**
without MHP treatment		3
MHP β_i [°]	**MHP direction**	**Number of specimens**
15	pushing	3
15	pulling	3
30	pushing	3
30	pulling	3
45	pushing	3
45	pulling	3

Results and Conclusion

The results of the experimental investigations on case-hardened 16MnCr5 gear analogue shaft specimens subjected to MHP provide insights into the extent to which MHP influences the performance characteristics of gears. The focus is on the changes observed in key mechanical properties, such as surface roughness and hardness.

Roughness. 2D geometry and depth of the impacts from MHP are determined through tactile measurements using a Hommel-Etamic nanoscan 855 contour and roughness measuring device. The measurements are taken with a resolution of 0.5 µm and a probe tip rounding of 2 µm, according to standards set by DIN EN ISO 4287 [14] and VDI 2612-5 [15]. In each experimental setup, three distinct measurement paths are traced along the central functional surface of the gear analogue shaft specimens, each with a tactile path length of 4.8 mm. The measurements are oriented longitudinally in relation to the axis of the gear analogue shafts. **Fig. 3** illustrates the average of the obtained data, showing the arithmetic average roughness Ra and the average maximum height Rz measured both before and after MHP surface treatment at various impact angles.

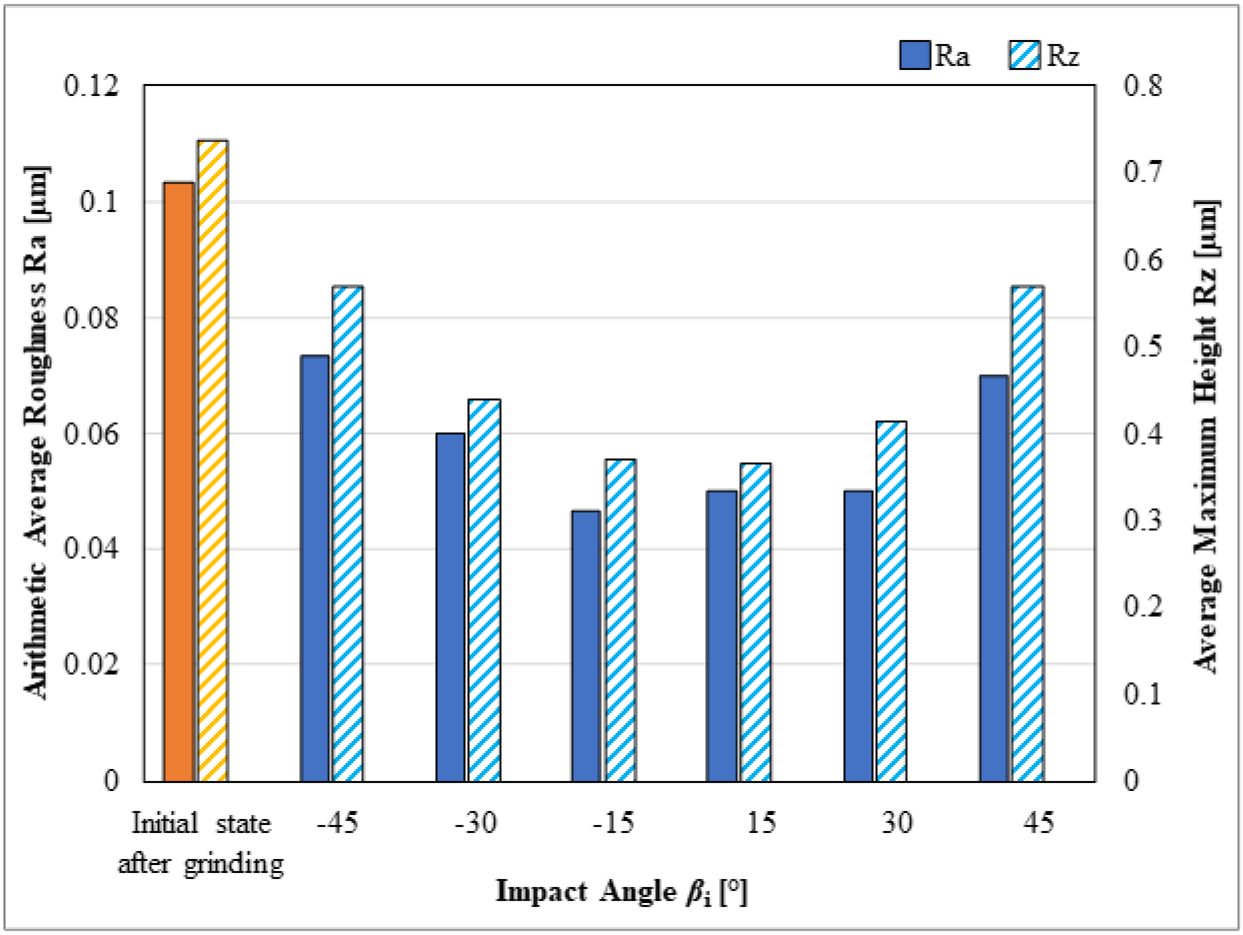

Fig. 3: Surface roughness Ra and Rz of the functional surface of the case-hardened 16MnCr5 specimens before and after MHP treatment at different impact angles.

Fig. 3 clearly demonstrates that MHP reduces surface roughness in comparison to the initial state after grinding, which did not receive any post-processing treatment. It is observed that smaller absolute impact angles in MHP correlate with lower values of Ra and Rz, suggesting that impacts closer to perpendicular to the surface are more effective in achieving plastic deformation, leading to a smoother finish. This improved surface smoothing is due to the higher energy input as a consequence of force being more directly applied into the material, which is more efficiently achieved with near-orthogonal impacts. Thus, the most significant reduction in average roughness is observed at the impact angle of $\beta_i = -15°$, where it is reduced from Ra = 0.1033 µm to Ra = 0.0467 µm. In addition, the most significant reduction in average maximum height is achieved at the impact angle of $\beta_i = 15°$, where it is reduced from Rz = 0.7367 µm to Rz = 0.3667 µm. The results also indicate that the direction of machining, whether pushing or pulling, does not substantially affect the surface roughness overall.

To avoid the possible issues that can come from 2D measuring surface roughness, which might miss some surface details, 3D surface topographies are also taken in a measuring field of 2×2 mm. **Fig. 4** shows the 3D topography of the case-hardened 16MnCr5 gear analogue shaft specimen before and after MHP at the impact angle of $\beta_i = -15°$. This comprehensive 3D view of the surface texture ensures a more accurate evaluation of the effect of MHP on enhancing surface finish. The detailed 3D representation confirms the uniform refinement achieved by MHP, which is crucial for optimizing the functional performance of the workpiece and extending its service life.

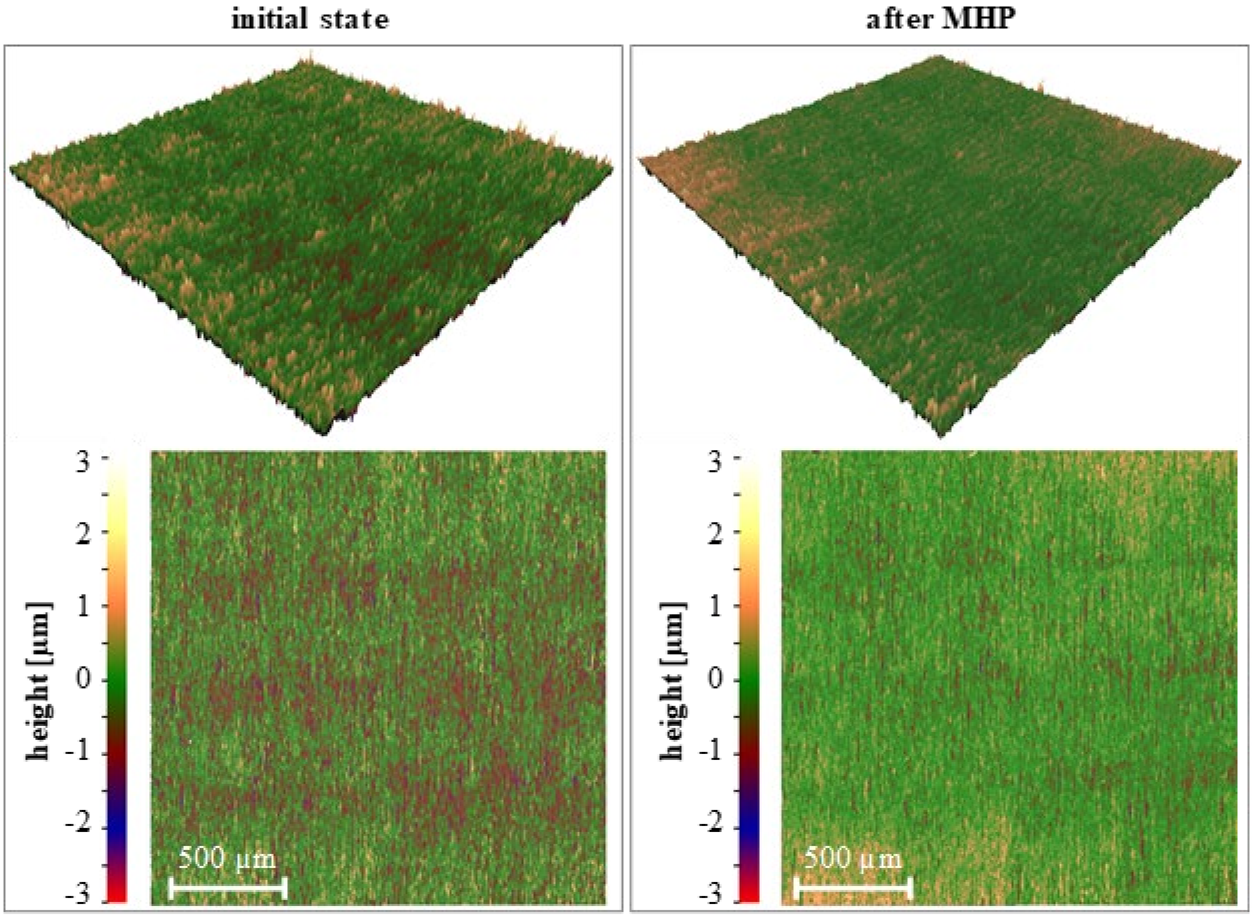

Fig. 4: 3D topographical measurements of the functional surface of the case-hardened 16MnCr5 specimens before and after MHP treatment at β_i = -15°.

The SEM images in **Fig. 5** effectively illustrate the surface smoothing effect induced by MHP. This phenomenon is attributed to the stress applied during the MHP process, which surpasses the yield stress of the material. As a result, plastic deformation occurs within the surface grooves, altering the surface topography and culminating in a more refined and smoother finish. It should be noted that the grooves that persist even after MHP are remnants of the initial machining process.

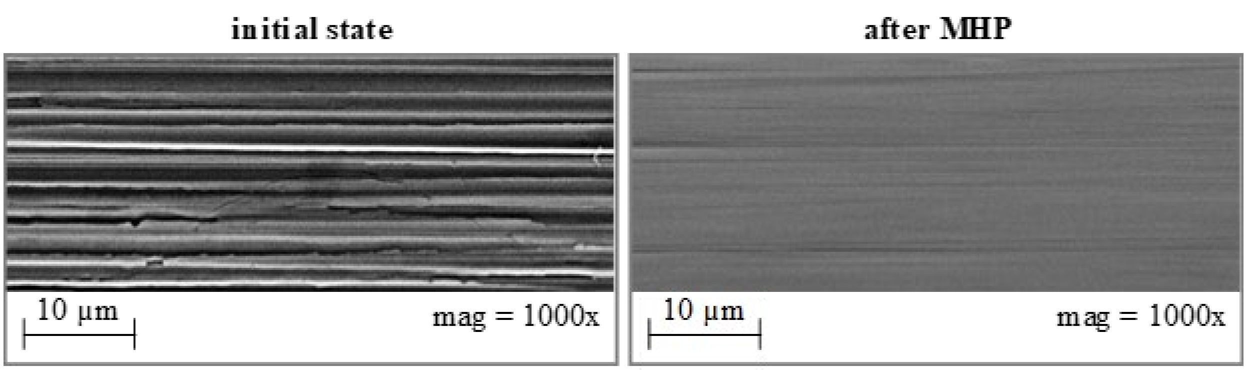

Fig. 5: SEM images of the functional surface of the case-hardened 16MnCr5 specimens before and after MHP treatment.

Hardness. Surface hardness measurements are conducted using the Vickers hardness test, following the standards outlined in DIN EN ISO 6507 [16]. For assessing macro hardness, five individual Vickers measurements are obtained from the functional surface of each specimen and subsequently averaged. **Fig. 6** illustrates the measured macro hardness before and after MHP surface treatment at various impact angles.

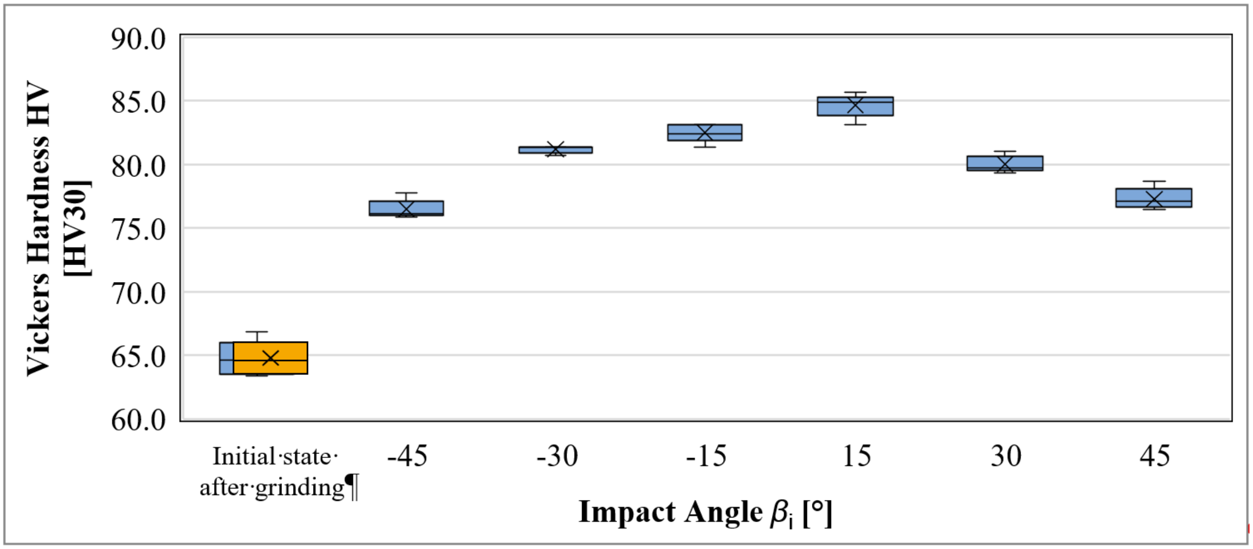

Fig. 6: Macro hardness of the functional surface of the case-hardened 16MnCr5 specimens before and after MHP treatment at different impact angles.

Fig. 6 reveals that MHP results in increased hardness compared to the initial state. Consistent with the roughness results, the most significant increase in hardness occurs at lower absolute impact angles, i.e. those closer to perpendicular. This is exemplified at an impact angle of $\beta_i = 15°$, where hardness notably increases from HV = 648 HV30 in initial state to over HV = 846 HV30 after MHP. This enhancement is attributed to the strain hardening induced in the edge zone during the MHP process. Similar to the observations for roughness, the machining direction, whether pushing or pulling, does not significantly influence the hardness outcome. Additionally, the consistency of hardness measurements within each specific impact angle, indicates a uniform and reliable response to the MHP process at that particular angle. This uniformity within the individual sets of measurements at each angle is crucial for confirming the stability and predictability of mechanical properties in gear analogue shafts treated with MHP.

Summary and Outlook

This study has yielded valuable insights into the surface topography and edge zone properties of case-hardened16MnCr5 gear analogue shaft specimens, both before and after undergoing surface treatment with MHP with varying machining directions and impact angles. The key observations are as follows:

- MHP effectively improves the surface integrity of case-hardened16MnCr5 gear analogue shafts by reducing surface roughness from Ra = 0.1033µm to Ra = 0.0467 µm and increasing hardness from HV = 648 HV30 to HV = 846 HV30.
- Impact angles closer to being perpendicular to the surface of the workpiece during MHP demonstrate a more pronounced positive effect on the surface integrity of the gear analogue shafts.
- The direction of machining in MHP, whether pushing or pulling, does not significantly influence the treatment outcomes on the workpiece.

The results of this study provide a foundation for future research in surface treatment processes for gear systems. Key areas for subsequent research, stemming from this study, include:

- The present study has addressed the surface integrity of case-hardened16MnCr5 gear analogue shafts affected by MHP. Future research should expand on this by exploring the broader impacts of MHP on the overall service life and performance of gears, with a focus on wear resistance, pitting endurance, and frictional characteristics.

- This study has primarily examined the benefits of MHP, leaving its potential drawbacks unexplored. A notable challenge of MHP is its application to components with complex geometries due to accessibility issues. Future research will therefore focus on applying MHP to case-hardened 16MnCr5 spur gears, which have more complex shapes than gear analogue shafts. This will enable a more comprehensive comparison between conventional shot peening technique and MHP.

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