On the correlation of hammer-peened surfaces and process, material and geometry parameters

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Abstract. Hammer-peening can replace extensive hand-polishing during the processing of freeform surfaces, but it is rarely applied in practice due to the interplay of numerous parameters, including the process and tool parameters as well as the geometry and the material of the workpiece. In the present study we systematically investigate the effect of tool radii, tool angles, pressure, path and impact distance and the path definition (with respect to the direction of previous surface milling) on the resulting surface roughness and strain hardening of a cast iron, a low- and a high-alloyed steel using a pneumatic tool setup and complementary Finite Element (FE) simulations. Our experimental results show that an impact and path distance of 0.18 mm, a pressure of 7.3 bar and a tool radius of 8 mm reduce the surface roughness of a face-milled surface with an average roughness of $R_a = 0.8 \, \mu\text{m}$ to an average roughness of $R_a = 0.5 \, \mu\text{m}$ for all materials under consideration. The FE simulations indicate that, for a ball-milled surface, the surface roughness $R_a$ decreases (and the arithmetical mean height $S_a$ increases) the most for a tool angle of 45° and for a hammer-peening path perpendicular to the previous ball-milling path. These results contribute to the development of a mathematical model that allows to identify suitable parameter combinations prior to hammer-peening processing for a given workpiece surface.

1. Introduction

Machine Hammer Peening (MHP) is a finishing technique that is manually applied on weld toes to increase fatigue strength [1] and recently automatized technologies are now also used on die and mould freeform surfaces [2]. An oscillating spherical hammer head is moved over the surface of the workpiece, producing incremental deformations in the surface layer. Typical frequencies are of the order of magnitude of 100 Hz according to the operating principle of the actuator. There are piezo-electric [3], electro-magnetic [4] and pneumatic tools [5] that can be attached to a tooling machine or to a robot. The surface is deformed by numerous impacts that are characterized by the mass of the hammer head, the impact angle and the feed rate. The impact paths and distances between the impacts and the paths themselves are well defined and result in several advantages compared to other surface treatments: a good accessibility of freeform surfaces compared to techniques with continuous contact of tool and workpiece (e.g., deep rolling) as well as a defined amount of deformation compared to treatments with non-uniform impact intensities (e.g., shot peening). MHP decreases the surface roughness, induces work hardening and compressive residual stresses and results in microstructural changes of the surface layer if appropriate process parameters are used [6]. These surface modifications can further result in an improvement of fatigue and wear resistance and beneficial
tribological properties. An overview of MHP in comparison to other burnishing technologies is given in [2].

Mannens et al. [7] investigated the influence of impact force, impact angle, stroke length and lubricant in an experimental study on the residual stresses and the roughness of stainless steel X3CrNiMo13-4 (DIN no. 1.4313). They achieved a roughness reduction of up to 80% for $R_a$ and 63% for $R_z$ and maximum residual stresses of 1100 MPa orthogonal and 800 MPa parallel to the impact path located in a depth of 0.15 mm below the surface. These residual stresses are induced from plastic deformation that can also result in a grain refinement up to ultra-fine grained microstructures, as demonstrated in a study of Revilla-Gomez et al. [8] on welded and hammer-peened samples of a low alloyed steel S690. Using electron backscatter diffraction, they demonstrated that MHP results in an increase of the dislocation density especially near the surface and up to 250 μm below the surface of the specimen. Bleicher et al. [9] studied the influence of the impact angle on the surface roughness of a high alloyed steel X155CrVMo12 (DIN no. 1.2379) and a plain carbon steel C45E (DIN no. 1.1191). They showed that a decreasing impact angle leads to a decrease of the normal component and to an increase of the transverse component of the impact force in a range of 80° to 60°. In addition, the surface roughness is decreasing for the softer plain steel. For larger angles the force components remain almost the same and in addition they increase if a higher peening distance is used for machining. Furthermore, they [9] presented experiments on embedding tungsten-carbide particles (in a powder suspension) in near surface layers by MHP. An almost homogeneous layer of embedded particles can be generated, significantly increasing the surface roughness and also the wear resistance. Baptista et al. [10] presented a fully dynamic FE simulation calculating multiple impacts on weld toes of the duplex stainless steel type S31803 and of an austenitic stainless steel type 304L. Their focus was on different weld toe radii, impact load and number of hammering passages of MHP and their effect on fatigue life improvement. Klocke et al. [11] used predefined fields in FE simulations to transfer strain hardening information and residual stresses from a first mechanical simulation to a second fluid-structure interaction simulation to study the potential of structured tool surfaces by MHP for foil-free forming of stainless steel sheets of cold work steel X155CrMoV12. They showed that MHP results in a reduction of the contact area to only 6 % and in low friction coefficients indicating that a total separation of the contact partners might mostly be achieved.

Despite the numerous studies on tools with different working principles and a large number of materials, there is no general approach for defining process parameters that result in the required surface properties. Due to the interaction of tool and process parameters with the geometry and material of the workpiece, suitable parameter combinations can differ for every machining task and even for different areas of the same workpiece. In this study we investigate these dependencies for three different materials experimentally using a pneumatic experimental setup and in complementary FE simulations. We determine roughness and hardness values of the initial face-milled and ball-cut surfaces and for the peened surfaces. These data contribute to a mathematical process model of MHP that offers useful starting values for a given machining task.

2. Methods

2.1. Materials

In the present study three typical materials used for the production of dies and moulds were considered. A cast iron EN-JS 2070 (GGG70), a low-alloyed steel 40CrMnMo8-6 (DIN no. 1.2312) and a high-alloyed steel X155CrVMo12-1 (DIN no. 1.2379) were tested in the as-received conditions with no further heat treatment. EN-JS 2070 was in an annealed condition (hardness: 224±5 HBW 2.5/187.5) and both steels 40CrMnMo8-6 (287±2 HBW 2.5/187.5) and X155CrVMo12-1 (223±3 HBW 2.5/187.5) were in a normalized condition.
2.2. Uniaxial compression tests

During MHP, elevated strain rates occur and it is important to consider this effect in the FE simulations. Compression tests on cylindrical specimens with a diameter and a height of 6 mm were therefore performed at room temperature for all three materials at three different strain rates to obtain the true plastic strain - true stress relations to describe the material behavior. Static ($\varepsilon_s = 10^{-3} \text{s}^{-1}$) and quasi-static ($\varepsilon_s = 10^{-2} \text{s}^{-1}$) compression tests were performed in a conventional testing machine Zwick/Roell Allround-Line Z020 with a 20 kN load cell. Furthermore dynamic compression tests ($\varepsilon_s = 10^2 \text{s}^{-1}$) were carried out using a drop tower with a drop weight of 600 kg. Strains were measured in all experiments by digital image correlation (GOM GmbH, Germany) at the surface of the compression specimens. Stresses were calculated from the reaction forces measured by the load cell of the conventional testing machine (static tests) and from data obtained from a strain gauge applied at the punch of the drop weight (dynamic tests), respectively.

2.3. MHP experiments

All experiments were performed on a machine tool Heckert HEC 630 by Starrag AG equipped with the interfaces for the pneumatic MHP tool (figure 1a). On the workpiece side, a flat plate (one for each of the three materials of this study) was mounted on a force measuring platform (Kistler 9255B with a range of 10 to 40 kN and a rigidity of 3 µm/kN). The three plates were face-milled with a roughness of $R_z = 10$ µm in order to ensure the same conditions for all experiments.

![Figure 1](https://example.com/figure1.png)

**Figure 1.** Experimental arrangement and process parameters of the MHP setup. a) Machine tool (Starrag AG HEC 630) with the pneumatic MHP tool on the right hand side and the face-milled plate on the left hand side. b) Schematic representation of the process parameter of MHP.

The following parameter ranges (see figure 1b) were selected as the scope of observation for the experimental investigations (table 1). They are based on the technical boundary conditions of the MHP tool and on results of first simple FE simulations. With the help of the predicted penetration depth of one indention, the investigation range of path distance as well as the feed rate could be narrowed. To reduce the number of trials, a design of experiments (DoE) using the software tool Cornerstone 7 was performed. A d-optimal design with a square model approach was used. In order to achieve the highest possible significances, the functions are adapted to a Gaussian distribution using a Box-Cox transformation plot. A qualitative review was done with the residuals probability plots. The software is also used to derive a mathematical process model that describes the relations of test and result parameters based on the different MHP tests (experiment and simulation). In addition to the already described input variables, essential output variables that characterize the surface of the workpiece after MHP were defined (table 1).

To evaluate the manufactured sample plates and to determine the parameters of the resulting surface, both mobile and stationary measuring devices were used. The stationary confocal microscope (Walter Uhl, technische Mikroskopie GmbH & Co. KG; z-resolution 5 to 20 nm and x/y-resolution of 1 to 3 µm) and the mobile roughness measuring device (Mahr Gmbh - MarSurf PS10; profile
resolution 8 nm) were used to determine the surface roughness. In addition, the mobile hardness measuring device (PCE Instruments GmbH - PCE-3500; range from 20 to 70 HRC) served to evaluate surface hardening.

Table 1: Overview of the selected input and output variables of the experimental investigations.

| test parameters       | result parameters          |
|-----------------------|----------------------------|
| description setting   | description                |
| feed rate             | roughness along the feed direction µm |
| path distance         | roughness across the feed direction µm |
| tool pressure         | surface hardness HRC       |
| us                    | reaction force at the work piece N |

2.4. FE simulations

Accompanying FE simulations were carried out using the commercial software ABAQUS 6.12. Figure 2a shows the initial geometry of a representative workpiece volume. In contrast to the experiments, the surface is ball-cut with a radius of 8 mm and a path distance of 0.7 mm. Two parameters were investigated using the FE method. First we studied the orientation of the MHP path with respect to the ball-cut paths as described by the angle φ. Figure 2b shows the four different MHP paths that were considered. The full circles correspond to the locations of impacts. In a second study, different impact or tool angles α (see also figure 1) were investigated for a MHP path of φ = 0°.

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Figure 2. Specimen geometry and MHP paths used in the FE simulation. a) Schematic representation of the specimen geometry and b) the definition of four different MHP paths with respect to the x-direction of the coordinate system of the FE-model. The FE mesh consists of about 100,000 finite elements. In a) only the colored nodes of the surface are shown (color corresponds to the y-coordinate). The specimen covers two full ball-cut paths to investigate subsequent MHP processing of the surface.

The FE mesh consisted of 100,000 brick elements of type C3D8R. True stress-true strain data, measured experimentally in static, quasi-static and dynamic uniaxial compression tests, was used as input to describe the elasto-plastic material behavior. To describe the elastic properties a Young’s modulus of E = 210 GPa and a Poisson’s ratio of ν = 0.3 were used for all three materials. A MHP path consists of several single impacts. Each impact is calculated in one simulation that consists of three steps: First, a displacement-controlled step to ensure the contact of sphere and workpiece. Second, loading and unloading using a gravity load boundary condition, and third a displacement-
controlled step to separate tool and workpiece. Sphere (master) and work piece (slave) contact is modeled using the penalty method in normal direction. Tangential friction is considered using a friction coefficient of $\mu = 0.1$. A gravity load is used to apply the load to the system consisting of the sphere with unity inertia and the massless workpiece. The gravity was chosen according to a validation with the experiment where a distance of 0.2 mm of two impacts results in an overlap of 50% of the areas of remaining indents for an impact angle of $\alpha = 90^\circ$. A displacement boundary with $u_x = u_y = u_z = 0$ is set at the bottom surface of the workpiece. The boundary conditions of the rigid sphere (with a radius of 6 mm) were defined at a reference point. A rotation boundary with $\theta_x = \theta_y = \theta_z = 0$ was used in all steps. The displacement boundary conditions (to ensure the contact of sphere and workpiece in the first step and to separate both parts in the last step) are applied in a local coordinate system according to the impact angle $\alpha$. The load boundary condition (gravity) is also defined in that local coordinate system. At the end of each simulation a so-called restart file was written that contains information about the displacements of all nodes and the strain hardening. This information is transferred in the following simulation using a predefined field.

3. Results and Discussion

3.1. Uniaxial compression tests

The three materials EN-JS 2070, 40CrMnMo8-6 and X155CrVMo12-1 were tested in uniaxial compression tests at static ($\dot{\varepsilon} = 10^{-3}\text{s}^{-1}$), quasi-static ($\dot{\varepsilon} = 10^{-2}\text{s}^{-1}$) and dynamic ($\dot{\varepsilon} = 10^{2}\text{s}^{-1}$) loading conditions. Figure 3 shows the true stress – true plastic strain curves. All three materials exhibit a positive strain rate sensitivity: An increasing strain rate results in higher yield stresses. The initial yield strengths for static loading are 364.2 MPa (EN-JS 2070), 703.4 MPa (40CrMnMo8-6) and 378.6 MPa (X155CrVMo12-1), respectively. These yield strengths increase with increasing strain rate up to 560.2 MPa (EN-JS 2070), 719.0 MPa (40CrMnMo8-6) and 526.9 MPa (X155CrVMo12-1) for dynamic loading conditions. This data was used as input to describe the plastic material behavior in the subsequent FE simulations.

Figure 3. Strain hardening behavior of a) EN-JS 2070, b) 40CrMnMoS8-6 and X155CrVMo12-1 under uniaxial compressive loading for three different strain rates. The yield stress – true plastic strain curves indicate a positive strain rate sensitivity for all three materials.

3.2. MHP experiments

Figure 4a shows a photograph of five machining test sections on an experimental plate of 40CrMnMoS8-6. Experimental results using the other two materials are not shown here, but are included in the relationships of roughness and process parameters (determined in the evaluation of the
DoE) presented later in this paper (see also figure 5). The evaluation of the test processing was performed in the marked middle section in order to minimize the influence of the acceleration behavior of the machine tool on the machining result. The roughness was measured along and across the feed direction for each test area (N1 to N35) in order to be able to independently evaluate the influence of individual parameters. Even very good optical results are possible, for example, with parameter set N5 (40CrMnMoS8-6, 2.5 bar, tool radius 4 mm, feed rate 1.0 m/min, path distance 0.1 mm). In contrast, parameter set N4 (40CrMnMoS8-6, 2.5 bar, tool radius 4 mm, feed rate 5.0 m/min, path distance 0.3 mm) does not offer a satisfactory surface quality. The only differences in these parameter sets are the feed rate and the path distance. The overlap of the individual ball impacts in connection with the plastic deformation in the workpiece is not sufficient to be able to produce a homogeneous surface. However, the different parameter sets are important in order to be able to evaluate the influence of individual parameters separately. As a result, all parameter sets in the test range (table 1) were evaluated and incorporated into the process model. For this purpose, the roughness values recorded for each parameter set with the mobile roughness measuring device were used.

Since the comparatively large test plates cannot be evaluated with the confocal microscope, parameter sets with a particularly large difference before and after peening were repeated with small samples. A corresponding, detailed evaluation is shown in figure 4b with parameter set N8 (40CrMnMoS8-6, 7.3 bar, tool radius 8 mm, feed rate 1.0 m/min, path distance 0.1 mm). Basically, the measuring methods of tactile and optical roughness measurement are fundamentally different and so are their numerical results (for milled surfaces they differ by a factor of 2 and for peened surfaces by a factor of 4). The roughness values of the optical method are generally larger than those of the tactile method, since the used probe tip (radii 2 µm) has a mechanically integrating effect. In contrast, the optical process captures the valleys in much greater detail and depth. The tactile, mobile measurement method can still be used for evaluation due to its flexibility, handling and the comparability of the measured values among themselves.

Using a confocal microscope, the real surface profiles before (figure 4b, left, \(R_a = 2.2 \, \mu m\)) and after hammer peening (figure 4b, right, \(R_a = 0.9 \, \mu m\)) can be clearly displayed. The three specimens were pre-machined by face milling. The individual milling grooves are clearly visible in both representations and remain in their basic structure even after hammer peening. However, the roughness peaks are largely leveled by the hammering process and pressed into the valleys.

![Figure 4](image-url)

**Figure 4.** Surface topology before and after peening. a) Width (7 mm, II) and length (21 mm, III) of each machining test (N1-N5 pictured). Due to the axle acceleration, only the middle range (7 mm, I) was used for the evaluation. b) Example of the evaluation by means of a confocal microscope for one parameter set (40CrMnMoS8-6, 7.3 bar, tool radius 8 mm, feed rate 1.0 m/min, path distance 0.1 mm) across the peening direction.

As a result of the DoE, where all experiments for all three materials as well as parameter sets were considered, the following relationships can be inferred: It can be seen that larger tool radii result in
A higher operating pressure of the pneumatic tool leads to a higher beat frequency. As a result, higher feed rates can be used. The surface roughness in the feed direction directly depends on this tool frequency. In contrast, the surface roughness across the feed direction depends directly on the selected path distance. That means that the surface roughness shows significant correlations in the evaluation. By contrast, the values of surface hardness and force signal vary strongly. The high variation in hardness can be attributed to the locally very different deformation. The hardness cannot be measured repeatedly at comparable locations using the mobile hardness tester. In addition, the force signal cannot be accurately evaluated due to strong noise effects and different beats (interference pattern between the impacts). In order to be able to make a statement about the relationships with the force acting on the workpiece, the first peak of each impact was evaluated and averaged over several successive impacts. Based on the DoE and under consideration of all MHP experiments so far the best parameter set for the investigated initial surfaces (face-milled with a roughness of $R_z = 10 \mu m$) of the three materials in this study consists of a pressure of 7.3 bar, a tool radius of 8 mm and a path distance of 0.18 mm. Specifically, MHP processing with these parameters results in an average reduction of the initial roughness of $R_a = 0.8 \mu m$ to $R_a = 0.5 \mu m$ in the case of 40CrMnMoS8-6 steel.
3.3. FE simulations

In contrast to the experiments, the initial surface of the work-piece was considered to be ball-cut (with a radius of 8 mm and a path distance of 0.7 – a technologically relevant initial surface condition) in the FE simulations in order to provide well-defined initial conditions. Two parameters, the orientation of MHP paths relative to the ball-cut paths and the impact angle, were investigated. All results presented below refer to the high-alloyed steel X155CrVMo12-1. In a first simulation (not shown here) a single impact on a flat surface was considered to validate the model. The gravity parameter was modified such that an impact distance of 0.2 mm results in an overlap of 50 % of the remaining indents of two adjacent impacts. This amount of gravity was then used in all simulations with ball-cut work-piece surfaces. Figure 6 shows the results of the first study with different MHP paths relative to the ball-cutting paths defined in figure 2. In these simulations the impact angle was always $\alpha = 90^\circ$ (tool radius 6 mm; path distance 0.2 mm). The initial surface is characterized by a roughness of $R_a = 1.9$ (dashed lines in figure 6). With increasing angle of the MHP path, the path distance from one minimum to the next minimum of the ball milling grooves increases. Due to the MHP processing the surface is deformed (full lines) and the roughness decreases. MHP along a path with $\varphi = 0^\circ$ results in $R_a = 0.74$. With increasing angle $\varphi$ a rougher surface can be expected, e.g., for $\varphi = 67.5^\circ$ the roughness increases to $R_a = 1.43$. In contrast, the maximum plastic strain is independent of the MHP path with approx. 6 % and is located at a depth of 50 μm (the location of that maximum is not on the plotted path in figure 6, but in the remaining work-piece volume). Minor changes are observed for the average equivalent plastic strain (arithmetic average) along the MHP path that ranges from 1.4 % ($\varphi = 0^\circ$) to 1.8 % ($\varphi = 67.5^\circ$). Figure 6 shows that the deformed surface is always located below the initial surface. This observation is only valid for the considered path in this analysis. The volume of the work-piece is constant, and therefore, regions with displacements relative to the indentation direction must exist. The largest plastic deformations along the MHP path occur at the maxima of the initial milling grooves. The global maxima of the equivalent plastic strain are located beside the considered path.

Figure 6. Results of the parameter study on the orientation of the MHP path relative to the previous ball-cutting path. a) Displacement of the surface in impact direction along the MHP path. The deformed surface (full lines) is always below the undeformed surface (dashed lines). b) Corresponding equivalent plastic strain along the MHP path. Most pronounced deformation occurs at the former ridges of the milling grooves.

A second study was focused on the impact angle $\alpha$. Four different angles (90°, 67.5°, 45° and 22.5°) were investigated for the same MHP path with $\varphi = 0^\circ$. The results for the impact perpendicular to the workpiece surface ($\alpha = 90^\circ$) are already presented in figure 6 (green lines). In this study the same amount of gravity as before was used, but the working direction was inclined relative to the surface.
Figure 7 shows the initial and deformed surface along the MHP path for a tool angle of \( \alpha = 45^\circ \) as well as the equivalent plastic strain. Furthermore, the displacements in all three directions are shown for a large part of the work-piece surface. The highest amount of deformation occurs again at the former maxima of the ball milling grooves. An average plastic strain of 2.6\% was evaluated, while the maximum overall plastic equivalent strain is 6.8\% (located beside path s). The location of this maximum is independent of the tool angle with a depth below the surface of 50 \( \mu \)m. The roughness is decreased due to the MHP to \( R_a = 0.77 \) (\( \alpha = 90^\circ \)), \( R_a = 0.73 \) (\( \alpha = 75^\circ \)), \( R_a = 0.66 \) (\( \alpha = 60^\circ \)) and \( R_a = 0.49 \) (\( \alpha = 45^\circ \)). Clearly, a decreasing tool angle (investigated here between 90\(^\circ\) and 45\(^\circ\)) results in a lower roughness. This result seems to disagree with previously reported experimental results, e.g. in [7], where a decreasing tool angle was associated with an increased roughness. Most likely this discrepancy is caused by the method of evaluation used in our FE simulation, which only considers the line path right below the MHP tool. Using, instead, the arithmetical mean height \( S_a \) to assess the roughness of the peened surface the reverse relation (in qualitative agreement with [7]) is found: A decreasing impact angle results in an increase of \( S_a \). For this two-dimensional parameter all nodes of the surface are used in contrast to the line parameter \( R_a \). Hence the different impact numbers may have an effect on the determined roughness parameter. Obviously, different roughness measures affect the physical interpretation of MHP simulations; further work is required to validate the effect of different theoretical approaches.

**Figure 7.** Results for a MHP path with \( \phi = 0^\circ \) and an impact angle \( \alpha = 45^\circ \). a) Initial and deformed surface after MHP processing as well as the equivalent plastic strain along path s. b) - d) displacements at the workpiece surface \( u_x \), \( u_y \) and \( u_z \).
Figure 7 also shows the displacement field after five impacts with a tool angle $\alpha = 45^\circ$ and $\varphi = 0^\circ$ according to figure 2. The displacement fields exhibit a mirror symmetry relative to the MHP path (parallel to the x-direction at $z = 1.0$). This evaluation with $u_{xx}$ ($u_{\text{max}} = 4.75 \, \mu\text{m}$, $u_{\text{min}} = -0.22 \, \mu\text{m}$), $u_{zz}$ ($u_{\text{max}} = 1.65 \, \mu\text{m}$, $u_{\text{min}} = -1.65 \, \mu\text{m}$) and $u_{yy}$ ($u_{\text{max}} = 0.98 \, \mu\text{m}$, $u_{\text{min}} = -8.57 \, \mu\text{m}$) shows that the material is deformed towards the x-direction (according to the tool angle) and also in positive and negative z-direction away from the MHP path. The displacements in y-direction also show that some material at greater distance from the MHP path is raised upwards with displacements of a smaller order of magnitude compared to the other components of $u$.

4. Summary and conclusions
In this study, experiments and accompanying FE simulations were performed considering the machine hammer peening (MHP) of three materials with face-milled and ball-cut surfaces. The results contribute to the early development of a mathematical model that captures the correlations of process, material and geometry parameters on the resulting surfaces. The experimental results presented in this paper refer to 40CrMnMoS8-6 while the numerical results correspond to X155CrVMo12-1 and represent only a part of the overall testing program. The main results and conclusions of this study can be summarized as follows:

- Uniaxial compression tests under static ($\dot{\varepsilon} = 10^{-3} \text{s}^{-1}$), quasi-static ($\dot{\varepsilon} = 10^{-2} \text{s}^{-1}$) and dynamic ($\dot{\varepsilon} = 10^{2} \text{s}^{-1}$) loading conditions provided true stress-true strain data indicating a positive strain rate sensitivity. These data sets were used to describe the material behavior in the FE simulations.
- On the basis of a statistical experimental design, detailed investigations of the peening process were carried out investigating various parameters (e.g., tool pressure, tool radius, path distance and feed rate) and their effect on the resulting surface geometry. Based on all experimental results included in the mathematical model, the lowest roughness can be achieved using a path distance of 0.18 mm, a pressure of 7.3 bar and a tool radius of 8 mm.
- Using FE simulations, the MHP of a ball-cut surface with different MHP paths and tool angles was investigated. The results demonstrate that the roughness $R_a$ is most effectively reduced for a MHP path perpendicular to the previous milling path and for a tool angle of $45^\circ$. Furthermore, the depth of the maximum plastic strain is independent of the MHP path or of the tool angle and is located at a depth of 50 $\mu\text{m}$ below the work-piece surface.

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