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Examining the impact of slide burnishing parameters on the 3D surface features of medium carbon steel

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ABSTRACT

Burnishing is a non-cutting finishing technique in which pressure is applied to plastically deform the irregularly distributed surface materials. In this process, the peaks of the surface are pressed into the valleys with a hard tool, resulting in a smoother surface with improved properties. The influence of brunishing parameters such as brunishing force, feed rate and number of passes on the 3D surface roughness of medium carbon steel was analyzed. An orthogonal L9 array Taguchi design was used to create a robust experiment. A CNC milling machine and a confocal microscope were used to grind and measure the workpiece surface. The topography roughness responses Sq, Sv, Sz and Sa were used to evaluate the roughness changes. The optimal parameters for brunishing were a feed rate of 0.05 m/min, 2 passes and a force of 80N for Sq and Sa and a force of 100N for Sv and Sz. This research is expected to provide insights into optimizing mass finishing processes to improve surface integrity, contributing to advances in manufacturing and materials science.

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1. INTRODUCTION

Burnishing is a non-cutting finishing method in which pressure is applied to plastically deform the irregularly distributed materials on the surface. This technique effectively moves the peaks of the surface into the valleys, resulting in a smoother surface with improved properties [1]. Depending on factors such as the pressure source, the shape of the brunishing tool, the contact movement and other criteria, this process can be categorized into different groups. Recent advances in process improvement techniques, such as ultrasonic-assisted brunishing [2], magnetic field-assisted brunishing [3] and localized heating with a laser beam for easier deformation [4], are gaining popularity due to their effectiveness in improving surface properties [5].

The finishing process is critical to the various surface properties and their overall performance. The brunishing process not only improves the surface roughness, corrosion resistance and wear resistance, but also changes the subsurface stresses and hardness. For example, Nagy A. et al. conducted a study on the effects of changing the number of passes and brunishing direction on the surface roughness of corrosion-resistant steel [6]. They found that the smoothness, load-bearing capacity and dimensional accuracy increased when the number of passes was increased from 1 to 2 and the direction was set to backward-forward. This indicates that the burnishing process can significantly improve the functional properties of materials by optimizing the process parameters.

Similarly, Han K. et al. conducted experiments to investigate the effects of burnishing on surface morphology, roughness, residual stress, micro-hardness and microstructure [7]. Their results showed that these properties improve significantly after burnishing. These improvements are crucial for applications where high surface integrity and performance is required, such as in the aerospace, automotive and medical industries. By understanding and optimizing brunishing parameters, manufacturers can achieve superior finishes that contribute to the longevity and reliability of their products [8].

The burnishing process is an important finishing technique that significantly influences the properties of the surface and substrate of materials. Through continuous development and optimization of brunishing parameters, the process can be tailored to specific requirements, contributing to advances in manufacturing and materials science. This continuous research and development in the

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field of brunishing techniques underlines their importance in achieving high quality surfaces and improved material properties.
Its simple system facilitates the application of various machining processes. In the extensive literature available, most studies focus on the use of lathes and milling machines. Grazesik W et al achieved a smoother surface by brunishing hard-turned, low-alloy 41Cr4 steel quenched to a hardness of about 60 HRC [9]. Similarly, research by [7] on a Ti60 alloy showed that the combination of turning and burnishing improved several reactions. A study in which a surface was milled with an 8 mm diameter ballnose end mill and then roller burnished with an 8 mm diameter Si3N4 nitride ceramic ball showed improved smoothness [10]. Specially developed roller burnishing tools are usually required for each machine, unless these tools are suitable for multi-purpose use. Felhő C. et al successfully modified a roller burnishing tool from a lathe for use in a milling machine, resulting in improved surface roughness [11].
Measurements of the surface roughness profile and topography and their analysis are performed according to ISO standards. The most commonly used standards are ISO 25178, ISO 21921-2:2021 and ISO 21920-3:2021. Key parameters such as Ra, Rz, Rq, Rp, Rv, Sa, Sz, Sq, Sp and Sv are often used to measure surface roughness and topography [12], [13], [14], [15]. These parameters can lead to various conclusions that significantly influence important decisions. The roughness profile results vary depending on the scan length, cut-off filters and position selection, as the surface smoothness is not uniformly distributed over the entire part. In contrast, the 3D surface topography parameters provide consistent results as they calculate the entire area under consideration. The aim of this experiment is to investigate the effect of changes in the vibratory finishing parameters on the 3D surface roughness.

2. METHODOLOGY

For this experiment, C45 medium carbon steel was used, the material properties of which are listed in Table 1. This material is preferred for its combination of strength, toughness, hardness and wear resistance. It is widely used in the automotive, aircraft and construction industries [16]. Its versatility and mechanical properties make it a popular choice for a wide range of industrial applications.
A workpiece measuring 60mm x 50mm x 20mm, additionally fixed with a force sensor, was prepared for three brunishing tests (8mm x 8mm), as shown in Figure 1. The L9 Taguchi test plan was used to select the parameter combinations for the burnishing test. Three workpieces, each with three brunishing areas, were used for the study. These workpieces were milled with identical parameters (1000 rpm spindle speed, 0.21 mm feed and 1 mm depth of cut with an 80 mm milling cutter fitted with two round indexable inserts), as the main objective was to investigate the effect of burnishing parameters on surface roughness. After milling, the workpieces were polished with a 6 mm diameter diamond ball according to the orthogonal arrangement. The topographic roughness indicators were measured both before and after the brunishing process. A proper cleaning procedure was followed to ensure that no residue was left behind, as residual particles could lead to inaccurate readings.

Table 1 – *Percentage of chemical composition and mechanical properties of C45 steel [17].*

Chemical Composition (average), [%]								
C	Mn	Si	P	S	Cr	Ni	Mo	Fe
0.48	0.74	0.36	0.011	0.01	0.09	0.02	0.002	rest
Yield Strength (min.)					Re=430 MPa			
Tensile strength(min.)					Rm=740 MPa			
Hardness(min.)					250 HB			

A robust Perfect Jet MCV-M8 CNC milling machine from Ping Jeng Machinery Co., Ltd. was employed for the face milling and burnishing processes. The initial face milling and burnishing were carried out using an 80mm R200-068Q27-12L SANDVIK cutter and a modified burnishing tool holder, supported by an R252.44-080027-1SM head. The workpieces were face-milled with the same cutter and milling parameters, utilizing two RCKT 1204M0-PM 4230 inserts, cutting at 0.21mm feed per tooth and a 1mm depth of cut, with the spindle running at 1000rpm. SAE 15W-40 grade traditional oil was used to minimize friction, ensuring optimal performance during the burnishing process.

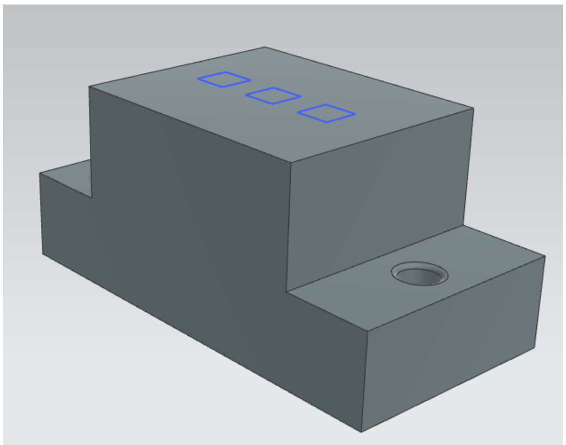

Fig. 1 *Workpiece geometry and burnishing area lay*

Precise control of the burnishing force was achieved using a Kistler 9257A force sensor, which was equipped with three signal-processing charge amplifiers to enhance the sensor signal. Additionally, a four-channel NI Compact DAQ 9171 signal acquisition system with LabView was used to facilitate real-time data display and control.
The milled and burnished surfaces were measured using three-dimensional topography with an AltiSurf 520 surface profiler, equipped with a CL2 confocal chromatic sensor and an MG140 magnifier. Surface roughness evaluation based on the 3D surface topography parameters was conducted using Altimap software, developed by Digital Surf. The analysis adhered to the standards outlined in ISO

25178, employing a 4mm sampling length and a 0.8mm cut-off for the specified measurements and assessment of the surface characteristics.

The best-practice Taguchi experimental design was employed to minimize the number of experiments, ensuring both economical and robust results. The L9 orthogonal array, as shown in Table 2, was utilized to conduct the experiments, encompassing variables such as burnishing force, feed, and the number of passes. Table 2 also presents the 3D surface roughness topography results and their Noise to Signal ratio (N/S).

Table 2 – *Factors and their levels.*

Factors	Level 1	Level 2	Level 3
Force (N)	60	80	100
Feed (m/min)	0.05	0.10	0.15
Number of passes	1	2	3

3. RESULTS AND DISCUSSION

The primary approach of Taguchi's experimental design to improve robustness is to maximize the signal-to-noise ratio to ensure resilience to external fluctuations. This strategy aims to reduce the impact of uncontrollable factors on the response variables. In this context, the 'signal' refers to controllable parameters such as brunishing force, feed rate and number of passes, while the 'noise' refers to external variables that could influence the responses.

The experiments are guided by the principles of quality characteristics, including smaller-the-best, nominal-the-best and bigger-the-best, depending on the response requirements. To minimize surface roughness, the "smaller-the-best" principle was applied. These principles are geared towards specific research objectives and allow optimization of the desired results while mitigating the effects of external variability on the results. The formula for the "smaller - better" (STB) S/N ratio is shown in Equation 1.

$$S/N = -10 \times log10\ \left(\frac{1}{n}\sum_{i=1}^{n}\left(\frac{yi}{\bar{y}}\right)\right) \quad (1)$$

In above equation for the signal-to-noise ratio (S/N ratio), y_i denotes each individual observation or measurement, $\bar{y}$ represents the average (mean) of these observations, and n indicates the total number of observations in the dataset or sample under consideration.

Table 3 – *L9 orthogonal array, response results, and their signal-to-noise ratio*

Run	Force[N]	Feed[m/min]	Pass	Sq[μm]	S/N Sq	Sv[μm]	S/N Sv	Sz[μm]	S/N Sz	Sa[μm]	S/N Sa
1	60	0.05	1	0.57	4.91	3.66	-11.27	6.95	-16.84	0.419	7.56
2	60	0.1	2	0.46	6.73	3.93	-11.89	7.16	-17.10	0.339	9.40
3	60	0.15	3	0.84	1.53	5.89	-15.40	11.40	-21.14	0.587	4.63
4	80	0.05	2	0.27	11.28	2.54	-8.10	4.93	-13.86	0.20	13.98
5	80	0.1	3	0.36	8.90	3.85	-11.71	8.02	-18.08	0.272	11.31
6	80	0.15	1	0.99	0.06	5.66	-15.06	9.95	-19.96	0.70	3.10
7	100	0.05	3	0.35	9.12	2.39	-7.57	4.87	-13.75	0.256	11.84
8	100	0.1	1	0.52	5.66	4.49	-13.05	7.36	-17.34	0.368	8.68
9	100	0.15	2	0.58	4.81	4.46	-12.99	7.48	-17.48	0.444	7.05

Table 3 shows the comprehensive results of the surface topography parameters obtained from nine different processing runs. These parameters, Sq, Sv, Sz and Sa, collectively referred to as elevation parameters, are central to characterizing the topographic features of surfaces. They describe the variations in the height or depression of points on the surface relative to the average plane and provide crucial insights into surface roughness and texture [18].

In particular, Root Mean Square Roughness (Sq) quantifies the average of the absolute height deviations from the mean plane within the sample area. Surfaces 6 and 3 exhibit strikingly high Sq values of 0.993 μm and 0.839 μm respectively, indicating significant deviations from the mean plane and thus a rougher surface texture. In contrast, surface 4 has the lowest Sq value at 0.273 μm, indicating a smoother surface profile. In comparison, the milled surface has a higher roughness of 1.55 μm, highlighting the effectiveness of the brunishing process in improving the surface finish under all conditions tested.

It is noteworthy that the surfaces with the highest Sq values were subjected to the highest feed rate of 0.15 m/min during brunishing, while the smoothest surface (surface 4) was processed at the lowest feed rate of 0.05 m/min. Interestingly, there does not appear to be a consistent correlation between the brunishing force and the number of passes on these surfaces, suggesting that other factors such as feed rate exert a stronger influence on surface roughness. The signal-to-noise ratios (S/N) calculated using Minitab Table 4 software emphasize the importance of feed rate, number of passes and brunishing force in determining surface quality. Higher feed rates tend to result in rougher surfaces as undeformed peaks may remain between successive feeds, whereas lower feed rates contribute to smoother surfaces as they promote more uniform deformation during brunishing.

Table 4 – *Response Table for Signal-to-Noise Ratios of Sq*

Level	Force	Feed	Pass
1	4.388	8.436	3.546
2	6.745	7.096	7.603
3	6.53	2.131	6.514
Delta	2.357	6.305	4.057
Rank	3	1	2

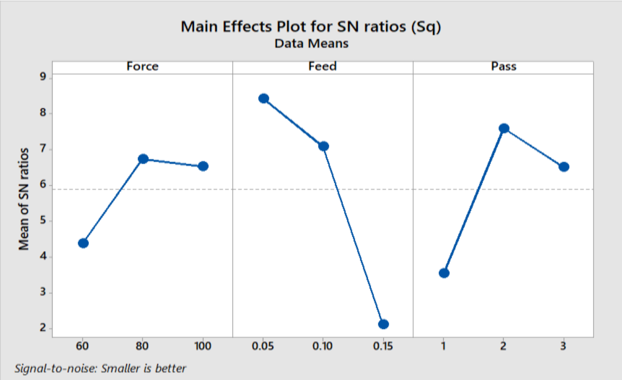

Fig. 2 *Main effect plot for S/N ratios of Sq*

To achieve lower Sq values and therefore smoother surfaces, the optimum conditions for brunishing were found to be a force of 80 N, a feed rate of 0.05 m/min and 2 passes. These conditions provide a balance that minimizes height variations and promotes a more uniform surface finish consistent with the desired specifications for the machined components.

Maximum pit height (Sv) represents the deepest valley within the sampled area, providing insight into the depth variations on the surface. Surface 3 recorded the highest Sv value at 5.89 µm, indicating significant valley depth, albeit an improvement over the initial milled surface's Sv of 6.25 µm. In contrast, surface 7 exhibited the lowest Sv value at 2.39 µm, suggesting a shallower depth profile.

Comparing the burnishing parameters across these surfaces reveals a consistent trend with Sq values: surfaces processed at higher feed rates and forces tend to exhibit higher Sv values. This suggests that deeper valleys are formed when higher forces are applied and the feed rate is not sufficiently low to close these valleys effectively.

The signal-to-noise (S/N) ratio response table in Table 5 highlights feed rate as the most influential factor, followed by the number of passes and burnishing force, in determining the surface quality in terms of Sv. This underscores the critical role of feed rate in controlling valley depth during the burnishing process.

Based on the findings from Figure 3, the optimal burnishing parameters identified for minimizing Sv values and thereby achieving more uniform surface depths include a force of 100 N, a feed rate of 0.05 m/min, and 2 passes. These parameters represent a balanced approach to reduce the depth of valleys on the surface, aligning with the desired surface finish specifications for the machined components.

Table 5 – *Response Table for Signal to Noise Ratios (Sv)*

Level	Force	Feed	Pass
1	-12.853	-8.978	-13.124
2	-11.621	-12.214	-10.99
3	-11.2	-14.482	-11.56
Delta	1.653	5.504	2.133
Rank	3	1	2

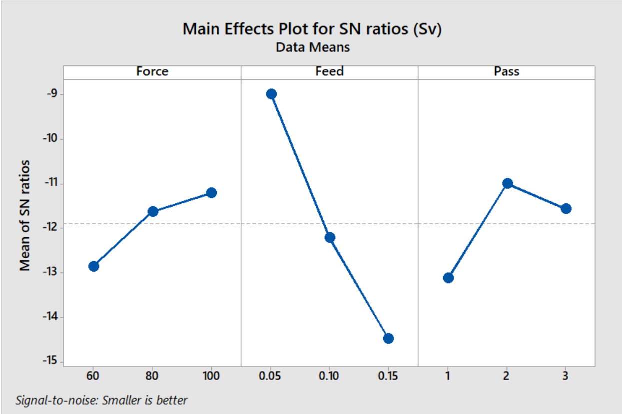

Fig. 3 *Main effect plot for S/N ratios of Sv*

Maximum Height (Sz): Represents the maximum peak-to-valley height within the sampling area. Experiment number 3 showed the highest Sz value of 11.4µm while experiment 7 got the lowest Sz value of 4.87µm. The worst Sz roughness after the burnishing process (surface 3) is better than the milled surface (13.80µm).

This indicates burnishing process modified the surface finish to a certain extent. Like Sv and Sq, feed as shown in table 6 is the most dominant factor in this measured response too. 100N force, 0.05m/min feed, and 2 passes are the optimal burnishing parameters from the main effect plot in Figure 4. Two passes close to each other (minimum feed) and maximum burnishing force for a good result is predicted when Taguchi smaller-the-better principle is used.

Table 6 – *Response Table for Signal-to-Noise Ratios (Sz)*

Level	Force	Feed	Pass
1	-18.36	-14.82	-18.04
2	-17.3	-17.51	-16.14
3	-16.19	-19.52	-17.66
Delta	2.17	4.71	1.9
Rank	2	1	3

The arithmetic mean surface elevation (Sa) is an average measure of the heights of surface peaks and valleys within a given sampling area. It is a crucial parameter for characterizing surface texture and is similar in concept to Sq, but offers a slightly different perspective due to its average nature. In many cases, either Sa or Sq can effectively represent the mean surface elevation as their differences are usually minimal.

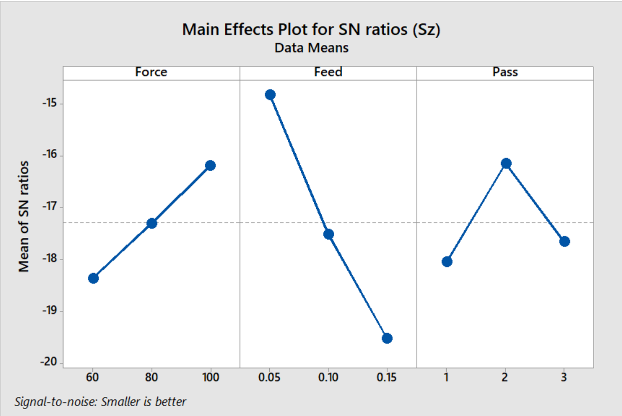

Fig. 4 *Main effect plot for S/N ratios of Sz*

During this experiment, it became clear that the measurements of Sa and Sq provided comparable results when examining the surface roughness values, response tables, and main effects plots for the signal-to-noise (S/N) ratio. This emphasizes their close correlation and interchangeable usefulness in evaluating the mean height and textural characteristics of the surface.

Similar to Sq, the surfaces with the highest and lowest Sa values also matched those identified as optimal under the brunishing conditions. Specifically, the surfaces with the highest Sa values were treated at higher feed rates and forces, while the surface with the lowest Sa value was typically treated at lower feed rates. This trend suggests that higher forces and insufficiently low feed rates can lead to greater peak heights and deeper valleys on the surface.

Consistent with the results for Sq, a force of 100 N, a feed rate of 0.05 m/min and 2 passes were determined to be the optimal brunishing parameters to minimize Sa values and achieve a more uniform surface profile. These parameters provide a balance in promoting smoother surface textures by effectively controlling the heights of peaks and valleys on the machined components.

4. CONCLUSIONS

A sliding burnishing process using a modified tool was conducted on face-milled C45 material to explore variations in topographic roughness with changes in burnishing parameters. The results underscore the significant influence of parameters such as force, feed rate, and number of passes on surface topography, each contributing uniquely to changes in surface roughness.

Throughout the study, feed rate emerged as the dominant factor affecting surface roughness. Higher feed rates consistently led to rougher surface textures, emphasizing the critical role of feed rate control in achieving desired surface finishes.

An important observation was the similarity in response between pairs of surface roughness parameters: Sq and Sa, as well as Sv and Sz, exhibited comparable trends with changes in burnishing parameters. This suggests that either parameter from each pair can effectively represent the measured surface characteristics within their respective contexts.

In conclusion, this research highlights the necessity of optimizing burnishing parameters to achieve specific surface roughness outcomes. By meticulously adjusting parameters like feed rate, burnishing force, and number of passes, manufacturers can effectively manage and enhance surface finish quality in machined components. Future investigations could delve into additional factors or advanced techniques to further refine and optimize surface finishing processes for industrial applications.

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