UNIVERSITY OF MISKOLC
FACULTY OF MECHANICAL ENGINEERING AND INFORMATICS

Enhancing Surface Integrity through Slide Diamond Burnishing: Tool Modification, Novel Process Strategies, and Multi-material Applications

Booklet of PhD Theses

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1. INTRODUCTION

Slide burnishing is a non-material-removal machining process that improves the surface integrity of a product by plastically deforming peaks into valleys using a hard tool. Force is applied to the hard tool, which is available in different shapes and material types, to deform the asperities by following a predefined tool path. Appropriate speed and feed and other technological parameters are selected for the required finishing quality. The process can be completed in one round or repeated several times, defined as the number of passes. Surface integrity (Roughness and mechanical and metallurgical properties) of the product is enhanced as a result, making the process a candidate for finishing machining [1], [2]. Depending on the capability of the process, the product can pass through different machining processes till the desired property is achieved. For example, grinding, burnishing, and honing could succeed face milling or the turning process to give the final surface property. The attained surface property defines the functionality of the product, such as fatigue life, wear resistance, corrosion resistance, tribological behavior, and others.

Based on the burnishing tool and product surface contact, the process is categorized as a sliding and rolling burnishing process. The shape of the tool also differentiates the type of burnishing as ball or cylindrical burnishing processes. These burnishing types appear as single or multiple (ball and cylindrical) tool burnishing. Due to the freedom of selection of contact, tool shape, tool material, and force application mechanism (spring-loaded and hydraulic), numerous burnishing types are available. Apart from the mentioned features, there are auxiliary technologies like ultrasonic vibration, laser heating, and magnetic field application that enhance the process's efficiency.

Functional properties are important when the product acts as a critical component working under dynamic conditions. Cyclic loads, harsh environments such as temperature and acidity, require a specially treated surface that enhances its service quality and life. This is true because most failures start at the surface due to poor roughness and the type of stress induced as a result of the selected finishing machining type. Milling, turning, and grinding produce tensile stress on the surface, which plays a greater role in crack initiation. The initiated crack becomes a stress concentrator and propagates with further application of the load. As a result, the fatigue life of the product decreased [3]. On the contrary, chip-less machining, such as burnishing and shot peening, induces compressive stress that delays crack initiation and propagation. With the ever-increasing demand for stringent surface quality and evolving new material types for critical engineering products in aeronautical, automotive, biomedical, marine, and other industries, there is a lack of comprehensive research on the approach of slide diamond burnishing process. Slide diamond burnishing is a sustainable (chip-less, less or no cooling requirement [4]), economical (easy technique and quick) process compared to the other conventional and non-conventional finishing processes.

A recent study by Varpe and Tajane [5] indicates that the Al family accounts for 36% of the materials that received a burnishing process, including Cu (6%), Brass (6%), Steel (47%), Ti-alloy (11%), Polymers (3%), and Wc (3%). Additive manufacturing provides wide opportunities for new material production that requires property studies after the printing process and different machining processes. It's poor surface roughness [6] requires post-machining to find its application in a wide range of industries. Grinding and burnishing are among the popular machining processes to give the required finishing appearance.

Burnishing performance relies heavily on the selection of technological parameters and their levels, especially on burnishing force, feed, tool radius, speed, and number of passes. For the selected parameters, optimization techniques like Taguchi design, Response Surface Methodology (RSM), and Genetic Algorithm (GA) are applied. The most frequently studied slide burnishing parameters, as per Maximov et al. [7] were burnishing force (33%), feed rate (26%), burnishing velocity (18%), and number of passes (8%). For the required plastic deformation to occur, optimized parameters must be applied. For example, if the applied burnishing force is low, there will not be plastic deformation. On the other hand, if a higher load is applied, the tool plows the surface, which worsens the surface integrity. Fewer or an excessive number of passes have the same effect. Conventionally, multi-pass burnishing processes were applied with the same setup to enhance the surface integrity, even though the first pass achieves most of the deformation task. Each pass takes equal time and energy unless parameters like feed or force are adjusted, and changing these parameters requires another cycle of passes. This repetitive approach leads to inefficiencies in time and energy, highlighting the need for different approaches to reduce redundancy while improving surface integrity.

This dissertation aims to study the effect of the slide burnishing process on 3D printed MetcoAdd 17-4PH-A using an interchangeable burnishing tool. The tool adapter was designed to develop the burnishing tool into an interchangeable tool that can be used in a lathe and a milling machine conveniently. By varying the burnishing force, feed, and number of passes, changes in surface roughness, residual stress, and microhardness were studied. Surface roughness of flat (C45) and cylindrical (42CrMo4) surface workpieces was studied after the burnishing process, which applied a novel feed application method. The results from the novel and conventional methods were compared to better understand the differences. By doing so, the present work seeks to contribute to the broader understanding of burnishing finishing techniques and their role in improving the functional performance of critical mechanical components.

1.1. OBJECTIVES

Maximov et al. [8] mentioned in their review article about slide burnishing, that there is no universal classification of burnishing methods. They advised the usage of the Differential Morphological Method (DMM), which has the advantage of expanding morphological signs with new features based on the researcher's preferences. Elements of the structure, such as workpiece, deforming element, and force control mechanism (spring and viscous), and morphological signs for example, geometrical form and motion, constitute the feature of the burnishing method. The burnishing parameters' magnitude range also varies depending on these phenomena. These parameters follow a specific order when applied to the burnishing process architecture to produce the desired output. By focusing on tool adaptation, workpiece material, and the process parameters application approach, the objectives listed below are the targets of the study.

- To modify a tool for flat surfaces burnishing, design an optimized path of the tool in terms of surface quality, time, and analyze its performance.
- To study and analyze the effect of burnishing parameters on surface roughness of 3D metal printed stainless steel (MetcoAdd 17-4PH-A).
- Develop a novel burnishing process feed application method and analyze its performance (surface roughness) on flat C45 medium carbon steel.
- To study the performance of the newly developed feed application on a cylindrical workpiece (42CrMo4) by analyzing its effect on surface roughness change.
- Comparing the old and the newly introduced burnishing methods' elapsed time to give their economic picture.

2. METHODOLOGY

After I comprehensively studied the literature and found the research gaps, I formulated the objectives mentioned above. To achieve this objective, the procedure shown in Figure 1 was followed to conduct the experiments and analyze the results.

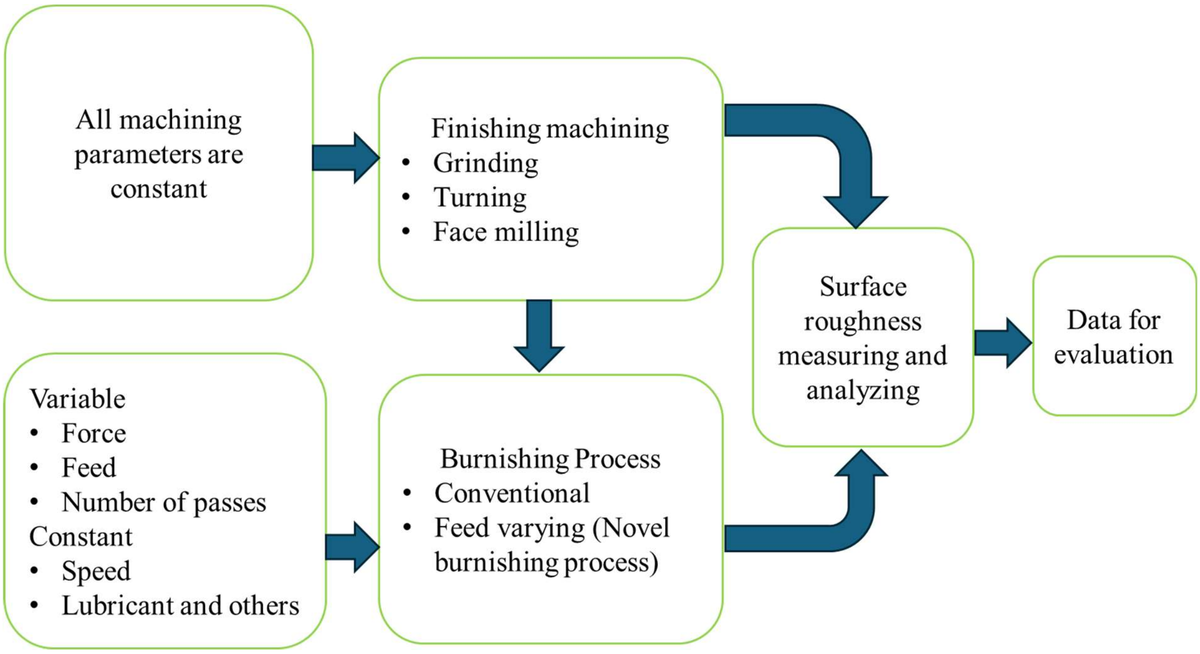

Figure 1. Flowchart of steps applied to conduct the experiment.

Surface integrity of three different materials, namely MetcoAdd 17-4PH-A, C45, and 42CrMo4, was measured and evaluated after the main machining process (grinding, face milling, and turning). Surface integrity was measured again after the slide burnishing process to compare the enhancement with its machined state.

A flat 60 mm ×26 mm × 10 mm size workpiece printed from MetcoAdd 17-4PH-A, a gas atomized powder, an iron-based alloy (FeCrNiCu), was applied to study the effect of slide burnishing. Laser powder bed fusion printing mechanism was applied by ORLAS CREATOR 3D Metal Printer (manufactured by OR LASER, Dieburg, Germany). Two stages, 50% and 85% maximum power of the laser, were used to complete the printing process. The printed workpieces were ground using a Metallkraft FSM 4080 series surface grinding machine (Stürmer Maschinen, Hallstadt, Germany) equipped with a 6A60M8V 38 Granit wheel operating at 1450 RPM.

The second material that received the proposed slide burnishing feed mechanism was C45 medium carbon steel. Three surfaces, 10 mm×10 mm each, were utilized from the 100 mm × 50 mm × 20 mm size sample with additional features for the force sensor fixture. The surfaces for the burnishing process were face milled by Perfect Jet MCV-M8 CNC milling machine, applying a cutting speed of 250 m/min, a feed rate of 0.25 mm/rev, and a depth of cut of 1 mm. R252.44-0800271SM milling head produced by Ping Jeng Machinery Industry equipped with SANDVIK cutter with 80 mm diameter and ATORN OCKX0606AD-TR HC4640 octagonal inserts, used to perform the face milling.

42CrMo4 low alloy steel in cylindrical shape (65 mm diameter) was the last tested material. Received with a hardness of 410 HV10, it was turned by Optimum OPTiturn S600 CNC lathe, produced by a German company called Optimum Maschinen Germany GmbH. A cutting speed of 120 m/min with 0.1 mm/rev feed and 0.1 mm depth of cut were utilized. SANDIV DCLNL 2525M tool with 4NC-CNGA120412 (PCBN Tipped Carbide coated by TiN) finishing insert was selected for the mentioned purpose. The 85 mm length of the workpiece was divided into supporting area, clearance areas for the tool, and two 12.5 mm long areas for the burnishing process with a 5 mm gap between them.

The burnishing process was performed by sliding a 4.4 mm diameter synthetic diamond ball, initially designed for a lathe machine and fitted with a modified adapter while used in a milling machine for flat surfaces. L16 Taguchi orthogonal array design of experiment was used to conduct the 3D printed stainless steel burnishing to manage the experiment cost without compromising the number of trials. Four levels of force (40, 60, 80, and 100 N), feed (0.02, 0.07, 0.12, and 0.17 mm), and number of passes (1, 2, 3, 4) were varied to study the response of workpieces. Arithmetic mean roughness (Ra), skewness (Ssk), kurtosis (Sku), core roughness depth (Sk), reduced peak height (Spk), reduced valley depth (Svk), surface and in-depth residual stress, and microhardness responses of the surfaces were studied. As the burnishing process affects the material physically, mechanically, and microstructurally, the response parameters are selected to study the change in these properties.

Researchers select the burnishing technological parameters, decide their levels, apply auxiliary apparatus that enhances the process, and select an experimental design based on their material types and intended applications. In addition to these procedures, in this research, I introduced a novel feed application method that changes the feed in every number of passes. This helps the tool to follow different paths in every number of passes which contributes to the surface integrity enhancement. This new approach works in a multi-pass burnishing process, as it needs at least 2 passes. After the feed level is selected, a group of feeds are applied (e.g. 2 feeds if the passes are 2 and 3 if the passes are 3) to perform the process. Since there are more possible feed combinations, a limited number of experiments were conducted for the C45 steel, and a full factorial for 42CrMo4. Three levels of force (70, 90, 110 N), four levels of feed (0.02, 0.08, 0.14, and 0.2 mm) and three levels of passes (2, 3, and 4) were used in the experiment of C45 burnishing. In the experiment of 42CrMo4 four levels of force (60, 90, 120, and 150 N), four levels of feed rate (0.02, 0.08, 0.14, and 0.2 mm/rev), and three levels of feed (2, 3, and 4) were applied. All flat surfaces (3D printed stainless steel and C45 steel) were burnished by Perfect Jet MCV-M8 CNC milling machine and the cylindrical surface (42CrMo4) by Optimum OPTiturn S600 CNC lathe. To compare the results by the new feed application method, the same burnishing parameters and levels were applied using the old burnishing approach. 3D amplitude and functional roughness parameters (Sa, Ssk, Sku, Sk, Spk, and Svk) were measured before and after the two burnishing approaches. Applying the new feed application method on a flat surface using a milling machine and on a cylindrical surface using a lathe machine tests the potential of the process.

Burnishing tool feed and number of passes were controlled using CAD and CAM codes while the burnishing force was controlled using force sensor. Kistler 9257A force sensor, a Kistler 5011A signal processing charge amplifier (both from Kistler Instrumente AG, Winterthur, Switzerland) were applied in all experiments. NI Compact DAQ 9171 four-channel signal acquisition unit (NI Hungary Kft. Debrecen, Hungary) was integrated with LabView for real-time data display and control.

AltiSurf 520 (Altimet SAS, Thonan-Les-Bains, France) was used to measure the 3D roughness parameters before and after the burnishing process. CL2 confocal chromatic sensor and MG140 magnification were applied to scan an area of 4mm×4mm. To capture the burnishing profile, the sensor was scanned perpendicular to the machining direction. Workpieces were cleaned of debris and lubricants with alcohol and compressed air to maintain the accuracy and reliability of the measurements. The device is equipped with Altimap 6.2 software of Digital Surf to analyze and process surface topography data obtained from measurement instruments. A Gaussian filter on a 4mm×4mm area, based on ISO 25178-2:2021 [9], was applied to evaluate the data.

The analysis of residual stresses were performed by the Xstress G3 diffractometer (Stresstech GmbH, Rennerod, Germany). For the purpose of measuring stress distribution at depth, the QETCH 100 M electrolytic etcher from QATM (ATM Qness GmbH, Mammelzen, Germany) was utilized for the removal of steel layers, with the thickness of these etched layers being precisely measured by the Mitutoyo ABSOLUTE depth gauge (Mitutoyo Europe GmbH, Neuss, Germany).

Concerning the microhardness analysis, a Tukon 2100B device, by Wilson Instruments, Norwood, MA (USA) was used to assess the variations in hardness across the burnished surfaces. Surfaces were prepared for the indentation process by cleaning them to avoid any possible errors. An indenter with a 1.96 N (0.2 kg) of load was applied for 10 s. Three measurements were achieved in three different places on each surface, and an average value was then taken for the purpose of the analysis.

Percentage changes realized due to the introduced surface enhancement machining methods are calculated using Equation (1) [10], [11] to help in understanding the increased or decreased degree of the surfaces' responses. The terms initial and final in the equation represent the starting measured value and the value after a specified machining process is applied.

$$\%\,change = \left(\frac{final - initial}{initial}\right) * 100 \qquad (1)$$

3. NEW SCIENTIFIC RESULTS – THESES

T1.

I developed and fabricated a custom-designed stepped shaft adapter that facilitates the seamless integration of a lathe-specific burnishing tool into a CNC milling machine, transformed it into an interchangeable tool, and validated it by applying it in all conducted experiments of the dissertation. This engineered solution directly addresses the limitation of tool incompatibility between machining platforms. By preserving the tool's native spring-force mechanism and enabling its use for planar surface finishing, the adapter eliminates the need for a dedicated burnishing tool for a milling machine. As a result, this research makes a significant contribution as it achieves significant cost reduction, enhances manufacturing process flexibility, and promotes resource efficiency, establishing a practical model for design for versatility in modern manufacturing. [FTK2, FTK3, FTK6, FTK9]

T2.

I proved through experiments that successive grinding and slide diamond burnishing with an interchangeable burnishing tool enhances the poor surface integrity of MetcoAdd 17-4PH-A 3D-printed stainless steel, which restricts its use in high-performance applications. The approach reduced arithmetical mean height (Sa) by 57 %, inducing compressive surface residual stresses up to +346 % (transverse), increasing near-surface microhardness by 77 %, and generating beneficial compressive layers to 0.22 mm depth. By studying the successive processes for the first time on MetcoAdd 17-4PH-A, this research establishes a scalable, milling-compatible framework for precision surface finishing, offering significant potential to improve surface integrity in applications such as automotive, aerospace and biomedical industries. Selected parameter level range are, force (40 - 100 N), feed (0.02 – 0.17 mm), and pass (1 - 4). [FTK6]

T3.

I introduced a novel burnishing strategy that modulates the inter-pass feed/feed rate to systematically shift the tool path, thereby overcoming the inherent inefficiency of conventional fixed-feed methods. A group of feeds is applied in a multi-pass burnishing process by changing the feed starting from larger to smaller in each pass. This ensures a more comprehensive plastic deformation of surface asperities by addressing peaks left unprocessed in previous cycles. Experimental results on C45 and 42CrMo4 steels confirm that this method yields a superior surface finish compared to conventional fixed-feed approaches. Its applicability across milling and lathe machines, along with its ease of use, makes it a convenient method for achieving an enhanced surface finish without requiring any capital investment or hardware modification. [FTK9, FTK10]

T4.

I demonstrated through experiment that changing the feed after each pass in the multi-pass diamond slide burnishing process of flat C45 steel improves the amplitude and functional roughness parameters within the applied range, burnishing force (70 - 110 N,) feed (0.02 – 0.2

mm), and pass (2 – 4). It achieved equivalent or superior reductions in arithmetic mean roughness (average Sa = 67.4%) compared to the conventional method. Furthermore, it transforms topographies from platykurtic to leptokurtic with kurtosis (Sku) increasing up to 198.3%, outperforming the erratic trends in conventional methods that range from 196.1% rises to 10.9% declines. It yields core roughness depths (Sk) that are smaller or comparable to the optimal values from conventional methods, with reduced sensitivity to feed and pass variations and an average 72% reduction versus 46.9% in traditional techniques. These results establish the feed changing method as a superior, low-cost approach for controlled functional surface texturing in load-bearing tribological applications. [FTK9]

T5.

Varying the feed in the multi-pass diamond slide burnishing applied on cylindrical 42CrMo4 low alloy steel significantly enhances amplitude roughness parameters compared to the conventional feed application method. I achieved average reductions of 56.7% in arithmetic mean height (Sa) and 86.5% in skewness (Ssk), alongside a 12.1% increase in kurtosis (Sku). The feed varying process outperformed the conventional method with 40.2% Sa reduction, 87.1% Ssk reduction, and 2.1% Sku increase, thereby demonstrating superior surface smoothness and topographic control for high-performance mechanical components. In the functional parameters, it achieved average reductions of 41.6% in core roughness depth (Sk), 77.9% in reduced peak height (Spk), and 61.6% in reduced valley depth (Svk). It enhances tribological performance by minimizing friction-inducing peaks and optimizing load-bearing capacity. Selected parameter level ranges are, force (60 - 150 N), feed (0.02 – 0.2 mm/rev), and pass (2 - 4). [FTK10]

T6.

Applying the novel slide burnishing feed application method finishes the process faster than the conventional method when it incorporates the lowest selected feed (0.02 mm/rev) in the feed combination of cylindrical 42CrMo4 alloy burnishing. In the conducted experiment, a smoother surface by both methods was achieved when v1 and 0.02 mm/rev feeds were applied. In this case, the new method is faster by 1.6 times when 2 passes are applied, and 2.15 times as well as 2.7 times when 3 and 4 passes are used. This proves that the proposed method can produce an enhanced surface finish in substantially less time, offering a direct competitive advantage in manufacturing efficiency for precision-focused industries. [FTK10]

4. SUGGESTIONS FOR FUTURE RESEARCH

All performed burnishing experiments were conducted using one tool, and the same tool path strategy was used while burnishing a flat surface. I suggest testing different tool diameters with a variety of tool paths to optimize the adaptability of the tool for the milling machine.

Three burnishing technological parameters (force, feed, and pass) with limited levels were tested in this PhD. study. Some technological parameters effect were not clear, especially with the proposed new method. Further research that can explore the role of other technological parameters, increased scope of their levels, and test the method in different material types can help to understand the effectiveness of the new method.

Nowadays, there are lots of assisting technologies (mentioned in the introduction section) to enhance the burnishing process. Ultrasonic vibration-assisted burnishing and laser-assisted burnishing are among the popular techniques for enhancing burnishing processes. I suggest the application of those assisting technologies to enhance the response quality.

5. LIST OF PUBLICATIONS RELATED TO THE TOPIC OF THE RESEARCH FIELD

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