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FLAT DIAMOND SLIDING BURNISHING SURFACE ROUGHNESS INVESTIGATION

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Abstract
The sliding diamond burnishing process is one among many burnishing post-machining processes applied for surface integrity enhancement purposes. This experimental study aims to investigate the effect of burnishing parameters on the surface roughness of the product. Taguchi design was used, and the machining parameters considered were burnishing force, feed rate, and the number of passes with three levels each. C45 steel alloy workpieces were face milled with the same machining variables and their surface roughness was measured before and after the diamond sliding burnishing process. Enhanced surface roughness was achieved with increasing burnishing force and minimum feed rate and higher number of passes.

Keywords: *C45 steel alloy, diamond burnishing, burnishing force, surface roughness, surface integrity*

1. Introduction

The type of surface treatment performed on critical components and devices used in structural and engineering applications plays a great role in its surface integrity. Its service life depends on its ability to resist different failure mechanisms which are directly related to the operations used to alter its physical and mechanical properties. Mechanical, thermal, and chemical in some cases combinations of these approaches are used to finish surfaces of products. Among many surfaces finish post-processes, the likes of polishing, grinding, honing, and burnishing process are cold working processes used to improve the mechanical and physical properties of the product to be manufactured are the popular processes. With its chip-less process which is environmentally friendly compared to other processes (Sachin et al., 2019) and its uncomplicated machining process, it is categorized as one of the promising machining processes. The required surface roughness with a compressive stress state can be achieved using the milling and turning burnishing process. Varga et al. (Varga et al., 2022) showed that diamond burnishing also has a positive effect on the quality of parts made with three-dimensional printing. Since many surface-initiated failures like creep, fatigue, fracture, and corrosion are common (Maximov et al., 2019), (Sequera et al., 2014), manufacturing industries are very cautious about the type of surface finish processes they use.

Research interest in the area is increasing as many factors affect the quality and service performance of the surface finish which are targets of the industries (Varga, 2016). Experiment-based and Finite Element Method (FEM) based research on different materials for different applications are going to study prominent factors that affect the final surface integrity. Different optimization methods are also highly focused on minimal surface roughness, increased microhardness, and so on.

Burnishing is a cold-working process by which peaks of the workpiece surface are plastically deformed to the valleys by applying a compressive load to a certain level using a hard deforming tool. Different controlling mechanisms are used on the source and magnitude of burnishing force, machining variables like feed rate, burnishing speed and number of passes, lubrication system, and type of burnishing tool materials. Ball, roller, and sliding burnishing types are popular in some cases referred as processes in other cases referred as methods based on the shape of the burnishing element or the type of contact between the workpiece and burnishing element. What makes this process different from the other surface finishing post-process is its good surface finishing ability and inducing positive compressive stress that boosts its surface integrity (Rodríguez et al., 2012; Ovali & Akkurt, 2011).

Apart from the surface finishing processes for purpose of attractive appearance, the majority of the surface machining processes are applied for particular surface functions. (Rotella et al., 2020) performed research on Ti6Al4V roller burnishing process cooling parameters' effect on the surface quality. Their report shows that cryogenic cooling and tools coating material improves the hardness, and the Minimum Quantity Lubrication (MQL) effect is more pronounced on surfaces roughness. Ball burnishing experiment on Ti-6Al-4V alloy showed an improvement in wear resistance with a wear rate decrease of 52% and coefficient of friction reduction by 64% (Revankar et al., 2017). Another research conducted by (Avilés et al., 2013) and (Maximov et al., 2020) on AISI 1045 normalized steel and 41Cr4 steel to investigate fatigue strength improvement concluded that low-plasticity ball burnishing and slide diamond burnishing increases fatigue strength. Microhardness is another very important characteristic of a material that defines surface failure phenomena. (Esme, 2010) used GREY based Taguchi method of ball burnishing to study the effect of the method on surface roughness and microhardness and they found an improved result for both surface roughness and microhardness. For a targeted Ra, from the different possible machining parameter combinations, some variables are dominant. The relation between maximum peak height and depth of ball penetration of aluminum alloy EC1350 was studied by (Imani et al., 2019). Their result shows that ball penetration depth approximately equal to the maximum peak height gives minimum surface roughness Ra.

Different optimization and analysis techniques were used to find the possible parameter combination to give good surface roughness, higher microhardness, increased corrosion resistance, decreasing residual stress, etc. (Teimouri et al., 2018) conducted a ball burnishing experiment to evaluate the optimization of surface properties and residual stress of AA6061-6 using Response Surface Methodology (RSM) and numerical simulation with ABAQUS software. In their research, they found out that increased hardness and reduced surface roughness were achieved with an ultrasonic vibration amplitude of 8 μm, feed rate of 1000 mm/min, and force of 38 N. Another experiment by (Ramesh et al., 2019) on Mg-4%, Zn-1% Ca alloy showed an increase in microhardness by 107 HV and Ra of 129 nm with Taguchi optimization technique, and the best parameter combination was 0.45 mm, burnishing force 250 N and feed of 450 mm/min. Response surface experiments with Nondominated sorting genetic algorithm-II were used to study the optimization of surface roughness and stress concentration coefficient induced by ball burnishing. The optimized result shows that 18 MPa of burnishing force, 0.05 mm/rev of burnishing feed and 600 rev/min of burnishing speed gives Ra = 64.6 nm and -901.4 MPa (compressive) residual stress values.

Factors that affect the surface roughness come from workpiece properties, cutting phenomena, cutting tool properties, and machining parameters (Benardos & Vosniakos, 2003). Burnishing force, feed rate, and the number of passes are parameters from the machining parameters which affect the surface roughness, the burnishing depth, microhardness, and other surface integrities of the surface (Korzynski et al., 2018; He et al., 2018). Depending on the governing factors source and their kinds of controlling mechanism, the final product surface integrity changes to certain degrees. In the current work, a combined and independent effect of these parameters' investigation has been performed.

2. Materials and methods

In the experimental investigation, steel alloy C45 workpiece material whose chemical and mechanical properties are summarized in Table 1 has been used. The workpiece top surfaces are rectangular shaped with 100 mm × 50 mm which is enough for three burnishing processes local zone (8 mm × 8 mm). It contains also an extra two 20 mm × 50 mm extension areas on both ends with a hole in its center for the clamping purpose on the CNC bed. The 3D CAD model of the workpiece is shown in Fig.1. CNC milling machine PERFECT-JET MCV-M8 with milling head R252.44-080027-1SM was used for face milling operation and this machine was also used to provide the kinematic movement of the burnishing process.

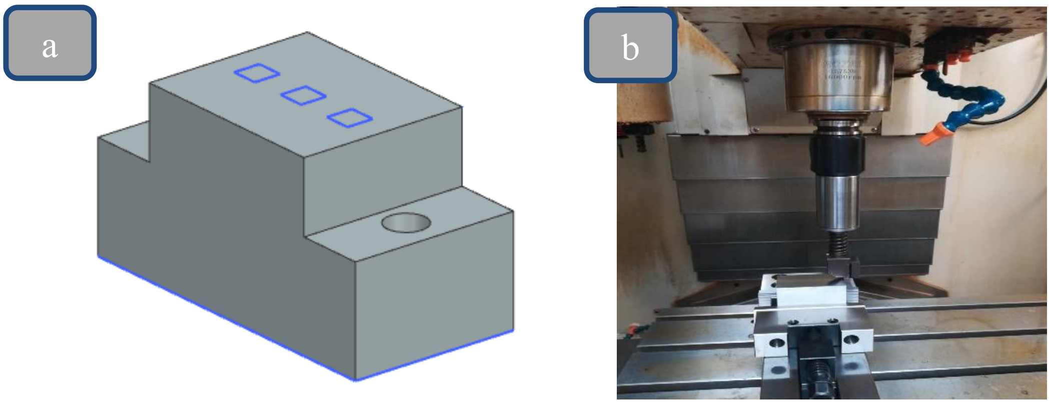

Figure 1. *a) Workpiece CAD model b) Milling head*

Table 1. *Percentage of chemical composition and mechanical properties of C45 steel (Skoczylas & Zaleski, 2016)*

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		

The milling head was used to hold the burnishing holder and provide the press (burnishing force) for the burnishing process. The CNC milling bed was programmed to move elliptically as depicted in Fig.

2. with constant speed against the fixed constant milling head burnishing tool holder motion (this provides the actual burnishing speed). The required burnishing force was provided by the vertical adjustment of the milling head with real-time monitoring by force sensors, the other factors were changing depending on the Taguchi design. Real-time force measurement using Kistler 9257A force sensor with signal processing device (Kistler 5011A charges amplifiers) and an NI CompactDAQ 9171 four-channel DAQ device for signal acquisition and LabView for data display and input signal control were used (Fig 3.).

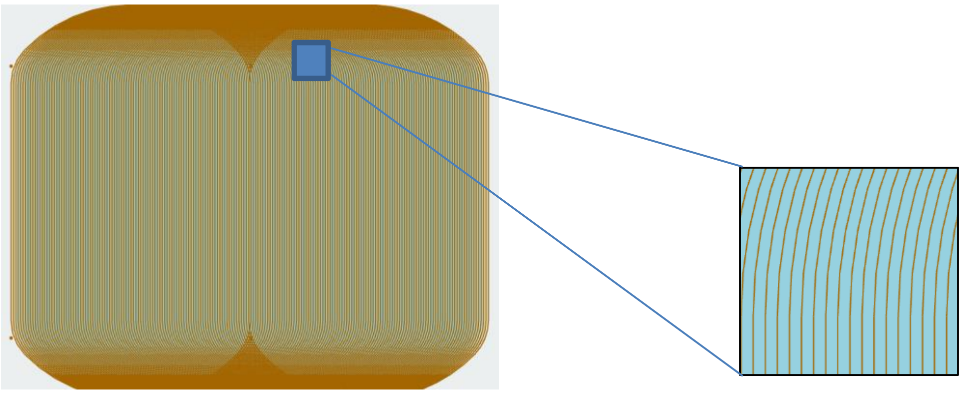

Figure 2. *Burnishing path*

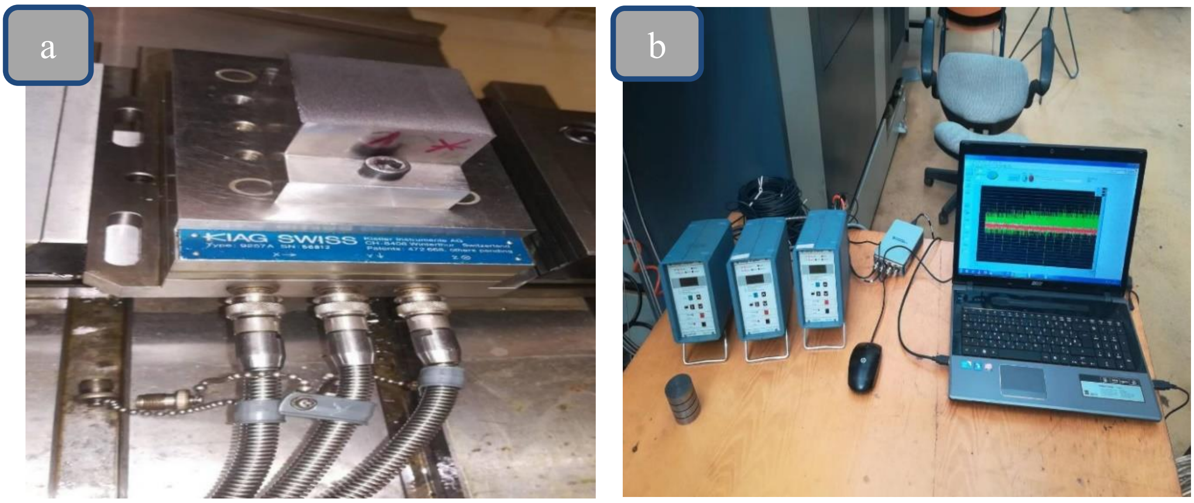

Figure 3. *a) force sensor, b) NI DAQs, signal processing, and LabView window*

As the objective of the current research work was to study the surface roughness change during the sliding burnishing machining process, the surface roughness value before the burnishing process was measured by the MITUTOYO SJ301portable surface roughness measurement device after face milling machining. All the workpieces were face milled with the same machining parameters (n = 500 1/min; v_f = 500 mm/min; a_p = 0.5 mm) and cutter. The specifications for the face milling operation were milling head R252.44-080027-1SM, milling cutter of FMRCM 4063RD-M. An AltiSurf® 520 series 3D surface roughness analyzer equipment with CL2 confocal chromatic probe was used for roughness measurement after the burnishing operation.

The sliding diamond burnishing tool used for this study was originally designed for the burnishing process in a lathe machine. A socket extension with a hole was prepared that matches the CNC milling spindle end. This modification was used for the first time in the laboratory for current research Fig. 4. An artificial diamond ball with a diameter of 3 mm was used to perform the burnishing process for all the workpieces. The burnishing tool includes a spring for the application of the required force to the diamond ball to press it against the workpiece surface.

Figure 4. *a) MITUTOYO SJ301 b) AltiSurf® 520 series equipment*

The burnishing parameters used in the experiments are shown in Table 2. Three parameters were changed during the tests: the burnishing force, the feed (which is the distance between each path line in the present machining), and the number of passes. The average roughness values obtained are also shown in Table 2.

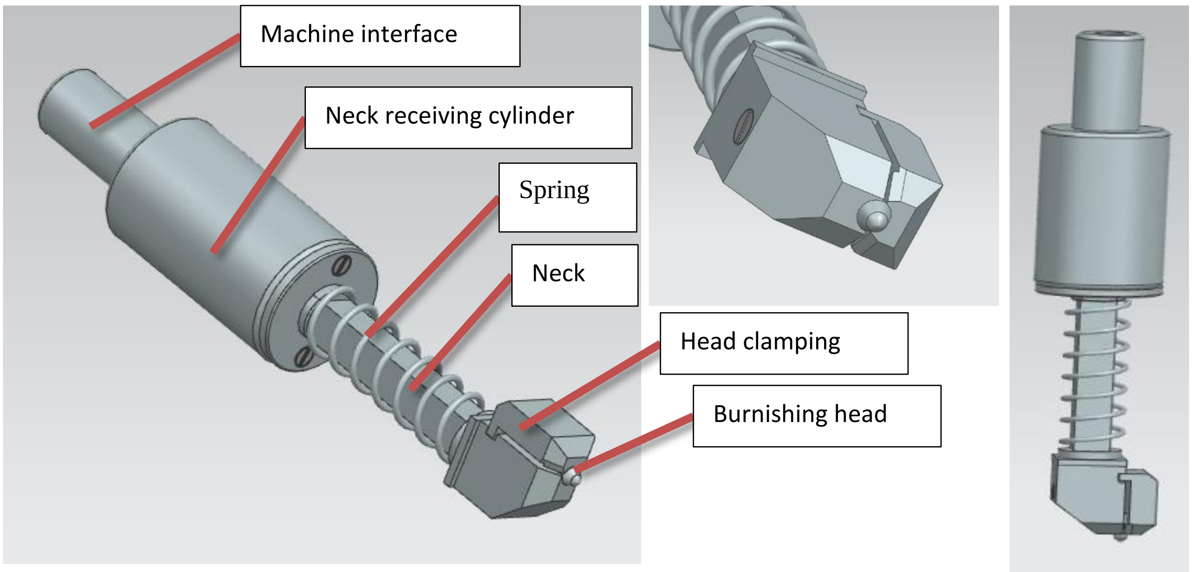

Figure 5. *CAD model of diamond sliding burnishing tool*

Table 2. *Burnishing parameters and results*

Force(N)	Feed(mm)	Pass	Ra(μm)
60	0.05	1	1.7
60	0.15	1	2.69
120	0.05	1	0.631
120	0.15	1	0.577
60	0.05	3	0.931
60	0.15	3	1.78
120	0.05	3	1.1
120	0.15	3	1.03
60	0.1	2	3.28
90	0.05	2	0.989
90	0.1	3	1.37
90	0.15	1	2.03
120	0.1	1	1.17
120	0.15	2	1.3

3. Results and discussion

When evaluating the data, it seems to be advisable to perform the analysis of the milled surfaces first, as this surface structure is modified during burnishing. The surface roughness values measured for milling are shown in Table 3. Based on the previously described experimental method, a total of 5 parts were used during the investigations, where flat burnishing was performed on 3 small surfaces on the machinable (top) surface of each part (except for the last one, which only contained two surfaces due to the experimental plan).

Table 3. *Measurement results after face milling*

Workpiece No.	Ra, µm
1	2.74
2	3.64
3	3.79
4	5.26
5	4.08

As it can be seen from the table, there was relatively a large difference between the Ra arithmetic mean roughness values measured on each surface. This difference may be due to significant depth scratches on the milled surface, indicating instability of the milling process. However, it can be a relatively typical surface for face milling, where the process instability limit can be reached relatively quickly due to dynamic effects. With properly selected burnishing parameters, the magnitude of these surface defects can be significantly reduced, even if they cannot be completely eliminated. Fig. 6 shows a typical milled surface where both pre-burnishing and post-burnishing conditions can be observed. It can be seen from Fig. 6 that diamond burnishing can smooth out the peaks and the deep valleys (shown in blue in the figure) remain almost untouched. Therefore, diamond burnishing not only has a role in converting the residual tensile stress to the compression type and in reducing roughness values, but it can also have the advantage of keeping the lubricant retention achieved in previous processes.

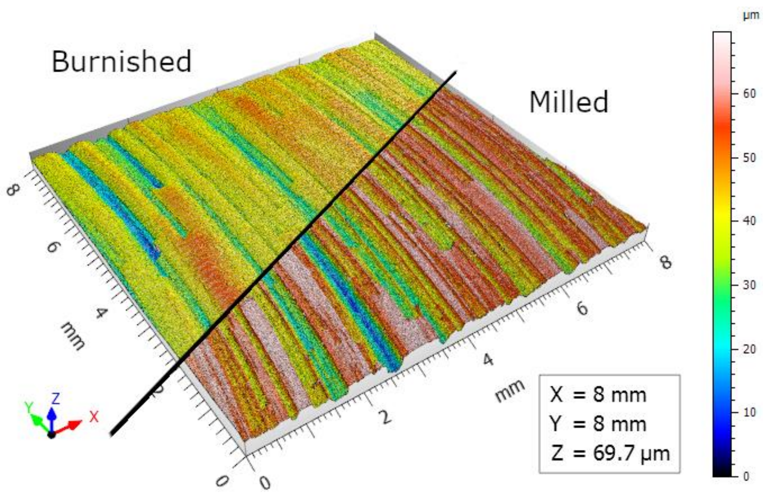

Figure 6. *Visual comparison of the burnished and milled surfaces*

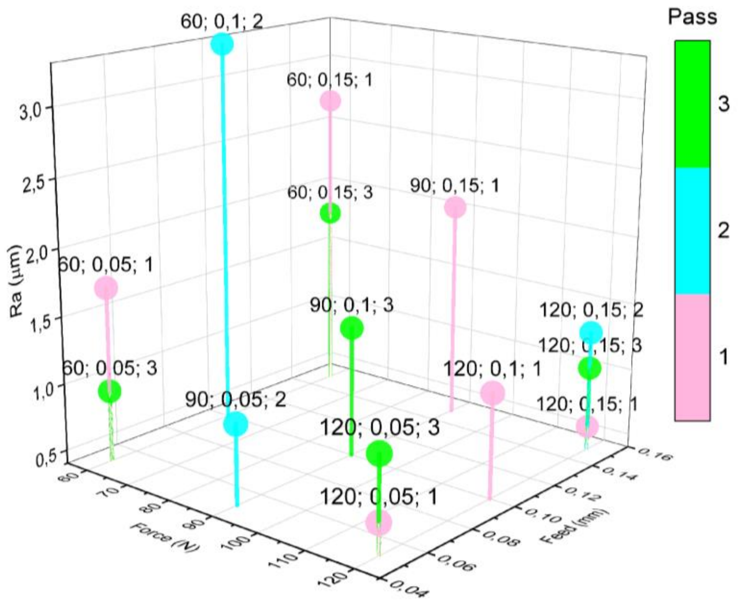

Figure 7. *Surface roughness values for different input parameters (indicated values on the graph: Force; Feed; No. of Passes)*

Fig. 7 provides a comparison of the roughness values obtained by applying each burnishing parameter. Here, the intention was to show the effect of the three variables (force, feed and number of passes) in one figure. The color shows the number of passes, the x and y axes show the force and the feed, while the vertical (z) axis (the height of the data series) shows the roughness value. It can be seen from the figure that the roughness of the burnished surfaces is most affected by the magnitude of the force: the higher the force, the finer the surface. Of course, this is only true in the studied range, it is well known that by increasing the burnishing force beyond a certain limit, the surface roughness begins to deteriorate (Korzynski, 2007), and the limit for this material is around 150 N. For feed, a smaller feed value usually means better roughness, but we can see a counterexample: for data points (120; 0.05; 1) and (120; 0.15; 1) the latter (where the feed is higher) resulted in finer roughness. Thus, the feed had only a limited effect on the available roughness, which again may be explained by the relatively coarse roughness of the milled surface, this tendency would certainly be more pronounced for finer surfaces. Concerning the number of passes, it can be stated that in the case of a lower force, it is worth going through the surface several times, however, if the burnishing force is high enough (around 120 N), multiple passes will only deteriorate the surface roughness.

4. Conclusions

In this paper, a possible method is presented for sliding diamond burnishing of flat surfaces, where the burnishing head is fixed to the milling machine using a clamping device of our design and manufacturing. In the developed method, the tool is in a stationary position, while the table of the milling machine moves in an elliptical path, thus providing the speed required for the process. The advantage of this method is that conventional burnishing tools (used on a lathe) can also be used for burnishing flat surfaces. Burnishing experiments were performed by changing the following technological parameters:

force, feed, and the number of passes. Based on these, it was found that the most favorable roughness was given by the burnishing force of 120 N, the feed of 0.15 mm, and the number of passes 1. Based on the comparison of the data, we conclude that the roughness of the burnished surfaces is mostly influenced by the force in the given case, while the effect of the other two parameters examined is not clear. To clarify this, further tests are required, where special attention should also be paid to the appropriate quality of the surfaces prepared by milling.

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