Hybrid methods of finishing wooden elements after milling: sanding, impregnation, varnishing in an automatic cycle

Leonid Dashkovskyi[1]

Received: 2025-09-03
Accepted: 2025-10-05
DOI: https://doi.org/10.5281/zenodo.17980664

Abstract. The production of modern wooden elements requires parts with much greater geometric accuracy and surface geometry (SG) precision than a few years ago. These requirements are met by so-called hybrid technologies, which must also be inexpensive to implement. The integration of processing procedures (usually in a single operation) is aimed at achieving a synergistic effect. The combination of different processes from different technologies provides synergy, i.e., advantages greater than the optimization of each individual process performed separately. This article presents experimental results and data from numerical experiments on the finishing of wooden elements. The hybrid technology used in the study was a combination of milling and finishing with lacquering. These processes were integrated on a multi-axis CNC machining center. The results show that milling across the grain produces more burrs on the wood surface than milling parallel to and against the grain. Plastic deformations of real surfaces were determined using simulations. The article also discusses the structure of the model and how it can be used for computer simulation using the finite element method (FEM). It has been proven that laser processing is more efficient than traditional manual processing. The aim of the study was to determine how to use the potentially developed hybrid processing model to predict surface characteristics expressed by amplitude, volume, and functional parameters of surface geometry.

Keywords: CNC, milling machine, woodworking, design, microcontroller, hybrid processing, surface geometry, manufacturing platforms.

[1] ORCID: https://orcid.org/0009-0009-1032-3624
Master of Rural Construction,
Owner of Brilliant Cars Inc.
e-mail: Dashkovskyileonid@gmail.com

Introduction

Modern technology for manufacturing wooden elements is becoming increasingly integrated (one machine, several tools, short production times, and reduced costs). Scientific research and industrial practice focus on combining types of processing [1-3], including turning [4], milling [5], drilling, and thread cutting, using machining centers with forming processes such as grinding [6-8]. The main goal of the new technology is to meet the requirements for smoothness and strength of wooden surfaces [9]. Optimization of the technological parameters of turning [10] or milling [11] allows for satisfactory surface geometry (with low roughness and a useful Abbott-Fairstone curve). Given the predetermined accuracy, the main problems for the technologist are the efficiency and economics of woodworking production.

In addition to the stress responsible for strength, the operational properties of the surface [12] also include a new set of additional requirements defined by designers and research and development specialists. A more common new requirement is a specified level of surface isotropy [13]. It is advantageous to prepare a surface with an isotropic geometric structure when the operating conditions have not been fully defined. An isotropic surface results in uniform wear of components during their use. Provided that the surface geometry has low roughness, an isotropic surface ensures uniform and high surface reflection in all areas, which is particularly important in modern industrial design [14]. The surface texture obtained using hybrid manufacturing methods largely depends on the kinematic-geometric conditions and technological parameters determined by the technologist. The surface of the finished product often has traces of the treatment applied to the finishing of wooden elements [15]. The processing of the remains of the last treatment creates a significant limitation for synergy in hybrid technological processes [16]. This article presents available digital manufacturing platforms for small woodworking businesses and discusses the role of DIY CNC in the development of craft design.

Literature Review

Various studies have been conducted to analyze digital manufacturing platforms for small woodworking businesses using experimental, numerical, and analytical approaches. Rodriguez et al. [17] introduced an experimental and numerical approach to investigate surface properties, hardness, and residual stresses after the shot peening process. They found that the shot peening process significantly improves surface properties and residual stress values. El-Tawil and El-Aksir [18] conducted an experimental study based on response surface methodology to analyze the effect of smoothing speed, feed rate, number of passes, and smoothing force on the surface roughness and hardness of turned parts. Dispersion analysis showed that smoothing force and feed rate had the greatest impact on surface roughness and hardness.

Abd Rahman et al. [19] conducted an experimental study using Taguchi's experimental design to determine the effect of smoothing parameters on the surface properties of AISI 1010 flat surfaces using a multi-ball tool. The results obtained from the variance analysis showed that the smoothing force had a significant effect on both hardness and surface roughness. Aviles et al. [20] investigated the effect of low-plasticity ball burnishing on the strength improvement of normalized AISI 1045 steel. Both untreated and blackened samples, polished with balls, were subjected to fatigue testing under rotary bending up to 3.25 × 106 cycles. It was shown that the strength of ball-treated samples improved by approximately 21.25% compared to untreated samples. Traveso-Rodriguez et al. [21] also integrated longitudinal vibration with a machining tool to improve the surface characteristics of G10380 steel. They analyzed the surface roughness, hardness, and residual stresses of the machined parts. The results showed that applying vibration to the machining tool significantly improved the roughness of the machined surface, but less stable results were observed in terms of sample hardness and residual stresses.

Revankar et al. [22] applied shot peening to round titanium bars. They investigated the surface roughness, hardness, wear resistance, and residual stresses of the treated wooden elements. They found that the use of shot peening significantly improves the relevant properties compared to turned samples. From the above observations, it can be seen that most of the research was based on experimental studies. However, theoretical studies are very useful for a better understanding of the mechanism of shot peening finishing of wooden elements and expanding its application. In this case, few studies have been conducted to analyze the equalizing forces or the mechanism of surface formation.

Sharizam et al. [23] conducted an analytical study to predict the equalizing force after milling wooden elements. They used Hertz's elastic contact model to determine the equalizing depth threshold for elastic deformation. In turn, they obtained the pressing depth values for elastic-plastic and plastic deformation of wooden elements. The results obtained from their analytical model were in good agreement with the experimental results. Higemann et al. [24] developed a theoretical model for predicting the surface roughness of wooden elements and the pressure on the coated surface. They also used Hertz's contact theory with appropriate simplifications to include the influence of the alignment depth in the model. The results showed that the experimental results were consistent with the analytical approach. Tengku Sulaiman et al. [25] developed an analytical model based on the theory of micromechanical slip lines to correlate the relationship between surface roughness and alignment force in hybrid finishing methods for wooden elements. The model included the mechanical parameters of the material, the grinding force, the number of surfaces roughnesses over a given length, the surface roughness angle, and the geometric parameters of the grinding process, such as the ball diameter. Using this model, it is possible to predict the surface roughness of a sample after a single grinding and polishing process.

Design Objectives and Computer Model of the Polishing Process

Four common types of wood were selected and milled separately in three different directions. The mechanism of microburr formation was analyzed under different working conditions. An experimental platform for laser ablation was then created and used to remove burrs caused by milling on the four types of wood. The ablated surfaces were observed under a scanning electron microscope (SEM). Based on the observations, the interaction between the laser and surface burrs was investigated, and laser ablation burr removal was simulated on ABAQUS. On this basis, the authors discussed how various laser parameters affect laser ablation burr removal.

To analyze changes in the structure of wooden elements obtained on CNC machines after hybrid processing, the finite element method (FEM) was used with a previously generated point cloud for the real surface (Figure 1).

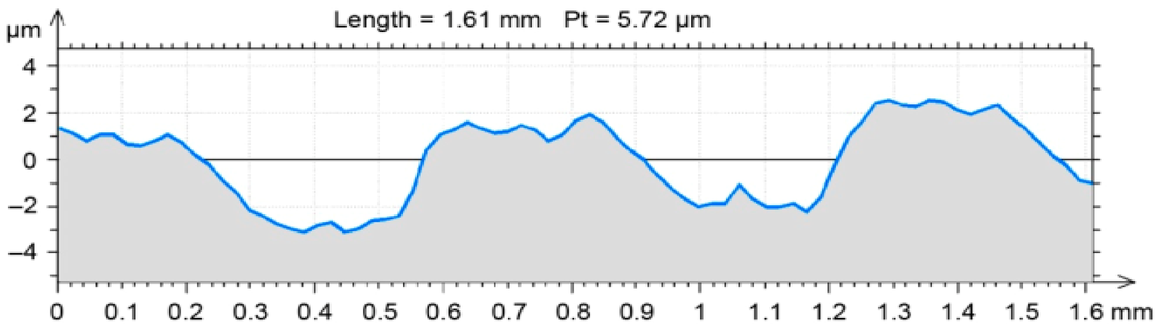


Figure 1 – Randomly selected profile used for polishing simulation.

Source: [17]

A randomly selected milled profile was set as a reference for the finite element method results (Fig. 2). After polishing, the profile was obtained in the same way as the milled surface profile. The selected parameters were determined for both profiles (Table 1).

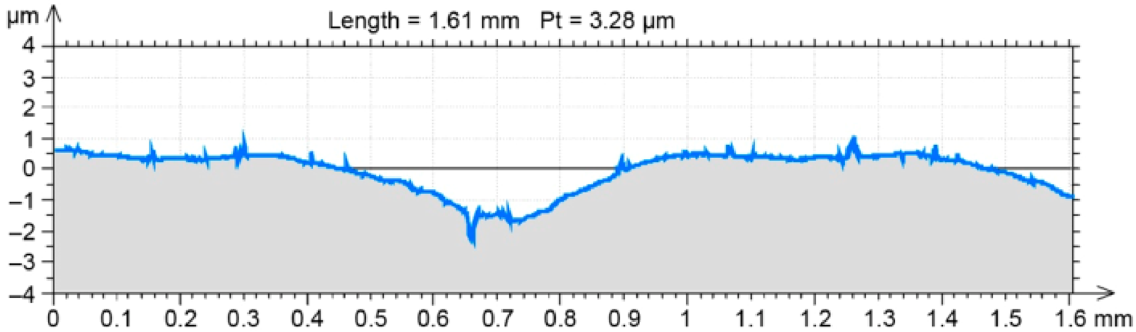


Figure 2. Randomly selected control profile obtained in experimental studies after milling.

Table 1 - Material balance parameters — roughness profile

Title	Parameter description	Context	Unit	After Milling	After Polishing parameters
Rmr	Relative material balance of roughness profile	c = 1 µm below the highest peak, Gaussian filter, 0.8 mm	%	35.90	81.50
Rdc	Difference in roughness heights of profile parts	p = 20%, q = 80%, Gaussian filter, 0.8 mm	µm	2.36	0.66

Milling with ball cutters leaves marks, with the feed per revolution and the diameter of the ball cutter being the dominant factors in roughness. Grinding smooths out the marks. Preliminary numerical simulations [18] demonstrated in a sensitivity analysis that a mesh size of less than 50 µm does not significantly affect the plastic deformation and residual stresses of milled and ground surfaces. Therefore, considering the hardware limitations of the physical model developed using Nastran FX, a mesh gap size of 20 µm was used for a single finite element.

Figure 3. Surface polishing model developed in the finite element model (FEM) environment.

Changes in roughness were observed in the selected profile of the milled surface in the physical model. The changes visible in Figure 3 are the result of changing the measuring grid (2 × 2 μm) to a FEM × 20 μm grid. The samples used in the experiments were 0.4 mm wide and 2 mm long. The simulated physical object resembled a pyramid with a cut-off top. It had a height of 10 mm, a base width of 1 mm, and a length of 25 mm (Figure 4). Nonlinearity was attributed to the sample material to account for residual stresses resulting from previous milling.

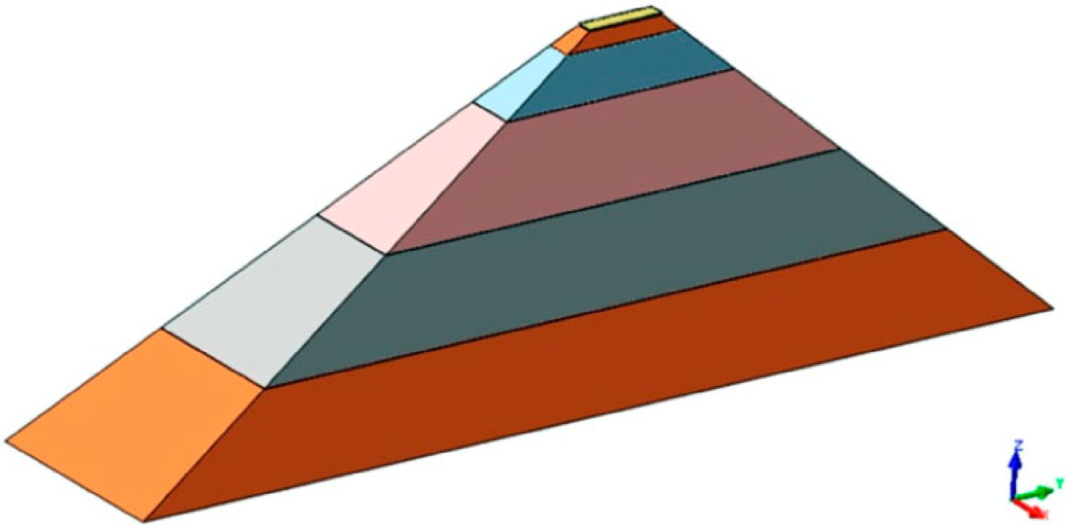


Figure 4. Sample prepared for Nastran FX modeling.

Results of Experimental Studies

The results show that milling across the grain results in more burrs on the wood surface than milling parallel to and against the grain. Due to hardware limitations and high computing power requirements in numerical studies, the selected segment of the actual milled surface was only 1.5 mm long. Therefore, only the unfiltered P-parameters of the profile were calculated in accordance with EN-ISO 4287 (Figure 5). The value of the Pa parameter can be easily interpreted by analogy with the Ra parameter (arithmetic mean deviation of the unfiltered profile).

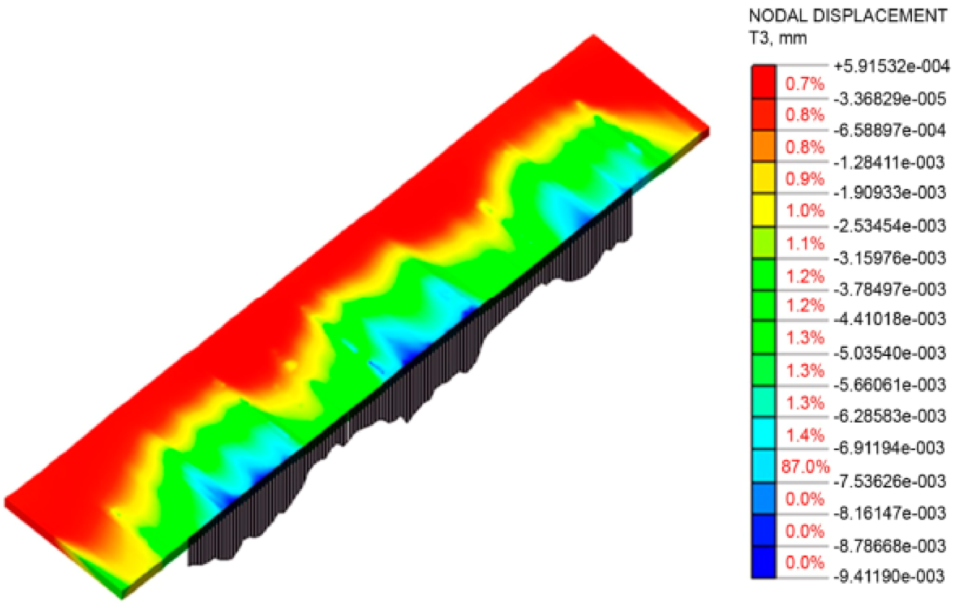


Figure 5. Plastic deformation of the sample after one pass of the polishing tool with a force of 500 N.

Source: [24]

The greatest deformations were observed near the “sharp” peaks. Deformations of the peaks caused by the force acting on the CNC machine tool in the normal and tangential directions to the surface led to uniform filling of the gaps across the entire area. In this particular case, polishing the surface peaks led to plastic “filling” of the profile. The trend observed in the numerical study was also confirmed in the experiment (Figure 6).

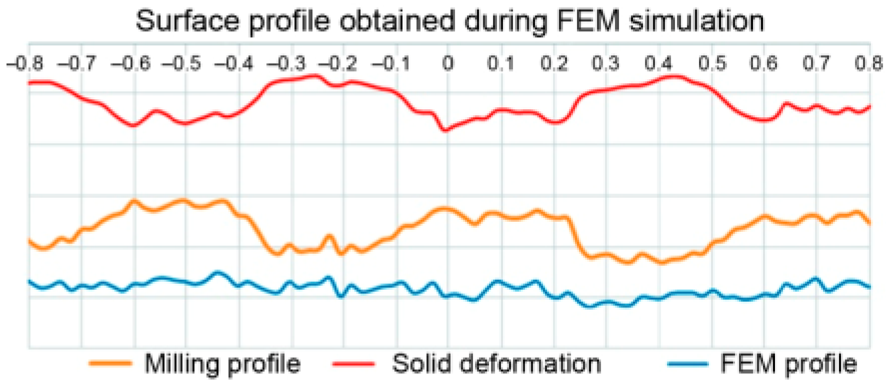
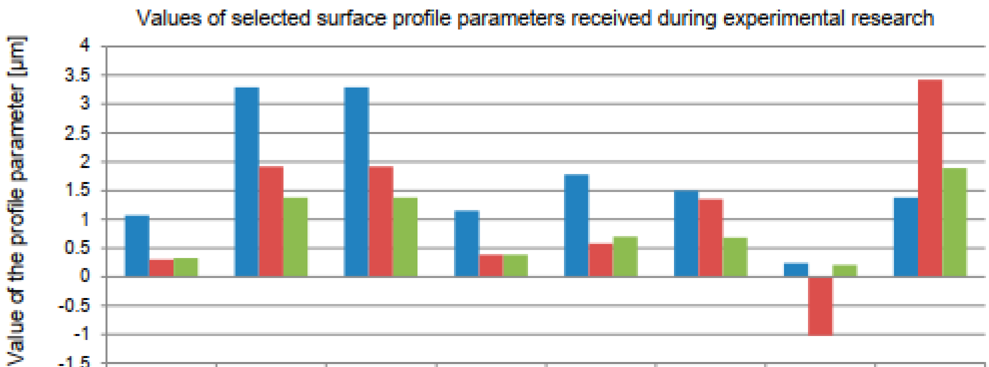


Figure 6. The graphs show the surface profile after milling, the permanent deformation in the tested profile, and the final profile after grinding with a force of 500 N.

Small differences (less than 10%) between experimental and numerical results were observed only for the parameters most commonly used in engineering: Pa and Pq (Figure 7). Similarly, a small difference was observed in the filtered profile for the roughness parameter Ra. The values of the 2D SG parameters depended on all points in the set formed by the profile, the variability of which was constant (for Pa) or root mean square (for Pq) relative to the defined arithmetic mean value.



	Ra [μm]	Rt [μm]	Rz [μm]	Rq [μm]	Rp [μm]	Rv [μm]	Rsk [-]	Rku [-]
Milling surface	1.07	3.29	3.29	1.15	1.78	1.50	0.237	1.38
Experimental surface	0.303	1.92	1.92	0.384	0.579	1.35	-1.02	3.42
Numerical experiment	0.328	1.38	1.38	0.385	0.701	0.682	0.207	1.89

Figure 7. Changes in the parameters of a two-dimensional layered material (2D SG) in the roughness profile (profile filtered in accordance with EN-ISO 4287).

Source: [25]

The degree of agreement between the experimental model and the experimental results for the unfiltered parameters of the Pt and Pz profile amplitudes was poorer. In this case, the coordinates of individual points were decisive in terms of their values. The extreme displacement of individual points on the surface decreased with an increase in the size of the FEM grid gap (decrease in the resolution of the FEM model). Similarly, significant differences were observed for the 2D SG parameters that determined the distribution of the profile ordinates, including Psk asymmetry and Pku excess. The observed asymmetry of the distribution of unfiltered profile points and the concentration of points around the mean value were greater in the experimental study. This was due to the very high resolution of the profilometer used in the study. The observed direction of changes in surface character after the use of hybrid technology was consistent.

Conclusions

The developed finite element model (FEM) allowed us to satisfactorily determine the parameters Rmr and Rdc of the core ratio of the material. Values based on the distribution of profile ordinates given by the Abbott-Fairstone curve are often used by technologists to determine the required tribological properties of a product surface.

To determine the parameters of the material core, the extreme points at the peaks and troughs of the profile are discarded. Based on a comparison of numerical research data and empirical experimental data, the following conclusions can be drawn. Due to hardware and software limitations, only one grinding pass was simulated in the initial study. That is why the results of residual surface deformation obtained in the numerical experiment and the experimental study differed slightly. The origin of the observed differences lay in the spread of residual deformation and stress beyond the zone of direct contact between the workpiece and the grinding tool. In practical terms, this means that each subsequent grinding pass took place on a surface that had already been ground.

References:

1. He, D.; Wang, B.; Zhang, J.; Liao, S.; Deng, W.J. Investigation of interference effects on the burnishing process. Int. J. Adv. Manuf. Technol. 2018, 95, 1–10.

2. Bounouara, A.; Hamadache, H.; Amirat, A. Investigation on the effect of ball burnishing on fracture toughness in spiral API X70 pipeline steel. Int. J. Adv. Manuf. Technol. 2018, 94, 4543–4551.

3. Kaczy´nski, P.; Ptak, M.; Fernandes, F.A.O.; Chybowski, L.; Wilhelm, J.; Alves de Sousa, R.J. Development and Testing of Advanced Cork Composite Sandwiches for Energy-Absorbing Structures. Materials 2019, 12, 697.

4. Ratajczak, M.; Ptak, M.; Chybowski, L.; Gawdzi´nska, K.; Bedzi´nski, R. Material and Structural Modeling Aspects of Brain Tissue Deformation under Dynamic Loads. Materials 2019, 12, 271.

5. Nozdrzykowski, K.; Grz ˛adziel, Z.; Dunaj, P. Determining geometrical deviations of crankshafts with limited detection possibilities due to support conditions. Measurement 2022, 189, 110430.

6. Kumar, S.S.A.; Ma, I.A.W.; Ramesh, K.; Ramesh, S. The synergistic effects of graphene on the physical, hydrophobic, surface, and thermal properties of acrylic-epoxy-polydimethylsiloxane composite coatings. Int. J. Adhes. Adhes. 2024, 128, 103546.

7. Sługocka, M.; Grochała, D.; Kwiatkowski, K.; Grzejda, R.; Zmarzły, P. Study of the impact of surface topography on selected mechanical properties of adhesive joints. Coatings 2024, 14, 944.

8. Grochała, D.; Jasiewicz, M.; Filipowicz, K.; Parus, A.; Powałka, B.; Grzejda, R.; Zmarzły, P. Assessment of the functional properties of the surfaces of ductile cast iron parts. Appl. Sci. 2024, 14, 9129.

9. Ouyang, W.; Zhang, L.; Wu, H.; Wu, D.; Zhang, S.; Qin, X.; Jiang, S.; Li, S.; Zhang, W.; Sheng, L. Optimized mechanical properties of the hot forged Ti–6Al–4V alloy by regulating multiscale microstructure via laser shock peening. Int. J. Mach. Tools Manuf. 2024, 201, 104192.

10. He, B.; Zheng, H.; Ding, S.; Yang, R.; Shi, Z. A review of digital filtering in evaluation of surface roughness. Metrol. Meas. Syst. 2021, 28, 217–253.

11. Pérez-Ruiz, J.D.; Marin, F.; Martínez, S.; Lamikiz, A.; Urbikain, G.; de Lacalle, L.N.L. Stiffening near-net-shape functional parts of Inconel 718 LPBF considering material anisotropy and subsequent machining issues. Mech. Syst. Signal Process. 2022, 168, 108675.

12. Zmarzły, P. Influence of bearing raceway surface topography on the level of generated vibration as an example of operational heredity. Indian J. Eng. Mater. Sci. 2020, 27, 356–364.

13. Daffara, C.; Mazzocato, S.; Marchioro, G. Multiscale roughness analysis by microprofilometry based on conoscopic holography: A new tool for treatment monitoring in highly reflective metal artworks. Eur. Phys. J. Plus 2022, 137, 430.

14. Li, Z.; Gröger, S. Investigation of noise in surface topography measurement using structured illumination microscopy. Metrol. Meas. Syst. 2021, 28, 767–779.

15. Qi, B.; Chai, Z.; Huang, X.; Guo, W.; Ren, X.; Chen, H.; Chen, X. Surface integrity improvement of the ground surface of Inconel 718 fabricated by forging and additive manufacturing using a robotic rotational burnishing method. J. Manuf. Process. 2024, 125, 566–579

16. Abd Rahman, Z., Mohamed, S.B., Kasim, M.S., Ariffin, M. K. A. & Zulkifli, AR (2021). The Development of Methodology for Tool Path Generation Using STEP Data Model Based on ISO 6983, International Journal of Engineering Trends and Technology. 69(6) 144-153.

17. Rodríguez, A.; López de Lacalle, L.N.; Celaya, A.; Lamikiz, A.; Albizuri, J. Surface improvement of shafts by the deep ballburnishing technique. Surf. Coat. Technol. 2012, 206, 2817–2824.

18. El-Taweel, T.A.; El-Axir, M.H. Analysis and optimization of the ball burnishing process through the Taguchi technique. Int. J. Adv. Manuf. Technol. 2009, 41, 301–310

19. Abd Rahman, Z., Mohamed, S.B., Kasim, M.S., Ariffin, M. K. A. & Zulkifli, AR (2021). The Development of Methodology for Tool Path Generation Using STEP Data Model Based on ISO 6983, International Journal of Engineering Trends and Technology. 69(6) 144-153.

20. Avilés, R.; Albizuri, J.; Rodríguez, A.; López de Lacalle, L.N. Influence of low-plasticity ball burnishing on the high-cycle fatigue strength of medium carbon AISI 1045 steel. Int. J. Fatigue 2013, 55, 230–244.

21. Travieso-Rodriguez, J.A.; Gómez Gras, G.; Jorba Peiró, J.; Carrillo, F.; Dessein, G.; Alexis, J.; González Rojas, H. Experimental study on the mechanical effects of the vibration-assisted ball-burnishing process. Mater. Manuf. Process. 2015, 30, 1490–1497.

22. Revankar, G.D.; Shetty, R.; Rao, S.S.; Gaitonde, V.N. Wear resistance enhancement of titanium alloy (Ti–6Al–4V) by ball burnishing process. J. Mater. Res. Technol. 2017, 6, 13–32.

23. Md Sharizam, M. A. R., Mohamed, S. B., Sulaiman, T. M. S. T., Abd Rahman, Z., & Awang, R. (2020). Development of the PC-based Integrated Interface System of STEP file for CNC Machining Application: Circular Features, International Journal of Integrated Engineering. 12(7) 195-203.

24. Hiegemann, L.; Weddeling, C.; Khalifa, N.B.; Tekkaya, A.E. Prediction of roughness after ball burnishing of thermally coated surfaces. J. Mater. Process. Technol. 2015, 217, 193–201.

25. Tengku Sulaiman, T. M. S., Mohamed, S. B., Minhat, M., Mohamed, A. S., Mohamed, A. R., & Yusof, S. N. A. (2020). File and PC-Based CNC Controller using Integrated Interface System (I2S), Journal of Advanced Research in Applied Mechanics, 70(1) 1–8.