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Comparative evaluation of roller burnishing of Al6061-T6 alloy under dry and nanofluid minimum quantity lubrication conditions

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ABSTRACT

Introduction. Roller burnishing is one of the most popular methods for improving the surface quality of a workpiece, increasing its wear resistance, microhardness and corrosion resistance. During the processing, the workpiece is compressed and smoothed under the pressure of hardened roller. **Purpose of the work.** The results of the research show that the introduction of minimum quantity lubrication (*MQL*) during roller burnishing makes it possible to increase the efficiency of the process by reducing friction and improving lubrication. Studies have shown that the use of nanofluids under *MQL* conditions improves the machining performance. However, very little attention has been paid to the roll burnishing of *Al6061-T6* alloy under nano minimum quantity lubrication (*NFMQL*) conditions. **The methods of investigation.** In light of this, this study compares the performance of roll burnishing of *Al6061-T6* alloy under dry friction conditions and *NFMQL* conditions. The microhardness, roundness, and surface roughness are evaluated, modeled, and optimized in the study by considering the cutting speed, feed rate, and number of passes. Based on the experimental results, mathematical models are established to predict the surface roughness, microhardness, and roundness deviation. **Results and Discussion.** The developed models of surface roughness, microhardness and roundness deviation show the *R*-square value higher than 0.9, which allows these models to be confidently used to predict the studied responses under dry friction conditions and under *NFMQL* conditions within the parameter domain selected in this work. According to this study, the machining performed in four passes at a cutting speed of 357 rpm and a tool feed of 0.17 mm/rev can obtain the lowest roundness deviation (3.514 μm), the best microhardness (130.19 HV) and the lowest surface roughness (0.64 μm). Further, the study shows that increasing the number of passes (more than four) does not lead to a significant improvement in surface roughness or microhardness. However, it leads to a slight increase in roundness deviation. Therefore, it is recommended to use a maximum of four passes during roll burnishing of *Al6061-T6* aluminum alloy specimens under dry friction conditions to achieve optimal results. The obtained results imply that roller burnishing can effectively improve the overall surface quality and hardness of the workpiece. In addition, roller burnishing is regarded as an affordable method to enhance the functionality and strength of the machined parts by reducing the occurrence of surface defects such as scratches and cracks. It is found that the surface roughness decreases with the increase of the cutting speed. However, it is observed to increase under both dry friction and *NFMQL* conditions when the cutting speed is increased to 360–380 rpm. Moreover, it is found to decrease with the increase of the feed and the number of passes. But after three or four passes at a feed rate of 0.2–0.25 mm/rev, a noticeable increase in the surface roughness is observed. It is noticed that with the increase of the feed, the microhardness and the roundness deviation increase. In addition, as the number of passes increases, the roundness deviation decreases and the microhardness increases. The number of passes under dry friction condition and feed rate under *NFMQL* rolling has significant effects on the surface roughness. The cutting speed seems to have the greatest effect on the microhardness, followed by feed rate and the number of passes. On the other hand, the effect of increasing microhardness under *NFMQL* conditions seems to be stronger. Under dry friction condition, the cutting speed has a significant effect on the roundness deviation, and under *NFMQL* conditions, the feed rate has an effect.

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Introduction

The search for new processing methods that can achieve high surface quality and improve mechanical properties is currently of great interest. One such method is roller burnishing. It is aimed at improving the surface quality and dimensional accuracy of various metals. This process uses a hard roller to smooth out surface irregularities, resulting in a shiny finish. It can also make the material harder at the micro level [1]. Many industries use aluminum alloy *6061-T6* (*Al 6061-T6*) because it is strong yet lightweight, easy to work with, and does not rust. But getting the best surface quality and mechanical properties from *Al 6061-T6* can be challenging using old-school finishing methods. Roller burnishing has shown promise in addressing these issues. It can smooth out rough surfaces and improve dimensional accuracy [2].

Minimum quantity lubrication (*MQL*) is a lubrication method in which a small amount of lubricant is applied directly to the cutting zone. This method reduces friction, extends tool life, and produces a smoother surface. All this is achieved without the environmental and financial problems that come with using large quantities of lubricant. Recent studies have shown good results when combining *MQL* with various machining processes, including turning and milling [3–6]. *Kurkute* and *Chavan* [7] optimized surface roughness and microhardness during roller burnishing of *Al63400* alloy. In their study, feed was considered as a significant parameter affecting surface roughness. *Patel* and *Brahmbhatt* [8] found that spindle speed and burnishing depth were the most important parameters for improving microhardness by 28 % compared to pre-machined surfaces.

A group of researchers performed roller burnishing by varying the process parameters such as feed, depth of cut, cutting speed, and number of passes. Most of the studies designed the experiments using the central composite design of response surface methodology. Some studies considered the cutting speed as the dominant parameter affecting the surface roughness, and some studies found that the feed significantly affected the surface roughness. Some studies reported that the depth of cut significantly affected the surface roughness, and the cutting speed and number of passes significantly affected the microhardness. Some studies reported the interaction effect of burnishing force and number of passes on the surface roughness. The cutting speed, feed, and number of passes significantly affected the surface roughness and microhardness. However, it can be noted that the significance of process parameters affecting the process response can be assessed as varying depending on the process parameters, the workpiece material and the cooling conditions.

Prasad and *John* [9] studied the roller burnishing process on *Mg-SiC* composite material. In their study, experiments were conducted by varying the cutting speed, feed, force, and number of passes. The authors observed a decrease in surface roughness at a speed of 171 rpm, a feed of 0.18 mm/rev, a force of 21 N, and three passes. The group of researchers observed changes in the surface and metallurgical textures due to the development of high contact stresses and an increase in plastic deformation of the surface layer of the component during roller burnishing [10]. The study showed an improvement in surface finish at lower burnishing speed and higher depth of penetration [11].

Okada et al. [12] analyzed the performance of roller burnishing under minimum quantity lubrication. In their study, an increase in workpiece hardness by 126–323 HV was observed. A group of researchers performed roller burnishing using different cooling methods such as cryogenic burnishing and using kerosene as a coolant. The group observed an increase in surface hardness and the surface finish when burnishing under *MQL* conditions and using kerosene as a cutting fluid [13–15]. The group evaluated the surface integrity by varying parameters such as speed, feed, number of passes, and cooling conditions, namely flood cooling, *MQL*, cryogenic cooling, and hybrid cooling. The results showed that the use of cryogenic cooling increased the strength of the material, while the use of hybrid coolant decreased the surface roughness. It was noted that microhardness depends to a small extent on the type of cooling conditions.

From the reviewed literature, it is evident that the roller burnishing process is effective in improving the overall surface quality and hardness of the workpiece. In addition, roller burnishing is considered as an affordable method to improve the functionality and reliability of the machined parts by reducing the occurrence of surface defects such as scratches and cracks. Studies have shown that the use of *MQL* in roller burnishing provides the opportunity to further improve the process by improving lubrication and reducing friction. Over the past decade, studies have shown higher machining performance using nanofluids under *MQL* conditions [16–19]. However, very few attempts have been made to process *Al6061-T6* alloy by roller burnishing using nanofluid under *NFMQL* process conditions.

From this point of view, this study comparatively evaluates the roller burnishing of *Al6061-T6* alloy in dry and nanofluid conditions under *MQL* cutting condition. The study evaluated, simulated and optimized the microhardness, roundness and surface roughness by considering the factors such as cutting speed, feed and number of passes. Mathematical models for predicting the surface roughness, microhardness and roundness error were developed based on the experimental results. The chemical composition of the material, conditions of the forming process and details of the roller burnishing tool are presented in the next section. The third section discusses the development of experimental-based mathematical models for predicting the surface roughness, microhardness and roundness of burnished workpiece under both cooling conditions. In the fourth section, the parametric effects of roller burnishing on the responses namely surface roughness, microhardness and roundness of roller burnished workpiece under both cooling conditions are comparatively discussed. Then, the optimized process parameters for minimum surface roughness and better microhardness and surface roundness for both cooling conditions are presented. Finally, the important results of the present study and the scope for future research in this area are presented.

Materials and Design

This study uses aluminum alloy *6061* (*Al6061-T6*), which is often used for general purposes. Due to its strength-to-weight ratio, corrosion resistance, and weldability, this alloy is popular in manufacturing processes and is suitable for various structural components. It is a precipitation-hardening aluminum alloy. The two most important components are silicon and magnesium. Weldability is the main advantage of aluminum alloy *6061*. The aerospace industry often uses aluminum alloy *6061* due to its exceptional strength and light weight. Due to its composition, it can also be used for automotive and marine parts. The selected specimen has a diameter of 30 mm and a length of 50 mm across all surfaces. Table 1 shows the characteristics and chemical composition of aluminum alloy *6061*.

Table 1

Chemical composition of *Al6061-T6* alloy

Element	*Al*	*Cu*	*Cr*	*Mg*	*Mn*	*Si*	*Zn*	*Fe*	*Ti*
Percentage	95.8	0.15	0.2	1.1	0.15	0.75	0.25	0.19	0.15

A single-roller burnishing tool with a carbide roller was used in this study. The carbide roller burnishing tool is versatile and can be used on a variety of machines for different applications. Its ability to restore and extend the tool life makes it a cost-effective solution for achieving high-quality surface finishes. The carbide roller is spring-loaded in both axial directions to maintain proper pressure throughout the burnishing process. By regrinding or lapping the worn carbide roller, it can be restored and its service life can be extended. The carbide roller tool can be used on *CNC* lathes, turret lathes or conventional lathes and is suitable for all external surfaces of shafts, tapered shafts, radii, shoulders, etc. Burnishing of the machined surface is possible up to 0.1–0.2 µm. Fig. 1 shows the burnishing tool used in this study.

Fig. 1. Roller burnishing tool used in the present study

A constant burnishing depth of 0.5 mm was maintained while varying the feed, cutting speed and the number of passes in the experiments without coolant and with nanofluid as coolant under *MQL* conditions. Alumina nanoparticles (Al_2O_3) were combined with a vegetable-based sunflower oil base fluid to create the nanofluid. Surface roughness, microhardness and roundness error, three main characteristics that contribute to the impact of stability performance, were studied using the design of experiments (*DOE*) method. All responses were analyzed and empirical models were developed using the central composite design (*CCD*). The experiments were designed using the central composite rotatable design (*CCRD*) test matrix, which has an alpha value of 1.6817. Five levels were used to vary each numerical parameter: center point, plus and minus 1 (factorial points) and plus and minus alpha (axial points). In this work, twenty roller burnishing tests were conducted under *NFMQL* and dry conditions with different process parameters to construct models of surface roughness, microhardness and roundness error. Table 2 lists the coded levels along with the corresponding actual cutting parameter values.

Table 2

Coded levels and corresponding actual cutting parameters

Parameters	Levels for alpha value				
	−1.6817	−1	0	+1	+1.6817
Cutting speed (*V*) (rpm)	100	200	300	400	500
Feed (*f*) (mm/rev)	0.1	0.15	0.2	0.25	0.3
Number of passes (*N*)	0.5	1	1.5	2	2.5

Taylor Hobson Talysurf, *Surtronic Duo* and an off-line surface roughness measuring device were used to determine the average values of surface roughness. The surface roughness was measured at three equally spaced points around the perimeter of the workpiece to obtain a statistically significant value. The surface quality assessment was performed accurately and consistently using this approach. A bridge type *CMM* (Manufacturer: *Zeiss*, Model: *Contura*, Range: 1,200×800×800 mm) was used to test the roundness. Geometrical errors were determined by measuring the roundness in twelve parts of a calibrated area using a millesimal dial indicator having a measuring range of 12.5 mm, a scale division value of 0.001 mm and a maximum permissible error (*MPE*) of 4 µm. Additionally, a *Vickers* microhardness tester was used to evaluate the microhardness using a 136° diamond indenter at 100 grams and a 20-second dwell time. Using surface roughness, microhardness tests and roundness measures together allowed a thorough examination of the workpiece properties.

Results and Discussion

In this section, the impact of roller burnishing process parameters on the process responses under dry and *NFMQL* cutting conditions is discussed based on the established regression equations. The curves showing the different responses are plotted by varying one of the input parameters while keeping the other parameters constant in order to understand the physics of the process and the interaction effects of the cutting parameters on the different responses. It also gives the contribution of the cutting parameters to the different responses. Finally, the optimization of the process responses in roller burnishing of *Al6061-T6* alloy is considered using the desirability function method.

The cutting speed, feed and number of passes (input parameters) were varied during the experiments. Table 3 shows the experimental matrix and the results of the largest roundness error (roundness error), microhardness and surface roughness in roller burnishing of *Al6061-T6* alloy under dry and *NFMQL* cutting

Table 3

Roller burnishing experimental matrix with responses

Cutting speed (V) (rpm)	Feed (f) (mm/rev)	No. of passes	Surface roughness (Ra) (μm)		Microhardness (HV)		Roundness error (Re) (μm)	
			Dry	*NFMQL*	Dry	*NFMQL*	Dry	*NFMQL*
300	0.2	3	0.81	0.62	117	128	7.7	4.8
200	0.15	2	0.82	0.68	114	120	9.6	5.6
200	0.15	4	0.89	0.69	116	118	8.6	4.8
200	0.25	2	0.92	0.77	116	122	5.4	8.8
200	0.25	4	0.9	0.78	125	131	8.7	7.7
400	0.15	2	0.94	0.78	118	129	10.1	3.4
400	0.15	4	0.84	0.71	111	131	1.6	3.2
400	0.25	2	0.97	0.81	110	126	8.4	9.2
400	0.25	4	0.79	0.75	113	136	2.9	7.4
300	0.2	3	0.81	0.61	117	128	8.4	5.5
300	0.2	3	0.81	0.61	117	128	8.6	5.7
100	0.2	3	0.92	0.72	112	108	13.2	9
500	0.2	3	0.93	0.75	104	131	4.2	6.1
300	0.1	3	0.94	0.70	123	121	1.5	2.8
300	0.3	3	0.96	0.79	124	132	2	9.2
300	0.2	1	0.95	0.83	123	119	8.7	7.7
300	0.2	5	0.86	0.73	125	133	4	3.6
300	0.2	3	0.83	0.65	117	125	6.9	5.2
300	0.2	3	0.82	0.61	113	128	8.3	5.4
300	0.2	3	0.81	0.62	118	131	8.7	5.9

conditions. The experimental results of roller burnishing of *Al6061-T6* alloy under dry cutting conditions are given in [20].

Response Surface Methodology (*RSM*) was the main method used to analyze the experimental results. Finding the region of interest where the response(s) reach its optimal or near-optimal value was another goal of using *RSM* in addition to investigating the response(s) in the entire factor space. In order to understand the physics of the process, an analysis of the experimental data was performed to create regression equations for surface roughness (Ra), microhardness (HV), and roundness error (Re). Using *Stat-Ease Design Expert*® (version 7.0), the regression approach was used to determine the values of the coefficients in the equation.

The equations developed for the responses in terms of actual values of surface roughness, microhardness and roundness error under dry conditions can be found in [20], and the equations for determining the responses when using nanofluid under *MQL* conditions are given below:

$$Ra = 1.4209 - 0.00064V - 4.0943f - 0.2224N - 0.00275Vf - 0.00019VN + 0.025fN + \\ + 3.11 \times 10^{-6}V^2 + 13.4545f^2 + 20.042N^2 \quad (1)$$

$$HV = 85.3181 + 0.213V + 40.1136f - 6.3238N - 0.325Vf + 0.00625VN + 47.5fN - \\ - 0.0002V^2 - 90.91f^2 - 0.3522N^2 \quad (2)$$

$$Re = 13.142 - 0.058V - 3.78f - 0.18N + 0.0975Vf - 1.3\times10^{-4}VN - 4.75fN + 5.43\times10^{-5}V^2 + 62.27f^2 + 0.0682N^2 \quad (3)$$

Using the analysis of variance (*ANOVA*) method, the adequacy of the resulting equations was verified. The data point variation proportion is measured by the coefficient of multiple determinations, or ***R**-squared*. A correlation coefficient (***R***-squared) that is between −1 and +1 is always ideal. If ***R*** is really close to +1, the equation is important. A measure of how much of the variance around the mean is explained by a model is called *adjusted **R**-squared*. A measure of the predictive accuracy of the model for the response value is the *predicted **R**-squared*. It is considered *reasonable agreement* when the *adjusted* and *predicted **R**-squared* values are within around 0.20 of each other. Otherwise, there may be a problem with the model or the data. The signal-to-noise ratio, or the range in the expected response relative to the corresponding error, is what is called *adequate precision*. Four or more is ideal value.

The *ANOVA* for surface roughness, microhardness and roundness error during roller burnishing under dry condition can be referred to [20], and that under *NFMQL* cutting condition is given in Table 4. The *ANOVA* for the investigated responses under dry condition is also mentioned in Table 4 for comparative evaluation. The *ANOVA* results for surface roughness under dry condition and *NFMQL* condition show model ***F***-values of 46.91 and 19.51, respectively, which means that the models are significant. The "*Prob > **F***" values less than 0.05 indicate that the model terms are significant. The significant model terms observed for surface roughness under dry cutting conditions are $V\times f$, $V\times N$, $f\times N$, V^2, f^2, N^2, and for *NFMQL* the significant model terms are V, f, N, $V\times N$, V^2, f^2, N^2.

Table 4

***ANOVA* for investigated responses under dry [20] and *NFMQL* cutting conditions**

Factors	Surface roughness (*Ra*) (μm)		Microhardness (*HV*)		Roundness error (*Re*) (μm)	
	Dry	*NFMQL*	Dry	*NFMQL*	Dry	*NFMQL*
R-squared	0.9769	0.9461	0.9152	0.9377	0.9407	0.9609
Adj. ***R***-Squared	0.956	0.89765	0.8389	0.8816	0.8873	0.9258
Pred. ***R***-Squared	0.8472	0.848529	0.855	0.8389	0.8933	0.7421
Adeq. Precision	19.328	12.74978	15.464	16.5655	16.002	18.2847
Model ***F***-value	46.91	19.51	11.99	16.71	17.62	27.35

The *ANOVA* results for microhardness show that the model ***F***-values are 11.99 and 16.71 for dry and *NFMQL* conditions, which means that the models are significant. There is only a 0.03 % chance that such a large "model ***F***-value" may be due to noise. In this case, V, $V\times f$, $V\times N$, $f\times N$, V^2, f^2, N^2 for dry conditions and V, f, N, $V\times f$, $f\times N$, V^2 for *NFMQL* conditions are significant model terms. And the *ANOVA* results for roundness show that the model ***F***-values are 17.62 and 27.35 for dry and *NFMQL* conditions, which means that the models are significant. In this case, V, N, $V\times N$, $f\times N$, f^2 for dry conditions and V, f, N, $V\times f$, V^2 for *NFMQL* conditions are significant model terms.

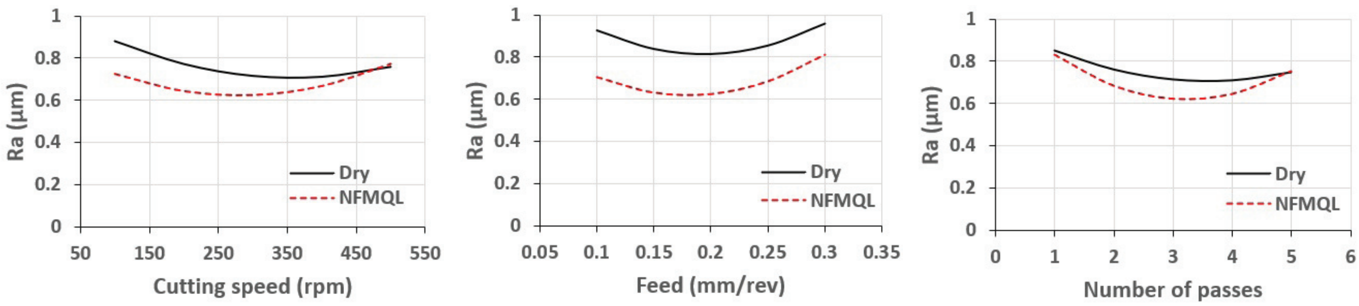
Each model created for dry and *NFMQL* cutting conditions has an ***R***-squared value above 0.9, indicating the proportion of variation in the data points. Therefore, during the roller burnishing of *Al6061-T6* alloy, the microhardness, surface roughness and roundness error can be accurately predicted by the established empirical equations.

To improve understanding, two-dimensional graphs are created for *NFMQL* cutting settings by adjusting the feed, speed, and number of passes using the derived equations 1–3. In order to facilitate comparison and better understanding, curves are also plotted for the studied responses under dry conditions using the models derived in [20]. Plotting the curves for surface roughness, microhardness, and roundness error involves changing one input parameter while maintaining the other two constant.

Using a feed value of 0.2 mm/rev and three passes, the variation in surface roughness with cutting speed is shown in Fig. 2, *a*. Fig. 2, *b* shows the dependence of surface roughness on feed at a cutting speed of 300 rpm and three passes. And Fig. 2, *c* shows the dependence of surface roughness on the number of passes at a cutting speed of 300 rpm and a feed of 0.2 mm/rev. Comparing the *NFMQL* cutting condition with the dry cutting condition, lower levels of surface roughness are observed. It can also be observed that as the cutting speed increases to 360–380 rpm, the surface roughness decreases before increasing. In addition, it decreases with the increase of feed and the number of passes. However, an increase in surface roughness can be seen beyond feeds of 0.2–0.25 mm/rev and 3–4 passes.

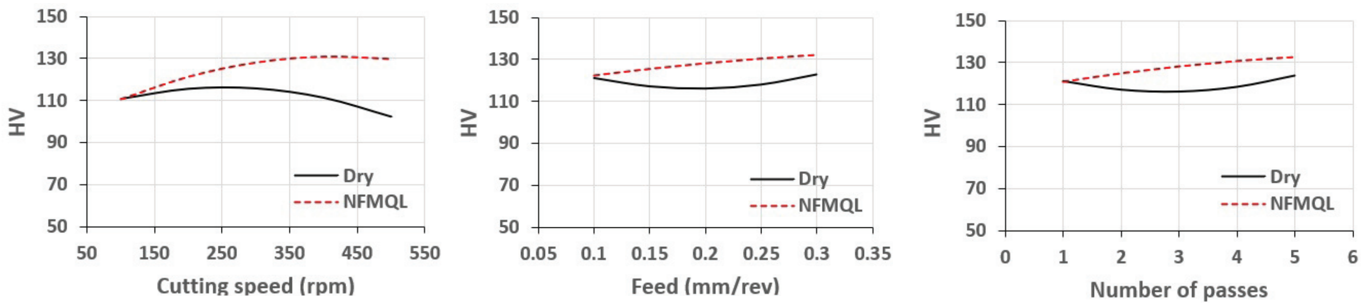
From Fig. 2, *b*, it can be seen that the optimum responses with varying feed can be obtained. The minimum surface roughness and roundness error can be obtained by using the feed values in the range of 0.18–0.22 mm/rev and the cutting speed and number of passes of 250–350 rpm and three, respectively. Fig. 3, *a* and Fig. 4, *a* depict the variation of microhardness and roundness error, respectively, depending on the cutting speed, obtained at a constant feed of 0.2 mm/rev and three passes. It can be seen that the microhardness increases with the cutting speed. However, this effect was more prominent for the *NFMQL* cutting condition. Higher microhardness values can be seen for the *NFMQL* cutting condition. It can be seen that the microhardness decreases beyond the cutting speed of 280–300 rpm. On the other hand, it can be seen that the roundness error decreases with the increase of the cutting speed (Fig. 4, *a*). However, it can be seen that it increases beyond the cutting speed of 300–350 m/min. The lower roundness error values can be seen when roller burnishing under *NFMQL* cutting conditions.

Fig. 3, *b* and Fig. 4, *b* show the variation of microhardness and roundness error, respectively, depending on the feed, plotted using the cutting speed value of 300 rpm and three passes. Fig. 3, *c* and Fig. 4, *c* show the variation of microhardness and roundness error, respectively, depending on the number of passes, plotted using the cutting speed value of 300 rpm and the feed of 0.2 mm/rev.



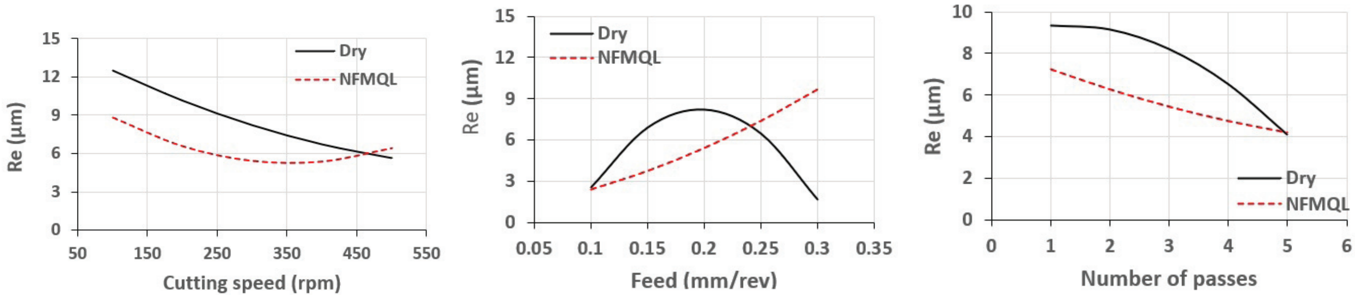
a *b* *c*

Fig. 2. Surface roughness varying with *a)* cutting speed, *b)* feed, and *c)* number of passes



a *b* *c*

Fig. 3. Microhardness varying with *a)* cutting speed, *b)* feed, and *c)* number of passes



a *b* *c*

Fig. 4. Roundness error varying with *a)* cutting speed, *b)* feed, and *c)* number of passes

It can be seen that the maximum microhardness, lower surface roughness and roundness error can be obtained by roller burnishing under *NFMQL* cutting condition compared with dry roller burnishing. The microhardness and roundness error can increase with the increase of feed. And the increase of microhardness and decrease of roundness error can be seen with the increase of the number of passes. It can be seen that the increase of feed leads to contradictory responses for surface roughness and microhardness. A compromise between roundness error and microhardness and lower surface roughness can be obtained by using a feed value in the range of 0.18–0.22 mm/rev. The surface roughness can decrease with the increase of the number of passes. However, no significant benefit is observed in reducing the surface roughness beyond the use of four passes. The roundness error can be minimized by using more passes. Similarly, the maximum microhardness can be obtained by using more passes.

Tables 5–7 show the *ANOVA* findings for the ***F***-values of surface roughness, microhardness, and roundness error for roller burnishing under dry and *NFMQL* cutting conditions, respectively. Referred to in [20], the *ANOVA* examined the responses for roller burnishing under dry cutting conditions. The ***F***-value is highlighted to indicate the factors that significantly influenced the responses. Tables 5–7 also include the percentage contributions of the various elements, which are calculated by dividing the ***F***-value of each element by the ***F***-value of the entire element.

Table 5 shows that under dry conditions, the surface roughness is primarily affected by the higher order of feed (contribution of about 30.76 %), the higher order of cutting speed, and the interaction effects

Table 5

***ANOVA* for surface roughness (*Ra*): *F*-values and % contribution of different parameters**

Elements	Dry		*NFMQL*	
	F-Values	*% contribution*	***F***-Values	*% contribution*
Cutting speed *(V)*	0.3382	0.07	4.2267	1.85
Feed *(f)*	6.3512	1.23	21.6487	**9.46**
Number of passes *(N)*	63.1738	**12.25**	11.2517	4.92
Interaction *V* x *f*	12.7024	2.46	2.8334	1.24
Interaction *V* x *N*	81.8517	**15.88**	5.2688	2.30
Interaction *f* x *N*	21.7218	4.21	0.0234	0.01
V^2	103.2749	**20.03**	45.6632	**19.96**
f^2	158.5728	**30.76**	53.2904	**23.29**
N^2	67.5406	**13.10**	84.6219	**36.98**
Total ***F***-value	515.5274	100.00	228.8283	100.00

* Significant elements are shown as underlined and contributions are in bold-case.

Table 6

***ANOVA* for microhardness: *F*-values and % contribution of different parameters**

Elements	Dry		NFMQL	
	F-Values	*% contribution*	*F*-Values	*% contribution*
Cutting speed *(V)*	15.8251	**16.91**	72.1848	**47.77**
Feed *(f)*	0.6335	0.68	18.5180	**12.25**
Number of passes *(N)*	1.5631	1.67	26.8943	**17.80**
Interaction $V \times f$	7.4668	7.98	4.1151	2.72
Interaction $V \times N$	5.8132	6.21	0.6087	0.40
Interaction $f \times N$	7.4668	7.98	8.7903	5.82
V^2	29.0338	**31.02**	19.1484	**12.67**
f^2	11.8708	**12.68**	0.2530	0.17
N^2	13.9156	**14.87**	0.6078	0.40
Total F-value	93.5887	100	151.1204	100.00

Table 7

***ANOVA* for roundness error: *F*-values and % contribution of different parameters**

Elements	Dry		NFMQL	
	F-Values	*% contribution*	***F***-Values	*% contribution*
Cutting speed *(V)*	40.2758	**25.89**	18.0635	7.28
Feed *(f)*	0.6619	0.43	167.1666	**67.36**
Number of passes *(N)*	24.0589	**15.47**	29.3038	**11.81**
Interaction $V \times f$	1.4796	0.95	6.0885	2.45
Interaction $V \times N$	28.7154	**18.46**	0.0040	0.00
Interaction $f \times N$	5.7595	3.70	1.4451	0.58
V^2	0.9816	0.63	23.7563	**9.57**
f^2	50.5574	**32.50**	1.9515	0.79
N^2	3.0571	1.97	0.3743	0.15
Total ***F***-value	155.5472	100	248.1536	100.00

of cutting speed and number of passes (contributions of about 20 % and 15.88 %, respectively). Cutting speed and feed, on the other hand, have minimal influence. However, it can be considered that the number of passes is crucial in reducing the surface roughness. Conversely, under *NFMQL* conditions, the surface roughness is most affected by the higher order of passes (contribution of about 36.98 %), followed by the higher order of feed and cutting speed (contributions of about 23.29 % and 19.96 %, respectively).

Table 6 shows the *ANOVA* results for the ***F***-values of roller burnishing microhardness under dry and *NFMQL* conditions. It is obvious that under dry burnishing condition, the higher order of cutting speed V^2 (contribution of about 31.02 %), cutting speed V (contribution of about 16.91 %), and the higher order of feed f^2 and passes N^2 (contributions of about 12.68 % and 14.87 %, respectively) have the greatest influence on the microhardness, while the feed f and the number of passes N have the least influence (contributions of about 0.68 % and 1.67 %, respectively). On the contrary, under *NFMQL* condition, the experimental results show that the number of passes N (contribution of about 17.8 %), feed f (contribution of about 12.25 %), first order cutting speed ***V*** (contribution of about 47.77 %) and second order cutting speed V^2 (contribution of about 12.67 %) have the greatest influence on the microhardness.

Table 7 shows the *ANOVA* results for the ***F***-values of the roundness error for roller burnishing under dry and *NFMQL* cutting conditions. Under dry conditions, the roundness error is significantly affected by the higher order of feed (contribution of about 32.5 %), cutting speed (contribution of about 25.89 %), number of passes (about 15.47 %), as well as the effect of interaction between the cutting speed and the number of passes (contribution of about 18.46 %). On the other hand, the roundness error for *NFMQL* condition is observed to be highly affected by the feed (contribution of about 67.36 %), number of passes (contribution of about 11.81 %), and higher order of cutting speed (contribution of about 9.57 %).

It is obvious that the feed under *NFMQL* cutting conditions and the number of passes under dry conditions had a significant effect on the surface roughness. Cutting speed seems to have the greatest effect on microhardness, and feed rate and number of passes come in second and third place. On the other hand, this effect seems to be more pronounced under *NFMQL* cutting conditions. Under dry conditions, cutting speed has a significant effect on roundness error; under *NFMQL* cutting conditions, feed has a significant effect. It is evident from Figs. 2-4 and Tables 5-7 that the process parameters are in contradiction with the beneficial responses. In addition, multi-objective optimization of these competing parameters is necessary to obtain the desired results.

In the current work, the desirability function method is used to optimize the parameters of the roller burnishing process under *NFMQL* conditions to achieve the minimum roundness error, maximum microhardness and minimum surface roughness. Using this method, the optimization of several response variables becomes the optimization of a single desire function, and each response variable is converted into a desirability function [20–23]. Table 8 lists the range of the response function and the process variables.

Table 8 illustrates the minimum and maximum limits of surface roughness, microhardness and roundness error based on the experimental results. A one-way transformation is used to transform each response into its corresponding desirability function [20–23]. Using the *Design-Expert*® software optimization module, a multi-objective optimization of roller burnishing was carried out in this study. The desirability of surface roughness, microhardness and roundness error was evaluated for each level of independent factors. The desirability of minimum surface roughness, maximum microhardness and minimum roundness error was then computed into one desirability function. The optimal process parameters for the smallest surface roughness, maximum microhardness and minimum roundness error under *NFMQL* conditions are shown in Table 9.

The current study reveals that the ideal parameters for roller burnishing of *Al6061-T6* alloy are a cutting speed of 357 rpm, a feed of 0.17 mm/rev and four passes. These results give a minimum surface roughness of 0.64 µm, a maximum microhardness of 130.19 HV and a minimum roundness error of 3.514 µm. However, it was found that the ideal parameters for roller burnishing of *Al6061-T6* alloy under dry conditions are a cutting speed of 344 rpm, a feed of 0.25 mm/rev and four passes. This gives a minimum surface roughness of 0.807 µm, a maximum microhardness of 119.2 HV and a minimum roundness error of 4.282 µm.

Table 8

Constraints for optimization of process parameters for *NFMQL* cutting conditions

Parameters	Goal	Min.limit	Max.limit
Cutting speed, *V* (rpm)	Is in range	100	500
Feed, *f* (mm/rev)	Is in range	0.1	0.2
Number of passes, *N* (mm)	Is in range	1	5
Surface roughness (R_a) (µm)	Minimize	0.61	0.83
Microhardness (*HV*)	Minimize	108	136
Roundness error (*Re*) (µm)	Minimize	2.8	9.2

Table 9

A family of optimized process parameters for *NFMQL* cutting conditions

Sr. No.	Cutting speed (*V*) (rpm)	Feed (*f*) (mm/rev)	No. of passes	Surface roughness (*Ra*) (μm)	Microhardness (*HV*)	Roundness error (*Re*) (μm)	Desirability
1	357.6	0.17	3.68	0.6435	130.1976	3.519	0.8417
2	357.64	0.16	3.68	0.6436	130.1916	3.515	0.8417
3	357.81	0.16	3.68	0.6436	130.1988	3.514	0.8417
4	357.68	0.17	3.68	0.6436	130.2047	3.518	0.8417
5	357.85	0.16	3.68	0.6436	130.1997	3.515	0.8417
6	357.67	0.16	3.68	0.6436	130.1962	3.515	0.8417

As can be seen, roller burnishing under *NFMQL* cutting conditions gives reduced values for surface roughness, roundness error, and maximum microhardness compared to dry conditions. The lowest surface roughness found was 0.64 μm. However, this study highlights the need for additional investigation on roller burnishing of *Al6061-T6* alloy to obtain improved finished work geometries that approach surface roughness of up to 0.3–0.4 μm with increased microhardness.

Conclusions

In the present work, an attempt is made to investigate the roller burnishing of *Al6061-T6* alloy. In this study, the roller burnishing of *Al6061-T6* alloy in dry condition and using nanofluid under minimum quantity lubrication (*NFMQL*) conditions is comparatively evaluated. The study evaluates, simulates and optimizes the microhardness, roundness and surface roughness by considering the factors such as cutting speed, feed and number of passes. Based on the experimental results, mathematical models are developed to predict the surface roughness, microhardness and roundness error. The following conclusions can be drawn:

- ***R***-square value above 0.9 was observed for the surface roughness, microhardness and roundness error models that represent the developed models and can be reliably used to predict the studied responses under dry and *NFMQL* cutting conditions and within the domain of the parameters selected in the present study.
- Roller burnishing under *NFMQL* cutting conditions gives reduced values of surface roughness (0.64 μm), roundness error (3.514 μm) and maximum microhardness (130.19 HV) compared with dry conditions. However, roller burnishing under dry cutting conditions gives comparatively higher surface roughness (0.807 μm), roundness error (4.282 μm) and lower microhardness (119.2 H reduced).
- Surface roughness is observed to decrease with increasing cutting speed. However, it increases with increasing cutting speed to 360–380 rpm under both dry and *NFMQL* cutting conditions. Furthermore, it is observed to decrease with increasing feed and number of passes. However, after three to four passes with a feed of 0.2–0.25 mm/rev, an increase in surface roughness is noticeable.
- Microhardness and roundness error increase with increasing feed. And an increase in microhardness and a decrease in roundness error are observed with an increase in the number of passes.
- Increasing feed is seen to result in inconsistent responses for surface roughness and microhardness. A compromise between roundness error and microhardness and lower surface roughness is obtained using a feed value in the range of 0.18-0.22 mm/rev. It is observed that roundness error decreases with higher pass counts and maximum microhardness was observed with higher number of passes.
- Surface roughness is significantly affected by the feed under *NFMQL* cutting conditions and the number of passes under dry conditions. Microhardness appears to be the most affected by cutting speed, with feed and number of passes coming in second and third. However, this effect appears to be more

noticeable when using *NFMQL* cutting conditions. Roundness error is significantly affected by dry cutting speed and feed under *NFMQL* cutting conditions.

- The cutting speed of 357 rpm, feed of 0.17 mm/rev and four passes are found as the optimum parameters for roller burnishing of *Al6061-T6* alloy to obtain the minimum surface roughness of 0.64 μm, maximum microhardness of 130.19 HV and minimum roundness error of 3.514 μm.

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Conflicts of Interest

The authors declare no conflict of interest.