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THE EFFECTS OF HYBRID NANOFLUID-ASSISTED MQL IN THE ROLLER BURNISHING PROCESS ON POWER CONSUMPTION AND SURFACE ROUGHNESS

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Abstract

It is known that performing the roller burnishing (RB) process in dry or wet conditions has negative effects on process outputs and sustainability. Therefore, the importance of using the minimum quantity lubrication (MQL) method is increasing. In this study, nano-molybdenum disulfide (MoS_2) doped nanofluid-assisted MQL (MoS_2-NMQL), nano-graphene (nGP) doped nanofluid-assisted MQL (nGP-NMQL) and MoS_2/nGP doped hybrid nanofluid-assisted MQL (HNMQL) burnishing conditions were used for the first time in the RB of AISI H11 steel and RB performance was investigated in terms of burnishing power and surface roughness improvement. Then, optimization was performed to minimize power consumption and maximize surface roughness improvement using NSGA-II and CoCoSo methods. Compared to the dry condition, using the HNMQL condition reduced the burnishing power and increased the surface roughness by 2.8% and 16.3%, respectively. Using the HNMQL condition, a burnishing speed value of 250 rpm, feed values between 0.075-0.084 mm/rev and depth of burnishing values between 0.391-0.412 mm provided optimum results in terms of power consumption and surface roughness improvement.

Keywords: Roller burnishing; Hybrid nanofluid; Minimum quantity lubrication.

Introduction

Roller burnishing (RB) is one of the surface improvement methodologies generally performed without chip removal to improve the surface integrity of mechanical parts and perform pre-processed workpieces smooth and hard, increasing fatigue strength, wear resistance, and corrosion resistance [1]. Despite the advantages offered by the method, not optimizing the process parameters and carrying out the process dry without lubrication or using plenty of lubricants brings with it some disadvantages. The increase in force applied by the RB tool in dry burnishing conditions, thus increasing the power required for burnishing, seriously damages the precision and life of the machine tool [2]. Increasing burnishing power also causes energy consumption to increase [3]. Additionally, as a result of high temperature in the burnishing zone, the productivity and surface integrity properties of the components are negatively affected [4]. Since the RB process is a cold-forming process with continuous friction, the use of lubricant is essential to overcome these problems, and the use of abundant lubricants has significant effects on the environmental burden [5].

In this regard, although strategies to reduce lubricating fluid consumption such as the minimum quantity lubrication (MQL) method are very interesting and discussed in the literature on various machining processes [6], they have been discussed in a limited number of studies in the RB process performed on the same machine tools. By Nguyen et al. [7], total energy consumption, surface roughness, and roundness deviation were reduced by 12.2%, 14.2%, and 42.5%, respectively, in the RB of hardened AISI 5150 steel with the in-hole MQL method. After that, Nguyen et al. [3] conducted a study that took into account the effects of the MQL parameters on the surface properties, and the optimum nozzle diameter, nozzle angle, flow rate, and air pressure were determined. In the study by Bobrovskij et al. [2], it was shown that using the MQL method in the RB of an AISI 1043 steel alloy increased energy efficiency by more than 20%. Although it is known that the use of

nanofluids in the MQL method greatly increases the processing performance [8], only the MQL method using nanofluids was used in the RB process by Khalilpourazary et al [9]. It was determined that the use of nanofluid prepared by adding alumina to ethanol alcohol in the RB process with the help of the MQL method provided an improvement of 15% and 20%, respectively, in the surface roughness and microhardness of the 7175 aluminum alloy.

In this study, nano-molybdenum disulfide (MoS_2) reinforced nanofluid-assisted MQL (MoS_2-NMQL), nano-graphene (nGP) reinforced nanofluid-assisted MQL (nGP-NMQL) and MoS_2/nGP reinforced hybrid nanofluid-assisted MQL (HNMQL) burnishing conditions were used for the first time in the roller burnishing of AISI H11 steel and burnishing performance was investigated in terms of burnishing power and surface roughness. Then, optimization was performed to minimize power consumption and maximize surface roughness improvement using multi-objective optimization with NSGA-II (Non-dominated Sorting Genetic Algorithm II) and multi-criteria decision-making with CoCoSo (Combined Compromise Solution) method.

Material and Methods

Mono and hybrid nanofluids preparation

In this study, two different mono-nanofluids and one hybrid-nanofluid were prepared for RB experiments. Mono-nanofluids were prepared by adding nano-molybdenum disulfide (MoS_2) and nanographene (nGP) nanoparticles separately to the commercial vegetable cutting oil at a ratio of 1% by weight. Also, Hybrid-nanofluid was prepared by using 0.2% by weight MoS_2 and 0.8% by weight nGP nanoparticles together for a total of 1% by weight. In the preparation of nanofluids, first of all, nGP and MoS_2 nanoparticles were dried in an oven at 120°C for 1 hour, and their moisture was removed. Then, the dried nanoparticles were added to the commercial vegetable cutting fluid at the above-mentioned weight ratios using precision balance. To increase the homogeneity of the mixtures and prolong the settling time, 10% of the nanoparticle weight of SDS (Sodium Dodecyl Sulphate) was added to the nGP-doped nanofluids as a surfactant [10] and to the MoS_2-doped nanofluids, 2 times the nanoparticle weight of lecithin was added as an emulsifier [11]. The prepared mixtures were mixed using digital homogenizer at 5000 rpm for 1 hour, and a homogeneous mixture was obtained.

Experimental setup and procedure

The experimental setup and applied procedure in the presented study are given in Figure 1. Roller burnishing (RB) experiments were carried out on a Goodway GA 230 CNC lathe. Before the experiments, the AISI H11 workpieces were cleaned with the turning process using the same cutting parameters to ensure that the AISI H11 workpieces reached the initial surface roughness range specified by the RB tool manufacturer and that all workpieces had approximately the same initial surface roughness. After this, RB experiments were carried out using the Yamasa SX8 single roller burnishing tool. To measure the power consumed by the lathe during the experiments, the Entes ES3-80LS three-phase power meter was connected to the electrical panel of the lathe. Before and after the RB experiments, the surface roughness values of the initial and burnished samples were measured using the Mitutoyo Surftest SJ-210 device, and the results of the improvement in surface roughness were given.

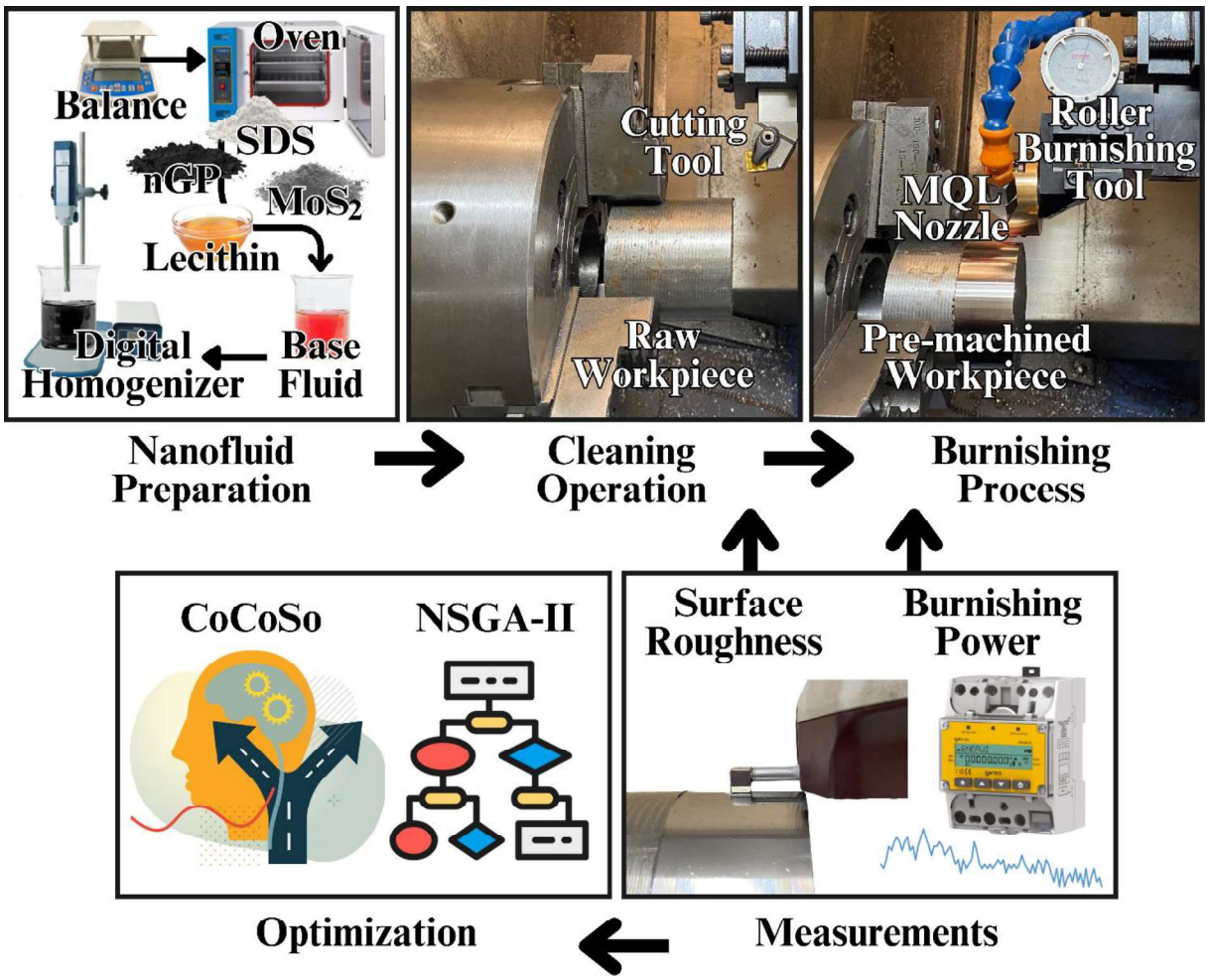


Figure 1: Experimental setup and procedure

Design of roller burnishing process experiments

Five variable factors (burnishing condition, burnishing speed, feed, and depth of burnishing) with five levels were studied as shown in Table 1; therefore, the L_{25} orthogonal array was selected for this study. The layout of the L_{25} orthogonal array is given in Table 2.

Factors	**Level 1**	**Level 2**	**Level 3**	**Level 4**	**Level 5**
Burnishing Condition (A)	Dry	MQL	MoS_2-NMQL	nGP-NMQL	HNMQL
Burnishing Speed (rpm) (B)	250	350	450	550	650
Feed (mm/rev) (C)	0.04	0.06	0.08	0.1	0.12
Depth of Burnishing (mm) (D)	0.2	0.3	0.4	0.5	0.6

Table 1: Variable factor levels

Exp. No.	Condition	Burnishing Speed (rpm)	Feed (mm/rev)	Depth of burnishing (mm)
1	Dry	250	0.04	0.2
2	Dry	350	0.06	0.3
3	Dry	450	0.08	0.4
4	Dry	550	0.1	0.5
5	Dry	650	0.12	0.6
6	MQL	250	0.06	0.4
7	MQL	350	0.08	0.5
8	MQL	450	0.1	0.6
9	MQL	550	0.12	0.2
10	MQL	650	0.04	0.3
11	MoS_2-NMQL	250	0.08	0.6
12	MoS_2-NMQL	350	0.1	0.2
13	MoS_2-NMQL	450	0.12	0.3
14	MoS_2-NMQL	550	0.04	0.4
15	MoS_2-NMQL	650	0.06	0.5
16	nGP-NMQL	250	0.1	0.3
17	nGP-NMQL	350	0.12	0.4
18	nGP-NMQL	450	0.04	0.5
19	nGP-NMQL	550	0.06	0.6
20	nGP-NMQL	650	0.08	0.2
21	HNMQL	250	0.12	0.5
22	HNMQL	350	0.04	0.6
23	HNMQL	450	0.06	0.2
24	HNMQL	550	0.08	0.3
25	HNMQL	650	0.1	0.4

Table 2: Taguchi L25 experimantal plan.

Optimization using NSGA-II and CoCoSo Methods

Optimization was performed to minimize power consumption and maximize surface roughness improvement using multi-objective optimization with NSGA-II (non-dominated sorting genetic algorithm II) and multi-criteria decision-making with CoCoSo (Combined Compromise Solution) methods. To apply NSGA-II, burnishing power and surface roughness must be modeled mathematically and given as input to NSGA-II as an objective function [12]. For this purpose, the Dummy Variable method was used to express the burnishing conditions numerically [13]. [1 0 0 0], [0 1 0 0], [0 0 1 0], [0 0 0 1], and [0 0 0 0] dummy variables were used for the burnishing conditions of dry, MQL, MoS_2-NMQL, nGP-NMQL, and HNMQL, respectively. Afterward, in establishing the regression equations, burnishing conditions, which were converted into dummy variables, burnishing speeds, feed values, and depth of burnishing values were defined as independent variables, while burnishing power and surface roughness improvement results were defined as dependent variables. The regression equations were defined as the objective function of the NSGA-II algorithm and the population size of NSGA-II was determined as 50, 50 result outputs were requested and the maximum number of generations was selected as 20000. Finally, the Pareto optimal results obtained as a result of NSGA-II were sorted by the CoCoSo method and the optimum results were selected in terms of power consumption and surface roughness improvements.

Results and Discussions

Burnishing power

The increase in power consumption for RB due to the force applied by the RB tool seriously damages the precision and life of the machine tool [2]. This situation will shorten the service life of the machine in the medium-long term, increase maintenance costs, cause disruptions in production due to the machine stopping

during maintenance, and cause industrial companies to suffer losses in terms of cost. In addition, high burnishing powers increase energy consumption, causing sustainability concerns [3]. For these reasons, the power consumption of the RB process needs to be reduced. The results obtained for burnishing power are given in Figure 2.

Compared to the dry burnishing condition, MQL, MoS_2-NMQL, nGP-NMQL, and HNMQL burnishing conditions reduced the average burnishing power by 0.4%, 2%, 2.5%, and 2.8%, respectively. The reason why HNMQL conditions yield better results is due to the synergistic effect between MoS_2 and nGP nanoparticles in the hybrid nanofluid [14]. The effect here is that the nGP nanoparticle increases the retention of MoS_2 on the friction surfaces, resulting in the formation of a thicker adsorbed tribofilm and thus increasing the lubrication between the tool and workpiece [15]. When the full quadratic variance analysis of the burnishing power results was performed, it was seen that the most effective parameter for burnishing power was the depth of burnishing value with a contribution ratio of 92.01%, followed by the burnishing condition with a contribution ratio of 4.46%.

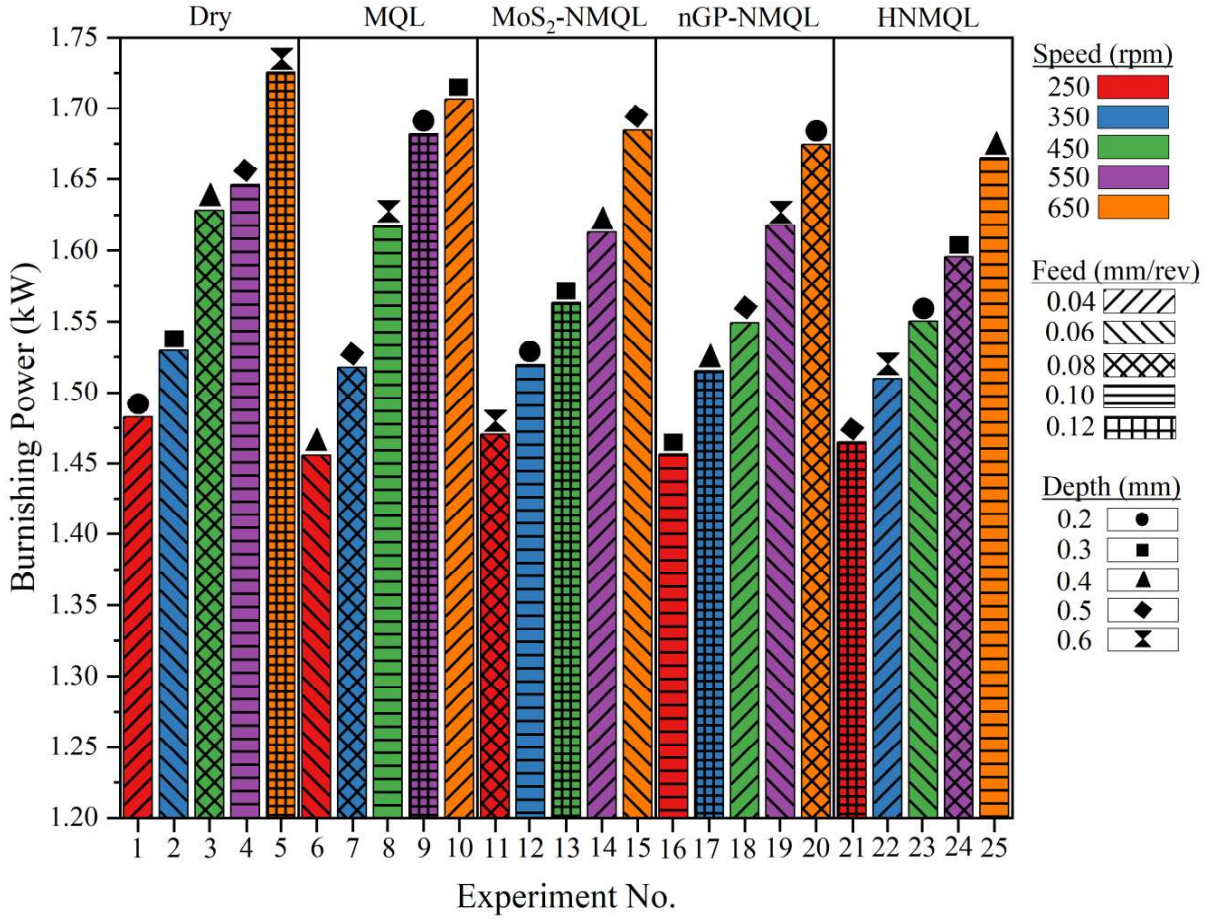


Figure 2: Burnishing power results.

Surface roughness improvement

Surface roughness is one of the most important characteristics of product quality, which directly affects product performance, aesthetic appearance, fatigue, corrosion resistance, etc. [16]. The RB is one of the surface improvement methodologies that is generally performed without machining to improve the surface integrity of mechanical parts and makes pre-processed workpieces smooth and hard, increasing fatigue strength, wear resistance and corrosion resistance [1]. In the RB process, the initial surface roughness of the workpiece is among the process parameters. However, since the effect of initial surface roughness was not examined in this study, a cleaning operation was performed before the RB experiments to ensure that the workpieces had the

same surface roughness as possible. Even though the workpieces are subjected to the cleaning process with the same parameters, differences in surface roughness may occur due to tool wear, small changes in the workpiece or zeroing. Therefore, in the presented study, surface roughness values before and after the process were determined and the results of the percentage improvement in surface roughness are presented in Figure 3.

Compared to the dry burnishing condition, MQL, MoS_2-NMQL, nGP-NMQL, and HNMQL burnishing conditions reduced the average surface roughness improvement by 4.2%, 9.6%, 14.8%, and 16.3%, respectively. In the HNMQL method, MoS_2 nanoparticles holds to the nGPs, preventing it from turning into small and defective nanoparticles and reducing wear between rubbing surfaces [15], which results in a decrease in surface roughness. When the full quadratic variance analysis of the test results was performed, it was seen that the most effective parameter for the improvement in surface roughness was the depth of burnishing value with a contribution ratio of 73.65%, followed by the burnishing condition and feed with a contribution ratio of 5.86% and 1.3%.

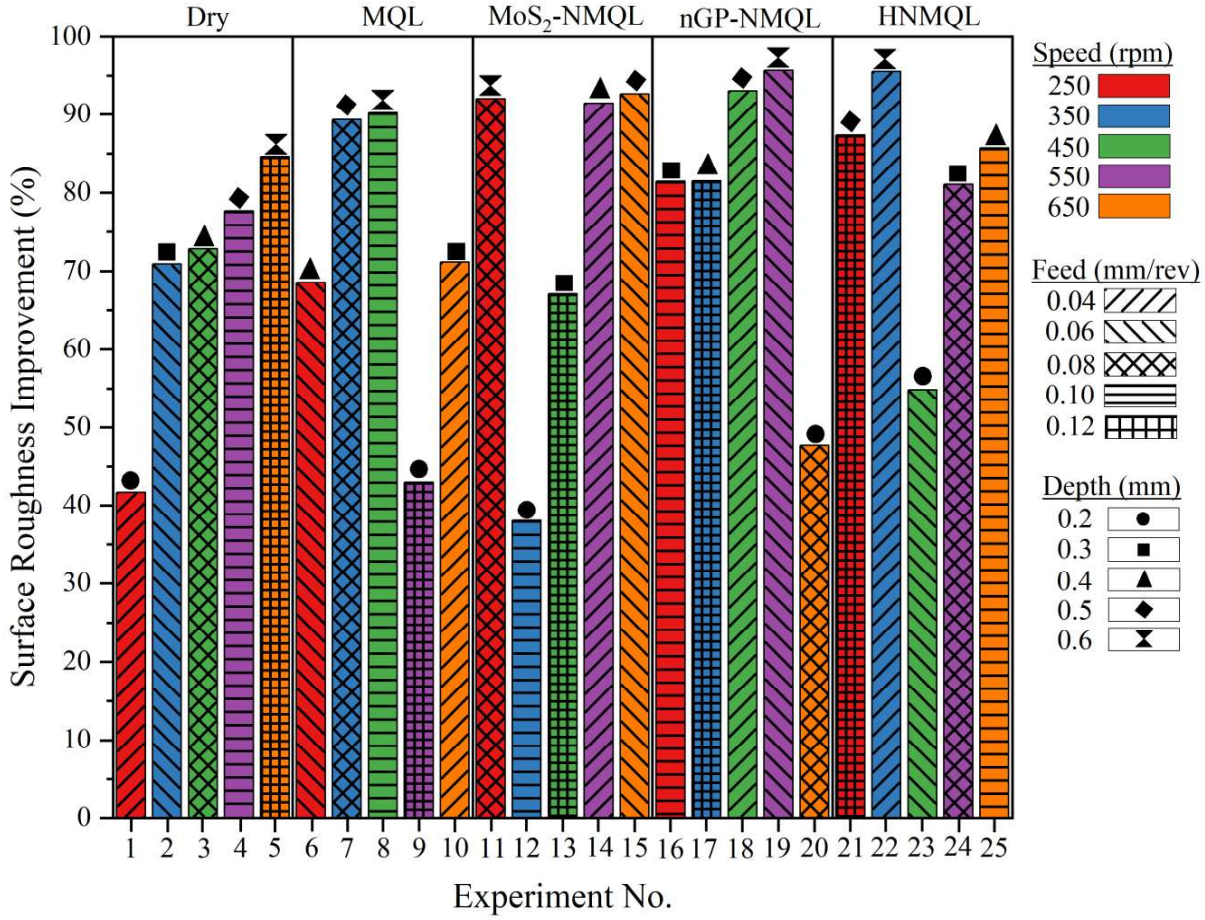


Figure 3: Surface roughness improvement results.

Optimization results

The regression equations for burnishing power and surface roughness improvement are given in Equation 1 and Equation 2, respectively. C1, C2, C3, and C4 in the equations represent dummy variables and, for example, correspond to values of 1, 0, 0, and 0 respectively for the dry burnishing condition. Also, V, F, and D refer to burnishing speed, feed, and depth of burnishing, respectively.The coefficient of determination (R^2) was used to assess the equations' accuracy in performing predictions. R^2 values for burnishing power and surface roughness improvement regression equations were successfully determined as 99.14% and 96.35%, respectively.

$$\text{Burnishing Power (kW)} = 1.3342 + 0.0132 * C1 - 0.1 * C2 - 0.0001 * C3 - 0.0491 * C4 + 0.000296 * V + 0.72 * F + 0.043 * D + 0 * V * V - 4.38 * F * F - 0.004 * D * D + 0.000072 * C1 * V + 0.000207 * C2 * V + 0.65 * C2 * F - 0.0162 * C2 * D + 0.00005 * C3 * V + 0.068 * K3 * F - 0.0374 * C3 * D + 0.000072 * C4 * V + 0.28 * C4 * F \quad (1)$$

$$\text{Surface Roughness Improvement (\%)} = -8.2 - 11.3 * C1 - 40.8 * C2 - 15.8 * C3 + 20.5 * C4 + 0.028 * V - 9 * F + 357 * D - 0.000018 * V * V - 453 * F * F - 326 * D * D - 0 * C1 * V + 0.0301 * C2 * V + 62 * C2 * F + 34.7 * C2 * D + 0.014 * C3 * V - 11 * C3 * F + 28.6 * C3 * D - 0.0442 * C4 * V - 21 * C4 * F \quad (2)$$

The NSGA-II algorithm was run with the obtained regression equations and the obtained Pareto optimum solutions are given in Figure 4. The figure shows the results of improvement in surface roughness corresponding to the polishing power obtained according to the RB parameter sets optimized in the given Pareto optimal solutions.

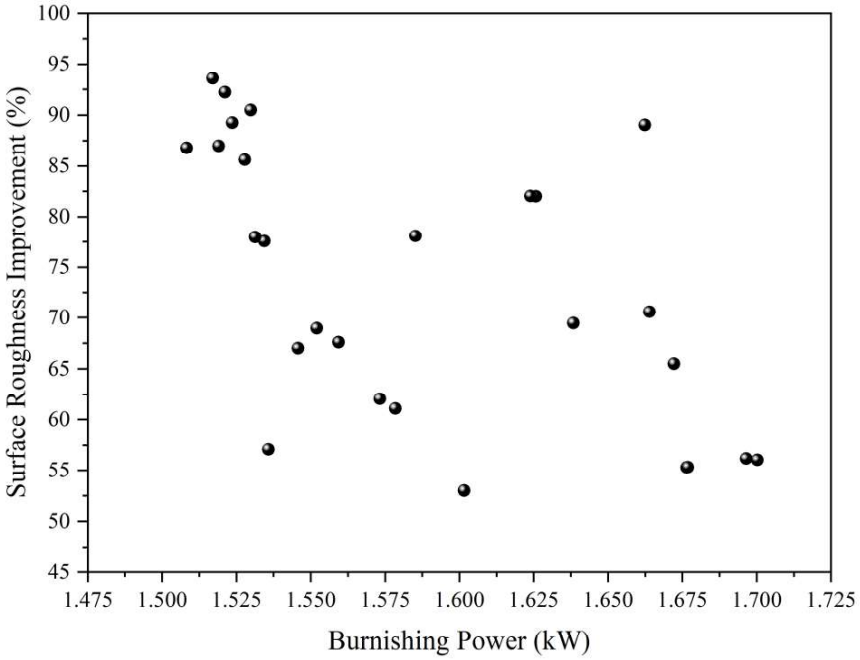


Figure 4: Pareto optimal solutions.

The final solution or solutions must be selected from the Pareto optimal solutions. In this study, the CoCoSo method, which is a multi-criteria decision-making method, was used to select the optimum results among the Pareto solutions given in Figure 4. The CoCoSo method's chosen best outcomes are shown in Table 3 as a consequence. As can be seen from the CoCoSo optimal results, it has been determined that the most suitable burnishing condition and burnishing speed for RB of AISI H11 steel is the HNMQL method and 250 rpm. When the outputs of burnishing power and surface roughness improvement are evaluated together, the use of feed values between 0.075-0.084 mm/rev and the depth of burnishing values between 0.391-0.412 mm appear as optimum process parameters that minimize each of them.

Burnishing Condition	Burnishing speed (rpm)	Feed (mm/rev)	Depth of Burnishing (mm)	Burnishing Power (kW)	Surface Roughness Improvement (%)
HNMQL	250	0.075	0.412	1.517	93.6
HNMQL	250	0.078	0.402	1.521	92.2
HNMQL	250	0.084	0.391	1.53	90.5

Table 3: Optimal results selected by the CoCoSo method.

Conclusions

In this study, nano-molybdenum disulfide (MoS_2) doped nanofluid-assisted MQL (MoS_2-NMQL), nano-graphene (nGP) doped nanofluid-assisted MQL (nGP-NMQL) and MoS_2/nGP doped hybrid nanofluid-assisted MQL (HNMQL) burnishing conditions were used for the first time in the roller burnishing of AISI H11 steel using different burnishing speed values, feed values, and depth of burnishing values, and burnishing performance was investigated in terms of burnishing power and surface roughness improvement. Then, optimization was performed to minimize power consumption and maximize surface roughness improvement using NSGA-II and CoCoSo methods. The findings from the studies conducted are listed below:

- Compared to the dry burnishing condition, using the HNMQL burnishing condition reduced the burnishing power and increased the surface roughness by 2.8% and 16.3%, respectively.
- The most effective parameter in both burnishing power and surface roughness improvement is the depth of burnishing with 92.01% and 73.65% contribution rates, followed by the burnishing condition with 4.46% and 5.86% contribution rates.
- The HNMQL burnishing condition, burnishing speed value of 250 rpm, feed values between 0.075-0.084 mm/rev, and depth of burnishing values between 0.391-0.412 mm should be used to obtain the values closest to the optimum result.

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