ASSESSMENTS OF ENERGY EFFICIENCY OF THE GREEN MQL-ASSISTED MULTI-ROLLER BURNISHING PROCESS

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ABSTRACT

Roller burnishing is a prominent solution for machining hardened steels and most investigations focused on improving the burnished quality. However, the impacts of process parameters on the energy efficiency (EF) under the minimum quantity lubrication condition (MQL) have not been considered. The purpose of this investigation is to analyze the impacts of burnishing factors, including the burnishing speed (S), depth of penetration (D), the air pressure (P), and the flow rate (Q) on the EF of the minimum quantity lubrication-assisted internal roller burnishing (MQLAIB) process. The EF model of were proposed with the aid of the adaptive neuro-based-fuzzy inference system (ANFIS). The results indicated that the S was found to be the most effective factor, followed by the D, Q, and P, respectively. The developed EF model could be applied to forecast the response values for the MQLAIB process.

Keywords: *Minimum quantity lubrication; Internal roller burnishing; Energy efficiency; ANFIS.*

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1. INTRODUCTION

The roller burnishing process is one of the efficient finishing operations, which is widely applied to yield excellent surface characteristics and enhance the production rate. This operation induced by plastic deformation has several benefits, such as higher surface hardness, higher compressive stress, and lower surface roughness criteria. The burnishing technology can be performed on both conventional and CNC machines and it is easily automated, resulting in great potential for mass production. Therefore, the industrial application of the roller burnishing process becomes simpler and more efficient, as compared to other finishing processes (e.g. lapping, grinding, honing, and polishing).

Many investigators have attempted to enhance the technology performances of different roller burnishing processes. The response surface methodology (RSM) model of the surface roughness (Rs) was developed in terms of the spindle speed (Vb), interference (I), feed rate (fr), and the number of passes (Np) for the roller burnishing of aluminum alloy 6061 [1], in which the interference and feed rate were named as primarily affecting parameters. Similarly, the RSM correlations of the surface hardness (Hs) and Rs for the burnished alloy steel regarding the burnishing force (Fb), contact width (CW), fr, and Np were developed by John et al. [2]. The results indicated that the improvements in the Rs and Hs were 95.0% and 42.0%, respectively. Yuan et al. emphasized that the Rs and micro-hardness (Hm) were improved by 63.0% and 28.0% for the burnishing operation of the TA2 alloy [3]. A low plasticity burnishing was proposed to enhance the surface integrity of TA2 alloy, in which the compressive stress (Sc) and Hm were significantly enhanced [4]. The RSM models of the Rs, bored size (Sb), and ovality (OV) regarding the Vb, fr, and penetration allowances (PA) were developed for the burnishing process of the cast iron [5]. The results revealed that the optimal values of the Rs, Sb, and OV were 31.74mm, 0.38µm, and 0.012mm, respectively. A new burnishing method namely the toroidal roller burnishing (STRB) was developed by Dunchave et al., in which the fatigue limit of the burnished 2024-T3 Al alloy was increased by 38.4% [6]. Furthermore, this method could be effectively applied to enhance the compressive axial and hoop stresses [7]. The impacts of the lubrication type, roller coating, Vb, and Np on the Rs and Hs for the burnishing operation of the metal matrix composites were analyzed by Shankar et al. [8], in which the enhancements in the burnishing objectives could be obtained using higher passes and uncoated rollers. For the multi-roller burnishing process of carbon steel, the impacts of the Vb, fr, and D on the Rs, Hs, and the depth of the affected layer (Dl) were deeply analyzed by Nguyen and Le [9]. Furthermore, the improvements in the Rs and Hs were 96.0% and 45.0%, respectively [10]. The Taguchi method was applied to optimize the Vb, fr, and D for improving energy responses, such as energy consumed (EC) and power factor (Pf), in which the enhancements in the Eu and Pf were 49.5% and 13.8%, respectively [11]. The EC and Rs were decreased by 39.5% and 7.8%, respectively, while the Hs was increased by

29.6%. However, the impacts of process parameters on the energy for the minimum quantity lubrication-assisted internal roller burnishing process have not been explored.

2. METHODS

The value the energy efficiency is calculated as:

$$E_f = \frac{E_{bo}}{E_{total}} = \frac{P_{bo} \times t_b}{P_{total} \times t_b} = \frac{P_{bo}}{P_s + Pop + Pbo} \quad (1)$$

Where, E_{bo} and E_{total} present the burnishing energy and the energy consumption by the machine, respectively. P_{bo}, P_{sb}, and P_{op} denote the burnishing power, standby power, and operational power, respectively.

In this work, process parameters (burnishing speed and burnishing depth) and MQL system parameters (air pressure and flow rate) are selected as optimizing inputs, as shown in Table 1. The ranges of each factor are determined based on the characteristics of the burnishing tool, MQL system, and milling machine. Other factors, including the feed rate, number of nozzles, and nozzle diameter are kept at the fixed values.

Table 1. MQLAIB parameters for optimization process.

Symbol	Parameters	Level 1	Level 2	Level 3
S	Burnishing speed (rpm)	480	800	1120
D	Burnishing depth (mm)	0.06	0.09	0.11
P	Air pressure (MPa)	0.2	0.3	0.4
Q	Flow rate (ml/h)	30	55	80

The systematic approach is expressed as:

Step 1: The physical experiments of the burnishing operation are conducted.

Step 2: The performance model of the EF is proposed.

ANFIS is a well-known approach comprising the best benefits of the artificial neural network (ANN) and fuzzy interface system (FIS). The Sugeno based-ANFIS model is widely applied to render the nonlinear relationships between the inputs and responses. In this investigation, the ANFIS having five layers are developed to model technological performances.

Layer I: This layer is employed to convert the inputs set to fuzzy set with the aid of the assigned membership function. The outputs of three burnishing responses are expressed:

$$L1,x = \mu Ax(E) \quad (2)$$

$$L1,y = \mu By(S) \quad (3)$$

$$L1,z = \mu Cz(P) \quad (4)$$

Where E, S, and P are the input variable nodes, while x, y, z, A, B, and C are connected labels having μ(E), μ(S), and μ(P) as memberships.

Layer II: This layer is employed to generate the fixed function of the input. The node function namely Π is expressed as:

$$L2,x = \omega_i = \mu Ax(E) \times \mu By(S) \times \mu Cz(P) \quad (5)$$

Where, ω presents the fuzzy strength rule.

Layer III: This layer contains the fixed node labeled N. The output namely the normalized firing strength is represented as:

$$L3x = \overline{\omega_i} = \frac{\omega_i}{\sum_{i=1}^{n} \omega_i} \quad (6)$$

Layer IV: This layer contains an adaptive node. The current layer is applied to assign the consequent parameters of the rules. The output of this layer is expressed as:

$$L4x = \overline{\omega_i} f_i(x) = \overline{\omega_i}(a_i x + b_i x + c_i) \quad (7)$$

where, a_i, b_i, and c_i are the consequent parameters, respectively.

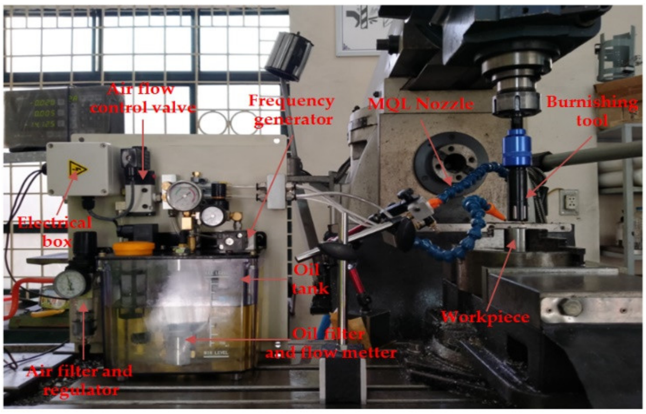
Layer V: This layer comprises of only one fixed node. The fifth layer is used to calculate the overall output all incoming signals. The output of this layer is expressed as:

$$L5x = \sum_i \overline{\omega}_i f_i \quad (8)$$

Step 3: Evaluation of the accuracy of the EF model at random points.

3. EXPERIMENTAL SETTING

The burnishing samples are made of the hardened steel labeled 5145 steel. The pre-machining processes, including the drilling and turning, are applied to produce the through-hole in each specimen. The dimensions are the length of 50.0mm, the internal diameter of 28.0 mm, and the outer diameter of 38.0mm, respectively. The burnishing trials are done with the aid of a milling machine, in which the workpiece is positioned and tightly clamped using a jaw-centering chuck. The burnishing tool is clamped on the machine spindle using the straight shank (Fig. 1).



(a)

(b)

Fig. 1. Experimental setting: (a) Performing burnishing experiments; (b) Typical burnished samples

The minimum quantity lubrication (MQL) system is used in conjunction with the soybean oil to supply the lubricant into the burnishing region. The minute amount of the soybean oil is mixed with the compressed air to form the mixture (air-oil mist). The pressure regulator and flow meter are used to control and regulate the compressed air and flow rate.

Fig. 2 presents the outcomes of the experimental No. 35.

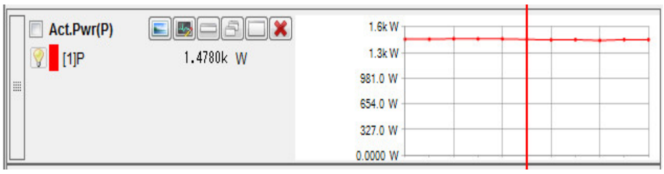


Fig. 2. Power consumed at the trail No. 35

4. RESULTS AND DISCUSSIONS

4.1. ANOVA results

The experimental results are presented in Table 2.

Table 2. Experimental data for the MQLAIB operation

No.	S (rpm)	D (mm)	P (MPa)	Q (ml/h)	EF (%)
1	480	0.06	0.2	30	13.25
2	800	0.06	0.2	30	15.95
3	1120	0.06	0.2	30	21.16
4	480	0.06	0.2	55	14.51
5	800	0.06	0.2	55	17.63
6	1120	0.06	0.2	55	22.39
7	480	0.06	0.2	80	19.03
8	800	0.06	0.2	80	21.70
9	1120	0.06	0.2	80	26.02
10	480	0.06	0.3	30	13.88
11	800	0.06	0.3	30	17.64
12	1120	0.06	0.3	30	23.04
13	480	0.06	0.3	55	16.32
14	800	0.06	0.3	55	19.64
15	1120	0.06	0.3	55	24.62
16	480	0.06	0.3	80	21.16
17	800	0.06	0.3	80	24.03
18	1120	0.06	0.3	80	28.55
19	480	0.06	0.4	30	16.14
20	800	0.06	0.4	30	20.09
21	1120	0.06	0.4	30	25.71
22	480	0.06	0.4	55	18.93
23	800	0.06	0.4	55	22.41
24	1120	0.06	0.4	55	27.57
25	480	0.06	0.4	80	24.07
26	800	0.06	0.4	80	27.13
27	1120	0.06	0.4	80	31.85
28	480	0.09	0.2	30	15.61
29	800	0.09	0.2	30	19.02
30	1120	0.09	0.2	30	24.07
31	480	0.09	0.2	55	17.86
32	800	0.09	0.2	55	20.82
33	1120	0.09	0.2	55	25.43
34	480	0.09	0.2	80	22.50
35	800	0.09	0.2	80	25.01
36	1120	0.09	0.2	80	29.18
37	480	0.09	0.3	30	17.19
38	800	0.09	0.3	30	20.79
39	1120	0.09	0.3	30	26.04
40	480	0.09	0.3	55	19.75
41	800	0.09	0.3	55	22.91
42	1120	0.09	0.3	55	27.72
43	480	0.09	0.3	80	24.72
44	800	0.09	0.3	80	27.43
45	1120	0.09	0.3	80	31.79
46	480	0.09	0.4	30	19.53
47	800	0.09	0.4	30	23.33
48	1120	0.09	0.4	30	28.78
49	480	0.09	0.4	55	22.42
50	800	0.09	0.4	55	25.78
51	1120	0.09	0.4	55	30.78
52	480	0.09	0.4	80	27.71
53	800	0.09	0.4	80	30.62
54	1120	0.09	0.4	80	35.18
55	480	0.12	0.2	30	19.53
56	800	0.12	0.2	30	22.78
57	1120	0.12	0.2	30	27.68
58	480	0.12	0.2	55	21.90
59	800	0.12	0.2	55	24.70
60	1120	0.12	0.2	55	29.15
61	480	0.12	0.2	80	26.66
62	800	0.12	0.2	80	29.02
63	1120	0.12	0.2	80	33.03
64	480	0.12	0.3	30	21.19
65	800	0.12	0.3	30	24.64
66	1120	0.12	0.3	30	29.73
67	480	0.12	0.3	55	23.88
68	800	0.12	0.3	55	26.88
69	1120	0.12	0.3	55	31.53
70	480	0.12	0.3	80	28.97
71	800	0.12	0.3	80	31.52
72	1120	0.12	0.3	80	34.73
73	480	0.12	0.4	30	23.63
74	800	0.12	0.4	30	27.27
75	1120	0.12	0.4	30	32.56
76	480	0.12	0.4	55	26.64

77	800	0.12	0.4	55	29.84
78	1120	0.12	0.4	55	34.69
79	480	0.12	0.4	80	32.04
80	800	0.12	0.4	80	33.86
81	1120	0.12	0.4	80	35.42
82	560	0.08	0.3	55	22.91
83	620	0.08	0.4	35	19.18
84	560	0.10	0.2	45	20.15
85	620	0.10	0.3	45	18.54
86	800	0.08	0.2	65	20.96
87	760	0.09	0.3	65	21.05
88	480	0.11	0.3	55	23.97
89	1120	0.11	0.4	75	22.43

ANOVA analysis is applied to evaluate parametric contributions and model significance. The ANOVA results of the EF model are presented in Table 3. The R^2 value of 0.9832 indicated that 98.32% of the experimental data was presented by the E_f model. The adjusted R^2 of 0.9764 indicated that 97.64% of experimental data could be presented using significant terms. Moreover, the predicted R^2 value of 0.9652 revealed that the E_f model could be used to explain the accuracy of 96.52% with any new data.

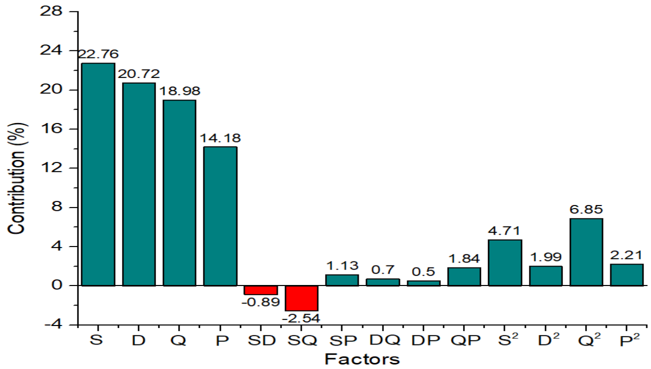


Fig. 3. The parametric contributions for EF model

The factors having a p-value less than 0.05 are named as significant terms. As a result,, single terms (S, D, P, and Q), interactive terms (SQ, SP, and QP), quadratic terms (S^2, D^2, Q^2, and P^2) are significant factors. Other factors having a p-value higher than 0.05 are listed as insignificant terms. The burnishing speed is the dominant factor having a contribution of 22.76%, followed by the burnishing depth (20.72%), flow rate (18.98%), and air pressure (14.18%), respectively. The contributions of the SQ, SP, and QP are 2.54%, 1.13%, and 1.84%, respectively. The contributions of the S^2, D^2, Q^2, and P^2 are 4.71%, 1.99%, 6.85%, and 2.21%, respectively (Fig. 3).

Table 3. ANOVA results for EF model

Source	Sum of Squares	Mean Square	F Value	P value	Remarks	Contribution (%)
Model	593.0251	42.3589	50.1645	< 0.0001	Significant	
S	206.2878	206.2878	244.3010	< 0.0001	Significant	22.76
D	187.7513	187.7513	222.3487	< 0.0001	Significant	20.72
Q	171.9775	171.9775	203.6683	< 0.0001	Significant	18.98
P	128.5141	128.5141	152.1958	< 0.0001	Significant	14.18
SD	8.0594	8.0594	9.5445	0.6481	In significant	0.89
SQ	23.0267	23.0267	27.2699	0.0194	Significant	2.54
SP	10.2469	10.2469	12.1351	0.0384	Significant	1.13
DQ	6.3465	6.3465	7.5160	0.7488	In significant	0.70
DP	4.5333	4.5333	5.3687	0.8189	In significant	0.50
QP	16.7084	16.7084	19.7873	0.0316	Significant	1.84
S^2	42.7266	42.7266	50.5999	0.0097	Significant	4.71
D^2	18.0034	18.0034	21.3209	0.0286	Significant	1.99
Q^2	62.0422	62.0422	73.4749	0.0040	Significant	6.85
P^2	20.0116	20.0116	23.6992	0.0236	Significant	2.21
Residual	10.1331	0.8444				
Cor. Total	603.1582					
R^2 = 0.9832; Adjusted R^2 = 0.9764; Predicted R^2 = 0.9652						

4.2. Development of ANFIS model for technological performance

The 2-2-2-2 structures are employed to present the correlations between MQLAIB parameters and the EF (Fig. 4).

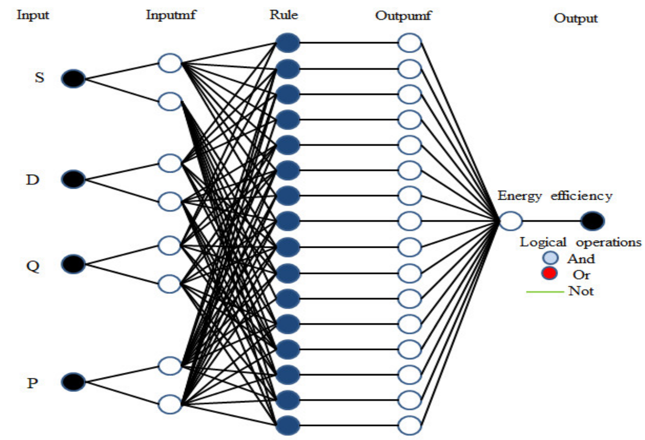


Fig. 4. The ANFIS structure for EF model

To investigate the accuracy of developed ANFIS models, a set of experiments is performed at random points. The comparisons between the obtained and ANFIS results are presented in Table 4. The accepted deviations (less than 5.0%) indicate that EF model performed well in predicting technical outputs.

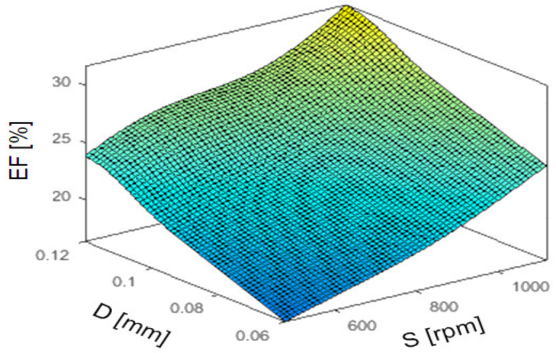
Table 4. Comparative errors for the burnishing response

No.	E_f (%)		
	Experiment	ANFIS	Error [%]
82	22.91	22.62	1.27
83	19.18	19.56	-1.98
84	20.15	19.86	1.44
85	18.54	18.24	1.62

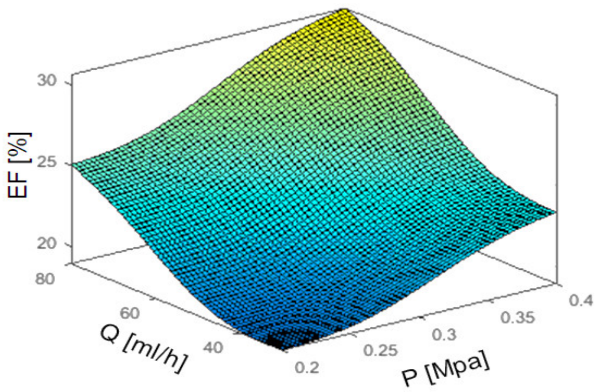
86	20.96	21.63	-3.20
87	21.05	21.42	-1.76
88	23.97	23.58	1.63
89	22.43	22.78	-1.56

4.3. Parametric influences

Fig. 5a presents the variety of the EF under the impacts of the S and D. When the burnishing speed increases, higher power consumption of the spindle system is required. The active machining power is then increased; hence, higher energy efficiency is obtained. Practically, a higher burnishing speed causes a reduction in the machining time and the energy consumed decreases, resulting in higher energy efficiency. An increased burnishing depth requires higher active burnishing power due to an increment in the workload. Energy efficiency is consequently improved.



(a)



(b)

Fig. 5. The interactive influences of the process parameters on the technological performances: (a) EF versus the S and D; (b) ED versus the Q and P

Fig. 5b presents the influences of the P and Q on the EF. When the air pressure increases, the diameter of the mist droplet is decreased. The number of droplets and their velocity increase; hence, more droplets can be penetrated into the burnishing region. The cooling-lubrication effectiveness is enhanced due to a decreased friction at the interfaces. Consequently, the burnishing force is decreased and energy efficiency is improved. When the flow rate increases, the droplet diameter is decreased and velocity is increased. Moreover, a higher amount of oil mist particles enters into the interfaces, which enhances the cooling-lubrication impact; hence, the burnishing force decreases. Therefore, energy efficiency increases with a higher flow rate.

5. CONCLUSIONS

In this study, the EF model was developed in terms of the burnishing speed, burnishing depth, air pressure, and flow rate using the ANFIS approach. The MQL system was proposed to facilitate the machining internal hole. The impacts of the process parameters on the EF were analyzed. The finding can be listed as bellows:

1. The maximum values of the process parameters are recommended to enhance energy efficiency.

2. All machining factors have significant contributions to the ANFIS models. For EF model, the burnishing speed is named as the most effective factor, followed by the burnishing depth, flow rate, and air pressure, respectively.

3. The 2-2-2-2 ANFIS structures can be used to render the relations between process parameters and the EF.

4. The performance model proposed by the ANFIS approach are adequate. The response values of the MQLIAB operation of the hardened 5145 steel can be precisely predicted with the aid of the proposed models.

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