Investigating the Surface Tribology of Roller-Burnished Polymer Using the Fuzzy Rule–Based Approach

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Burnishing is specified as the plastic deformation cold working process applied as surface treatment and smoothing following machining to obtain a superior surface roughness finish. The present experimental study was carried out on roller-burnished polyurethane using a roller burnishing tool. An analysis was done to investigate the effect of burnishing depth, speed, feed rate, and roller width on the surface roughness of the polymer workpiece. Roughness (R_a) prediction was achieved with a fuzzy rule–based system. The results indicate 95% accuracy between the fuzzy predicted roughness values and experimental results.

KEY WORDS

Surface Roughness; Burnishing; Polymers; Fuzzy Logic

INTRODUCTION

Burnishing has long been recognized as a surface treatment process. Initially applied to influence the surface characteristics of nonferrous materials, it is a chipless machining process, unlike several conventional finishing processes. A surface is subjected to the force of a highly polished ball or roller. After machining, materials are left with peaks and valleys, such that when the burnishing tool makes frictional contact between its surface and the workpiece surface, the irregular heights will fill up the valleys. This operation yields enhanced surface finish and hardness properties (Hassan *(1)*). A literature survey of burnishing is limited with regard to processing of polymers. Polymers have a good surface performance and service life when used for production of sliding members in machining. Polymers also have a good shock loading absorption, better bending, and shaft misalignments than metals (Low and Wong *(2)*). It was reported that ball burnishing is capable of improving the scratch hardness and indentation hardness of poly oxymethylene (Low, et al. *(3)*). The mobility of dislocations is responsible for the amount of plastic deformation during burnishing, whereby dislocation is initiated upon reaching the material's critical shear strength (Smith and Hashemi *(4)*). Burnishing is also distinguished from other surface treatment processes by the compressive residual stress produced, which improves surface hardness and other mechanical properties, such as corrosion resistance and fatigue life (El-Axir *(5)*). By application of a ball burnishing process, the surface characteristics of cast Al-Cu workpieces have shown good improvement (Hassan *(6)*). Applying optimal burnishing parameters to free-form surface injection molding has shown good improvement in surface roughness (R_a; Shiou and Chen *(7)*). Fatigue is initiated in the surface region, so there is a reduction tendency in the burnished parts due to the compression state encountered at the surface (Prevéy and Cammett *(8)*). Fatigue life is improved due to the residual compressive with sufficient depth and magnitude for crack initiation (Zhuang and Halford *(9)*). It has also been reported that burnishing is capable of producing adequate friction and wear of the machined part (Hamadache, et al. *(10)*). The improvement in roughness and hardness have a good impact on wear resistance as shown by experimental results (Mahmood Hassan and Al-Dhifi *(11)*). The process is capable of improving the friction coefficient and weight loss reduction of aluminium 6061 (El-Tayeb, et al. *(12)*). In polymeric materials, the modification of surface characteristics has shown a good reduction in the coefficient of friction and wear performance (Low *(13)*). A decrease in the coefficient of friction of MoS_2 has been reported and it was concluded that its frictional properties are dependent on parameters such as contact pressure and prevalent humidity (Kohli and Prakash *(14)*). One of the most significant factors prior to performing burnishing procedures is selection of the control parameters. According to a literature survey, parameters with major influence on the process are burnishing force, burnishing speed, burnishing feed, burnishing tool diameter, number of tool passes, and lubrication used in the experiment. Researchers have predominantly studied the effects of burnishing force, feed, and speed along with the number of tool passes (Rajesham and Tak *(15)*). The use of roller burnishing results in a reduction in surface roughness when the force and number of tool passes are high (Hassan and Al-Wahhab *(16)*). This study empirically investigates the effects of working parameters on surface integrity. The burnishing parameters considered are burnishing depth, speed, feed, and roller width. These are deemed the key influencing parameters on surface finish (Rao and Shunmugam *(17)*).

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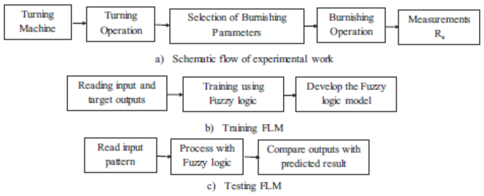
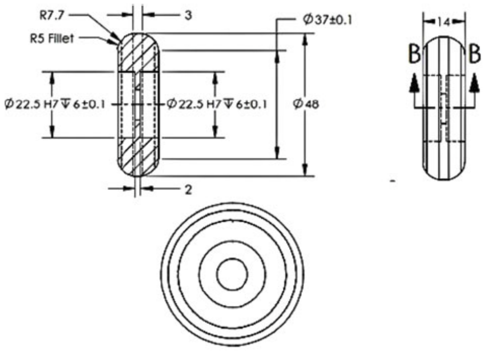


Fig. 1—Experimental work and analysis: (a) schematic flow of experimental work; (b) training FLM; and (c) testing FLM.

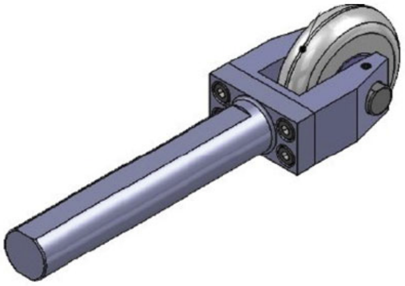
In the present work, a fuzzy logic model (FLM) was employed as an approach to predicting the burnishing process state variable. Fuzzy logic is a soft computing technique that plays a significant role in input–output matrix relationship modeling. It is used when subjective knowledge and expert suggestions are substantial in defining objective function and decision variables.

Fuzzy logic is preferred for predicting burnished surface roughness based on input variables due to the nonlinear condition in the burnishing process (Oktem, et al. *(18)*). Fuzzy logic is a simple rule based on: If *X* and *Y* then Z fuzzy mathematics is a metaset of Boolean logic and denotes relative correctness (Leung, et al. *(19)*). The fuzzy theory is still prominent, although at times it describes uncertain and indefinite phenomena, and it has the following structure:

1. Fuzzification: Denotes making something fuzzy.
2. Fuzzy rule base: In the rule base, the if–then rules are fuzzy rules.
3. Fuzzy inference engine: Produces a map of the fuzzy set in the space entering and that leaving the fuzzy set, according to the if–then rules.
4. Defuzzification: Signifies making something non-fuzzy (Zalnezhad, et al. *(20)*).



(a) Workpiece geometry



(b) Typical roller burnishing tool

Fig. 2—Roller burnishing tool: (a) workpiece geometry and (b) typical roller burnishing tool.

TABLE 1—DETAILS OF THE MATERIAL

Properties	Polyurethane
Tensile strength	60 MPa
Yield strength	45 MPa
Flexural strength	65 MPa
Specific gravity	1.20 g/cm^3
Water absorption	0.13%
Service temperature	−100 to 100°C

EXPERIMENTAL DETAILS

Schematic of Investigation

This experiment is divided into two main stages. The first stage targets the preparation of the experiment, measurements, and results collection. The implementation of fuzzy logic makes up the second stage. These procedures are shown in Fig. 1.

Experimental Procedure

The burnishing process is performed using an OKUMA LB15 lathe machine. A roller burnishing tool is utilized in this experiment with three different roller widths: 1, 3, and 5 mm. Figure 2 shows a schematic drawing of a burnishing tool. Rigid thermosetting polyurethane material was employed in this experiment and its mechanical properties are listed in Table 1.

The polymer materials employed in this study were supplied in the form of solid rods 1 m long and 50 mm in diameter. These workpiece materials were divided into portions of 250 mm each and were then turned to a 46 mm diameter. The turning operation was carried out at 330 rpm and a constant feed rate of 0.087 mm/rev for all specimens to provide a similar condition for all specimens prior to burnishing process because the initial roughness value affects the burnished surface tribology. Next, the

TABLE 2—BURNISHING CONDITIONS

		Experimental Conditions		
	Parameters	1	2	3
A	Burnishing depth (mm)	0.1	0.15	0.2
B	Burnishing speed (rpm)	110	245	490
C	Burnishing feed rate (mm/rev)	0.035	0.105	0.210
D	Roller width (mm)	1	3	5

TABLE 3—DESIGN MATRIX OF THE EXPERIMENT

	Parameter Combinations			
Exp. No.	A	B	C	D
1	1	1	1	1
2	1	2	2	2
3	1	3	3	3
4	2	1	2	3
5	2	2	3	1
6	2	3	1	2
7	3	1	3	2
8	3	2	1	3
9	3	3	2	1

workpieces were burnished under different parameters. One region was left intact for each specimen to be used for initial roughness measurements. To measure burnishing force corresponding to a certain depth, the burnishing tool was connected to a Kistler three-axis dynamometer (type 9255B), a Kistler charge amplifier, and an oscilloscope where data can be collected.

To investigate the influence of burnishing parameters on the specimen's surface integrity (R_a), the number of parameters was specified for the experiment and they are presented in Table 2. This process was designed according to the experimental matrix shown in Table 3. ECOCUT SSN 322 lubricant oil type with 40.2 cSt from Fuchs was used for fluid conditioning at 1,500 mL/h for 20 MPa delivery pressure, 50 mm from the cutting zone.

EXPERIMENTAL RESULTS

Surface roughness measurements were taken before and after burnishing using a profilometer (Mitutoyo SJ.201) with a cutoff distance and sampling length of 1.2 and 4 mm, respectively. Five readings were taken and their average is reported in Table 4.

There are many different roughness parameters, which include average variation from mean line (R_a), the highest peak to the deepest valley (R_t), and average (R_t) over a given length (R_z). R_a values are more accurate than the R_t and R_z values because they consider the average of peaks and valleys on the surface. Hence, R_a was selected as the measuring parameter for surface roughness. The data provided are for both dry and fluid burnishing operations.

TABLE 5—FUZZY LINGUISTICS AND ABBREVIATION OF VARIABLES FOR EACH PARAMETER

Parameters	Linguistic Variables	Range
	Inputs	
Burnishing depth °C(mm)	Low (L), medium (M), high (H)	0.1–0.2
Burnishing speed (rpm)		110–490
Burnishing feed rate (mm/rev)		0.035–0.210
Roller width (mm)		1–5
	Output	
Roughness (μm)	Good, average, poor	1.78–4.472 (Dry) 2.026–5.03 (Fluid)

FUZZY LOGIC–BASED MODEL TO PREDICT THE SURFACE ROUGHNESS

To construct the fuzzy rules, the input variables, namely, burnishing depth, burnishing speed, and burnishing feed rate, were related to the output, which is surface roughness. The fuzzy variables and fuzzy expressions for the inputs and output are given in Table 5.

Membership Functions and Fuzzy Rules Structure

In this model, each input and output has three membership functions. Triangular membership functions are generally used for output (Shamshirb, et al. *(21)*). The fuzzy membership functions of this work for input and output variables are shown in Figs. 3 and 4.

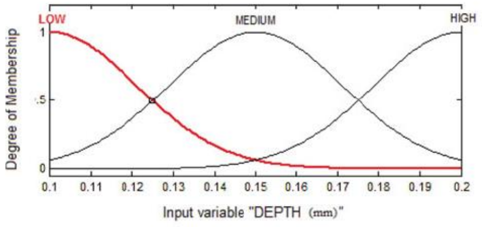
A set of nine experimental rules was simulated in MATLAB on the basis of Mamdani fuzzy rules, which are provided in Table 6. These rules were produced based on the surface roughness measured values found in Table 4.

Defuzzification

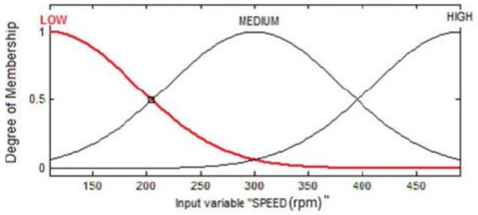
Defuzzification is the conversion of a fuzzy quantity to a precise value (Zalnezhad, et al. *(22)*). Seven methods are available in the literature that may be used for defuzzification, including

TABLE 4—EXPERIMENTAL RESULTS

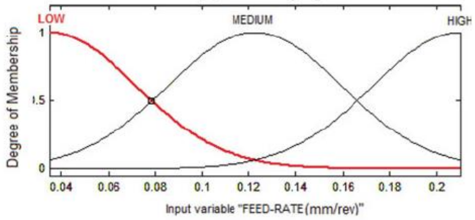
	Dry Readings						Fluid Readings					
Exp. No.	1	2	3	4	5	Average	1	2	3	4	5	Average
1	3.97	4.07	4.07	3.94	3.92	3.994	5.17	5.02	4.95	4.9	5.07	5.022
2	4.28	4.55	4.57	4.41	4.55	4.472	4.82	4.68	4.6	4.55	4.72	4.674
3	1.89	1.8	2.03	2.35	2.02	2.018	2.97	3.03	3.25	2.85	2.97	3.014
4	2.75	2.68	2.69	2.69	2.63	2.688	3.78	3.89	3.68	3.88	4.02	3.85
5	4.16	3.9	3.73	3.76	3.75	3.86	4.94	5	4.81	4.83	4.82	4.88
6	3.7	3.6	3.71	3.64	3.68	3.666	4.91	4.99	4.99	5.17	5.09	5.03
7	2.02	1.7	1.69	1.79	1.7	1.78	3.32	3.16	3.32	3.32	3.32	3.288
8	1.92	2.13	2	1.91	1.91	1.974	2.86	3.21	2.76	3.02	2.84	2.938
9	3.96	3.83	3.84	3.74	3.77	3.828	1.86	2.08	1.94	2.21	2.04	2.026



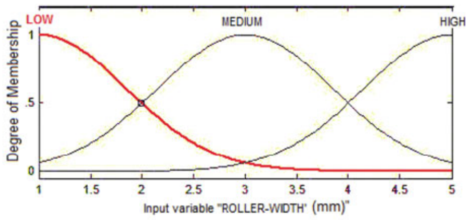
(a) Burnishing Depth



(b) Burnishing Speed



(c) Burnishing feed rate



(d) Roller width

Fig. 3—Membership function for variables of inputs: (a) burnishing depth; (b) burnishing speed; (c) burnishing feed rate; and (d) roller width.

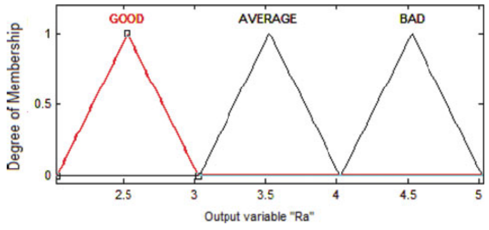
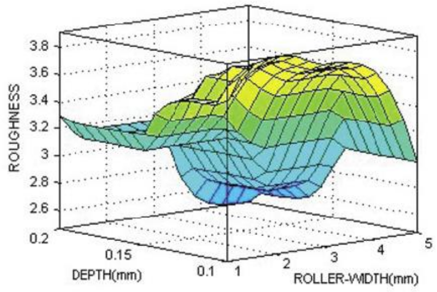
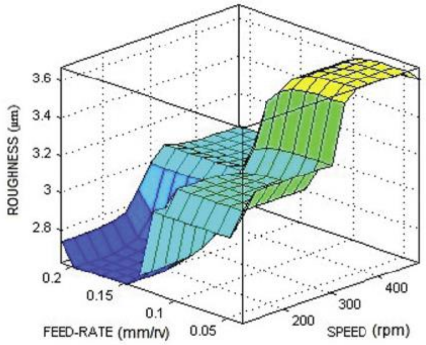


Fig. 4—Membership function for variables of outputs.



a) Surface roughness in relation to roller width and depth



b) Surface roughness in relation to feed rate and speed

Fig. 5—Predicted surface roughness by fuzzy model in relation to parameter changes for dry burnishing: (a) surface roughness in relation to roller width and depth and (b) surface roughness in relation to feed rate and speed.

centroid, weight average, mean of max, center of sum, center of largest area, and first (or last) of maximum method. Method selection is important because it greatly influences the model's speed and accuracy. In the current model, the centroid of area defuzzification method is used due to its wide acceptance and capability to produce more accurate results compared to other techniques (Oktem, et al. *(18)*). In this method, the resultant membership functions are developed by considering the union of the output of each rule, meaning that the overlapping area of the fuzzy output set is counted as one, providing additional results (Hashmi, et al. *(23)*).

FUZZY PREDICTION MODEL RESULTS AND DISCUSSION

The predicted surface roughness values by fuzzy logic for both dry and fluid burnishing in relation to burnishing parameters are shown in Figs. 5 and 6, respectively. The figures represent burnishing speeds ranging from 110 to 490 rpm at different burnishing depths (0.1–0.2 mm), feed rates (0.035–0.210 mm/rev), and roller widths (1–5 mm). The graphs clearly show a decrease and increase in burnishing roughness at various working parameters as measured in this study. The experimentally obtained lowest

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