STUDY ON THE INNER SURFACE FINISHING OF ALUMUNUM ALLOY 2014 BY BALL BURNISHING PROCESS

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الملخص

تلعب جودة الأسطح الداخلية دورا هاما في أداء الكثير من الأجزاء الميكانيكية. ومن الصعب الحصول على أسطح داخلية ذات جودة عالية للمواد غير الحديدية باستخدام طرق التشطيب العادية مثل عملية التجليخ والتي تعتبر الطريقة المثالية للمواد الحديدية. و حتى نتجنب ما يحدث لأحجار التجليخ من كثرة إعادة السن نتيجة انسداد الحدود القاطعة للمواد الحاكة أثناء تجليخ المواد غير الحديدية، لذا تعتبر عملية الصقل بالضغط الداخلي (Internal burnishing) هي العملية الأكثر ملائمة للحصول على أسطح داخلية عالية الجودة.

وقد تم تصميم و تنفيذ أداه صقل خاصة من النوع الكرة بحيث يمكن تركيبها بسهولة على حامل الأقلام لأحدى ماكينات الخراطة من النوع CNC وكان قطر الكرة المستخدمة لهذه الكرة 8 مم. وتم دراسة تأثير أربعة متغيرات للصقل الداخلي وهى: سرعة الصقل، التغذية، عمق التغلغل و عدد مشاوير الصقل على أهم متغيرات شكل السطح (Surface profile parameters) و ذلك لسبيكة الألمنيوم 2014.

وقد أجريت التجارب باستخدام إحدى أساليب تصميم التجارب بهدف تخفيض عدد التجارب بدون اي فقد في الدقة وكذلك لزيادة الثقة في نتائج هذه التجارب. وتم استنتاج نماذج رياضية تعتمد على نتائج التجارب العملية وتربط بين متغيرات عملية الصقل وكل متغير من المتغيرات التي تمثل شكل السطح الناتج من عملية الصقل الداخلي.

أوضحت النتائج إمكانية الحصول على خشونة متوسطة للسطح المصقول تصل إلى 0.14 ميكرو متر حيث كانت الخشونة المتوسطة قبل عملية الصقل في حدود 4 ميكرو متر. أظهرت النتائج أن سرعة الصقل ، التغذية و عدد مشاوير الصقل هي أهم متغيرات عملية الصقل الداخلي التي تؤثر على شكل السطح الناتج.

ABSTRACT

Tubular parts are important in many industrial applications (e.g. joints, fitting, etc.). The internal surface quality plays an important role in the part performance. Internal surfaces of non-ferrous materials are difficult-to-finish due to many problems encountered in grinding which is optimum for ferrous metals. Internal burnishing process is believed to be more suitable since it eliminates sticking, wheel dulling and overheating. In the present study, Aluminum alloy 2014 is selected as workpiece material, 8 mm carbon chromium balls were used for the internal burnishing process.

Statistically-based on experimental design (Response Surface Methodology) using central composite second-order rotatable design was used to improve the experimentation design without loss of accuracy of results. Mathematical models are presented for predicting five different surface profile parameters caused by internal-ball burnishing process parameters namely; burnishing speed, feed, depth of penetration, and number of passes.

The results show that from an initial roughness of about Ra 4 μm, the specimen could be finished to a roughness average of 0.14 μm. The burnishing speed, feed and number of passes have the most significant effect on all surface profile parameters studied in this work.

KEYWORDS: Ball burnishing; Surface profile parameters; Aluminum alloy

INTRODUCTION

Surface quality is an important factor by which the technological quality of machined component can be evaluated [1], other factors include material properties, shape and dimensional accuracy. Engineering components are usually subjected to large stresses, high temperature and great speeds. More work is required to understand and optimize the relationships between surface geometry and function. The most suitable specification for a surface, hence, is dependent on its intended application. For this reason, surface geometry and function should be isolated, especially in investigations of a tribological nature.

The surface roughness of engineering parts is a significant design specification that is known to have considerable influence on properties such as wear resistance and fatigue strength. Perfectly flat surface can never be generated. Surfaces have always irregularities in the form of peaks and valleys. Processes by which surfaces are finished differ in its capabilities concerning finishing action, mechanical and thermal damage, residual stresses and materials [1]. These processes are divided according to running in mechanisms into two types: one involves material loss such as grinding and the other depends on plastic squeezing of the surface where by a redistribution on material is performed with no material loss [2]. The latter is seen in finishing process such as burnishing which can be achieved by applying a highly polished and hard ball onto metallic surface under pressure. This will cause the peaks of the metallic surface to spread out permanently, when the applied burnishing pressure exceeds the yield strength of the metallic material to fill the valleys and some form of smoothing takes place. Besides producing a good surface finish, the burnishing process has additional advantages over machining processes, such as securing increased hardness, corrosion resistance and fatigue life as result of the produced compressive residual stress on the surfaces [3].

A literature survey shows that work on burnishing has been conducted by many researches. The process also improves the properties of the parts, increases hardness [4-9], surface quality [4, 10-14], increases maximum residual stress in compression [15], and attains higher wear resistance [16,17]. The parameters affecting the surface properties are: burnishing speed, force, feed rate, number of burnishing tool passes, ball material, workpiece material, ball size and lubricant [10]. It can be said that most of these investigators have studied the effect of the external burnishing parameters on some surface characteristics (such as surface roughness) of the external surfaces by taking one parameter at a time, which requires carrying out many experiments in order to be able to draw a conclusion. Knowing that only few analytical models are available, provided that the present models represent only the relationship between burnishing parameters and the average roughness Ra as the main parameter on the surface profile. Average roughness Ra does not tell the whole information about a surface. For example, see Figure 1, there are three surfaces that all have the same Ra, but they are quite different surfaces. In some applications they will perform very differently as well. Accordingly, it is very clear that information concerning surface profile parameters of the burnished surface will be very valuable in part manufacturing.

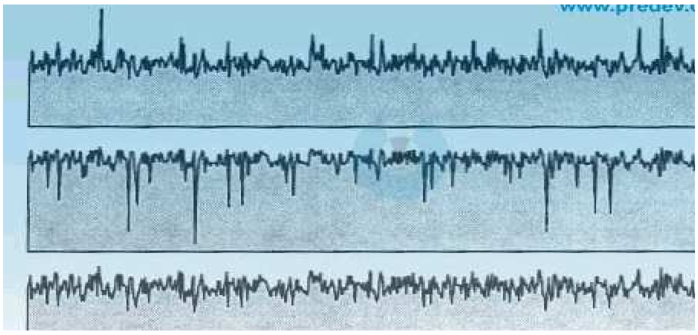


Figure 1: Surface profile of three different cases

This paper studies the use of the internal ball burnishing process to improve internal surface quality for 2014 aluminum alloy using CNC lathe machine. To explore the optimum combination of internal ball burnishing process parameters in an efficient and quantitive manner, the experiments were designed on the basis of the response surface methodology (RSM) with central composite rotatable design and mathematical model for five different surface profile parameters were developed to give the production engineers more details about the real profile of the produced internal surfaces. The effect of four internal ball burnishing parameters; namely, speed, feed, depth of penetration and number of passes on average roughness, as example, were investigated using the derived mathematical model.

EXPERIMENTAL WORK

Aluminum alloy 2014 was used as a test material. This material was selected because of its importance in industry. The chemical composition in weight percent and the mechanical properties are shown in Table 1 (a and b). The material was received in the form of bars, external diameter of 70mm. Workpieces were prepared to the required dimensions as shown in Figure 2. The workpieces were prepared with two parts A and B, part A was left without burnishing for the purpose of comparison. Initial turning conditions were unified for all workpieces as speed = 400 rpm, feed = 0.2 mm/rev and depth of cut = 0.5 mm. A CNC lathe machine (Model, Biglia B56/1 CNC) was used for machining and burnishing the inner surface of the tubular workpieces.

Table 1a: Chemical composition of the workpiece material

Material	Aluminum 2014							
Element	Si	Fe	Cu	Mn	Mg	Cr	Zn	Ti
Weight %	0.50	0.7	4.0	1.2	0.8	0.10	0.25	0.15

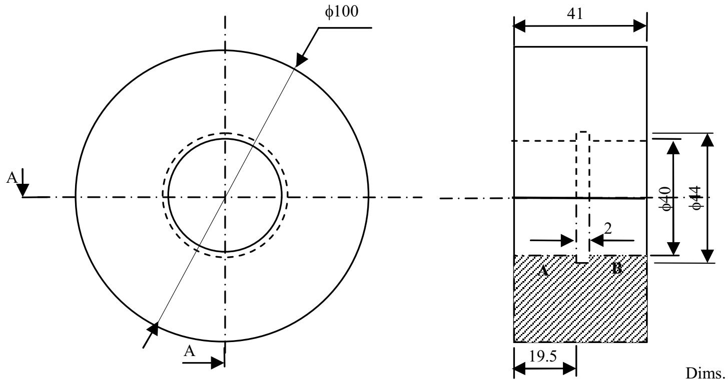
Table 1b: Mechanical properties of the workpiece material

Strength (MPa)	Yield (MPa)	Hardness (BHN)	Shear (MPa)	Modulus (MPa)
186	96	45	124	$6.89\text{x}10^{4}$

A simple tool was designed and constructed to carry out the experimental work as shown in Figure 3. Carbon chromium steel balls were used, having HRc 62 and Ra 0.015 mm. A ball diameter of 8 mm was implemented. The shank of the burnishing tool is designed in such a manner that it can be simply mounted or fixed onto the tool holder of the CNC lathe machine. The workpiece to be burnished is clamped by the three-jaw chuck of the CNC lathe.

After turning the inner diameter of the workpiece to a diameter of 40 mm, the internal cutting tool is replaced by the proposed internal ball burnishing tool to enable the burnishing process to be carried out on the inner surface of the workpieces using the same CNC lathe machine. The initial surface roughness Ra of most work materials was found to be in the range of 3.5 to 4.6 μm.

The set-up for the burnishing process used in this work is shown in Figure 4. Dry turning and burnishing were used in all the experimental work, but alcohol was used to clean the workpieces before burnishing. Cleaning of the ball was carried out continuously in order to prevent hard particles from entering the contact surface between the tool and the workpiece. Such hard particles usually leave deep scratches, which may damage the burnished surface of the workpiece.



Dims. in mm

Figure 2: Workpiece geometry

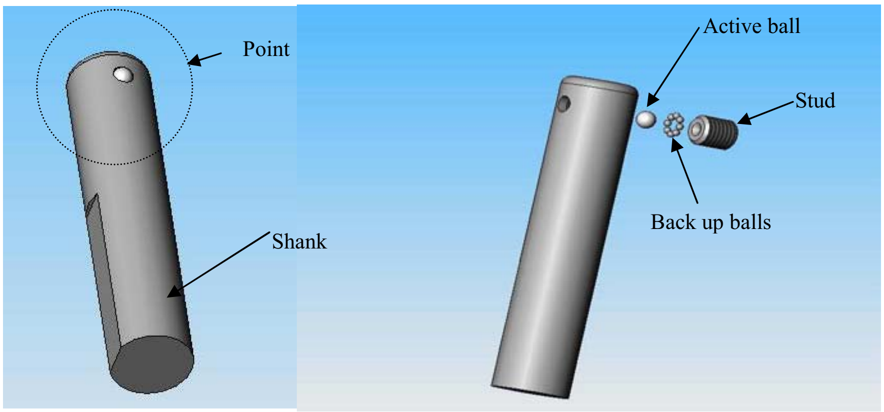


Figure 3: The proposed burnishing tool

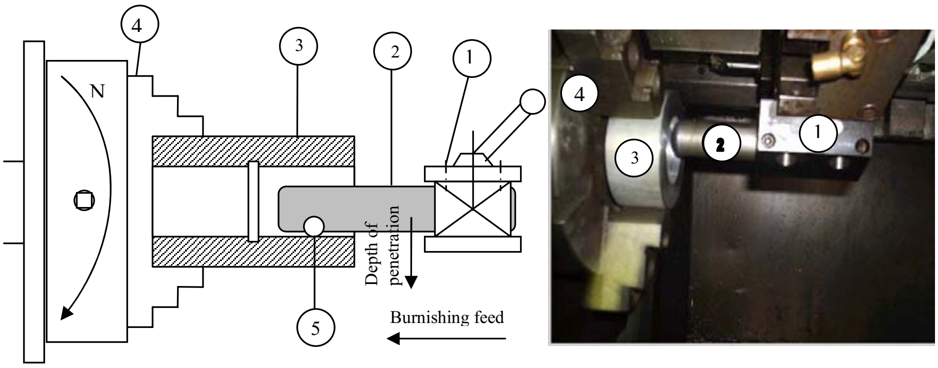


Figure 4: Schematic representation of the experimental set up; (1) Tool holder (2) Burnishing tool (3) Workpiece (4) Lathe three-jaw chuck (5) Active ball

Five different surface profile parameters of unburnished and burnished part of each workpiece were measured. These profile parameters are; average roughness (Ra), Root mean square roughness (Rq), Maximum height of the profile (Ry), Average maximum height of the profile (Rz) and Mean spacing of the profile irregularities (Sm). The average values of three measurements being reported for each part. A Surtronic 3+ instrument was used to measure these five surface profile parameters

EXPERIMENTAL DESIGN AND ANALYSIS

The main objective of this work is the investigation of the effect of the stated parameters of internal ball burnishing process on the work material characteristics. Therefore, a simple and adequate experimental design, response surface methodology (RSM), with the Box and Hunter method [19] was found to be suitable for this study. A detailed description of this method is presented elsewhere [20]. In this study, each parameter has five levels selected from practice, as shown in Table 2. According to a central composite-second-order rotatable design with four independent variables, thirty one experiments were conducted with the combination of values that are shown in Table 2 which summarize the burnishing conditions and their coded levels.

Table 2: Coding of burnishing process parameters

Parameters	Symbol	Levels				
		-2	-1	0	1	2
Speed, (m/min)	X_1	15	25	35	45	55
Feed, (mm/rev)	X_2	0. 05	0.15	0.25	0.35	0.45
Depth, (mm)	X_3	0.005	0.015	0.025	0.035	0.045
No. of passes	X_4	1	2	3	4	5

The values of the levels of each burnishing parameter used in this work were coded to simplify the experimental arrangement. The range of each parameter was also coded in five levels (-2, -1, 0, 1, 2) using the following transformation equations:

Burnishing speed, $X_1 = \dfrac{V-35}{10}$, Burnishing feed, $X_3 = \dfrac{f-0.25}{0.10}$,

Burnishing depth, $X_2 = \dfrac{a_p-0.025}{0.010}$, and Burnishing passes, $X_4 = \dfrac{n-3}{1}$

Where V is the cutting speed, f is the feed rate, a_p is the depth of penetration and n is the number of passes.

MODELS, RESULTS AND DISCUSSION

Table 3 shows the arrangement and the results of the thirty one experiments carried in this work based on the central composite second–order rotatable design. These results are used to deduced the mathematical models which is one of the main objectives of this work.

Mathematical Models

This section presents a study of the development of response models for internal ball burnishing in terms of burnishing speed (x_1), feed (x_2), depth of penetration (x_3) and number of passes (x_4). Using the results presented in Table 3 the response surface for five different profile parameters Ra, Rq, Ry, Rz, and Sm, as functions of the four parameters used in this work are deduced as the following final models.

$$\begin{aligned} Ra = {} & 0.5169361 - 0.090489\, x_1 + 0.254787\, x_2 - 0.07797901\, x_4 \\ & + 0.1827869\, x_2^2 \ldots + 0.1827869\, x_4^2 + 0.133125\, x_1x_4 \\ & + 0.198125\, x_2x_4 \ldots \end{aligned} \tag{1}$$

$$\begin{aligned} Rq = {} & 0.7025763 - 0.115926\, x_1 + 0.244362\, x_2 - 0.232686\, x_4 + 0.2050278\, x_2^2 \\ & + 0.2075239\, x_4^2 + 0.17875\, x_1x_4 + 0.27375\, x_2x_4 \end{aligned} \tag{2}$$

$$\begin{aligned} Rz = {} & 2.870282 - 0.52959\, x_1 + 0.56295\, x_2 - 1.06335\, x_4 + 0.6877092\, x_2^2 \\ & + 0.8249893\, x_4^2 + 0.86875\, x_1x_4 + 1.06875\, x_2x_4 \end{aligned} \tag{3}$$

$$Ry = 3.398638 - 0.7047301x_1 - 1.858986\ x_4 + 0.8148062\ x_2^2 + 0.9271264\ x_4^2 + 1.06875\ x_1x_4 - 0.8437498\ x_2x_3 + 1.46875\ x_2x_4 \quad (4)$$

$$Sm = 245.3304 + 11.1756\ x_1 + 70.8066\ x_2 + 12.7602\ x_3 + 9.924601\ x_4 - 9.93171\ x_3^2 - 11.125\ x_1x_2 - 30\ x_1x_4 + 21.25\ x_2x_3 + 8.25\ x_2x_4 \quad (5)$$

Table 3: Experimental design matrix and results of surface profile parameters

Exp. No.	Speed, m/min		Feed, mm/rev		Depth of penetration, mm		No. of passes		Surface profile parameters, µm				
	code	Actual	code	actual	code	actual	code	actual	Ra	Rq	Ry	Rz	Sm
1	-1	25	-1	0.15	-1	0.015	-1	2	1.25	1.76	9.80	6.80	098
2	+1	45	-1	0.15	-1	0.015	-1	2	0.60	0.94	4.90	4.20	296
3	-1	25	+1	0.35	-1	0.015	-1	2	1.58	1.94	10.4	7.90	217
4	+1	45	+1	0.35	-1	0.015	-1	2	0.84	1.02	5.40	3.90	296
5	-1	25	-1	0.15	+1	0.035	-1	2	1.76	2.46	15.8	11.3	109
6	+1	45	-1	0.15	+1	0.035	-1	2	1.00	1.32	8.60	5.30	169
7	-1	25	+1	0.35	+1	0.035	-1	2	1.20	1.40	5.20	4.80	354
8	+1	45	+1	0.35	+1	0.035	-1	2	1.10	1.34	4.30	4.00	353
9	-1	25	-1	0.15	-1	0.015	+1	4	0.36	0.46	0.46	2.20	179
10	+1	45	-1	0.15	-1	0.015	+1	4	0.14	0.20	1.40	1.30	125
11	-1	25	+1	0.35	-1	0.015	+1	4	1.06	1.22	4.50	4.00	352
12	+1	45	+1	0.35	-1	0.015	+1	4	0.80	0.96	0.96	3.50	277
13	-1	25	-1	0.15	+1	0.035	+1	4	0.22	0.30	1.30	1.10	186
14	+1	45	-1	0.15	+1	0.035	+1	4	0.34	0.44	1.80	1.60	167
15	-1	25	+1	0.35	+1	0.035	+1	4	1.12	1.26	4.00	3.70	352
16	+1	45	+1	0.35	+1	0.035	+1	4	1.36	1.56	4.20	5.10	356
17	-2	15	0	0.25	0	0.025	0	3	0.54	0.62	3.10	2.30	194
18	+2	55	0	0.25	0	0.025	0	3	0.64	0.74	4.10	2.40	232
19	0	35	-2	0.05	0	0.025	0	3	0.54	0.68	4.70	2.70	121
20	0	35	+2	0.45	0	0.025	0	3	1.90	2.20	8.10	7.90	356
21	0	35	0	0.25	-2	0.005	0	3	0.32	0.40	2.00	1.50	162
22	0	35	0	0.25	+2	0.045	0	3	0.52	0.60	2.50	2.40	212
25	0	35	0	0.25	0	0.025	-2	1	1.18	1.40	6.80	5.80	172
24	0	35	0	0.25	0	0.025	+2	5	1.26	1.50	6.90	5.90	240
25	0	35	0	0.25	0	0.025	0	3	0.74	1.22	6.40	5.10	217
26	0	35	0	0.25	0	0.025	0	3	0.84	0.76	4.90	3.00	252
27	0	35	0	0.25	0	0.025	0	3	0.38	0.44	2.70	1.50	254
28	0	35	0	0.25	0	0.025	0	3	0.56	0.60	2.50	2.10	253
29	0	35	0	0.25	0	0.025	0	3	0.36	0.44	2.20	3.80	239
30	0	35	0	0.25	0	0.025	0	3	0.38	0.74	2.50	2.80	250
31	0	35	0	0.25	0	0.025	0	3	0.36	0.72	2.60	1.80	253

It can be noted from the above final equations that some coefficients were omitted. These coefficients are non-significant according to Students t-test. The results of t-test are presented in Table 4. The final models which were also tested by variance analysis (F-test) indicate that the adequacy of the model was established (see Table 5).

Table 4: Student's t-test[a]

	Value of coefficient					Computed t-value				
	Ra	Rq	Ry	Rz	Sm	Ra	Rq	Ry	Rz	Sm
b_o	0.51693*	0.70257*	3.398*	2.8702*	245.33*	6.8010	7.0176	5.6065	6.0445	47.9102
b_1	-0.0905*	-0.1159*	-0.704*	-0.5295*	11.175*	2.2030	2.1427	2.1513	2.0638	4.03872
b_2	0.25478*	0.24436*	0.1126	0.56295*	70.806*	6.2031	4.5167	0.3437	2.1938	25.5886
b_3	0.07797*	0.082566	0.3911	0.2043	12.760*	1.8985	1.5261	1.1940	0.79628	4.61137
b_4	-0.1572*	-0.2326*	-1.85*	-1.0633*	9.9246*	3.8274	4.3009	5.6749	4.1439	3.5866
b_{11}	0.02553	0.01533	0.1159	-0.0486	-3.442	0.67966	0.30977	0.3868	0.20707	1.3597
b_{22}	0.18278*	0.2050*	0.8148*	0.6877*	2.9226	4.8644	4.1424	2.7189	2.9295	1.1545
b_{33}	-0.01689	-0.02959	-0.22103	-0.1484	-9.931*	0.4495	0.5979	0.7375	0.63237	3.9233
b_{44}	0.18278*	0.2075*	0.9271*	0.8249*	-5.189*	4.8644	4.1929	3.0937	3.5142	2.0499
b_{12}	0.04062	0.07125	0.1512	0.3187	-11.13*	0.80789	1.0757	0.3771	1.0146	3.2839
b_{13}	0.08562	0.09375	0.3812	0.1937	-6.5	1.7027	1.4154	0.9506	0.61674	1.9187
b_{14}	0.13312*	0.1787*	1.0687*	0.8687*	-30*	2.6474	2.6987	2.6649	2.7653	8.8556
b_{23}	-0.02937	-0.0462	-0.8437*	-0.40625	21.25*	0.5841	0.69828	2.1039	1.2931	6.2727
b_{24}	0.19812*	0.2737*	1.4687*	1.06875*	8.25*	3.940	4.1330	3.6623	3.4020	2.43531
b_{34}	-0.0069	-0.0087	0.0099	-0.13125	3.125	0.1367	0.1321	0.2462	0.4278	0.9224

[a] The standard critical value of the t-test; $t_{0.05,\,16}=2.056$

* The significant coefficient

Results and discussion

Figures 6-11 Show three-dimensional curves , as example, for the effects of various combinations of the internal ball burnishing parameters (burnishing speed, feed, depth of penetration and number of passes) on average roughness (Ra) of 2014 aluminum alloy workpieces that were burnished under dry burnishing conditions. The graphs were constructed from the experimental results using response surface methodology (RSM) and the above final equation (Ra). The same procedure can be applied to study the effect of the internal ball burnishing parameters on the other surface profile parameters.

It is worth mentioning that each curve represents the effects of two input parameters while the other two parameters were kept constant at level 0 (see Tables 2 and 3).

In the following paragraphs, the burnishing results will be discussed in terms of each of the burnishing parameters.

Burnishing speed

The effect of burnishing speed on average roughness at various feeds, depth of penetrations, and number of passes can be assessed from Figures 6-8. It can generally be seen from these Figures. that the surface average roughness decreases slightly with an increase in burnishing speed at any value of feed, depth of penetration and at low number of passes. This is may be due to the stability of the ball burnishing tool at high speeds. The best results from these Figures were obtained at the highest speed used in this work (55 m/min). However, an increase in burnishing speed at high number of passes deteriorates the surface roughness because of the overhardening and consequent flaking of the surface layers. This means that there is an interaction between burnushing speed and number of passes, see Figure 8.

Table 5: F-test[a] for the surface profile parameters

	Source	Sum of squares	Degree of freedom	Mean square	F-ratio
Ra	First –order term	2.345788	4	0.5864469	14.49551
	Second –order term	2.35062	10	0.235062	5.81015
	Lack of fit	1.617618	10	0.1617618	3.998349
	Experiment error	0. 2427429	6	0.04045714	
	Total	6.556768	30(=N-1)		
Rq	Source	Sum of squares	Degree of freedom	Mean square	F-ratio
	First –order term	3.052624	4	0.7631559	10.87264
	Second –order term	4.080958	10	0.4080958	5.814118
	Lack of fit	2.296858	10	0.2296858	3.272321
	Experiment error	0.4211429	6	0.07019048	
	Total	9.851583	30(=N-1)		
Rz	Source	Sum of squares	Degree of freedom	Mean square	F-ratio
	First –order term	41.44104	4	10.36026	6.561082
	Second –order term	76.61003	10	7.661003	4.851661
	Lack of fit	33.67400	10	3.36740	2.132551
	Experiment error	9.474285	6	1.579048	
	Total	161.1994	30(=N-1)		
Ry	Source	Sum of squares	Degree of freedom	Mean square	F-ratio
	First –order term	94.78355	4	23.69589	9.208246
	Second –order term	111.5316	10	11.15316	4.334128
	Lack of fit	102.8368	10	10.28368	3.996250
	Experiment error	15.4400	6	2.573334	
	Total	324.592	30(=N-1)		
Sm	Source	Sum of squares	Degree of freedom	Mean square	F-ratio
	First –order term	129491.4	4	32372.84	176.3044
	Second –order term	44699.32	10	4469.932	24.34351
	Lack of fit	6643.555	10	664.3555	3.618119
	Experiment error	1101.714	6	183.619	
	Total	181935.9	30(=N-1)		

a) The standard valued of F- ratio for the significance level a = 0.05 and degrees of freedom 4 and 6 is $F_{0.05(4,6)} = 4.53$ and at degree of freedom 10 and 6 is $F_{0.05(10,6)} = 4.06$.

Burnishing feed

Burnishing feed is one of the very important internal burnishing parameters that affect the results of this internal ball burnishing tool. It can be seen from Figure 6 and Figure. 9 that for a given burnishing speed, and/or depth of penetrations, the average roughness decreases with an increase in burnishing feed, reaching a minimum value at burnishing feed of (0.15-0.25 mm/rev). A further increase in burnishing feed causes an increase in average roughness. Therefore, low feeds are favourable because the deforming action of the ball burnishing tool is greater and metal flow is regular at low feed.

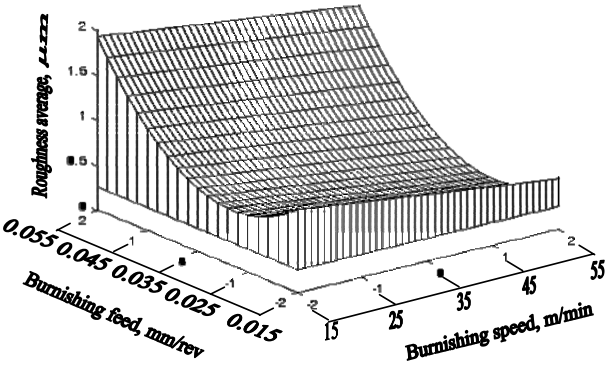


Figure 6: Effect of burnishing speed and feed on surface average roughness

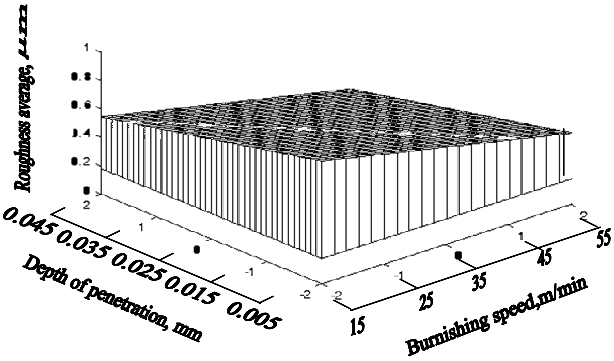


Figure 7: Effect of burnishing speed and depth of penetration on surface average roughness

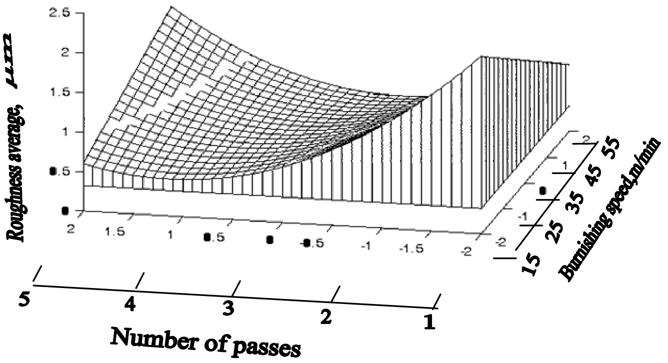


Figure 8: Effect of burnishing speed and number of passes on surface average roughness

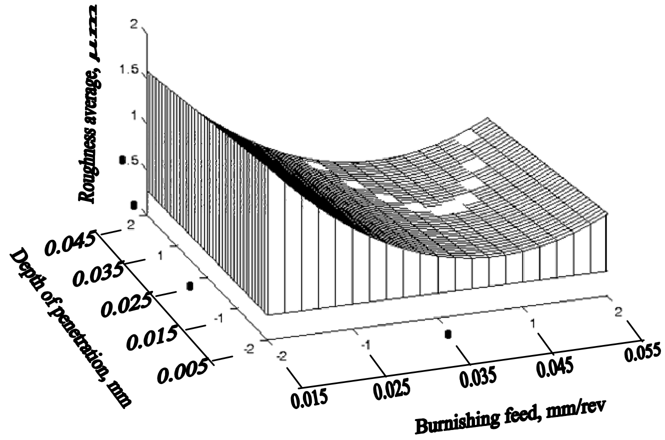


Figure 9: Effect of burnishing feed and depth of penetration on surface average roughness

However, the effect of burnishing feed on the average roughness depends upon the number of passes, see Figure 10. When burnishing at very low number of passes an increase in feed leads to a considerable reduction in surface roughness.

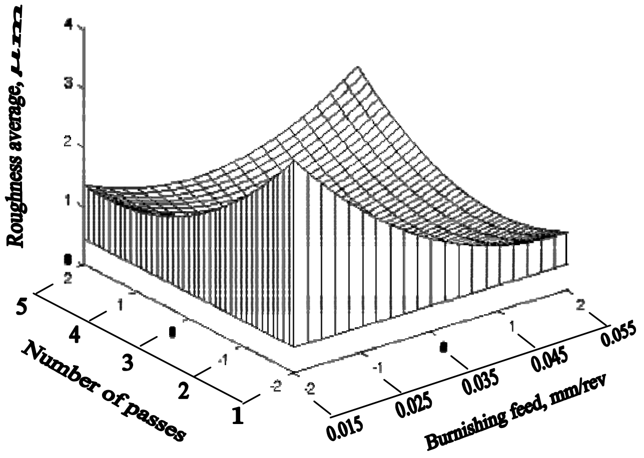


Figure 10: Effect of burnishing feed and number of passes on surface average roughness

A combination between high value of feed and number of passes increases the surface roughness. This may be due to change in contact area between the ball and workpiece which is dependent on the burnishing parameters, especially number of passes. It is recommended that to burnish at low feeds because the deforming action of the internal ball burnishing tool is greather.

Depth of penetration

The effect of depth of penetration on average roughness for different speeds, feeds, and number of passes can be assessed from Figure 7, Figure 9, and Figure 11, respectively.

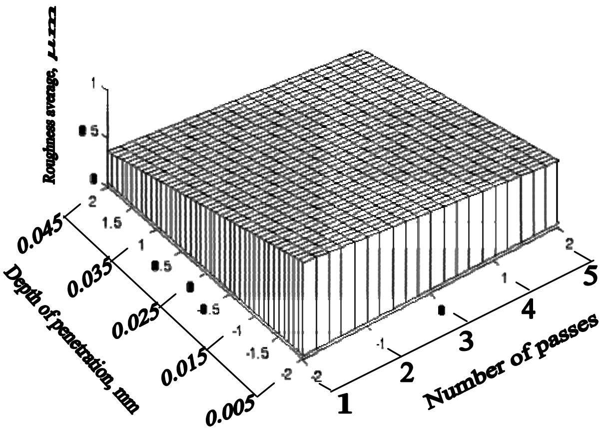


Figure 11: Effect of burnishing depth of penetration and number of passes on surface average roughness

The general trend of the results reveals that an increase in depth of penetration, within the range used in this study, leads to a reduction of the burnished surface average roughness. The reduction in burnished surface roughness can be attributed to the increase of the ball pressure on the workpiece surface resulting in compressing the most aspirities and increasing the metal flow which leads to the filling of more voids and/or valleys that were exited in subsurface layer due to machining operation (internal turning).

Number of passes

Figures 8, 10, and 11 present the effect of the burnishing number of passes on average roughness at various speeds, feeds, and depth of penetration. The results show that the number of passes is one of the most significant factors affecting the surface roughness.

There are two interactions, the first is between number of passes and burnishing speed, as shown in Figure 8. A combination of low burnishing speed with high number of passes leads to a subsantial improvement in the burnished surface average roughness. A combination of high burnishing speed with high number of passes deteriorates the burnished surface finish. It is believed that this occurs because of the over hardening and conseqently flaking of the surface layers.

The second interaction is between number of passes and burnishing feed, as shown in Figure 10. It can be realized that the combination between high number of passes and low feed results in a considerable reduction in burnished surface roughness. This is because of the repeating action of the burnishing process on the same workpiece at low feed which leads to an increase in the surface structural homogeneity resulting in an increase in the surface finish. When carrying out the internal ball burnishing process at high feed, where the irregularity of the metal flow occurs, an increase in number of passes leads to an increase in burnished surface average roughness.

CONCLUSIONS

The present work has led to the following conclusions:

1- Inner surface finishing of non-ferrous metals which are difficult-to-grind with conventional grinding-could be carried out successfully using the proposed internal ball burnishing tool. The technique is simple, easy to apply and economical.

2- Second-order surface profile parameters prediction models have been developed. Analysis of variance has indicated that these models are adequate for the obtained experimental results.

3- An increase in internal ball burnishing speed leads to a slight decrease in surface average roughness.

4- The results have revealed that the effect of burnishing feed is much more pronounced than the effects of burnishing speed on surface average roughness. An increase in internal burnishing feed leads to a decrease in surface average roughness, reaching a minimum value at burnishing feed of (0.15 - 0.25 mm/rev). A further increase in burnishing feed causes an increase in average roughness.

5- The best results for average roughness is obtained when applying high depth of penetration.

6- Number of passes interacts with both burnishing speed and burnishing feed. The best results obtained at both high number of passes with low burnishing speed and/or high number of passes with low burnishing feed.

7- The results can be interpreted in terms of the workpiece overhardening. Flaking generally occurs when using a combination of high burnishing speed with a high number of passes, and the great deforming action of the internal ball tool and the increase of structural homogeneity of the surface layers that occurs when using low burnishing feed.

8- Response surface methodology with the central composite second-order rotatable design is a better alternative than the traditional-one-variable-at-a-time approach. This provide a large amount of information with less number of experiments.

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