Experimental techniques for studying the effects of milling roller-burnishing parameters on surface integrity

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Roller-burnishing is used in place of other traditional methods to finish 6060-T6 Aluminum alloy. How to select the burnishing parameters to improve surface integrity (reduce surface roughness, increase surface microhardness and produce compressive residual stress) is especially crucial. This paper presents an investigation of the effect of roller-burnishing process upon surface roughness, surface microhardness and residual stress of 6061-T6 Aluminum alloy. The residual stress distribution in the surface region that was burnished is determined using a deflection-etching technique. Mathematical models correlating three process parameters; burnishing speed, burnishing depth of penetration and number of passes are established. A Group Method of Data Handling Technique, GMDH, is used. It is shown that low burnishing speed and high depth of penetration produce much better surface finish, whereas a combination of high speed with high depth leads to less surface finish because of chatter. The optimum number of passes that produces a good surface finish was found to be 3 or 4. The maximum value of compressive residual stress decreases with an increase in burnishing speed. The maximum compressive residual stress increases with an increase in burnishing depth of penetration and/or number of passes.

تم فى هذا البحث دراسة بعض عوامل عملية الصقل التدحرجى باستخدام ماكينة الفريزة الرأسية مثل (سرعة الصقل، مقدار عمق التغلغل ، و عدد المشاوير) على بعض عناصر تكاملية السطح الناتج مثل (خشونة السطح ، صلادة السطح و الجهود المتبقية) لسبيكة الألومنيوم 6061-T6. حيث تم معرفة توزيع الجهود المتبقية فى منطقة السطح المصقول بأستخدام طريقة التحليل الكيميائى. تم استنتاج نماذج رياضية تربط بين متغيرات عملية الصقل مع كل من نواتج هذه العملية وذلك بأستخدام طريقة المجموعات لأستخدام البيانات . أوضحت نتائج البحث انه باستخدام سرعة صقل منخفضة أو/مع مقدار تغلغل منخفض يمكن الحصول على سطح افضل بينما استخدام سرعات عالية مع تغلغل عالى يؤدى إلى جودة منخفضة للسطح. كذلك اوضحت نتائج البحث ان عدد المشاوير المثالى للحصول على سطح ذو جودة عالية يتراوح بين ٣-٤ مشوار. كذلك بين البحث ان القيمة العظمى للجهود المتبقية (جهود ضغط) تتناقص مع زيادة سرعة الصقل وتزداد مع زيادة كل من مقدار التغلغل و/ أو عدد المشاوير وذلك فى حدود القيم المستخدمة للمتغيرات فى هذه الدراسة

Keywords: Roller burnishing, Milling, Surface integrity, GMDH method.

1. Introduction

It appears that it is the outer layer, small in volume relative to the core, that determines major functional properties such as: friction, grindability, corrosively, fatigue life, load capacity. Improper physical and stereometrical properties of the outer layer cause failure damage in approximately 85% of the modern machine units [1].

During recent years, considerable attention has been paid to the post-machining metal finishing operations, to form the outer layer, such as burnishing rolling which improves the surface characteristics by plastic deformation of the surface layers[2]. Beside producing a good surface finish, the burnishing process has additional advantages over other machining processes, such as securing increased hardness, corrosion resistance and fatigue life as result of the producing compressive residual stress. Residual stresses are probably the most important aspect in assessing integrity

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because of their direct influence on performance in service, compressive residual stresses generally improve component performance and life because they reduced service (working) tensile stresses and inhibit crack nucleation and propagation. However, tensile residual stress significantly increase service (working) stress which can lead to premature failure of component. Thus control of the burnishing conditions of the burnishing process in such a way as to produce compressive residual stresses in the surface region could lead to considerable improvement in component life.

These advantages of burnishing and, further, the efficiency, the simple construction of tooling, the economy, and the possibility of using typical machine tools in the process and work parts of various types made of various materials (even of cast iron [1]), make the burnishing process attractive in comparison with abrasive-methods such as grinding, honing, super-finishing and polishing.

A literature survey shows that work on the burnishing process has been conducted by many researchers and the process also improves the properties of the parts, e.g. wear resistance [3,4] hardness [5-7], surface quality [2,8,9] and increased maximum residual stress in compression [10-12].The parameters affecting the surface finish are: burnishing force, feed rate, ball material, number of passes, workpiece material, and lubrication [2].

Majority of the research existing in literature on the effect of burnishing parameters on burnished surface have been experimental in nature. Very few analytical models are available. A much better strategy calls for the use of experimental design such as a factorial design in which all the factors are varied simultaneously. This factorial design concept is powerful experiment design strategy. Response surface methodology (RSM) is another systematic method for using the influential factors in a process for improvement and optimization.

Accordingly, it is very clear that information concerning surface integrity (surface quality, surface microhardness, and residual stresses) of the burnished surface region will be very valuable in the design and manufacture of parts.

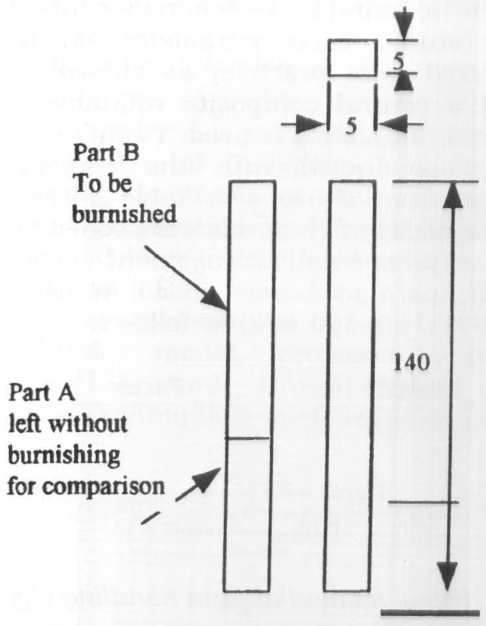
This paper studies the use of the roller burnishing process to improve surface integrity for 6061 Aluminum alloy through vertical milling machine. To explore the optimum combination of burnishing parameters in an efficient and quantitative manner, the experiments were designed based on the response surface methodology (RSM) with central composite rotatable design and mathematical model was developed through GMDH technique which is applied for the first time in this area. The effect of three mill-burnishing parameters, namely; mill-burnishing speed, depth of penetration, and number of passes on the burnished surface finish, microhardness and residual stress were investigated using the derived mathematical models.

2. Experimental work

In this study, workpieces of 6061 Aluminum alloy were used. The chemical composition in weight percent is shown in table 1. This material was chosen because of its importance in industry and its susceptibility to degradation when burnished, through surface and subsurface damage. Aluminum alloys are particularly well suited for parts and structures requiring high strength-to-weight ratio and is probably the best known material used extensively in aircraft's and truck wheels. The work material was received in the form of strips having a cross section of 6 x 6mm with 140mm length. The as-received material was first machined on a milling machine to the dimensions shown in fig. 1. The surface roughness of the milling process was measured for each specimen and was found in the range from 2.25 to 3.2 μm (R_a). Also, the initial hardness was measured and found in the range from 170 to 173 HV.

The workpieces were then prepared with two parts A and B (fig. 1). Part A was left without burnishing for the purpose of comparison. In the burnishing tests, the specimens were held rigidly in a specially-designed fixture which is shown in Fig. 2. fig. 3 shows a specially-designed burnishing tool. It consists of two parts which the first one is tapered to match the inside tapered part of milling machine spindle and the other part is made to hold the roller freely. It should be pointed out here that the spindle of the milling machine was not rotated during the burnishing tests. However, the rollers were obviously rotated about their axis as a result of the friction between the roller and workpiece surfaces.

The first independent parameter chosen was the burnishing speed (V). In this study five burnishing speeds in the range from 63 to 160 mm/min were used. The second parameter chosen was the burnishing depth. Five depths were used in this study, ranging from 0.05 to 0.25 mm. The third parameter chosen was the number of passes. Five different passes from 1 to 5 were carried out in this work to study their effects on the produced surface characteristics. The burnishing conditions used in this work is summarized in table 2.



Dimensions in mm

Fig. 1. Geometry of workpiece

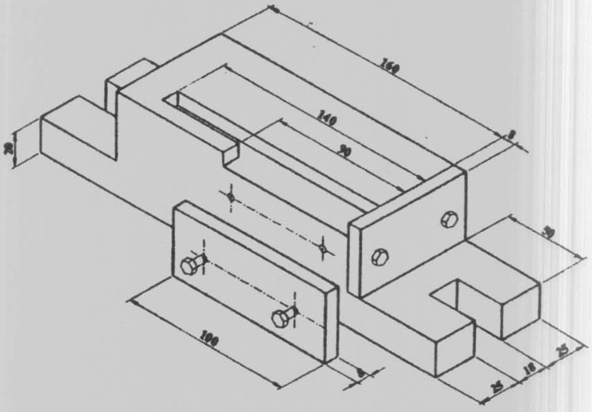


Fig. 2. A specially designed fixture.

Table 1
The chemical composition in weight percent for 6061-aluminum alloy

Si	Fe	Cu	Mn	Mg	Cr	Zn	Ti	Al
0.6	0.7	0.25	0.15	1.0	0.35	0.25	0.15	Balance

Table 2
Summary of burnishing conditions

Parameters	Symbol	Levels in code form				
		-1.652	-1	0	1	1.652
Burnishing speed, mm/min	X_1	63	80	100	125	160
Burnishing depth, mm	X_2	0.05	0.10	0.15	0.20	0.25
Number of passes	X_3	1	2	3	4	5
Burnishing condition		Lubricated				

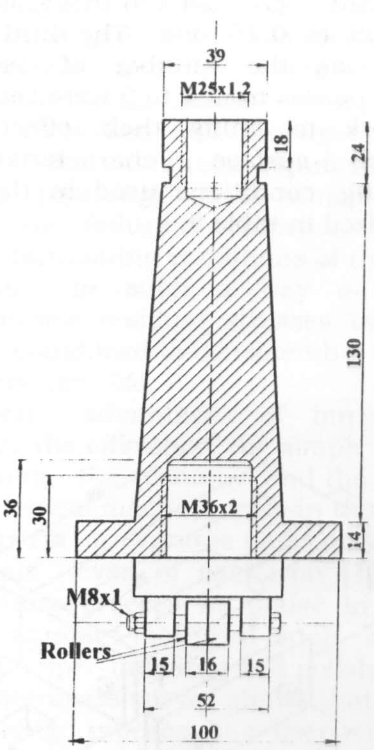


Fig. 3. A specially designed tool.

Surface roughness, surface microhardness and residual stresses were carefully measured using standard techniques. The arithmetic average surface roughness was measured on the burnished surface of the workpieces in the direction parallel to the direction of relative tool-motion. The measurements were made for all surfaces on a surftest-402 system. A microhardness tester (Shimadzu Micro Hardness tester Type-M) was used to measure the microhardness of the burnished surface along the length of each test strip. The electrolytic etching-deflection technique is used for the determination of the average residual stress distribution in the burnished surface region [13]. The deflection etching technique is based on the fact that a burnished component which contains residual stresses will undergo a change in shape as the layer of material are removed from the surface. As the burnished surface layer are removed by electrolysis, the stresses are relieved and the remaining stresses are redistributed until a new equilibrium position is reached. This change in shape can be measured from which residual stresses can be calculated.

3. Experimental design and analysis

It is necessary to investigate the effect of the burnishing process parameters used in this work and their interactions. Therefore, a more simple and adequate experimental design; response surface methodology (RSM) with the Box and Hunter method [14], is found to be a suitable technique for this study. In the study, each parameter has five levels selected from practice, as shown in table 2, and a central composite rotatable design as shown in table 3 is used. Twenty experiments were conducted with the combination of values that shown in table 2. The values of each of the five levels were coded to simplify the experimental arrangement . The range of each parameter was coded in five levels (-1.682, -1, 0, 1, 1.682) as follows:

$$X_1 = \frac{\text{Speed} - 100}{20}, \qquad X_2 = \frac{\text{Passes} - 3}{1},$$

and $X_3 = \dfrac{\text{Depth} - 0.15}{0.05}$.

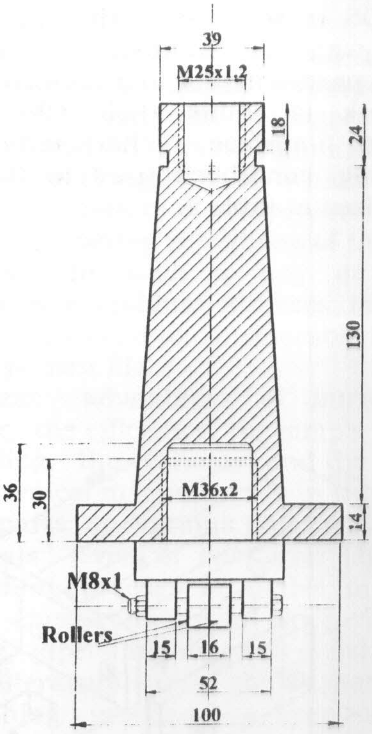
3.1. Group method of data handling algorithm

In order to determine the independent, interactive, and higher-order effects of the different variables on the burnished surface roughness, hardness, and maximum residual stress, a special technique of partial description that can be adopted to present the response surface function is the Group Method of Data Handling (GMDH) [15].

The GMDH procedure uses partial description in the form of second order polynomial with

$$Y_k = b_0 + b_1 X_i + b_2 X_j + b_3 X_i^2 + b_4 X_j^2 + b_5 X_i X_j,$$

where Y_k denoting an intermediate variables and X_i, X_j are the input variables to develop a model that successively approximates to complete description. Fig. 4 shows the flow



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where Y_k denoting an intermediate variables and X_i, X_j are the input variables to develop a model that successively approximates to complete description. Fig. 4 shows the flow diagram for computer analysis of the GMDH technique.

4. Models , results and discussion

Table 3 shows the arrangement and the results of the twenty experiments carried out in this investigation based on central composed second order rotatable design. These results are used to deduce the mathematical models that is one of the main objectives of this work.

4.1. Mathematical models

This section presents a study of the development of response models for burnishing in terms of burnishing speed, depth of penetration and number of passes. These models are developed utilizing Group Method of Data Handling Technique. A comparison between the results of both the second-order model, proposed by Box and Hunter [13], and Group Method of Data Handling Technique is made through the mean square error. All results showed that GMDH models are more accurate than that of Box and Hunter. Table 4 shows, as example, the predicted results of both models for the burnishing roughness, R_a, (center line average). It can be seen from the end of the table that the mean square error of GMDH model is less than that of Box and Hunter model. This means that the GMDH algorithm is more accurate. The same result was obtained for the other responses. Therefore, the present paper shows the proposed mathematical models utilizing the GMDH technique for all responses and Box and Hunter model only for mean roughness, as example.

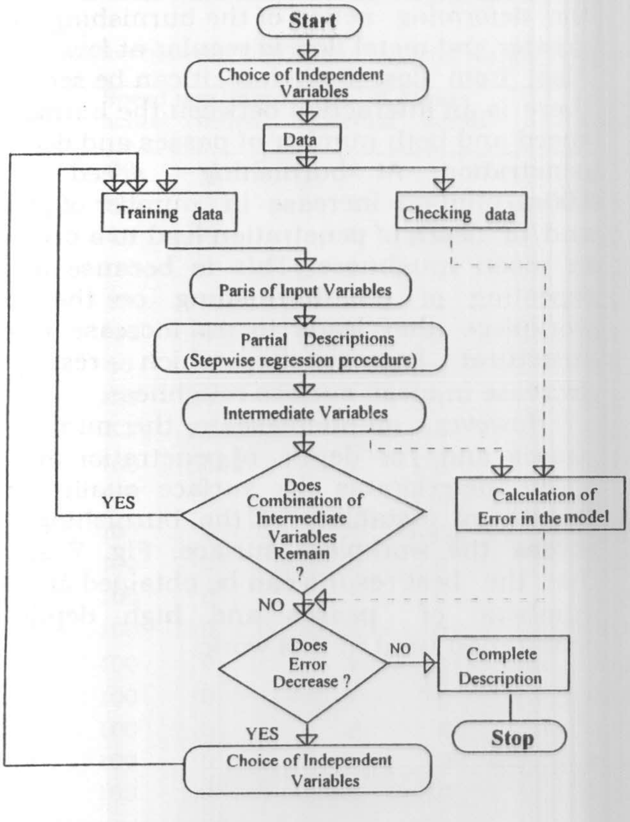

Fig. 4. A flow chart for the GMDH algorithm.

Box and Hunter model for mean roughness;

$$Ra = 0.3703 - 0.1235X_1 - 0.1336X_2 - 0.1302X_3 + 0.1359X_1^2 + 0.1907X_2^2. \quad (1)$$

GMDH model for mean roughness:

$$Ra(actual) = 0.52685Ra + 0.52685$$

The partial descriptions for each layer as follows; In the third layer:

$$Ra = -0.5181 + 12.33U_1 - 11.67U_3 + 1180.57U_1^2 + 1127.56U_3^2 - 1207.48U_1U_3. \quad (3)$$

In the second layer:

$$U_1 = -0.00467 + 1.0615Y_1 + 1.0382Y_2$$
$$U_3 = -0.0000127 + 0.00718Y_2 + 0.9957Y_3.$$

In the first layer:

$$Y_1 = -0.0239 - 0.0371X_1 - 0.7514X_2,$$
$$Y_2 = 0.0797 - 0.3365X_1 - 0.9266X_3,$$
$$Y_3 = 0.0503 - 0.7886X_2 - 0.9555X_3.$$

GMDH model for Microhardness:

$$Hv(actual) = 200.55Hv + 200.55 .$$

The partial descriptions for each layer as follows; In the second layer:

$$Hv = 0.00876 + 0.684Y_1 + 0.6383Y_2 - 0.426Y_1^2 . \quad (4)$$

In the first layer:

$$Y_1 = 0.0046 - 0.293X_1 + 0.208X_2,$$
$$Y_2 = -0.186 - 0.305X_1 + 0.1902X_3 + 0.0037X_1^2,$$

GMDH model for residual stress:

$$\sigma_{max}\,(\text{actual}) = 15.445\sigma_{max} + 15.445\,.$$

The partial descriptions for each layer as follows; In the third layer:

$$\sigma_{max} = 0.002515 + 0.4719U_1 + 0.5907U_2\,. \tag{5}$$

In the second layer:

$$U_1 = 0.00644 + 0.5208Y_1 + 0.6397Y_2$$
$$U_2 = 0.04298 + 0.7136Y_1 + 0.6365Y_3 - 0.1943Y_1^2$$

In the first layer:

$$Y_1 = 0.02197 - 1.3807X_1 + 0.5278X_2,$$
$$Y_2 = -0.0455 - 1.3933X_1 + 0.5891X_3,$$
$$Y_3 = -0.0697 + 0.6699X_2 + 0.6992X_3 - 0.00448X_2.$$

The proposed model of maximum residual stress, σ_{max} as example, can be applied firstly by substituting the values of the input parameters (X_1, X_2, and X_3) into the first layer equations (Y_1, Y_2, and Y_3). Secondly, the obtained values of the first layer then can be substituting into the second layer equations (U_1 and U_2), and so on until σ_{max} equation is reached. The latter value of σ_{max} is a normalized value which should be converted into actual value using the σ_{max} (actual) equation.

Similarly, this procedure can be applied for surface roughness and microhardness models.

4.2. Results and discussion

GMDH models obtained in the previous section were used to show the relationship between both burnishing parameters and burnishing responses. In this section the main results and their reasons will be presented and discussed.

4.2.1. Mean roughness

Fig. 5 and 6 show the effect of the burnishing speed on the burnished surface roughness at various number of passes and depth of penetration. In general, An increase in burnishing speed up to about 100m/min leads to a decrease in mean roughness. With a further increase in burnishing speed mean roughness gradually increases. The deterioration of the surface roughness in the burnishing process at high burnishing speeds (as shown in figs. 5 and 6) is believed to be caused by the chatter that results in instability of the burnishing tool across the workpiece surface. In addition, the low surface roughness can be interpreted by the low deforming action of the rollers at high speeds and also because the lubricant looses its effect due to the insufficient time for it to penetrate between the roller and the workpiece surfaces. It is better then to select low speeds because the deforming action of the burnishing tool is greater and metal flow is regular at low speed. Also, from figs. 5 and 6 it can be seen that there is an interaction between the burnishing speed and both number of passes and depth of penetration. At burnishing speed up to 100m/min an increase in number of passes and/or depth of penetration lead to a decrease in mean roughness. This is because of the repeating of the burnishing on the same workpiece that leads to an increase in the structural homogeneity which results a decrease in mean surface roughness.

However, an increase in the number of passes and /or depth of penetration at high speed deteriorates the surface quality as a results of instability of the burnishing tool across the workpiece surface. Fig. 7 shows that the best results can be obtained at three numbers of passes and high depth of penetration used in this work.

Table 3
Experimental results

Exp. No.	Speed,mm/min		No. of passes		Depth, mm		Surface roughness, μm	Micro - hardness, HV	Comp. residual stress MPa
	actual	coded	actual	coded	actual	coded			
1	80	-1	2	-1	0.1	-1	0.39	200	21.01
2	125	+1	2	-1	0.1	-1	0.35	178	6.427
3	80	-1	2	-1	0.2	+1	0.30	240	23.98
4	125	+1	2	-1	0.2	+1	0.14	200	4.285
5	80	-1	4	+1	0.1	-1	0.20	204	23.69
6	125	+1	4	+1	0.1	-1	0.25	184	23.62
7	80	-1	4	+1	0.2	+1	0.10	265	23.67
8	125	+1	4	+1	0.2	+1	0.22	245	3.226
9	63	-1.682	3	0	0.15	0	1.34	270	30.02
10	160	1.682	3	0	0.15	0	0.61	180	7.729
11	100	0	3	0	0.05	-1.862	0.26	180	17.43
12	100	0	3	0	0.25	+1.682	1.50	200	18.46
13	100	0	1	-1.682	0.15	0	0.42	150	25.69
14	100	0	5	+1.682	0.15	0	0.77	240	20.26
15	100	0	3	0	0.15	0	0.75	195	15.79
16	100	0	3	0	0.15	0	0.67	170	6.230
17	100	0	3	0	0.15	0	0.77	150	15.18
18	100	0	3	0	0.15	0	0.57	170	21.44
19	100	0	3	0	0.15	0	0.71	195	13.76
20	100	0	3	0	0.15	0	0.77	195	24.08

Table 4
Comparison between GMDH and Box and Hunter results for R_a

Exp. No.	Speed,mm/min		No. of passes		Depth, mm		Surface roughness, μm	GMDH Results	Box and Hunter Results
	actual	coded	Actual	coded	actual	coded			
1	80	-1	2	-1	0.1	-1	0.69	0.743	0.824
2	125	+1	2	-1	0.1	-1	0.45	0.384	0.577
3	80	-1	2	-1	0.2	+1	0.40	0.599	0.557
4	125	+1	2	-1	0.2	+1	0.32	0.324	0.309
5	80	-1	4	+1	0.1	-1	0.35	0.719	1.084
6	125	+1	4	+1	0.1	-1	0.25	0.253	0.837
7	80	-1	4	+1	0.2	+1	0.24	0.180	0.817
8	125	+1	4	+1	0.2	+1	0.20	0.471	0.570
9	63	-1.682	3	0	0.15	0	1.44	1.189	0.963
10	160	1.682	3	0	0.15	0	0.71	0.760	0.547
11	100	0	1	-1.682	0.15	0	1.60	1.010	1.134
12	100	0	5	+1.682	0.15	0	0.86	0.770	0.685
13	100	0	3	0	0.05	-1.862	0.67	0.940	0.151
14	100	0	3	0	0.25	+1.682	0.10	0.140	0.589
15	100	0	3	0	0.15	0	0.45	0.360	0.370
16	100	0	3	0	0.15	0	0.56	0.350	0.370
17	100	0	3	0	0.15	0	0.57	0.340	0.370
18	100	0	3	0	0.15	0	0.27	0.340	0.370
19	100	0	3	0	0.15	0	0.31	0.359	0.370
20	100	0	3	0	0.15	0	0.27	0.428	0.370
Mean square error								0.07199	0.1309

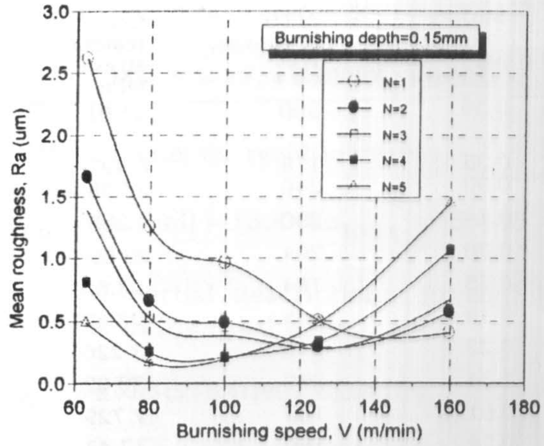

Fig. 5. Mean roughness vs. burnishing speed at different numbers of passes.

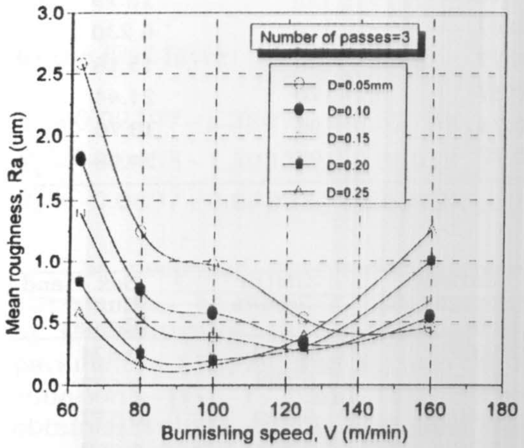

Fig. 6. Microhardness vs. burnishing speed at different numbers of passes.

4.2.2. Microhardness

Figs. 8 and 9 show the effects of the burnishing speed on the microhardness of the burnished surface at different number of passes and depth of penetration, respectively. The microhardness of the surface considerably decreases with increasing burnishing speed within the range used in this work. It is believed that the deforming action of the roller decreases with an increase in burnishing speed. From the same figs. 8, 9 and fig. 10, it can be seen that microhardness increases with an increase in number of passes and/or depth of penetration.

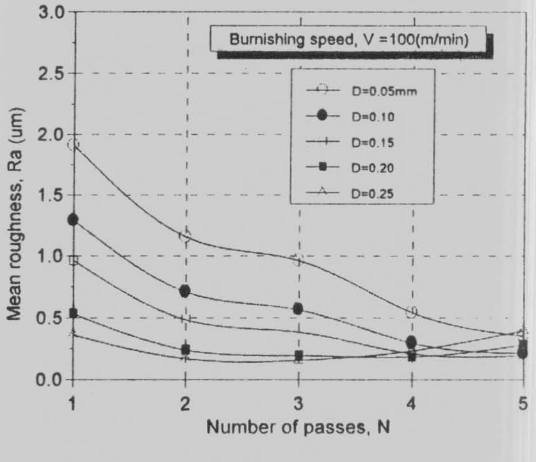

Fig. 7. Mean roughness vs. number of passes at different depths of penetration.

The highest surface microhardness was obtained with the combination of high number of passes and high depth of penetration used in this work. It is believed that the increase of the number of passes increases the surface microhardness at high speed beside low speed as a result of the increasing impact between the burnishing tool and workpiece surface.

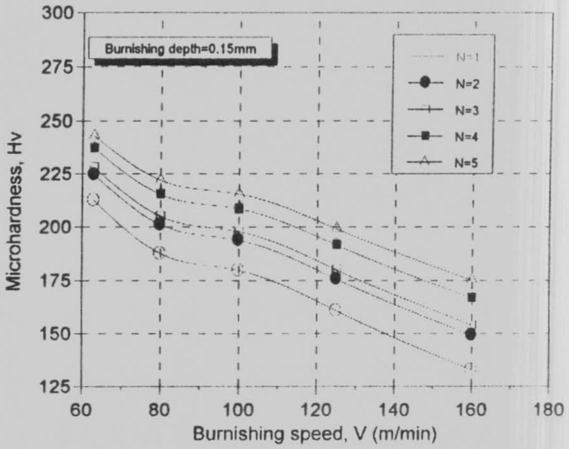

Fig. 8. Microhardnesss vs. burnishing speed at different numbers of passes.

The increase in burnishing depth of penetration causes an increase in the amount of surface deformation as the tool passes along the surface of the workpiece. This will lead to an increase in the work hardening of the surface layers, which have been affected by plastic deformation, so that surface microhardness will increase via the increase in burnishing depth of penetration, as shown in fig. 10.

4.2.3. Residual stress

The effects of burnishing speed on the maximum residual stress at different number of passes and depth of penetration are shown in figs. 11 and 12, respectively. It can be seen that an increase in burnishing speed within the range used in this work produces a significant decrease in the maximum compressive residual stress and may be changed gradually to tensile. This is because of the decrease in the deforming action of the roller burnishing tool with the increase in burnishing speed.

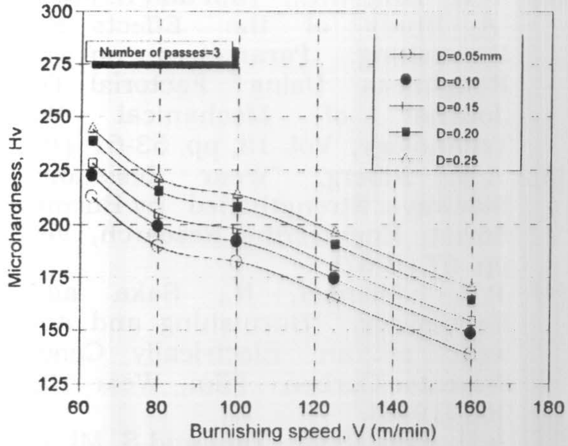

Fig. 9. Microhardnesss vs. burnishing speed at different depths of penetration.

It is well known [10] that the generation of residual stress depends upon the interplay of many factors-such as in homogeneous plastic deformation induced by mechanical and thermal events associated with the process. The increase in the deformation action of the roller burnishing tool at low speed produces high plastic deformation at the burnished surface which leads to compressive residual stress. figs. 11 and 12 show that maximum compressive residual stress increases with an increase in number of passes and /or depth of penetration. The increase in the number of passes and/or burnishing depth of penetration produces an increase in both the depth of plastic deformation in the surface region and extent of surface work hardening. It is believed that the increase in surface region deformation brought about the maximum residual stress, as may be seen in fig. 13. The highest value of compressive residual stress was obtained with the combination of high number of passes and high depth of penetration.

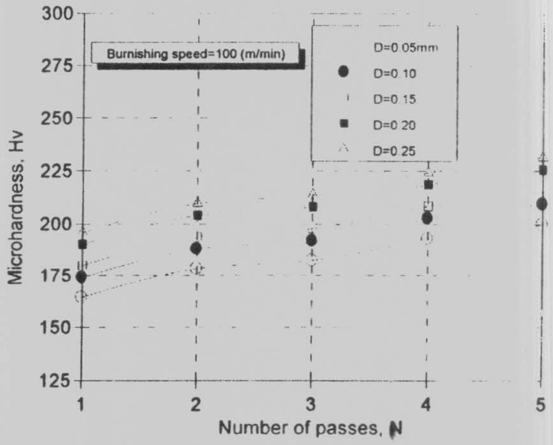

Fig. 10. Microhardnesss vs. number of passes at different depths of penetration.

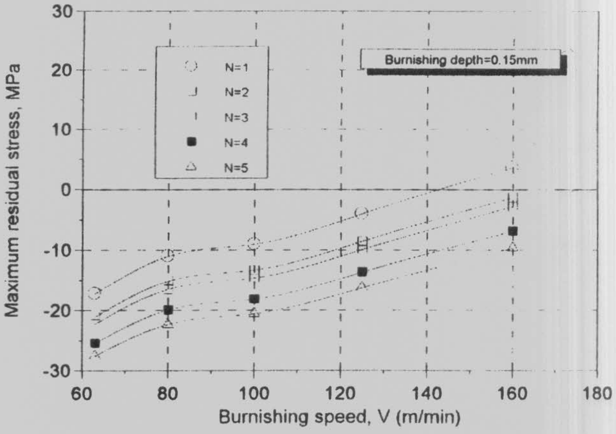

Fig. 11. Maximum residual stress vs. burnishing speed at different numbers of passes.

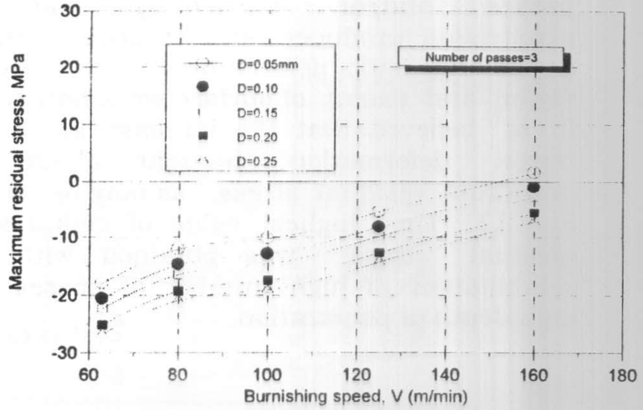

Fig. 12. Maximum residual stress vs. burnishing speed at different depths of penetration.

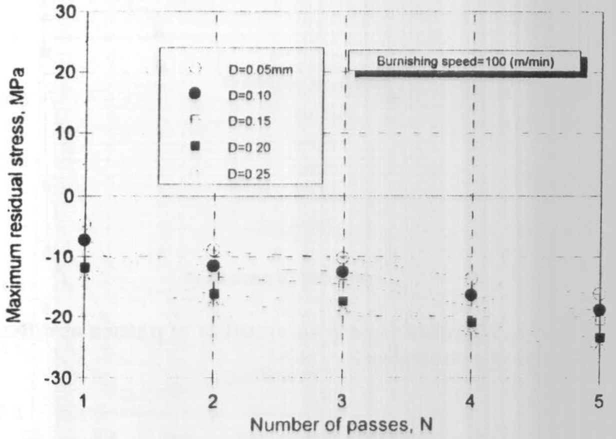

Fig. 13. Maximum residual stress vs. number of passes at different depths of penetration.

5. Conclusions

According to this study, the following conclusions may be drawn:

1. The mathematical models for burnishing responses (mean roughness, burnished surface microhardness, and maximum residual stress) are identified by GMDH considering burnishing speed, depth of penetration and number of passes.
2. The established models are useful in improving the quality of the burnished surface responses which can be predicted by selecting proper input parameters that used in this work before conducting out burnishing process.
3. The extent of the influence of selected variables on all burnished surface responses can be deduced quantitatively from the models.
4. Increasing both number of passes and burnishing depth of penetration within the range used in this work is very useful for all responses studied.
5. Burnishing speed should not exceed about 120m/min to obtain high surface quality.

References

[1] L. Kukielka, "Designating the Field Areas for the Contact of A Rotary Burnishing Element with the Rough Surface of A Part, Providing A High-Quality Product", Journal of Mechanical Technology, Vol. 19, pp. 319-356 (1989).

[2] N.H. Loh, S.C., Tam and S. Miyazawa, "A Study of the Effects of Ball-Burnishing Parameters on Surface Roughness Using Factorial Design", Journal of Mechanical Working Technology, Vol. 18, pp. 53-61 (1989).

[3] A.N. Niberg, "Wear Resistance of Sideways Strengthened by Burnishing", Soviet Engineering Research, Vol. 7(5) pp. 67 (1987).

[4] P.C. Michael, N., Saka and E. Rabinowicz, "Burnishing and Adhesive wear of an Electrically Conductive Polyester-Carbon Film, Wear 132, pp. 265 (1989).

[5] N.H. Loh, S.C. Tam and S. Miyazawa, "Statistical Analyses of the Effects of Ball Burnishing Parameters on Surface Hardness", Wear 129, pp. 235 (1989).

[6] I. Yashcheritsyn, E.I. Pyatosin and V.V. Votchuga, " Hereditary Influence of Pre-Treatment on Roller-Burnishing Surface Wear Resistance" Soviet Journal of Friction and Wear, Vol. 8 (2), pp. 87 (1987).

[7] M. Fattouh, M.H. El-Axir and S.M. Serage, " Investigation Into the Burnishing of External Cylindrical Surface of 70/30 Cu-Zn-Alloy", Wear. pp. 127 (1988).

[8] Miyazawa, "An Investigation Into the Ball Burnishing of an AISI 1045 Free-Form Surface", Journal of Materials

Processing Technology, Vol. 29, pp. 203 (1992).

[9] S.S.G. Lee, S.C. Tam and N.H. Loh, "Ball Burnishing of 316L Stainless Steel", Journal of Materials Processing Technology, 37, pp. 241 (1993).

[10] M. Fattouh and M.M. El-Khabeery, "Residual Stress Distribution in Burnishing Solution Treated and Aged 7075 Aluminum Alloy", Int. J. Mach. Tools Manufact., Vol. 29 (1), pp. 153 (1989).

[11] F. Klocke and J. Liermann "Roller Burnishing of Hard Turned Surface", Int. J. Mach. Tools Manufact., Vol. 38 (5-6), pp. 419 (1998).

[12] S. Mittal and C.R. Liu "A Method of Modeling Residual Stresses in Superfinish Hard Turning", Wear, 218, pp. 21 (1998).

[13] A.B. Sadat and J.A. Bailey, "Residual Steess Distribution in Machining Annealed 18% Nickel Maraging Steel", Trans. ASME, J. of Enfineering Material and Tech., Vol. 180 (2), pp. 93 (1986).

[14] M.N. Das and N.G. Giri, "Design and Analysis of Experiments", John Wiley & Sons, New York, Second Edition (1980).

[15] A.G. Ivakhnenko, M.M. Todua and Yu. V. Chukin, "GMDH Algorithm with Successive Determination of Polynomial Trends Using the Most Essential Variables", Soviet Automatic Control, Vol. 5 (2) (1972).

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