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Modeling the Abrasive Flow Machining Process (AFM) on Aluminum Alloy

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ABSTRACT

Abrasive flow machining (AFM) is gaining wide spread application finishing process on difficult to reach surfaces in aviation, automobiles, and tooling industry. A multiple regression model is proposed by using SPSS to simulate and predict the surface roughness, and material removal for different machining conditions in (AFM) on aluminum alloys. Based upon the experimental data of the effects of AFM process parameters, e.g., length of stroke, extrusion pressure, number of cycles, percentage of abrasive concentration, and abrasive grain size. The mathematical models for Ra, and material removal are established to investigate the influence of AFM parameters. Conformation test results verify the effectiveness of these models and optimal parametric combination within the considered range. The statistical model could predict about 96.1%, and 99.38% accuracy.

تمثيل عملية أنسياب المادة الحاكة على سبيكة المنيوم

الخلاصة

يكتسب التشغيل بأنسياب المادة الحاكة تطبيقات واسعة للوصول الى السطوح المعقدة والتي لايمكن تشغيلها بالطرق التقليدية في مجال الطيران , السيارات وصناعة العدد وغيرها.تم اقتراح نموذج الانحدار المتعدد بواسطة برنامج احصائي لمحاكاة والتنبؤ بالخشونة السطحية ومعدل ازالة المعدن في ظروف تشغيل مختلفة على سبائك من الالمنيوم.بالاعتماد على بيانات الاختبارات الناتجة من طول الشوط, ضغط البثق,عدد الدورات, نسبة تركيز المادة الحاكة و حجم حبيبة المادة الحاكة.

النموذج الرياضي انشأ بالاستناد على تأثير اعتبارات العملية. نتائج اختبار العملية للبرنامج الاحصائي للتنبؤكانت ذات دقة 96.1% للخشونة السطحية و 99.38%للمادة المزالة.

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INTRODUCTION

Abrasive flow machining (AFM) is a non-traditional finishing process that performs critical deburring and polishing operation by forcing abrasive-laden viscoelastic putty across the workpiece surface. In AFM, two vertically opposed cylinders Figure (1) extrude medium back and forth through passages formed between the workpiece and tooling.[1] Two cylinder strokes, one from the lower cylinder and one from the upper cylinder ,make up one process cycle .Both semiautomatic machines and high-production fully automated system are widely used. AFM process is an efficient method of the inner surface finishing process. In practical application, it has an obvious effect on surface finishing of the industrial valves, and the parts/components of die, etc [2].

Abrasive flow machining (AFM) was developed by Extrude Hone Corporation, USA in 1960. There are three types of AFM machines that have been reported in the literature: one way AFM, two way AFM and orbital AFM. Commonly used AFM is Two-way AFM in which two vertically opposed cylinders extrude medium back and forth through passages formed by the workpiece and tooling [3]. AFM has three major elements, namely, the machine, workpiece fixture (tooling), and media. The machine in a typical two –way AFM flow process hydraulically clamps the work holding fixtures between two vertically opposed media cylinder. These cylinders extrude abrasive laden semisolid pliable substance known as the media back and forth through the workpiece [4].

H.S.Mali and A.Manna (2012) presents the use of artificial neural networks (ANN) for modeling and simulation of response characteristics during AFM process in finishing of Al/SiCp metal matrix composites (MMCs) components [5]. J. Kenda et.al (2011) present the influence of the process parameters on surface integrity, i.e. surface roughness and induced residual stresses, is investigated. The electrical discharge pre-machined hardened tool steel AISI D2 samples have been used to be processed with AFM [6]. M.R.Sankare et.al (2011) Presented different media are made using specially co-polymered soft styrene butadiene based polymer, plasticizer and abrasives. Static and dynamic rheological properties of these in-house prepared media are evaluated, and it is found that these media follow viscoelastic behavior with shear thinning nature. For a small rise in temperature, the medium starts losing its original properties [7].

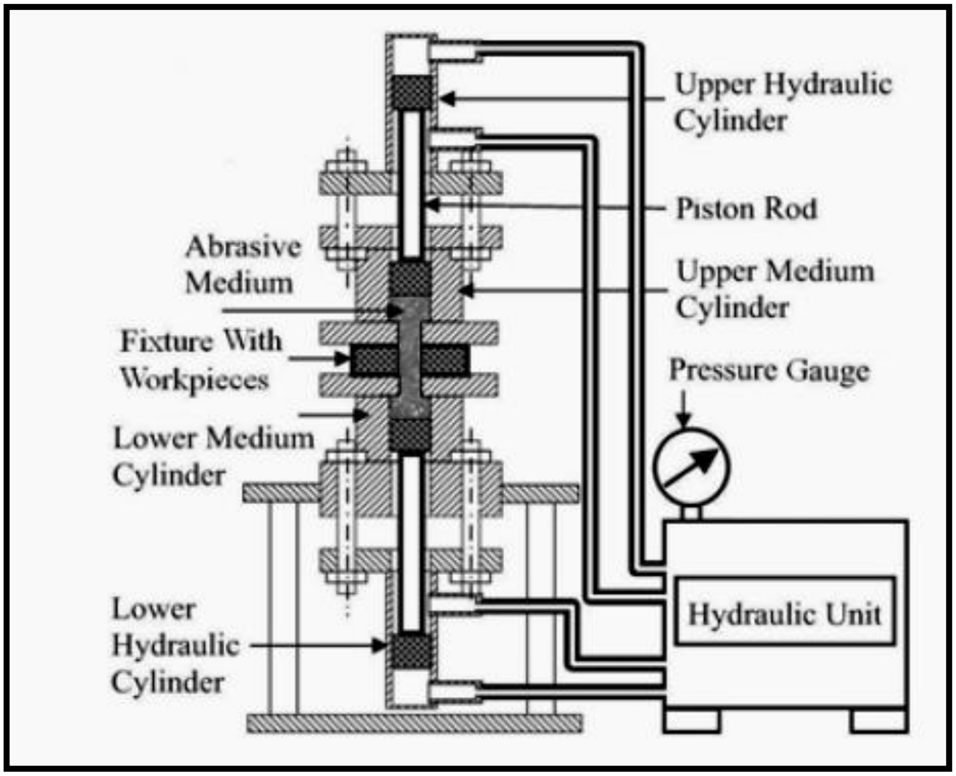

Figure (1) Scheme of the abrasive flow machining process [6].

PROCESS TECHNOLOGY

The largest effort in AFM development was put into the carrier material. This material consists of a visco-elastic polymer of high viscosity, which keeps the abrasive grains almost homogeneously distributed. Depending on the impact velocity, this material can show a flowing behaviour, or – under quick impact – offer the mechanical resistance needed for the grains to cut the workpieces surface [4]. The material has to be temperature-resistant and needs to show a good wearing behaviour. Prior to machining, the grinding medium is inserted into the lower cylinder. The workpiece is positioned in the specifically designed workpiece-holder and clamped between the cylinders Figure (2a). The two main functions of the workpiece-holder are to clamp the workpiece and to assure a controlled media flow in a closed system. Inside the fixture the medium flows through a narrowing channel before reaching the workpieces cavities. Initially, the grinding medium is heated to working temperature by the heater/cooler.

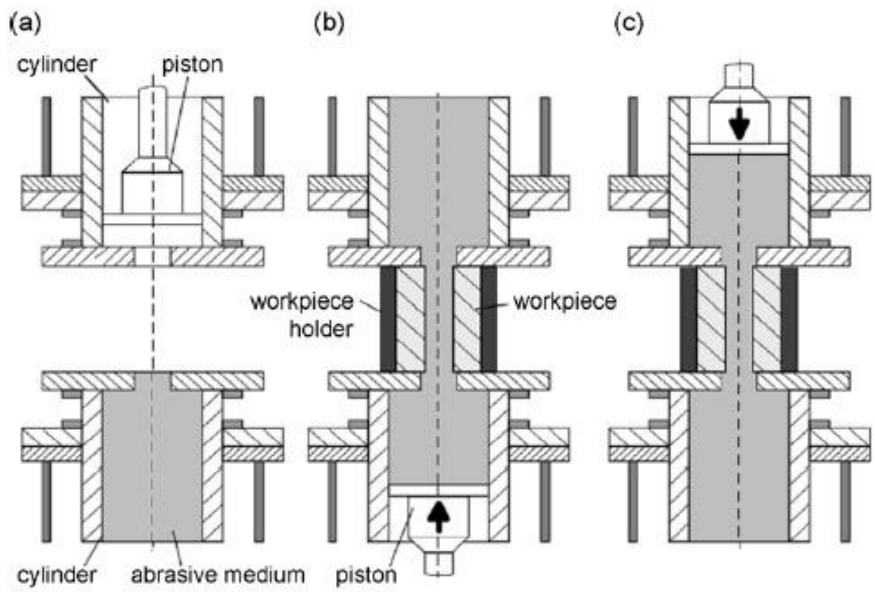

Figure (2) Process principle during abrasive flow machining (AFM)).

Then the grinding medium is pressed upwards into the workpiece-holder along the machined workpiece shapes Figure (2b). After that, the process is repeated in the opposite direction Figure (2c). This machining cycle is repeated until the desired work result is obtained.

MULTIPLE REGRESSION PREDICTION MODEL

The proposed multiple regression models is a three-way interaction Equation [8]:

$$Yi = \alpha_i + \beta_1 X_{1i} + \beta_2 X_{2i} + \beta_3 X_{3i} + \beta_4 X_{4i} + \beta_5 X_{5i} \qquad \dots (1)$$

Where:

Yi: surface roughness Ra (micro meter) or material removal (MR)
X1i: Length of stroke (mm)
X2i: Extrusion Pressure (Mpa)
X3i: Number of cycles
X4i: Abrasive Concentration %
X5i: Abrasive grain size (µm)

In this model, the criterion variables are the surface roughness (Ra), material removal (MR) and the predictor variables are length of stroke, extrusion pressure, number of cycles, percentage abrasive concentration and abrasive grain size. Because these variables are controllable machining parameters, they can be used to predict the surface roughness, improvement of average surface roughness and material removal rate which will then enhance product quality.

The full regression model containing all the main effects and interactions terms was listed in equation (1).

In order to judge the accuracy of the multiple regression prediction model, percentage deviation (φ_i) and average percentage deviation (Φ) are used and defined as:

$$\varphi_i = \frac{|Ra'_i - Ra_i|}{Ra'_i} \times 100\% \quad \text{... (2)}$$

Where:

φ_i: percentage deviation of single sample data

$Ra`_i$: actual Ra measured by a profilometer

Ra_i : predicted Ra generated by a multiple regression equation

$$\Phi = \frac{\sum_{i=1}^{m} \varphi\, i}{m} \quad \text{… (3)}$$

Where:

Φ: average percentage deviation of all sample data

m: the size of sample data

This method would test the average percentage deviation of actual Ra (measured by an off-line Pocket Surf profilometer) and predicted Ra (produced by the multiple regression model) then test the average percentage deviation of actual MRR (measured by analytical balance) and predicted MRR (produced by the multiple regression model) as well as its ability to evaluate the prediction of this model. [8]

EXPERIMENTAL SET-UP

An indigenously developed, hydraulically powered experimental set-up for AFM process has been designed and fabricated as shown in Figure (3). The AFM set-up consists of upper and lower medium cylinders with pistons, work piece fixture, hydraulic drive and supporting frame. The primary function of the abrasive medium cylinders is to contain required quantity of AFM medium and to guide the piston during up and down reciprocating motion for extruding the abrasive medium.

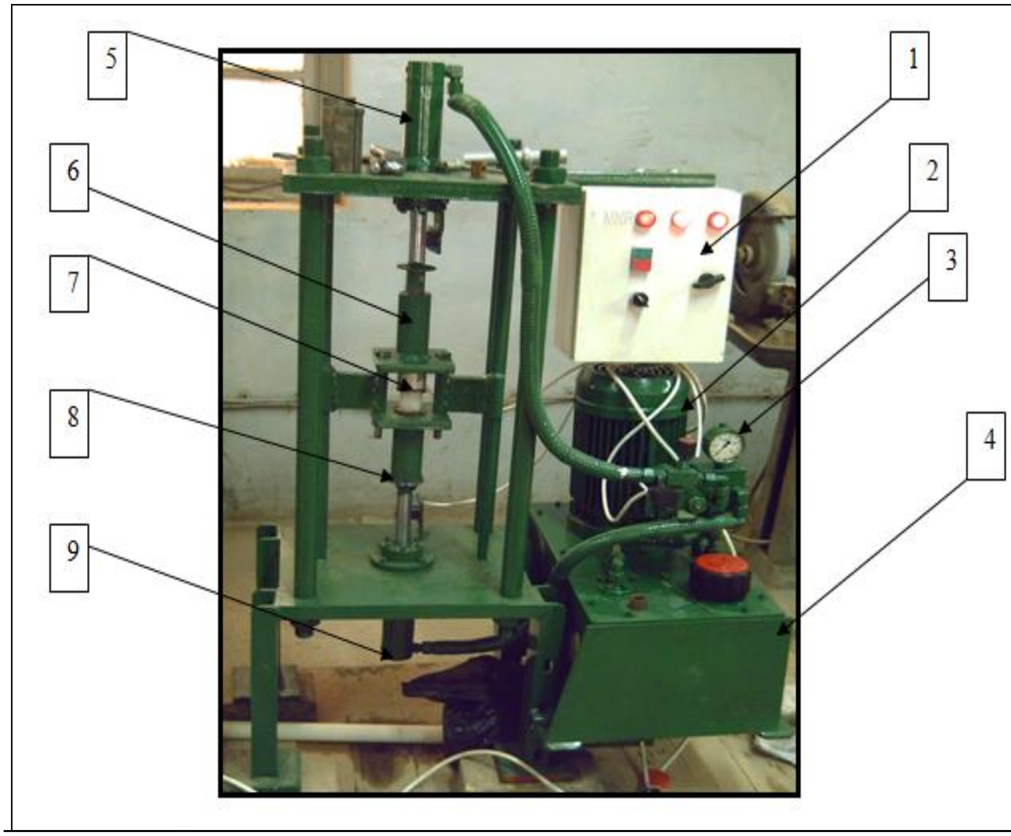

Figure (3) AFM setup:(1) control box,(2) electrical pump, (3) pressure gage, (4) hydraulic unit, (5) upper hydraulic cylinder, (6) upper medium cylinder, (7) workpiece And fixture, (8) lower medium cylinder, lower ydraulic cylinder

Experiments are carried out on Al alloy specimens they have been prepared by cutting workpiece to the following dimensions: length =40mm, O.D. =46mm, I.D. =18mm. The volume percentages of various elements as shown in Table (1) .White silica is used in this process as abrasive grains, and the mechanical properties as shown in Table (2). The medium is composed of silicone gel, silicone carrier oil, and white silica as abrasive grains. A Mettler Toledo AB 204-S/Fact instrument precision weighing balance of least count 0.01mg is used to measure the weight of specimen before and after each AFM operation.

Table (1) Elemental analysis of Al alloy 6061 specimens.

element	Percentage %
Si	0.64
Mg	1.12
Fe	0.70
Cu	0.36
Cr	0.35
Al	96.93

Table (2) Mechanical properties of Al alloy 6061 specimens.

Ultimate Tensile Strength	310Mpa
Tensile yield Strength	276Mpa
Modulus of Elasticity	68.9Gpa
Poisson ratio	0.33
Shear modulus	26Gpa
Shear Strength	207Mpa

RESULTS AND DISCUSSION

After 18 specimens were machined for experimental purposes, they were measured off-line with a (Pocket Surf) type profilometer to obtain the roughness average value Ra. All original 18 samples as shown in Table (3) were randomly divided into two data sets - the training set and the testing set. The training set contained 12 samples which were used to build a prediction model as shown in Table(4) and the testing set contained 6 samples which were used to test the flexibility of the prediction model as shown in Table (5). Each sample consisted of eight elements: stroke of length, extrusion pressure, number of cycles, percentage abrasive concentration and abrasive grain size, measured surface roughness (Ra), and material removal (MR). A statistical model was created by regression function in (SPSS) from the training data set. The R square (ability the independent variables to predict dependent variable) was 0.989 and 0.999 which showed that 98.9% and 99.9% of the observed variability in Ra and MR respectively could be explained by the independent variables. The multiple R (correlation value between dependent and independent variables) was 0.994 and 0.999 which meant that the correlation coefficient between the observed value of the dependent variable and the predicted value based on the regression model was high. The value of F (value represent signify R^2 to Ra , MR) was 11.88 and the significance of F was 0.08 for Ra , 99.676 and the significance of F was 0.01 in the ANOVA table as shown in Tables (6, 7) for Ra and MR respectively. In

Tables (8, 9) the coefficients for the independent variables were listed in the column B. using these coefficients the multiple regression equation could be expressed as:

$$Ra = 1.111 - 0.046B - 0.019C - 0.002E + 0.001AB - 0.004AD - 2.312*10^{-5}AE - 0.065BD - 0.003CD + 8.703*10^{-5}CE + 0.003DE \quad \ldots (4)$$

$$MR = -10.992 + 3.028B + 0.738C + 0.039E - 0.009AB + 0.265AD - 4.826BD - 0.002BE - 0.767CD - 0.001CE + 0.123DE \quad \ldots (5)$$

Where:

Ra = the predicted Surface roughness (μm).
MR =predicted material removal (mg).
A=Length of Stroke (mm).
B=Extrusion Pressure (Mpa).
C= Number of Cycle.
D=Abrasive Concentration%
E=Abrasive Particle Size (μm)

It is also apparent the interaction of extrusion pressure and abrasive concentration (BD) is the most significant machining parameter to influence surface roughness (Ra) in equation (4), in equation (5) the interaction of extrusion pressure and abrasive concentration (BD) is the most significant machining parameter to influence material removal. The Scatterplot of the predicted values and measured values of 18 data sets for surface roughness, material removal as shown in Figure 4 and 6 respectively by using (SPSS). This indicates that the relationship between the actual values and the predicted values is linear in Figure (5 and 7). The result of average percentage deviation (Φ) showed that the training data set (m=12) was 3.92%, 0.62% and the testing data set (m=6) was 4.68%, 2.35%. This means that the statistical model could predict the surface roughness and material removal with about 96.1%, 99.38% accuracy of the training data set and approximately 95.32%, 97.65% accuracy of the testing data set for Ra and MR respectively.

Table (3) Experimental Design for Prediction and Measured Surface Roughness and Material Removal.

No.	A	B	C	D	E	Ra Measured (μm)	Ra Predicted (μm)	MR Measured (mg)	MR Predicted (mg)
1	40	4	20	0.25	150	0.5067	0.5109	12.40	12.3947
2	40	6	30	0.5	250	0.5300	0.5189	17.20	17.4647
3	40	8	40	0.75	355	0.5433	0.5426	27.20	27.1260
4	60	4	20	0.5	250	0.4600	0.4486	16.80	16.7023
5	60	6	30	0.75	355	0.3333	0.3410	23.70	23.8779
6	60	8	40	0.25	150	0.3000	0.3050	13.40	13.2765

7	80	4	30	0.25	355	0.3133	0.3333	15.60	15.4810
8	80	6	40	0.5	150	0.2500	0.2537	15.90	16.0108
9	80	8	20	0.75	250	0.2933	0.3032	19.30	19.0704
10	100	4	40	0.75	250	0.3000	0.2868	20.80	20.5629
11	100	6	20	0.25	355	0.3200	0.3075	13.20	13.2307
12	100	8	30	0.5	150	0.2967	0.2905	15.80	15.9358
13	120	4	30	0.75	150	0.3133	0.3356	16.40	16.4245
14	120	6	40	0.25	250	0.2200	0.1963	15.20	15.2189
15	120	8	20	0.5	355	0.2367	0.2341	17.60	17.6573
16	140	4	40	0.5	355	0.0933	0.0963	19.10	19.2089
17	140	6	20	0.75	150	0.2000	0.1864	16.10	16.1484
18	140	8	30	0.25	250	0.1800	0.1992	14.80	14.7083

Table (4) Training Data set (SPSS) for Surface Roughness.

NO.	A [Length of Stroke (mm)]	B [Extrusion Pressure (Mpa)]	C [No. of Cycle]	D [Con. Of abrasive]	E [Size of abrasive grain (μm)]	Ra Measured (μm)	MR Measured (mg)
1	40.0	4.0	20.0	0.25	150.0	0.5067	12.40
2	40.0	6.0	30.0	0.5	250.0	0.5300	17.20
3	60.0	4.0	20.0	0.5	250.0	0.4600	16.80
4	60.0	8.0	40.0	0.25	150.0	0.3333	23.70
5	80.0	4.0	30.0	0.25	355.0	0.3133	15.60
6	80.0	6.0	40.0	0.5	150.0	0.2500	15.90
7	100.0	4.0	40.0	0.75	250.0	0.3000	20.80
8	100.0	8.0	30.0	0.5	150.0	0.3200	13.20
9	120.0	6.0	40.0	0.25	250.0	0.3133	16.40
10	120.0	8.0	20.0	0.5	355.0	0.2200	15.20
11	140.0	4.0	40.0	0.5	355.0	0.0933	19.10
12	140.0	6.0	20.0	0.75	150.0	0.2000	16.10

Table (5) Testing Data set (SPSS) for Surface Roughness.

NO.	A [Length of Stroke (mm)]	B [Extrusion Pressure (Mpa)]	C[No. of Cycle]	D [Con. Of abrasive]	E [Size of abrasive grain (μm)]	Ra Measured (μm)	MR Measured (mg)
1	40	8	40	0.75	355	0.5433	27.20
2	60	8	40	0.25	150	0.3000	13.40
3	80	8	20	0.75	250	0.2933	19.30
4	100	8	30	0.5	150	0.2967	15.80
5	120	8	20	0.5	355	0.2367	17.60
6	140	8	30	0.25	250	0.1800	14.80

Table (6) ANOVA Table for surface roughness (SPSS).

Model	Sum of square	df	Mean square	F	Signify
Regression	.255	15	.017	11.888	.080
Residual	.003	2	.001	/	/
Total	.258	17	/	/	/

Table (7) ANOVA Table for Material Removal (SPSS).

Model	Sum of Squares	df	Mean Square	F	Sig.
Regression	234.491	15	15.633	99.676	.010[a]
Residual	.314	2	.157	/	/
Total	234.805	17	/	/	/

Table (8) Coefficients Table for surface roughness (SPSS).

Model	Unstandardized Coefficients		Standardized Coefficients
	B	Std.Error	Beta
(Constant)	1.111	.000	
B	-0.046	.000	-0.597
C	-0.019	.000	-1.342
E	-0.002	.000	-1.536
AB	0.001	.000	1.447
AD	-0.004	.000	-0.856
AE	-2.312E-5	.000	-2.482
BD	-0.065	.000	-0.598
CD	0.000	.000	0.516
CE	-0.003	.000	-0.138
DE	8.703E-5	.000	2.312

Table (9) Coefficients Table for Material Removal (SPSS).

	Unstandardized Coefficients		Standardized Coefficients
Model	B	Std. Error	
(Constant)	-10.992	.000	Beta
B	3.028	.000	1.623
C	0.738	.000	2.132
E	0.039	.000	1.070
AB	-0.009	.000	-.742
AD	0.265	.000	2.458
AE	0.000	.000	-1.637
BD	-4.826	.000	-1.834
BE	-0.002	.000	-.377
CD	-0.767	.000	-1.689
CE	-0.001	.000	-1.110
DE	0.123	.000	2.103

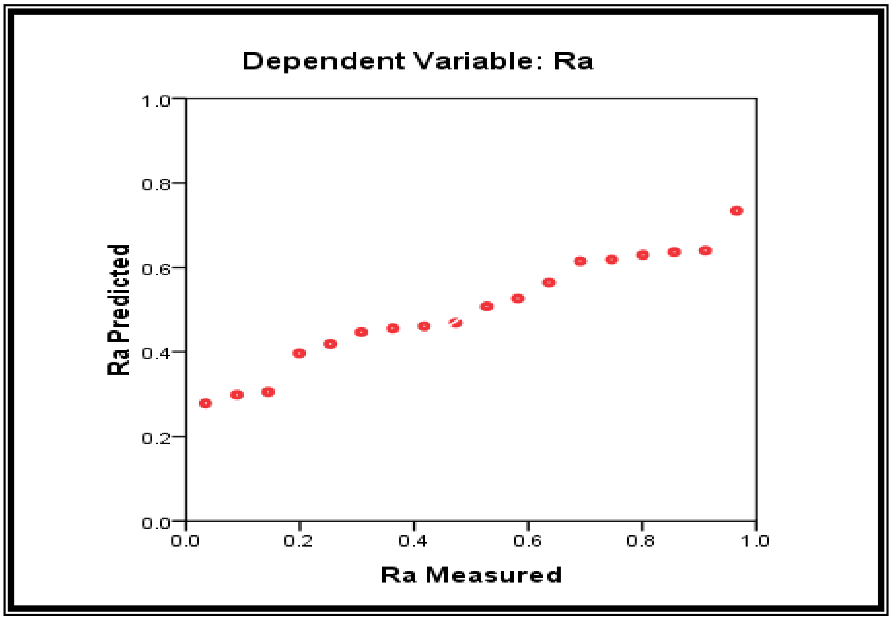

Figure (4) Scatter plot of the Measured Ra and the Predicted Ra of the Multiple Regression Prediction Model using (SPSS).

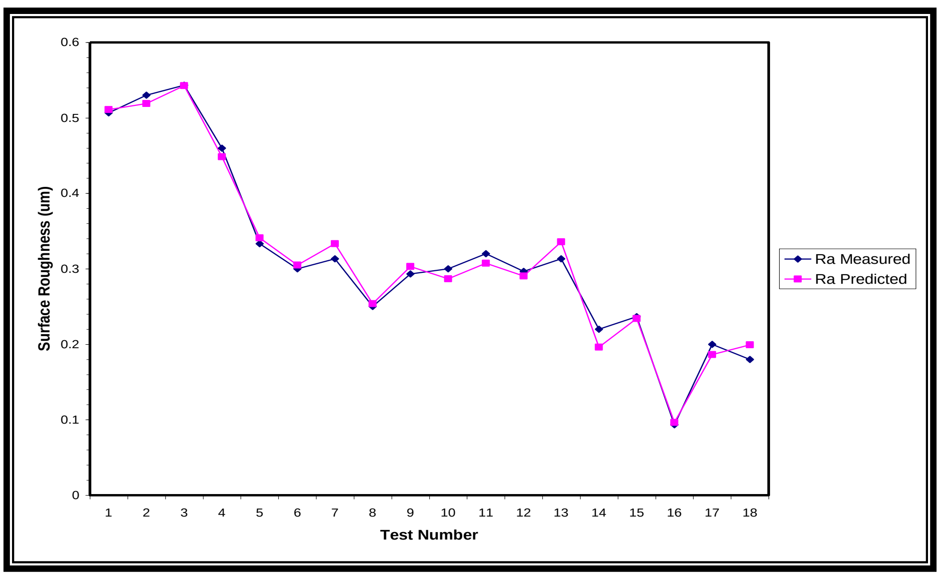

Figure (5) The diagram of the measured and predicted surface roughness for the experimental data using the commercial statistical package (SPSS).

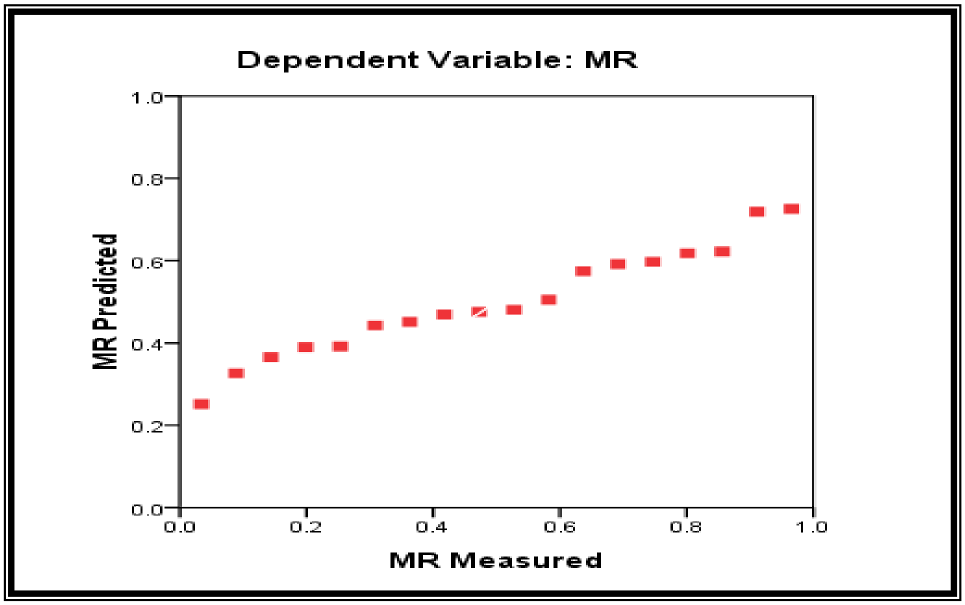

Figure (6) Scatterplot of the Measured MR and the Predicted MR of the Multiple Regression Prediction Model using (SPSS).

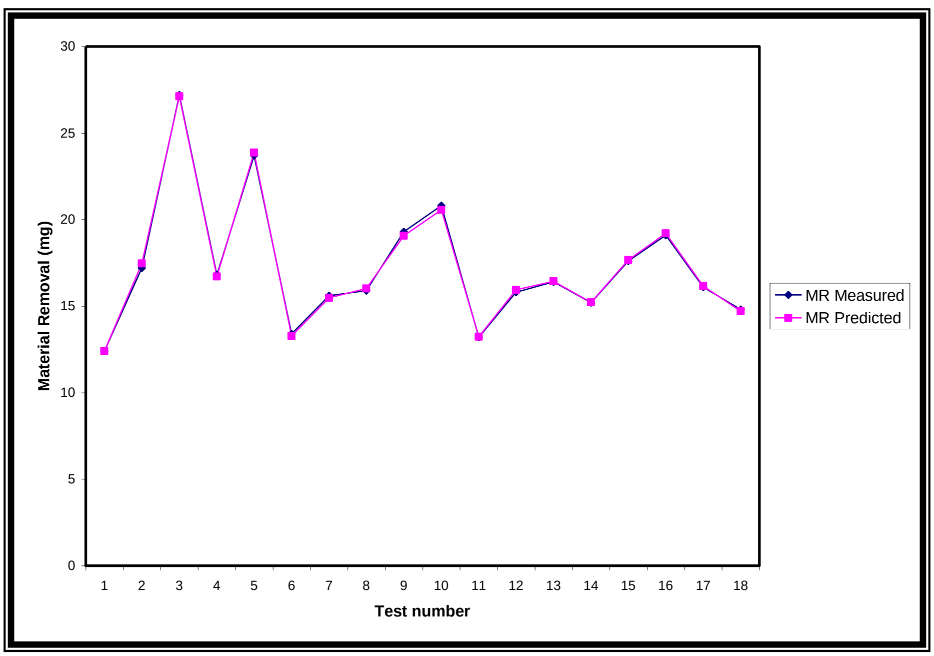

Figure (7) The diagram of the measured and predicted Material Removal for the experimental data using the commercial statistical package (SPSS).

Conclusions

The main conclusions which can be deduced from the present work can be summarized as follows:

1- AFM process can be utilized for finishing of Aluminum alloys. However, plowing and rubbing are observed on aluminum alloy workpiece during AFF operation, indicating a spoil of surface finish if process parameters are not controlled effectively.

2- The interaction of extrusion pressure and abrasive concentration (BD) is the most significant machining parameter to influence surface roughness (Ra).

3- The interaction of extrusion pressure and abrasive concentration (BD) is the most significant machining parameter to influence material removal.

4- The statistical model could predict about 96.1%, 99.38% accuracy when use (SPSS), for surface roughness (Ra) and material removal respectively.

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