Studying Abrasive Flow Machining Conditions by Using Taguchi Method

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ABSTRACT

Abrasive Flow Machining (AFM) process can not only promote product's inner surface quality but also economize the labor cost. However, the issue of inner surface quality includes not only the surface roughness but also the geometric variability before/after the AFM process. 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, Taguchi experimental design concept, L18 ($6^1 \times 3^4$) mixed orthogonal array, is used to determine the S/N ratio and optimize the AFM process parameters. The statistical model could predict about 91.39%, and 96.4% for surface roughness (Ra), and material removal respectively. Length of stroke was more effect on surface roughness while percentage of abrasive concentration was more effect on material removal.

دراسة ظروف التشغيل بأنسياب المادة الحاكة بأستخدام طريقة تاكوجي

الخلاصة

عملية التشغيل بانسياب المادة الحاكة لاتستطيع فقط رفع نوعية انتاج السطح الداخلي بل تستطيع ايضا التوفير في كلفة العمالة. ومع ذلك فأن مسألة جودة السطح الداخلي لاتتضمن فقط الخشونة السطحية كذلك التغير الهندسي قبل /بعد عملية التشغيل بأنسياب المادة الحاكة . بالاعتماد على بيانات الاختبار من تاثيرات متغيرات العملية اعلاه طول الشوط, ضغط البثق, عدد الدورات, نسبة تركيز المادة الحاكة و حجم حبيبة المادة الحاكة,استخدام مفهوم اختبار تاكوجي $L18(6^1*3^4)$ مجموعة مختلطة متعامدة استخدمت في البحث لحساب نسبة الاشارة الى الصوت والاعتبارات المثالية للعملية. امكانية التنبؤ بقيمة الخشونة السطحية وازالة المادة كانت بحدود 91.39% و 96.4% على التوالي.طول الشوط كان اكثر تأثير على الخشونة السطحية بينما تركيز المادة الحادة كان اكثر تأثير على ازلة المادة.

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INTRODUCTION

Abrasive flow machining (AFM) is a non-conventional finishing process, which is being used for deburring, polishing, radiusing, removing recast layers, and producing compressive residual stresses on difficult to reach surfaces. 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(s). Two strokes are obtained, one from the lower cylinder and the other from the upper cylinder, making up one process cycle [1]. In AFM, the media determines the aggressiveness of the action of abrasives, which is resilient enough to act as a self deforming grinding stone when forced through a passageway [2]. Production of extremely thin chips allows fine surface finish, closer tolerances, and generation of more intricate surface texture. Recently, diesel injector nozzles [3], microchannels [4], and spring collets [5] have been finished by abrasive flow finishing (AFF) process, and the researchers claim that the AFF process directly improved the performance of their systems. Monolithic materials from soft aluminum to tough nickel alloys, ceramics, and carbides can be successfully micromachined by this process [6]. 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 [7]. 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 [8]. M.R.Sankare et.al (2011) Present's different media are made using especially 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 [9]. Taguchi experimental quality design concept, L18 ($6^1 \times 3^4$) mixed orthogonal array is used to determine the S/N ratio, analysis of variance (ANOVA), and F test values to indicate the significant AFM parameters affecting the finishing performance. Selecting the significant parameters mathematical models have been developed and validated.

PROCESS TECHNOLOGY

The grinding medium consists of the components base, abrasive and additives. The base which is also referred to as carrier binds the abrasive. Depending on the respective machining task, the abrasive is supplied with additives to obtain particular flow properties of the grinding media. The carrier is produced in a variety of intrinsic viscosities. [10]

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 (1a). Initially, the grinding medium is heated up to working temperature by the heater/cooler. After clamping, the grinding medium is pressed upwards into the workpiece holder along the machined workpiece shapes Figure (1b).

After that, the process is repeated in the opposite direction Figure (1c). This machining cycle is repeated until the desired work result is obtained.

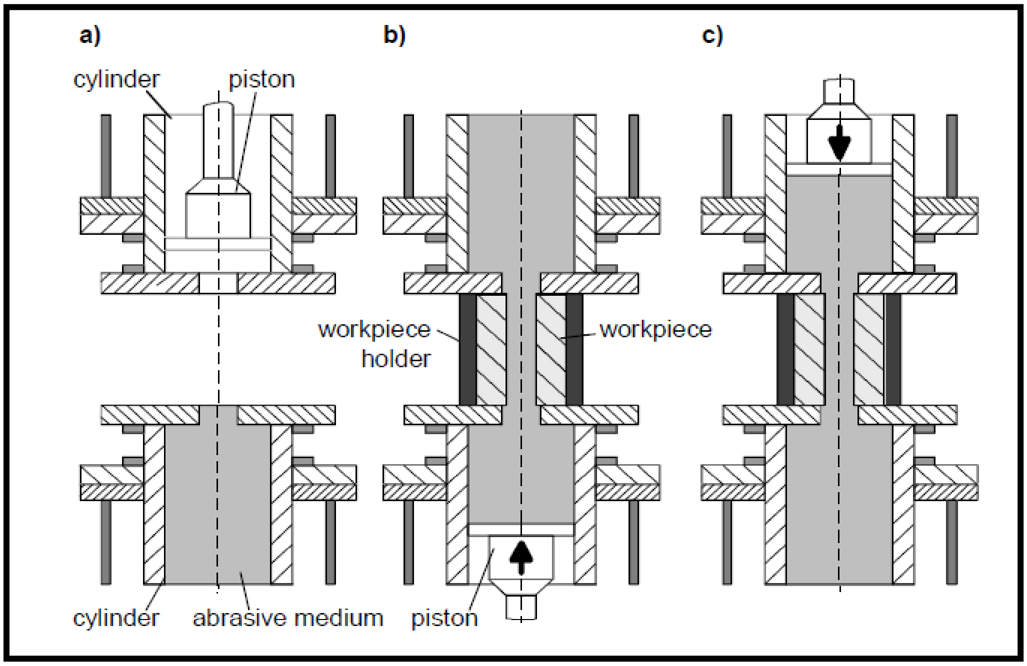

Figure (1) Process course during abrasive flow machining [10].

The two main tasks of the work piece holder are to clamp the work piece and to control the media flow. During the conception of the device, special attention has to be paid to the requirements of abrasive flow machining in order to minimize frictional loss. When parts with similar shapes or high batch numbers are produced it often occurs that exchangeable inserts are used. This way it is possible to buffer parts and to automatically charge the machine [11].

The basic principle of AFM is that the abrasive and material removing effect of the grinding medium is in direct proportion to the speed of the abrasive. Following this principle, the conception of the work piece holder determines the position of the highest speed of the grinding medium. The conception of the work piece holder allows for an arrangement of the surfaces of the work piece in such a way that there is no removal where machining is not supposed to take place. Often it is necessary to install sleeves, tubes or cores to obtain constant and high flow velocities. The mixture ratio and the proportion of additives depend on the machining task, e.g. deburring or precise polishing. A high viscosity grinding medium works as a relatively elastic mass and enables extremely high material removal rates during machining. Such a medium is mainly used to deburr of very strong burrs, for removing of recast layers after EDM machining and for the machining of large bore holes with a high diameter/length ratio. Thanks to good flow properties it is possible to machine grooves and orifices of a size of up to 0.1 mm if the viscosities are kept low. In some cases it was even possible to machine bore holes of a size of 0.02 mm with AFM. Grinding media with low viscosities are further used for the precise rounding of edges and for the machining of deep bore holes or bore holes with small diameter/length ratios [6].

AFM process parameters and their levels

There are several factors that affect the quality characteristics of the AFM process, such as extrusion pressure, abrasive mesh size, number of working cycle, media flow volume, media rheology, jig and fixture, length of restricting passage, etc. In the present study, five main AFM parameters, namely, length of stroke, extrusion pressure, number of cycles, percentage of abrasive concentration, and abrasive grain size, are considered for experimental investigation. Taguchi method-based design of experiment and L18 ($6^1 \times 3^4$) mixed orthogonal array is utilized for the parametric design. Table (1) represents the various parameters considered with their levels for conducting the experiments. S/N ratio is used to determine the optimal combination of control parameters, which will be recognized to gain the surface quality and reduce variability. According to Taguchi method, S/N ratio is the ratio of "signal" representing the desirable value, i.e., mean for the output characteristics and the "noise" representing the undesirable value, i.e., the square deviation for the output characteristics. It is a summery statistics and denoted by S/N, and the unit is decibels. According to quality engineering [14], the characteristic that the lower observed values represents the better machining performance, e.g., surface roughness is known as "lower the better." The summery statistic S/N (decibels) of the lower the better performance characteristic is expressed as:

$$S/N = -10 \log_{10}\left[\frac{1}{n}\sum_{i=1}^{n}(y_i^{\,2})\right] \quad ; \quad i=1,2,\ldots\ldots\ldots n \quad [14] \qquad \ldots (1)$$

This equation is used to determine the S/N ratio (decibels) for surface roughness Ra. The quality characteristic for material remove (MR) is of the-higher-the-better type. Therefore, the S/N ratio is given by:

$$S/N = -10 \log_{10}\left[\frac{1}{n}\sum_{i=1}^{n}\left(1/y_i^{\,2}\right)\right] \quad ; \quad i=1,2,\ldots\ldots\ldots n \quad [14] \qquad \ldots (2)$$

Where n is the number of measurements, and y_i the measured characteristic value. The unit of S/N ratio is decibel.

Table (1) process input parameters.

parameter	1	2	3	4	5	6	unit
Stroke length (A)	40	60	80	100	120	140	mm
Extrusion pressure (B)	4	6	8	/	/	/	MPa
Number of cycles (C)	20	30	40	/	/	/	/
Percentage of abrasive concentration (D)	25%	50%	75%	/	/	/	/
Abrasive particle size (E)	150	250	355	/	/	/	µm

EXPERIMENTAL SET-UP

An indigenously developed, hydraulically powered experimental set-up for AFM process has been designed and fabricated as shown in Figure (2). The AFM set-up consists of upper and lowers 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 (2) AFM setup.

Experiments are carried out on Al alloy as shown in Figure (3). The volume percentages of various elements as shown in Table (2) .White silica is used in this process as abrasive grains, and the mechanical properties as shown in Table (3). The medium is composed of silicone gel, silicone carrier oil, and white silica as abrasive grains.

Figure (3) Al alloy workpiece.

Table (2) Elemental analysis of Al alloy 6061.

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

Table (3) Mechanical properties of Al alloy 6061.

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 DISCUSSIONS

Taguchi Orthogonal Array results

Table (4) represents the experimental results of abrasive flow finishing of Al alloy according to Taguchi L18 ($6^1\times3^4$) mixed orthogonal array. Various response characteristics, namely, Ra in micrometers and MR in milligrams, have been measured and calculated, respectively. Average (mean) of these characteristics and S/N ratio (in decibels) is shown for each characteristic.

Parametric optimization for response characteristics

Figures (4and 6) show that the predicted values are close match of the measurement values for surface roughness, and materials removed using Taguchi Orthogonal array (TOA), In Figure (4) the predicted values are also very similar to the measured values (91.39%), but there is larger error between the predicted values and measured values in (1, 3, 4 and 5) testing data sets. Figure (5) shows the graph of effects Plot of Factors (Surface Roughness). From this graph, it is clear that the optimal parametric combination for minimum Ra is A_6 B_3 C_3 D_1 E_3, i.e., at 140 mm length of stroke, 8 Mpa extrusion pressure, 40 cycles, 25% abrasive concentration, and 355µm grain size. It is suggested that the parametric combination with in the considered range as mentioned above gives lowest surface roughness height Ra for finishing of Aluminum cylindrical alloy work piece. In Figure (6) by using (TOA) to predict material remove the error between predicted values and measured values is small (96.4%).

Using the aforementioned data, one could predict the optimum surface roughness performance using the cutting conditions as:

Predicted Mean (Ra) = $A_6 + B_3 + C_3 + D_1 + E_3 - 4$(average mean) [14]
From Table (5):
Predicted Mean (Ra) = 0.1578+0.3083+0.2844+0.3067+0.3067-4*0.3161
=0.0995µm

Figure (7) shows the graph of effects Plot of Factors material removal. From this graph, the optimal parametric combination for maximum MR is A_1 B_3 C_3 D_3 E_3, i.e., at 40mm stroke of length, 8MPa extrusion pressure, 40cycles, 75% abrasive concentration, and 355µm grain size.
Predicted mean (MR) = $A_1 + B_3 + C_3 + D_3 + E_3 - 4$(mean average) [14]
From Table (6):
Predicted mean (MR) = 18.93+18.02+18.60+20.58+19.40-4(17.25)
=26.53 mg

ANOVA for Ra and material removal

The main purpose of the analysis of variance (ANOVA) is to investigate the designed parameters and to indicate parameters, which significantly affect the quality characteristic. In the analysis, the sum of the square deviation is calculated from the value of S/N ratio by separating the total variability of S/N ratio for each control parameter [14].

From Table (7), it is concluded that the abrasive concentration (parameter D) is the most significant parameter for minimum Ra. Abrasive particle size (parameter E) is next significant parameter for minimum Ra. From Table (8), it is concluded that the length of stroke (parameter A) is the most significant parameter for maximum MR. Extrusion pressure (parameter B) is next significant parameter for maximum MR.

Table (4) AFM parameters according to Taguchi method.

No.	**AFM parameters**					**AFM parameters**					**Ra Measured (µm)**	**Ra Predicted (µm)**	**MR Measured (mg)**	**MR Predicted (mg)**
	A	B	C	D	E	S.L mm	E.P MPa	No .of cycle	A.C %	A.P.S µm				
1	1	1	1	1	1	40	4	20	0.25	150	0.506	0.547	12.40	11.783
2	1	2	2	2	2	40	6	30	0.50	250	0.530	0.5405	17.20	18.483
3	1	3	3	3	3	40	8	40	0.75	355	0.543	0.4922	27.20	26.533
4	2	1	1	2	2	60	4	20	0.50	250	0.460	0.4088	16.80	16.133
5	2	2	2	3	3	60	4	30	0.75	355	0.333	0.3738	23.70	23.083
6	2	3	3	1	1	60	8	40	0.25	150	0.300	0.3105	13.40	14.683
7	3	1	2	1	3	80	4	30	0.25	355	0.313	0.2933	15.60	15.533
8	3	2	3	2	1	80	6	40	0.50	150	0.250	0.2366	15.90	15.483

9	3	3	1	3	2	80	8	20	0.75	250	0.293	0.3266	19.30	19.783
10	4	1	3	3	2	100	4	40	0.75	250	0.300	0.3177	20.80	20.983
11	4	2	1	1	3	100	6	20	0.25	355	0.320	0.2994	13.20	13.883
12	4	3	2	2	1	100	8	30	0.50	150	0.296	0.2994	15.80	14.933
13	5	1	2	3	1	120	4	30	0.75	150	0.313	0.2927	16.40	17.083
14	5	2	3	1	2	120	6	40	0.25	250	0.220	0.2227	15.20	14.333
15	5	3	1	2	3	120	8	20	0.50	355	0.236	0.2544	17.60	17.783
16	6	1	3	2	3	140	4	40	0.50	355	0.093	0.1266	19.10	19.583
17	6	2	1	3	1	140	6	20	0.75	150	0.200	0.1800	16.10	16.033
18	6	3	2	1	2	140	8	30	0.25	250	0.180	0.1666	14.80	14.383

Table (5) Response for Surface Roughness smaller is better (TOA).

Level	A	B	C	D	E
1	0.527	0.331	0.336	0.307	0.311
2	0.364	0.308	0.328	0.311	0.331
3	0.286	0.308	0.284	0.331	0.307
4	0.306	/	/	/	/
5	0.257	/	/	/	/
6	0.158	/	/	/	/
Delta	0.369	0.0228	0.052	0.024	0.024
Rank	1	4	2	3	3

Table (6) Response for MR Ratios Larger is better (TOA).

Level	A	B	C	D	E
1	18.93	16.85	15.90	14.10	15.00
2	17.97	16.88	17.25	17.07	17.35
3	16.93	18.02	18.60	20.58	19.40
4	16.60	/	/	/	/
5	16.40	/	/	/	/
6	16.67	/	/	/	/
Delta	2.53	1.17	2.70	6.48	4.40
Rank	4	5	3	1	2

Table (7) Analysis of Variance for Surface Roughness (TOA).

Source	DF	Seq. SS	Adj. SS	Adj. MS	F	P
A	5	0.229	0.229	0.046	13.46	0.013
B	2	0.002	0.002	0.001	0.30	0.758
C	2	0.009	0.009	0.005	1.36	0.355
D	2	0.002	0.002	0.001	0.28	0.766
E	2	0.002	0.002	0.001	0.28	0.766
Residual Error	4	0.014	0.014	0.003	/	/
Total	17	0.258	/	/	/	/

DF=Degree of Freedom, SS=Sum of Square, MS=Mean of Square, P=Percent of contribution

Table (8) Analysis of Variance for MR (TOA).

Source	DF	Seq. SS	Adj. SS	Adj. MS	F	P
A	5	14.798	14.798	2.960	1.43	0.375
B	2	5.293	5.293	2.647	1.28	0.375
C	2	21.870	21.870	10.935	5.29	0.075
D	2	126.403	126.403	63.202	30.57	0.004
E	2	58.170	58.170	29.085	14.07	0.015
Residual Error	4	8.270	8.270	2.068	/	/
Total	17	234.805	/	/	/	/

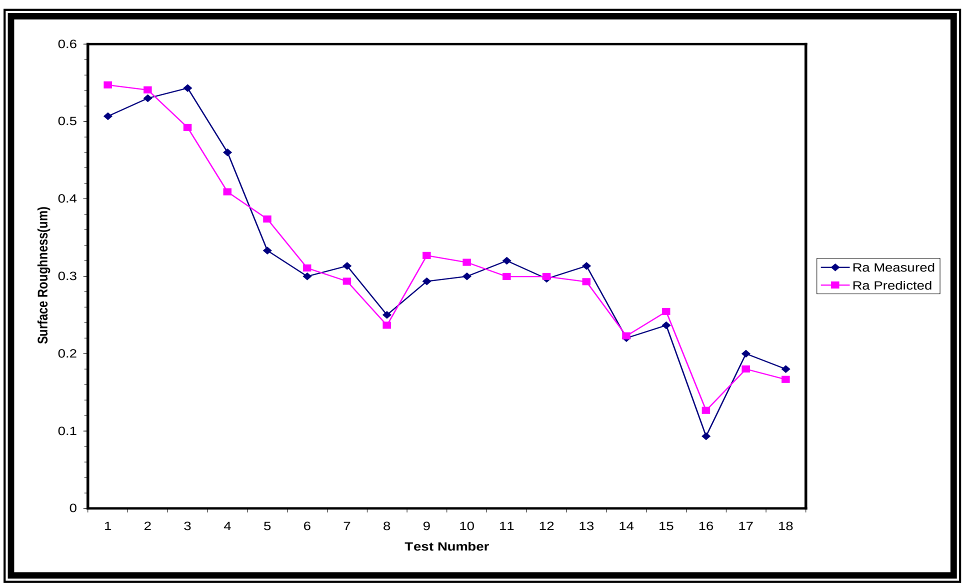

Figure (4) the diagram of the measured and predicted surface roughness for the experimental data using the (TOA).

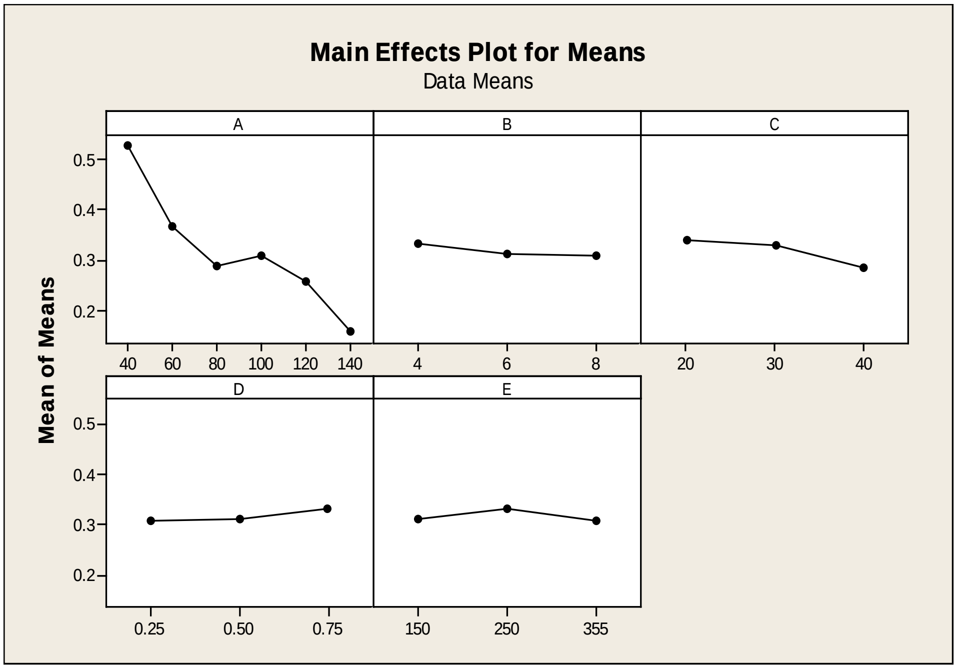

Figure (5) Main effects Plot of Factors (Surface Roughness).

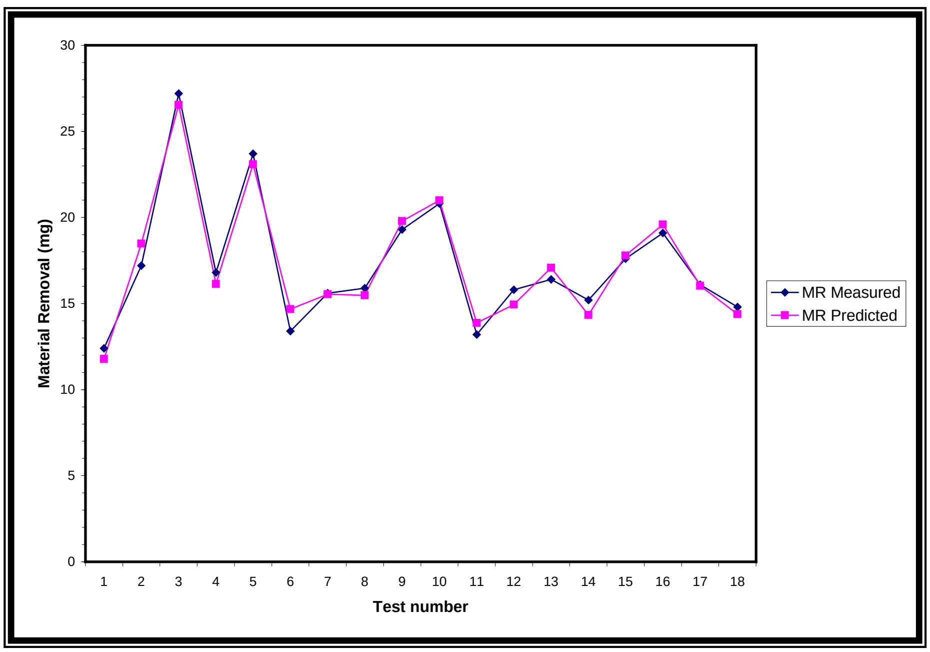

Figure (6) the diagram of the measured and predicted Material Removal for the experimental data using the (TOA).

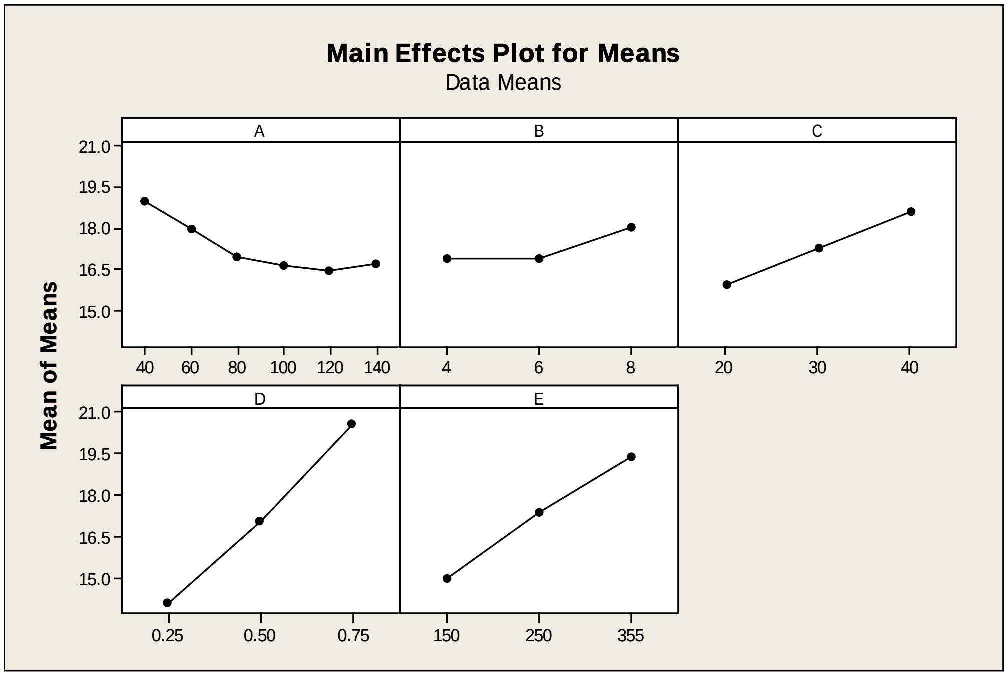

Figure (7) Main effects Plot of Factors Material Removal.

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 optimal parametric combination for minimum surface roughness (Ra) is A_6 B_3 C_3 D_1 E_3, i.e., at 140 mm length of stroke, 8 Mpa extrusion pressure, 40 cycles, 25% abrasive concentration, and 355µm grain size.

3- The optimal parametric combination for maximum MR is A_1 B_3 C_3 D_3 E_3, i.e., at 40mm stroke of length, 8Mpa extrusion pressure, 40cycles, 75% abrasive concentration, and 355µm grain size.

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