IOSR Journal of Mechanical and Civil Engineering (IOSR-JMCE)
e-ISSN: 2278-1684,p-ISSN: 2320-334X, Volume 12, Issue 2 Ver. VI (Mar - Apr. 2015), PP 42-50
www.iosrjournals.org

Application of Taguchi method in the optimization of process parameters for surface roughness in machining of Acetal homopolymer

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Abstract: *Acetal homopolymer is a crystalline plastic that gives an excellent balance of properties that fulfill the gap between metals and plastics. Due to their excellent properties, this paper deals to optimize machining parameters of Acetal homopolymer on lathe machine. During the experimentation, the use of tool material and process parameters such as cutting speed, feed rates and depth of cut, with cutting fluid are used to explore their effect on the surface roughness (Ra) of the work piece. This experimentation uses a standard orthogonal array for determining the optimum machining parameters with an applied noise factor. The signal-to-noise (S/N) ratio, the analysis of variance (ANOVA) are employed to find the optimal levels and to analyze the effect of the turning parameters on surface roughness to perform the machining operation. MINITAB is used to find out (S/N) ratio and mean. It is also useful for response table for means and signal-to-noise ratio, main effect plot for mean and signal-to-noise ratio.*
Keywords: *Acetal homopolymer, ANOVA, machining, surface roughness, (S/N) ratio.*

I. Introduction

It is very important for a manufacturing company to respond effectively to secure competitiveness and increasing demand of quality product in the market. The current structure shows that the most of manufacturing industries basically concerned with dimensional accuracy and surface finish. Surface roughness has become the most significant technical requirement and also affects the life of any product. There are two major practical problems that engineers face in a manufacturing process industry. The first problem is to determine the exact value of process parameters that will meet the desired technical specification (Product Quality) and the second is to maximize manufacturing system performance using the available resources of manufacturing unit. To fulfill such requirements from the manufacturing industries, introduces the Acetal homopolymer have a combination of physical, tribological and environmental properties not available with either metals or most other plastics. Acetal homopolymer is a thermoplastic engineering polymer manufactured by the polymerization of formaldehyde. It has gained wide spread recognition for reliability of performance over thousands of engineering components all over the world. Delrin is the DUPONT registered trademark for its Acetal homopolymer also commonly referred to as polyoxymethylene (POM).

II. Review Of Literature

M. Nalbant, H.Gokaya, G. Sur showed that the Taguchi method is to find the optimal cutting paramaters for surface roughness in turning. The cutting parameters like insert radius, feed rate and depth of cut, are optimized with considerations of surface roughness[1]. Ersan Aslan a, Necip Camuscu a, Burak Birg ren investgated that, due to high hardness and wear resistance, Al_2O_3- based ceramics are one of the most feasible cutting tool materials for hardened steels and their high degree of brittleness usually leads to inconsistent results and sudden catastrophic failure. The Taguchi method was used to optimize cutting speed, feed rate and depth of cut on two performance measures, flank wear (VB) and surface roughness (Ra), were investigated employing an orthogonal array and the analysis of variance (ANOVA)[2]. U Datta, P.Saha, R.W. Linjewar, S. Jain and S.Sen investigate the use of different tool material and process parameters for minimum machining forces for selected parameters range. Comparative studies are made to select the process parameters for turning operation on AISI 304 austenitic stainless steel on auto sharpening machine in order to get optimum machining parameter[3]. Sandeep Salodkar and Alakesh Manna give the procedure to obtain the machining conditions for turning operation considering unit cost of production as an objective function. In this, the Taguchi method is used to optimize the cutting parameters to achieve better surface finish and to identify the most effective parameter for cost evolution during turning[4]. J.A. Ghani, G. Akhyar, C.H. Che Haron investigated that Taguchi optimization is applied to optimize cutting parameters in turning Ti-6% Al-4% V extra low interstitial with coated and uncoated cemented carbide tools under dry cutting condition and high cutting speed[5]. Davim J.P. investigated that Taguchi orthogonal arrays (OA) is applied to optimize cutting parameters in turning metal matrix composites[6]. Sijo M.T., Biju N. found that for efficient use of machine tools, optimum cutting parameters are required. In this paper, Taguchi parameter optimization is highly complex and time consuming[7]. Dr. S.S.Mahapatra, Amar Patnaik, Prabina Ku.Patnaik stated that in order to enable manufacturers to maximize their gains from utilizing hard turning, an accurate model of the process must be constructed. Several statistical modeling techniques have been used to generate models including regression and Taguchi method[8]. Farhad Kolahan, Mohsen Manoochehri, Abbas Hosseini showed that the surface roughness of AISI 1045 is selected as process output measure of performance. A Taguchi approach is employed to gather experimental data. Then based on signal to noise (S/N) ratio, the best sets of cutting parameters and tool geometry specifications have been determined[9]. E. Daniel Kirby found that, Taguchi parameter design is used for optimizing quality and performance output of manufacturing processes. This study utilizes a standard orthogonal array for determining the optimum turning parameters, with an applied noise factor[10]. V.B. Magdum, V.R. Naik evaluates the machining parameters for turning on EN 8 steel on lathe machine. This study investigates the use of tool materials and process parameters for machining forces for selected parameter range using Taguchi orthogonal array (OA) and ANOVA[11]. Acetal homopolymer finds its application in general industrial, automotive, hardware, electronics and consumer goods industry etc. But it is found that no work has been reported in the literature on optimization of process parameters in machining of Acetal homopolymer. In the present investigation, full factorial experiment has been employed to determine the best combination of the machining parameters such as cutting speed, feed rate, depth of cut and tool material to attain the minimum surface roughness while considering a noise factor.

III. Taguchi Method

The Taguchi method developed by Genuchi Taguchi is a statistical method used to improve the quality of the product. The traditional design experimentation are too complicated and not easy to use. A large number of experimental work have to be carried out when the number of process parameters increases. To solve this problem, the Taguchi method uses a special orthogonal arrays to study the entire parameter space with only a small number of experiments. Taguchi methods have been widely utilized in engineering analysis and consist of a plan of experiments with the objective of acquiring data in a controlled way, in order to obtain information about the behavior of a given process. The greatest advantage of this method is the saving of efforts in conducting experiments; saving experimental time, reducing the cost and discovering significant factors quickly. Taguchi's robust design method is a powerful tool for the design of a high quality product. The Taguchi method is a quality tool that helps improve the work efficiently.

The objective is to design the quality in each and every product and their corresponding process. Quality is measured by the deviation of quality characteristics from its target value. Therefore, the objective is to create a design that is insensitive to all possible combinations of uncontrollable factors and is at the time effective and cost effective as a result of setting the key controllable factors at optimum levels. Taguchi offers a simple and systematic approach to optimize a performance, improving quality and reducing the cost. The quality of design can be improved by improving quality and productivity in various activities of company. Those activities concerned with quality include in quality of product planning, product design and process design. S/N ratio and OA are two major tools used in robust design. S/N ratio measures quality with emphasis on variation and OA accommodates many design factors simultaneously.

IV. Selections of materials

4.1 Tool material

Un-reinforced thermoplastics can be machined using high speed steel (HSS) tools. For glass-reinforced materials, carbide-tipped sharpened tools should be used. Due to the low thermal conductivity and low melting temperatures of plastics, good heat removal must be ensured through proper chip removal and cooling with clean dry air or a mild water-based cooling fluid.

Fine, C-2 grade carbide inserts are recommended for turning. Polished top surfaces will help to reduce material build-up, allowing for better surface finishes. Cutting edges should have generous relief angles and negative back rake to minimize any rubbing action.

4.2 Work piece material

The main available Acetal homopolymer compositions can be classified as follows:

Low viscosity grades: 900P, 911P;
Medium viscosity grades: 500, 500P, 507, 527UV, 511P;
High viscocity grades: 100, 100P, 111P, 107, 127UV;
Toughened grades: 100ST, 100T, 500T;
Low friction/ low wear grades: 500AF, 500CL and
Glass filled grades: 570.

In this paper Acetal homopolymer as DELRIN 500 CL material is used over the several compositions of grades.

4.1.1 Properties of work piece material

Table 1: Comparison of properties of work piece material vs. other plastics

PROPERTIES	UNITS	ACETAL Delrin 500CL	RUBBER	NYLON	POLY URETHANE
Mechanical properties					
Density	Mg/m^3	**1.39-1.43**	0.9-0.92	1.12 - 1.14	1.12 - 1.24
Young's Modulus(E)	GPa	**2.5- 5.0**	.001 - .002	2.62 – 3.2	1.31 – 2.07
Tensile Strength (σ_{ts})	MPa	**60 – 89.6**	5 - 10	90 - 165	31 - 62
Hardness	Durometer	**117 – 120R**	18-90	70-120R	A55-A95R
Yield stress (σ_y)	MPa	**48.6 – 72.4**	2 - 3	50 – 94.8	40 – 53.8
Ductility (% EL) in	2 in(50 m)	**5 – 80 %**	1-9 %	10- 30 %	100 – 500%
Fracture Toughness (K_{IC})	MPa√m	**1.71 – 4.2**	0.07 – 0.1	2.22 – 5.62	1.84 – 4.97
Thermal properties					
Thermal conductivity(25˚C)	W/m-˚K	**0.23-0.31**	0.09	0.17- 0.29	0.03
Coefficient of expansion	(10^{-6} m/(m K)	**106.5**	77	72	57.6
Melting point T_m	˚C	**163 -179**	-73 to -63*	216 - 221	204- 232
Other					
water absorption 24 hr.	0.2%	**0.16-0.35%**	0.10 -0.15 %	0.25-3.0 %	0.10- 0.60 %

V. Metal Cutting Process

5.1 Turning Process

Turning process is very essential process in which a single point cutting tool removes unwanted material from the surface of a rotating cylindrical work piece. The cutting tool is fed linearly in a direction parallel to the axis of rotation of cylindrical work piece. Turning is carried out on a lathe that provides the power to turn the work piece at a specified rotational speed and to feed to the cutting tool at a specified rate and depth of cut. Therefore the cutting parameters namely cutting speed, feed and depth of cut need to be determined in a turning operation. The main purpose of turning operation is to produce low surface roughness of the parts.

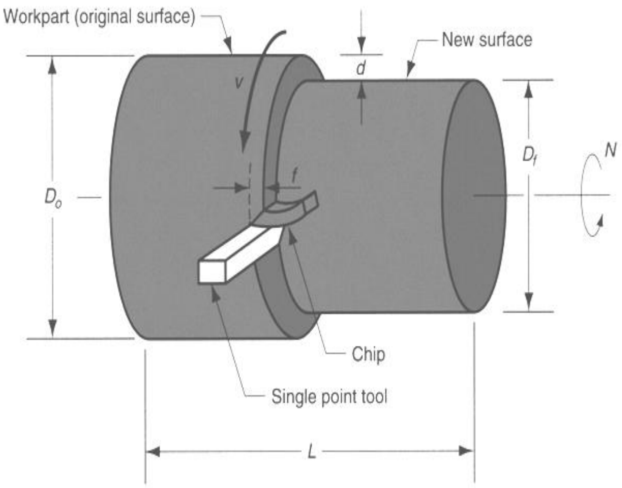

Fig. 1 Turning process

In machining process, there are two basic requirements. The first is high- quality surfaces and second is high production rate. An extremely high quality surface can produce higher production costs and time consumption. Therefore, the machine tool operators would not push the cutting tool to its limit, rather using less risky process factors for that reason, which neither guarantees the achievements of the desired surface quality nor attains maximum production rate or minimum production cost. Hence, it is of great importance to exactly quantify the relationship surface roughness and cutting conditions. The work piece is a piece of re-shaped material that is secured to the fixture, which itself is attached to the turning machine and allowed to rotate at high speeds. The cutter is typically a single point cutting tool that is also secured in the machine. The cutting tool feeds into the rotating work piece and cuts away material in the form of small chips to crate the desire shape.

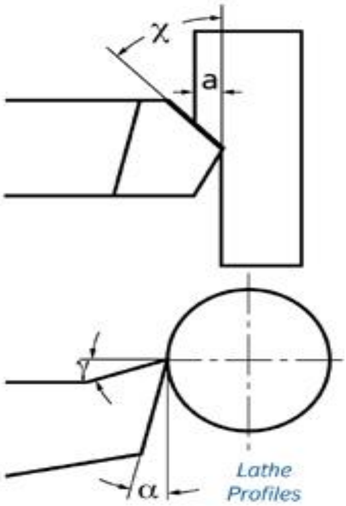

Fig. 2 Lathe Profile

5.1.1 Turning on a Lathe

Since most plastics produce unbroken chips, it is important to ensure that the chips are removed, as they would otherwise catch and revolve with the part being turned on the lathe. In addition, because of the low degree of stiffness of plastics, there is a great danger of longer parts sagging, and it is thus advisable to use a steady rest. The values given in Table apply to the cutter geometry. The point radius should be at least 0.5 mm.

Table 2: Tool geometry tool (Turning)

	Acetal (POM)
α = Clearance angle(˚)	6-8
γ = (rake)Effective cutting angle (˚)	0-10
X= side angle (˚)	0-45
V = Cutting Speed (m/min)	200- 500
S = Forward feed (mm/rev)	0.05 - 0.5
a = rate of cut (mm)	Up to 15
Nose radius (r)	0.02 in.

The “Factors” that affect Turning operation on a lathe machine are listed in the table.

Table 3: Factors that affect turning operation

Control factors	Noise factors
Cutting speed	Vibration
Feed rate	Machine condition
Depth of cut	Raw material variation
Coolant	Operator skill

5.2 Guidelines For Machining Acetal Components

If these machining guidelines are followed, complex parts made of engineering plastics can be finish-machined to the highest quality standards.

- The highest possible cutting speed should be chosen.
- Optimum chip removal must be ensured so that the chips are not drawn in by the tool.
- The tools that are used must be very sharp. Blunt tools can cause extreme heat, which results in deformation and thermal expansion.
- The clamping pressures must not be too high as this would result in deformation of the work piece and the clamping tool would leave marks in the work piece.
- Because of the low degree of stiffness, the work piece must be adequately supported on the machine table and should lie as flat as possible.
- High-quality surfaces can only be obtained when the machines operate with low vibration.
- As a rule, it is not absolutely necessary to cool the work piece during machining. If cooling is to be applied, it is recommended that compressed air is used. This has the advantage that, in addition to the cooling effect, the chips are removed from the working area and cannot be drawn into the work piece or tool.

VI. Experimental Design, Setup And Methodology

6.1. Experimental Design And Setup

In the present work, the machining process was studied under Taguchi parameter design methodology. This includes selection of parameter, utilizing an orthogonal array, conducting experimental runs, data analysis, determining the optimum combination and verification. The cutting experiments were carried out on lathe machine under dry or wet conditions. Machining tests were perform on Acetal homopolymer Delrin 500 CL raw material having diameter 1" (25.4)mm. In this experiment, the process parameters like cutting speed (Vc), feed rate (f) and depth of cut (d) are included as controlled parameter. Literature survey shows that feed rate has a much higher effect on surface roughness than other two. It was determined that a robust but efficient experiment would include feed rate with more levels than other factors. It is also intended that this would allow the selection of an orthogonal array with as few runs as possible, while still allowing for a robust experiment. In this study, tool 9 work pieces diameter 25 mm × 30 mm is prepared. These work pieces cleaned prior to the experiments by removing 0.5 mm thickness of the top surface from each work piece in order to eliminate any surface defects and wobbling. The surface roughness of machined surfaces is measured by portable stylus type Profilometer and measurements were repeated 3 times.

Table 4: Experimental conditions

1.	Work piece material	Acetal homopolymer Delrin 500CL
2	Tool material	C-2 grade carbide inserts
3	Machine used	Lathe
4	Size of work piece	Ø 25 mm × 50 mm.
5	Machining condition	Coolant

6.2. Steps In Taguchi Method

The parameter optimization process of the Taguchi method is based on 8 steps of planning, conducting and evaluating results of matrix experiments to determine the best levels to control parameters. Those eight steps are given as follows:-

1. Identify the performance characteristics (response) to optimize and process parameters to control (test).
2. Determine the number of levels for each of the tested parameters.
3. Select an appropriate orthogonal array and assign each tested parameters into the array.
4. Conduct an experiment randomly based on the arrangement of the orthogonal array.
5. Calculate the surface roughness for each combination of the tested parameters.
6. Analysis the experimental result using the S/N ratio and ANOVA test.
7. Find the optimal level for each of the process parameters to find out the minimum surface roughness.
8. Conduct the confirmation experiment to verify the optimal process parameters.

6.3. Determine The Control Factors And Their Levels

Table 5: Cutting parameters and their levels

Factors	Cutting parameters	Levels			Units
		1	2	3	
A	Depth of cut (D)	0.8	1.0	1.2	mm
B	Feed (F)	0.15	0.20	0.25	mm/rev
C	Cutting speed (V)	200	240	280	m/min

6.4. Selection Of The Orthogonal Array

It is possible to select suitable factors as shown in Table1, which indicates factors and their levels in the machining experiments with lathe machine, which contains 3 factors, and each factor has 3 levels. The table 2 is shown the form of orthogonal array L9 for data collection.

Taguchi method has been used to study the effect of cutting speed, feed rate and depth of cut on surface roughness. For proper selecting of orthogonal array, degree of freedom (DOF) is calculated.
The total degree of freedom for three machining parameters each at three levels is given by
(DOF)R = P (L – 1) ----------- (1)
Where,
P = number of factors, L = number of levels, so DOF = 3 X (3-1) = 6.
Therefore, a three level orthogonal array with at least 6 DOF was to be selected. So, L9 orthogonal array was selected. The degree of freedom (DOF) for three parameters in each of three levels was calculated as follows:
DOF= number of levels – 1, For (A,B,C) DOF = 3-1= 2,2,2
In this research nine experiments were conducted at different parameters. For this Taguchi L9 orthogonal array was used, which has nine rows corresponding to the number of tests, with three columns at three levels.

Table 6: Taguchi design (L9 orthogonal array)

Experiment number	Process parameter level			Parameter setting
	A	B	C	
	Depth of cut	Cutting speed	Feed rate	
1	1	1	1	A1B1C1
2	1	2	2	A1B2C2
3	1	3	3	A1B3C3
4	2	1	2	A2B1C2
5	2	2	3	A2B2C3
6	2	3	1	A2B3C1
7	3	1	3	A3B1C3
8	3	2	1	A3B2C1
9	3	3	2	A3B3C2

VII. Analysis Of Experimental Data And Results

7.1 Signal-To-Noise Ratio

The Taguchi method uses a loss function to determine the quality characteristics. Loss function values are converted to a signal-to-noise (S/N) ratio. S/N ratio is the ratio of the mean to standard deviation. Signal represents the square of the mean value of the quality characteristics while noise is the measure of the variability of the characteristics. In general, there are three different quality characteristics equations in S/N ratio analysis, namely “Smaller is the better”, “Larger is the better” and “Nominal is the best”.

Smaller-the-Better

This category of S/N ratio is selected when the performance characteristic like surface roughness, circularity, power consumption, etc. are required to minimize. For ideal case desired value of S/N ratio is zero. The general formula for calculating the S/N ratio is as follows;
S/N ratio = -10 $\log_{10}$ [mean of sum of square of measured data]

Larger-the-Better

This case is opposite to the lower the better case and it is obtained by taking the reciprocals of measured data. This category of S/N ratio is selected when objective function like ―Material Removal Rate‖ is required to maximize. The general formula for calculating the larger the better S/N ratio is as follows;
S/N ratio = -10 $\log_{10}$ [mean of sum of squares of reciprocals of measured data]

Nominal-the-Best

This case arises when a specified value is most desired, meaning that neither a smaller nor a larger value is desirable. The general formula for calculating the nominal the better S/N ratio is as follows;
S/N ratio = -10 $\log_{10}$ [square of mean / variance]

Since, surface roughness is a ‘lower the better’ type of quality characteristic (because objective is to minimize surface roughness, therefore, the S/N ratio for ‘lower the better’ type of response was used.

Table 7: Observed values of surface roughness and signal-to-noise ratio

Trial no.	Process parameters			Observed value	
	Depth of cut	**Cutting speed**	**Feed rate**	**Ra(μm)**	**S/N ratio**
1	0.8	0.15	200	0.29	10.75
2	0.8	0.20	240	0.73	2.73
3	0.8	0.25	280	0.64	3.87
4	1.0	0.15	240	0.60	4.44
5	1.0	0.20	280	0.54	5.35
6	1.0	0.25	200	0.99	0.09
7	1.2	0.15	280	0.46	6.74
8	1.2	0.20	200	0.59	4.58
9	1.2	0.25	240	0.61	4.29

7.2. Analysis Of Signal-To-Noise Ratio

Table 8: Response table for signal-to-noise ratio (smaller is better)

Level	Speed	Feed	Depth of cut
1	5.78	7.31	5.14
2	3.29	4.22	3.82
3	5.20	2.75	5.32
Delta	2.49	4.56	1.5
Optimum	3.29	2.75	3.82
Rank	1	1	3

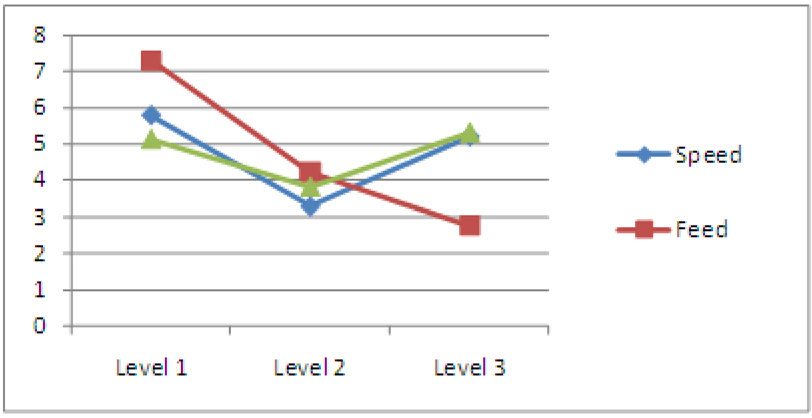

Fig. 1: Signal-to-noise ratio response graph for process parameters

Table 9 Response table for surface roughness

Level	Speed	Feed	Depth of cut
1	0.55	0.45	0.62
2	0.71	0.62	0.64
3	0.57	0.74	0.54
Delta	0.16	0.29	0.1
Optimum	0.55	0.45	0.54
Rank	1	1	3

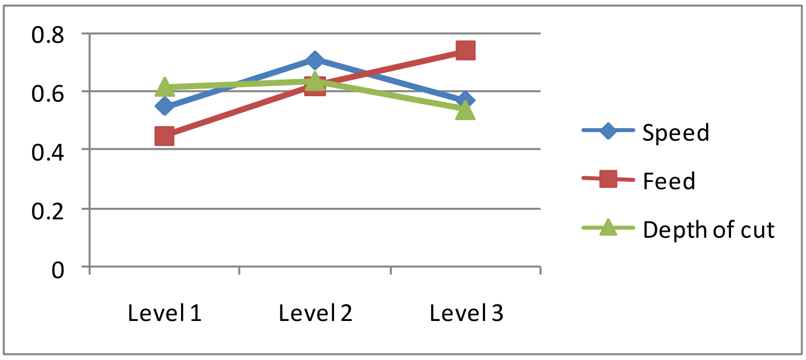

Fig. 2: Surface roughness response graph for process parameters

7.3. ANOVA

The ANOVA procedure performs Analysis of Variance (ANOVA) for balanced data from a wide variety of experimental designs. In analysis of variance, a continuous response variable, known as a dependent variable, is measured under experimental conditions identified by classification variables, known as independent variables. The variation in the response is assumed to be due to effects in the classification, with random error accounting for the remaining variation.

The ANOVA study performed to investigate the statistical significance of the process parameters affecting the response (tool life). This is achieved by separating the total variability of the S/N ratios, which is measured by the sum of the squared deviations from the total mean of the S/N ratio, into contributions by each of the process parameters and the error.

Table 10: ANOVA for S/N ratio

Factors	DOF	Sum of squares	Mean squares	% contribution
Speed (V)	2	10.19	5.09	15.16
Feed (F)	2	32.49	16.24	48.33
Depth of cut (DOC)	2	4.03	2.01	5.99
Error	2	20.52	10.26	30.52
Total	8	67.23	8.40	100.00

Table 11: ANOVA for surface roughness

Factors	DOF	Sum of squares	Mean squares	% contribution
Speed (V)	2	0.048	0.024	16.55
Feed (F)	2	0.132	0.066	45.5
Depth of cut (DOC)	2	0.016	0.007	5.56
Error	2	0.095	0.048	32.39
Total	8	0.290	0.036	100.00

It can be seen from this table ANOVA for the surface finish (Ra), the contribution of feed rate (45.50%) is more significant than speed which is (16.55%) and depth of cut which is (5.56%)

VIII. Conclusion And Recommendation

This paper illustrates the application of the parameter design (Taguchi method) in the optimization of machining operation. The following conclusions can be drawn based on the above experimental results of this study:

- Taguchi's Method of parameter design can be performed with lesser number of experimentations as compared to that of full factorial analysis and similar results.
- It is found that the parameter design of the Taguchi method provides a simple, systematic, and efficient methodology for optimizing the process parameters.

The objective of the present work is to find out the set of optimum values in order to reduce surface roughness, using Taguchi's robust design methodology considering the control factors for the Acetal homopolymer Delrin 500 CL work piece material. The levels of machining parameters to minimize the surface roughness are cutting speed at level (200 m/min), feed rate at level (0.15 mm/rev) and depth of cut at level (1.2

mm). The percentage contribution of machining parameters to surface roughness are cutting speed 16.55%, feed rate 45.5% & and depth of cut 5.56%. Due to the high need of dimensional accuracy and low manufacturing cost, I would like to recommend this material for most of the multinational companies.

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