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Cost of Manufacturing: Experiment to Establish Process-Specific Cost Functions for a Deviation Based Cost Formulation

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Abstract

In the present day global competition, there is incredible pressure on manufacturing unit of a company to reduce the cost of manufacturing, so that company can offer products at low cost. Cost of manufacturing is essential to determine final cost of the product. The cost depends on the type of manufacturing techniques used and the desired level of tolerance, it varies with the tolerance. To formulate the detail cost of manufacturing all the geometric tolerance given has to be evaluated including material, dimensions and machining operations. It is vital to the survival of any business to forecast more effectively the cost of product. The deviation based cost model established [1-4] could be used to correctly estimate the process-specific cost.

This research examined the effect of machining parameters on the cost of manufacturing, especially in turning operation, by conducting the experiment, collecting data and fitting it to the deviation based cost model. The author proposed to establish cost function for turning operations using deviation based cost formulation.

COST OF MANUFACTURING: EXPERIMENT TO ESTABLISH PROCESS-SPECIFIC COST FUNCTIONS FOR A DEVIATION BASED COST FORMULATION

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in Partial Fulfillment
of the Requirements for the Degree
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Parikshit Rajendra Deshmukh
University of Northern Iowa
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Table of Contents

LIST OF TABLES

LIST OF FIGURES

INTRODUCTION

In the present day global competition, there is incredible pressure on manufacturing unit of a company to reduce the cost of manufacturing, so that company can offer products at low cost. Cost of manufacturing is essential to determine final cost of the product. The cost depends on the type of manufacturing techniques used and the desired level of tolerance, it varies with the tolerance. To formulate the detail cost of manufacturing all the geometric tolerance given has to be evaluated including material, dimensions and machining operations. It is vital to the survival of any business to forecast more effectively the cost of product. The deviation based cost model established [1-4] could be used to correctly estimate the process-specific cost.

This research examined the effect of machining parameters on the cost of manufacturing, especially in turning operation, by conducting the experiment, collecting data and fitting it to the deviation based cost model. The author proposed to establish cost function for turning operations using deviation based cost formulation.

Problem Statement

Conduct manufacturing (turning) experiments to establish surface variation and to fit deviation based cost function.

Purpose Statement

The purpose of this study was to investigate the deviation based cost of manufacturing formulation for representing the cost of manufacturing for circular-planar surface.

Research Question

To establish cost function for turning operations using deviation based cost formulation.

Statement of Need

To conduct the experiment study was proposed by [1], to collect manufacturing process-specific (turning) data and apply to the deviation based cost of manufacturing formulation developed. This would help to determine how speed, feed and depth of cut affect the cost of manufacturing.

Assumptions

The experiment was based on following assumptions:

1. Machine was working at desired set-up accuracy during the entire period of experiment.
2. No defects in work piece.
3. Tool performance was similar during 15 minutes of life period.
4. The profilometer was working at verified level of accuracy during the entire time of measurement.
5. Material (SAE1018) used in the research meets material specifications.
6. Part was located properly in machine fixture during machining and measurement process.

Limitations

The experimentation was limited to:

1. Circular planar surface using turning process.
2. Machining parameters were limited to the capacity of the Harrison M 300 Lathe machine.

Definition of Terms

Brinell Hardness Number (BHN): Measure value of indentations in the surface of the material based on a specific load and size of ball being forced into material [8].

Cutting Speed: The velocity of the cutting tool relative to the work piece [6].

Feed: The distance the tool travels horizontally relative per unit revolution of the work piece [6].

Depth of Cut: The penetration of the cutting tool below the original work surface [6].

Tolerance: The permissible deviation of a dimension from the specified basic dimension [5].

Deviation Based Method: Tolerances impose restrictions on the possible deviations of features from their nominal sizes/shapes. These variations of size/shape are deviations of a set of generalized coordinates defined at some convenient point on a feature. This method has been presented for transforming tolerance specifications given by ASME Y14.5 into constraints in a generalized coordinate frame (deviation space) [3].

Evaluation Length: The overall length traveled by the stylus when acquiring the traced profile from where the values of the surface parameters are determined [9].

Profilometer: An instrument for the measurement of the degree of surface roughness expressed in micrometers or micro-inches [9].

Budget

The experiment was conducted in Industrial Technology (IT) department. Department provided the infrastructure, the machines, the material and tool used for experimentation.

REVIEW OF LITERATURE

The Machining cost is affected by type of material, dimensions, geometric shape, cutting speed, feed, depth of cut, sequence of manufacturing operations, tolerance and the process capacity to convert the raw part into finished product, typically it has to go through more than one operation. The total cost of manufacturing hence became sum of all the above mentioned costs associated with each operation of the process.

Tolerance of a part is required to accomplish high quality requirements, functional requirements and assemblability of parts. Tolerance of a part plays a major role in manufacturing cost, tighter the tolerance higher the cost. As stated [1] "This cost-tolerance relation is used in most cost formulations by constructing some form of an inverse power function of a single tolerance parameter ". However, there are several limitations with the one parameter cost of manufacturing formulation. Mostly, a manufactured part has more than a single tolerance values like, size, form, positional, orientation tolerances etc. It would be difficult to calculate the cost of manufacturing representing all these tolerance in a single parameter formula. Researcher [1] has demonstrated that estimation of cost of manufacturing on a basis of a single representative tolerance parameter is very difficult to capture the overall effect of tolerances. In order to avoid problems related with the single parameter formula, new deviation-based formulation for cost of manufacturing was proposed [1]. Tolerance allows some deviations of the nominal surface/feature relative to a datum feature to facilitate the interchangeability of the part during assembly. As compared to the over all dimensions of the part these deviations are very small and are called as small displacement torsor (SDT). These SDT's are used to accurately explain deviation of a surface/feature from nominal surface. In the proposed deviation based formulation, these SDT's [2] are used for calculating the deviations of features from their nominal shapes/sizes. This will help to take into account deviations of all the machined surfaces and the assembly relation between the parts.

This paper focuses on gathering the experimental data and applying to the deviation-based formula developed [1-4]. Planar feature was selected for data collection. For planar surface, only size tolerance is considered as planar feature is a non-size feature.

EXPERIMENTAL SETUP

Shaper Machine, Jet made Horizontal Bandsaw model number HBS 916W, was used to cut rod into pieces.

Harrison M 300 Lathe machine was selected for machining application, as it was available in IT department workshop.

Taylor/Hobson Precision made Surtonic25 model was used for measuring the surface roughness after machining. Fixture was designed and manufactured, Figure 1, to hold the work piece during measurement.

Figure 1 (Fixture)

EXPERIMENTAL PROCEDURE

Plain carbon steel rod of diameter one inch, SAE1018 material with Brillness Hardness Number in the range of 125-175 was selected. SAE 1018 has higher mechanical properties and better machining characteristics. Applications include gears, pinions, worms, king pins, ratchets etc. [10]. Originally material was 6 ft. in length. Then the material was cut on shear machine into 24 pieces of 2 inch in length.

For machining the circular planar surface , From table1 [7] of cutting feeds and speeds for turning plain carbon steels for SAE1018 material, Brillness Hardness 125-175, cutting tool, Valentine TPFE, was made of uncoated carbide, optimum feed of 17 and speed of 745 was selected. The optimum values with higher feed and lower speed will achieve greater productivity reducing the cost. However the same feed and speed was not available with Harrison lathe, the closest speed of 800 and feed rate of 18 (.018 inc/rev) was used for machining sample for example 1 and 2, with the depth of cut of 0.01 inch.

After selection of the feed and depth of the cut, if the selected feed was not either from the two standard feed, optimum or average, Table 5a [7] was used to determine the cutting speed for turning. The new cutting speed was calculated by the formula Vopt x Ff x Fd. Where, Vopt is the optimum speed, Ff and Fd were the adjustment factor taken from table5a [7] for selected feed and depth of cut. To evaluate the cost relationship between speed, feed and depth of cut, 24 different combinations of machining parameters were selected as shown on table 1.

The other face for all the work pieces were machined with feed of 0.009 inch/rev, with depth of cut 0.01 and speed of 800 rpm. This side was proposed to use for placing the work piece on the table for measuring the surface finish of the experimental surface.

Additionally, this surface was used for marking of sample number on the work piece, to identify the samples during the course of experimentation as shown on figure 2.

Figure 2 (Work Piece)

Table 1

Sample Cutting Speed, feed and Depth of cut and Machining time

Parameter	Sample 1	Sample 2	Sample 3
Feed (inch/rev)	0.018	0.018	0.009
Speed (RPM)	800	800	800
Depth of Cut	0.01	0.01	0.02
Time (Second)	19	19	17
	Sample 4	Sample 5	Sample 6
Feed (inch/rev)	0.009	0.009	0.009
Speed (RPM)	800	1200	1200
Depth of Cut	0.02	0.01	0.01
Time (Second)	17	11	11
	Sample 7	Sample 8	Sample 9
Feed (inch/rev)	0.009	0.009	0.004

Speed (RPM)	1200	1200	1200
Depth of Cut	0.02	0.02	0.01
Time (Second)	12	12	22
	Sample 10	Sample 11	Sample 12
Feed (inch/rev)	0.004	0.004	0.004
Speed (RPM)	1200	1200	1200
Depth of Cut	0.01	0.02	0.02
Time (Second)	22	22	22
	Sample 13	Sample 14	Sample 15
Feed (inch/rev)	0.002	0.002	0.002
Speed (RPM)	1200	1200	1200
Depth of Cut	0.01	0.01	0.02
Time (Second)	45	45	45
	Sample 16	Sample 17	Sample 18
Feed (inch/rev)	0.002	0.0361	0.0361
Speed (RPM)	1200	1200	1200
Depth of Cut	0.02	0.01	0.01
Time (Second)	45	11	11
	Sample 19	Sample 20	Sample 21
Feed (inch/rev)	0.0361	0.0361	0.0361
Speed (RPM)	1200	1200	800
Depth of Cut	0.02	0.02	0.01
Time (Second)	11	11	19
	Sample 22	Sample 23	Sample 24
Feed (inch/rev)	0.0361	0.0361	0.0361
Speed (RPM)	800	800	800
Depth of Cut	0.02	0.01	0.02
Time (Second)	19	19	19

DATA COLLECTION

After the parts were machined, Taylor/Hobson Precision, Surtonic25, Profilometer was used for measuring the surface deviation. The part was mounted on the metal base and was used to fasten the work piece during measurement (Figure 3).

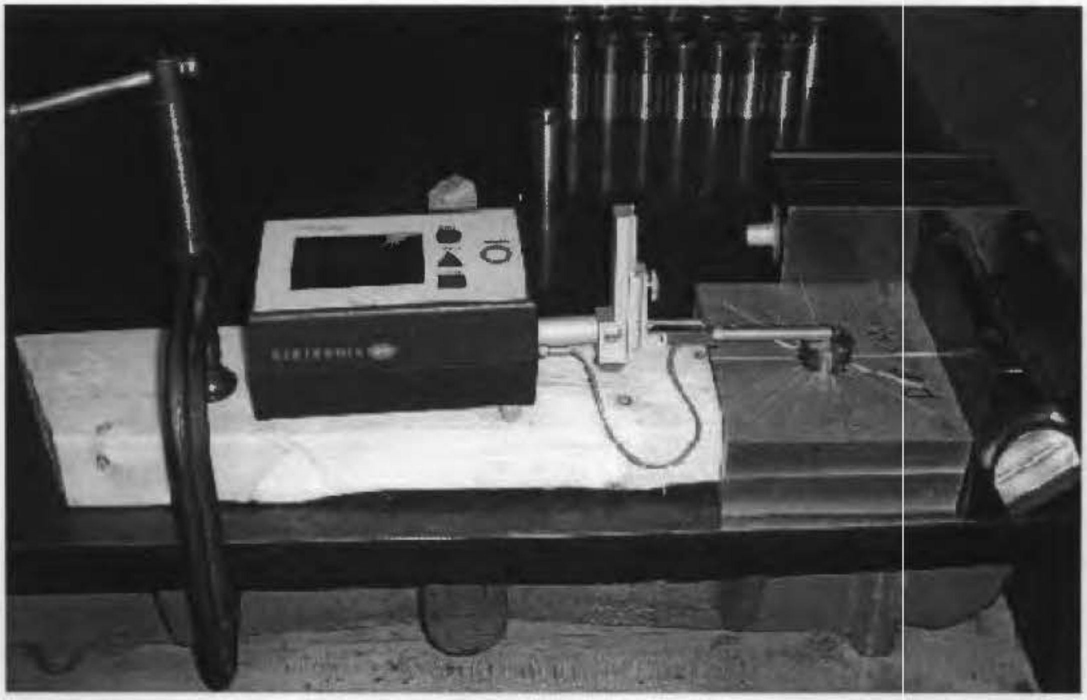

Figure 3 (Surface Measurement Arrangement)

The setup was used until all the parts were measured. Data collected was recorded in a Microsoft Excel spreadsheet (table 3). The reliability of the data measurement was very important to understand the effects of parameters on the cost of manufacturing. Evaluation Length of 2.4mm was used during the measurement. The measurements were taken on a circle of diameter 17 mm (FIG). The units of measurement used were Metric. Normalized (x, y) coordinates and actual (X, Y) of measurement points for 17mm circle are shown on table 2. The points on the table correspond to the points shown on figure 4.

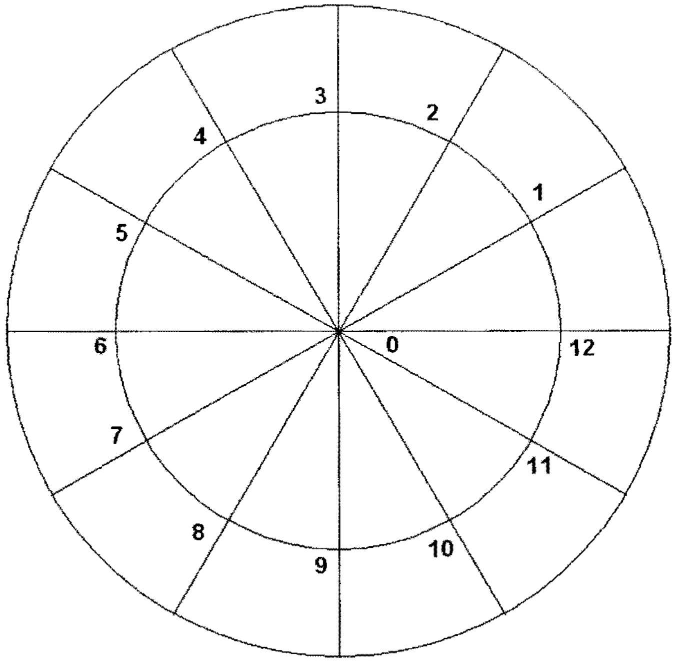

Figure 4 (Nominal Surface X-Y co-ordinates)

Table 2

Normalized (x, y) coordinates and actual (X, Y) of measurement points

Point	x	y	X	Y
0	0.00	0.00	0.00	0.00
1	0.87	0.50	7.36	4.25
2	0.50	0.87	4.25	7.36
3	0.00	1.00	0.00	8.50
4	-0.50	0.87	-4.25	7.36
5	-0.87	0.50	-7.36	4.25
6	-1.00	0.00	-8.50	0.00
7	-0.87	-0.50	-7.36	-4.25
8	-0.50	-0.87	-4.25	-7.36
9	0.00	-1.00	0.00	-8.50
10	0.50	-0.87	4.25	-7.36
11	0.87	-0.50	7.36	-4.25
12	1.00	0.00	8.50	0.00

Table 3

Planar surface roughness recorded (μm)

	Point												
Workpiece	**0**	**1**	**2**	**3**	**4**	**5**	**6**	**7**	**8**	**9**	**10**	**11**	**12**
1	2.28	2.74	3.04	3.06	3.14	3.08	2.72	2.58	2.62	2.78	2.82	2.5	2.72
2	2.9	3.04	3.2	3.1	3	2.94	3.02	2.94	3.22	3.08	3.14	3.12	3
3	5.64	4.5	4.98	4.84	4.64	4.7	4.8	4.68	4.62	4.82	4.64	4.56	5.14
4	2.84	2.64	2.34	2.26	2.44	2.42	2.32	2.16	2.43	2.32	2.21	2.5	2.54
5	1.5	2.82	3.34	3.54	3.36	3.46	3.24	3.56	2.92	3.16	3.24	2.97	3.6
6	3.24	2.4	2.2	2.18	2.58	2.32	2.16	2.28	2.14	2.22	2.4	2.36	2.4
7	2.44	2.2	1.9	1.92	1.72	1.6	1.62	1.78	1.82	2.06	1.96	2.24	2.12
8	3.44	3.14	3.22	3.12	3.28	2.94	3.3	3.42	3.2	3.38	2.94	2.82	2.78
9	2.04	1.82	1.74	1.86	1.76	1.86	1.72	1.78	1.94	1.72	1.86	1.82	1.9
10	1.54	2.8	3.04	3.18	2.74	3.02	3.56	3.12	3.06	2.98	2.66	2.44	2.26
11	2.34	1.58	1.58	1.7	1.56	1.72	1.64	1.74	1.62	1.7	1.66	1.62	1.54
12	2.14	2.14	1.66	1.74	2.04	1.86	1.94	2.06	1.8	1.82	1.88	2.12	2
13	1.34	0.64	0.54	0.5	0.58	0.7	0.52	0.64	0.56	0.58	0.54	0.56	0.54
14	1.18	1.62	1.4	1.56	1.46	1.44	1.44	1.44	1.48	1.42	1.36	1.24	1.52
15	0.7	0.82	0.76	0.76	0.8	0.72	0.7	0.86	0.8	0.78	0.78	0.8	0.82
16	0.9	0.72	0.62	0.56	0.6	0.66	0.56	0.56	0.54	0.5	0.52	0.58	0.64
17	3.32	2.94	2.82	3.12	3.08	3.06	3.02	2.92	2.94	2.84	2.88	2.98	3.04
18	3.66	3.18	2.82	2.7	2.62	2.9	2.96	3	2.78	2.88	3.36	2.88	3.16
19	Over Range	2.4	2.8	2.5	2.12	2.3	2.18	2.38	2.28	2.56	2.42	2.4	2.48
20	5.78	2.28	2.36	2.46	2.34	2.14	2.04	2.22	1.88	2.06	2.1	2.3	2.28
21	4.8	3.4	3.7	3.58	3.66	3.54	3.76	3.8	3.34	3.74	3.54	3.66	3.48
22	3.28	2.14	2.44	2.4	2.38	2.36	2.58	2.44	2.52	2.5	2.44	2.02	2.48
23	5.22	5.22	5.1	4.76	4.44	4.12	4.34	4.48	4.4	4.52	3.78	4.02	3.88
24	3.02	2.81	2.98	2.68	2.98	3.24	2.78	2.68	2.84	2.7	2.92	3.04	2.6

DATA ANALYSIS

After the deviations are measured at the 13 points, the equation of a best-fitted plane was derived as below: For these computations a local coordinate frame is placed on the flat circular face with x along a diameter, y along a perpendicular diameter and z along the axis of the cylinder figure 5 [1}. The values for work piece 19 were not taken into consideration, since the deviation values at the center of the circular plane were out side the range of 100 μm

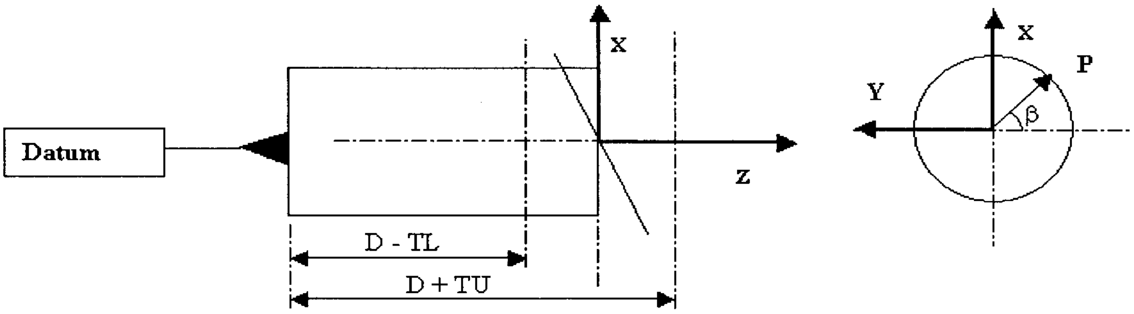

Figure 5 (Coordinate Frame)

With the above coordinate system the equation of the plane representing the nominal surface is z = 0, which would take the standard form:

$$0*x+0*y+z=0 \quad \text{with the normal vector n1} = (0, 0, 1).$$

The equation of a deviated plane would be represented by z = a*x + b*y + c, which in standard form would be:

$$-ax-by+z=c \qquad \text{with the normal vector n2} = (-a, -b, 1)$$

The coefficients for the best fitted deviation plane have been computed using the least square minimization schemes and are shown in Table 4.

Table 4

Co-coefficients for best fitted plane

WorK Piece	1			2			3		
	A	B	C	A	B	C	A	B	C
	0.0832	0.025311	-0.2051	0.09158	-0.0031	0.185	0.144	0.006	0.159
WorK Piece	4			5			6		
	A	B	C	A	B	C	A	B	C
	0.0725	0.0051224	0.35633	0.09391	0.0142	-0.36	0.071	0.004	0.208
WorK Piece	7			8			9		
	A	B	C	A	B	C	A	B	C
	0.0585	-0.007619	1.03176	0.094533	-0.0006	-0.67	0.055	-0	0.085
WorK Piece	10			11			12		
	A	B	C	A	B	C	A	B	C
	0.084	0.0074894	-1.3923	0.05075	-0.003	-0.19	0.058	-0	0.134
WorK Piece	13			14			15		
	A	B	C	A	B	C	A	B	C
	0.019	0.0001435	-0.0858	0.042814	0.0068	-0.02	0.023	-0	0.081
WorK Piece	16			17			18		
	A	B	C	A	B	C	A	B	C
	0.0184	0.0062464	0.09761	0.089873	0.0078	-0.13	0.09	-0.01	0.476
WorK Piece	20			21			22		
	A	B	C	A	B	C	A	B	C
	0.0744	0.019089	0.35996	0.110727	-8E-05	-0.26	0.074	-0	-0.43
WorK Piece	23			24					
	A	B	C	A	B	C			
	0.1344	0.0360352	0.07471	0.085975	0.0062	-0.13			

The dihedral angle between the two planes θ can now be calculated as

$$\theta = \cos^{-1}\left(\frac{(n1.n2)}{\| n1 \| . \| n2 \|}\right) = \cos^{-1}\left(\frac{1}{\sqrt{a^2+b^2+1}}\right)$$

Thus the deviation parameters corresponding to the deviation plane are:

$$(\delta_z, \theta) = (c, \cos^{-1}(\frac{1}{\sqrt{a^2+b^2+1}}))$$

Table 5 gives the computed values of these deviations. From the above values, the tolerance parameter that needs to be used in the cost function can now be calculated as:

$$L \pm \Delta L = c \pm \cos^{-1}(\frac{1}{\sqrt{a^2+b^2+1}})$$

For each work piece in a group, with machining parameters (speed, feed and depth of cut), two parameters were computed using the above relation. These values are also shown in Table 5.

Table 5

Values for δz, Θ, δz+Θ, δz-Θ

Work Piece	1	2	3	4	5	6
δz	-0.20513	0.184703	0.158801	0.35633	-0.36302	0.208292
Θ	0.086775	0.091378	0.143451	0.07253	0.094689	0.07123
δz+Θ	-0.12	0.276	0.302	0.429	-0.27	0.28
δz-Θ	-0.29	0.093	0.015	0.284	-0.46	0.137
Work Piece	7	8	9	10	11	12
δz	1.031761	-0.67111	0.085	-1.3923	-0.19299	0.133678
Θ	0.058972	0.094254	0.054915	0.0841	0.050793	0.058143
δz+Θ	1.091	-0.58	0.14	-1.31	-0.14	0.192
δz-Θ	0.973	-0.77	0.03	-1.48	-0.24	0.076
Work Piece	13	14	15	16	17	18
δz	-0.08581	-0.01786	0.081496	0.09761	-0.12551	0.476369
Θ	0.019006	0.043325	0.023372	0.01939	0.08997	0.09049
δz+Θ	-0.07	0.025	0.105	0.117	-0.04	0.567
δz-Θ	-0.1	-0.06	0.058	0.078	-0.22	0.386
Work Piece	20	21	22	23	24	
δz	0.359959	-0.26316	-0.4343	0.074706	-0.13118	
Θ	0.076632	0.110277	0.07374	0.138298	0.085988	
δz+Θ	0.437	-0.15	-0.36	0.213	-0.05	
δz-Θ	0.283	-0.37	-0.51	-0.06	-0.22	

The other parameters (like set up time, etc) remaining unchanged, cost of manufacturing would be proportional to the cutting time (Tc). Thus, for the present experiment, with machining of circular planar features, the cost coefficients are generated using the relation:

$$C_{com} = T_c * | L \pm \Delta L | = T_c * | c \pm \cos^{-1}(\frac{1}{\sqrt{a^2+b^2+1}}) |$$

The two coefficients corresponding to the tolerance are calculated as given in Table 6.

Table 6

Time and Tolerance Coefficients

Work Piece	1	2	3	4	5	6
Tc	19	19	17	17	11	11
Upper Coefficient	2.248782	5.245536	5.13828	7.290661	2.951671	3.07474
Lower Coefficient	5.546218	1.773182	0.26095	4.824535	5.034829	1.507682
Work Piece	7	8	9	10	11	12
Tc	12	12	22	22	22	22
Upper Coefficient	13.08879	6.922319	3.07813	28.78068	3.128422	4.220059
Lower Coefficient	11.67347	9.184425	0.66187	32.48118	5.363294	1.661771
Work Piece	13	14	15	16	17	18
Tc	45	45	45	45	11	11
Upper Coefficient	3.006305	1.14579	4.71908	5.265026	0.390977	6.235448
Lower Coefficient	4.716874	2.753497	2.61556	3.519648	2.370316	4.244666
Work Piece	20	21	22	23	24	
Tc	11	19	19	19	19	
Upper Coefficient	4.802499	2.904857	6.85099	4.047071	0.858565	
Lower Coefficient	3.1166	7.0954	9.65323	1.208243	4.126115	

Similarly, the Tolerance coefficient, for different combinations of Depth of cut and Speed were calculated as shown on table 7, table 8, table 9 and table 10.

Table 7

Coefficient for Depth of Cut 0.01

Work Piece	1	2	5	6	9	10
Upper Coefficient	2.248782	5.245536	2.951671	3.07474	3.078132	28.78068
Lower Coefficient	5.546218	1.773182	5.034829	1.507682	0.661868	32.48118
Work Piece	13	14	17	18	21	23
Upper Coefficient	3.006305	1.14579	0.390977	6.235448	2.904857	4.047071
Lower Coefficient	4.716874	2.753497	2.370316	4.244666	7.0954	1.208243

Table 8

Coefficient for Depth of Cut 0.02

Work Piece	3	4	7	8	11	12
Upper Coefficient	5.138281	7.290661	13.08879	6.922319	3.128422	4.220059
Lower Coefficient	0.260947	4.824535	11.67347	9.184425	5.363294	1.661771
Work Piece	15	16	20	22	24	
Upper Coefficient	4.719084	5.265026	4.802499	6.850987	0.858565	
Lower Coefficient	2.61556	3.519648	3.1166	9.653226	4.126115	

Table 9

Coefficient for Speed 800 RPM

Work Piece	1	2	3	4
Upper Coefficient	2.248782	5.245536	5.138281	7.290661
Lower Coefficient	5.546218	1.773182	0.260947	4.824535
Work Piece	21	22	23	24
Upper Coefficient	2.904857	6.850987	4.047071	0.858565
Lower Coefficient	7.0954	9.653226	1.208243	4.126115

Table 10

Coefficient for Speed 1200 RPM

Work Piece	5	6	7	8
Upper Coefficient	2.951671	3.07474	13.08879	6.922319
Lower Coefficient	5.034829	1.507682	11.67347	9.184425
Work Piece	9	10	11	12
Upper Coefficient	3.078132	28.78068	3.128422	4.220059
Lower Coefficient	0.661868	32.48118	5.363294	1.661771
Work Piece	13	14	15	16
Upper Coefficient	3.006305	1.14579	4.719084	5.265026
Lower Coefficient	4.716874	2.753497	2.61556	3.519648
Work Piece	17	18	20	
Upper Coefficient	0.390977	6.235448	4.802499	
Lower Coefficient	2.370316	4.244666	3.1166	

The average time coefficient for depth of cut 0.01 was found out to be 3.23 and for depth of cut 0.02 as 4.67 indicates general trend that with increase in depth of cut the cost increases. Similarly, the average coefficient for 800 RPM was found out to be 4.31 and that for 1200 RPM as 3.7 indicates the general trend that with increase in speed the cost decreases. The values for sample number 7 and 10 were not considered, the higher values indicates the presence of assignable cause and needs to be eliminated. However, detail mapping of these coefficients with the proposed deviation base cost model needs to be done to see the effect of these coefficient on the deviation.

CONCLUSION, RECOMMENDATION AND FUTURE RESEARCH

In this experiment author wanted to establish cost coefficient for various machining operations using deviation based cost function. The author generated corresponding deviation parameters experimented on limited combination of speed and depth of cut. This could be used to estimate the cost of manufacturing (turning operation) for the speed, feed, depth of cut and the material. These deviations could be extended to range of parameters like different material, cutting speed, feed and depth of cut.

Further experimental studies could be conducted to generate cost coefficients for machining other features like cylindrical features, spherical features. Also, different experiments will be needed to establish parameters for other machining operations like milling, drilling, etc.

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APPENDIX-A

DEVIATION-BASED MODEL FOR COST OF MANUFACTURING FORMULATION

Following derivation is reproduced here from [4] for completeness of this report and ready reference to the cost formulations. The concepts presented below have been used for calculating the cost coefficients corresponding to the experimental data.

5.5.2 Deviation-based Model for Cost of Manufacturing

In general, a part will have more than one feature, connecting to other features of other parts and since each feature could possibly have up to six degrees of freedom, this cost formulation uses six deviation parameters to represent the variations associated with each feature. Since these deviation parameters could be mapped into a tolerance zone (see section 5.7), the cost formulations could be mapped from the tolerance domain to the deviation space. Thus, for example, the cost function g(δ) defined as a function of some tolerance value δ, would become a function of the six parameters $g(\delta) = g(\ \delta(\theta_x\ \theta_y\ \theta_z\ \ \delta_x\ \ \delta_y\ \ \delta_z))$ and then the cost functions could be treated as functions of the small deviation parameters associated with the feature/part.

The cost of manufacturing a part is proposed as an explicit product of six positive functions of the six deviation parameters in the form:

$$DCOM(\mathrm{d}) = C_1(d_1)*C_2(d_2)*\ldots.C_6(d_6) \qquad \ldots.\ (5.5.2\text{-}1)$$

where $\mathrm{d} = (d_1,\ d_2,\ d_3,\ d_4,\ d_5,\ d_6) = (\theta_x\,,\ \theta_y\,,\ \theta_z\,,\ \delta_x\,,\ \delta_y\,,\ \delta_z)$ is a 6-componenet torsor representing the six deviation parameters characteristic of the feature.

The form of the individual functions could be varying depending on specific surfaces and manufacturing process. Sometimes, some of the functions could be of similar form. It is to be mentioned here that, depending on the nature/type of the feature, some of the functions will be constants and could be eliminated (i.e. for $\forall x$, $f(x) \equiv 1$). This will correspond to the deviation parameters that are invariants of the surface.

As for an example, for a planar surface there are only three independent parameters given by: $d = (d_x, 0, 0, 0, \theta_y, \theta_z)$ that could affect the deviation of the surface from it's nominal shape and any change in the remaining three parameters keep the surface invariant. The cost function can then be represented as:

$$DCOM(\mathrm{d}) = C_x(d_x) * C_\theta(\theta_y) * C_\theta(\theta_z) \qquad \text{.... (5.5.2-2)}$$

Also, in this case, since the surface is symmetric about the y & z axes, the form the two functions for rotational components of the deviation along these two directions are also same, namely C_θ

Since the tolerance specification as per standard codes of practice maps to a zone in the deviation space the deviation parameters are restricted by the tolerance specification. In other words, all the parameters in the cost formulation are not necessarily independent. For example, for the planar feature this mapping forms a convex hull in the form of a diamond in the 3-d space. For a rectangular planar section with cross-section ('a' x 'b'), (vide section 5.7), following are the restrictions:

$$T_{SL} \leq \min(d_X + a*\theta_y + b*\theta_z,\ d_X + a*\theta_y - b*\theta_z,\ d_X - a*\theta_y + b*\theta_z,\ d_X - a*\theta_y - b*\theta_z)$$

$$T_{SU} \geq \max(d_X + a*\theta_y + b*\theta_z,\ d_X + a*\theta_y - b*\theta_z,\ d_X - a*\theta_y + b*\theta_z,\ d_X - a*\theta_y - b*\theta_z)$$

where (T_{SL}, T_{SU}) are the lower & upper values of the tolerance parameter for the planar surface. Thus the parameters d_x θ_y θ_z are restricted. The above two would impose restrictions on the cost function.

To illustrate the cost function, a generic function of the form: $C(x) = a + b/|x|$ is assumed, where x is the deviation parameter and a & b are constants. The basis for this type of cost functions is that the cost of machining (apart from dependency on the machining process itself), is assumed to be directly proportional to the area of the surface to be machined and inversely proportional to the net amount of deviation of the feature from its nominal shape and a constant deviation-independent cost (setup cost, etc.). Thus, the cost function is assumed to be of the form $C(x)=K_p*Area/Deviation$, where K_p is some constant.

For the planar case, the cost function becomes,

$$DCOM(\mathrm{d}) = C_x(d_x)*C_\theta(\theta_y)*C_\theta(\theta_z)=(a_1+b_1/|d_x|) * (a_2+b_2/|\theta_y|) * (a_3+b_3/|\theta_z|)$$

Further simplification carried out (for illustrative purposed only) by assuming, $a=b=1$ and $a_2 = a_3$, $b_2 = b_3$ then leads to following:

$$DCOM(\mathrm{d}) = (a_1+b_1/|d_x|) * (a+b/|\theta_y|) * (a+b/|\theta_z|)$$

$$-T_{SL} \leq (d_X + \theta_y + \theta_z) \leq T_{SU} \quad -T_{SL} \leq (d_X + \theta_y - \theta_z) \leq T_{SU}$$

$$-T_{SL} \leq (d_X - \theta_y + \theta_z) \leq T_{SU} \quad -T_{SL} \leq (d_X - \theta_y - \theta_z) \leq T_{SU}$$

Removing the z-parameter θ_z so that a visual representation of the cost function could be given, we have:

$$DCOM(\mathrm{d}) = (a_1+b_1/|d|) * (a+b/|\theta|)$$

$-T_{SL} \leq (d+\theta) \leq T_{SU} \quad \text{and} \quad -T_{SL} \leq (d-\theta) \leq T_{SU}$

In the *d-θ* plane, this would look like a tent bounded by four vertical planes (by the tolerance specification) approaching infinity along the two axes (figures 5.5.2-1, 2).

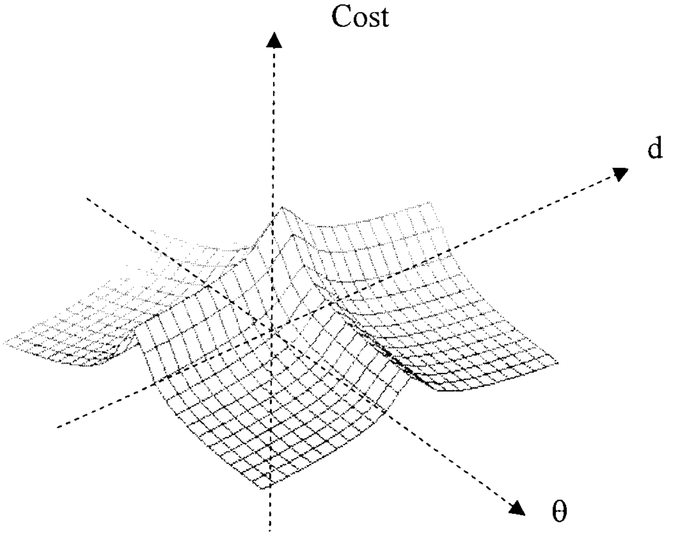

Figure 5.5.2-1 Cost as function of deviation parameters

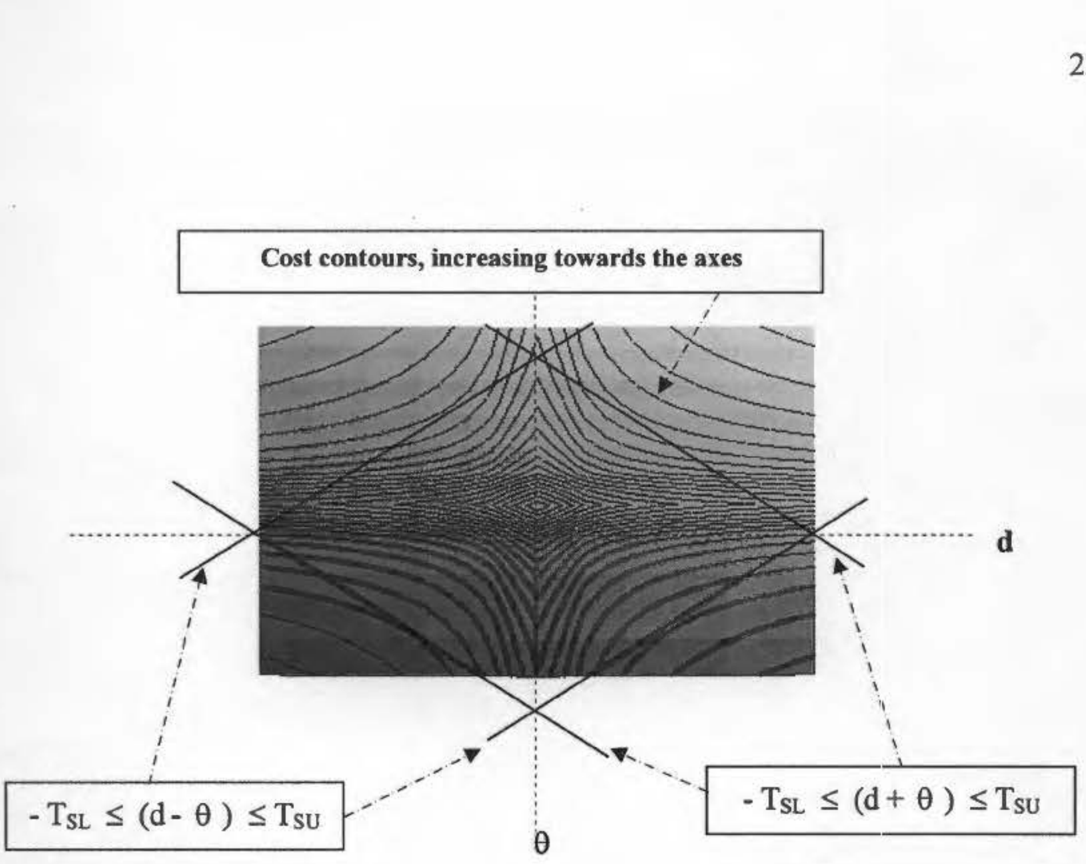

Figure 5.5.2-2 Cost contour lines and the bounds

It is to be noted that the actual form of the individual cost functions are yet to be determined. Also, it is evident that since the deviation parameters limit the tolerance values in some way or other, the cost functions of these deviation parameters should also be monotone non-increasing in nature.

For practical application of the above cost of manufacturing formulation, extensive experimental data would be required to establish the constants for different machining processes.