FEA modeling and prediction of surface roughness of aluminum alloy (LM4) during turning process

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KEYWORDS

Turning,
surface Roughness,
Equivalent Stress,
Cutting Parameters.

ABSTRACT

Different cutting parameters have different influences on the surface finish. A study of effect of some of these parameters on the surface roughness of Aluminum alloy grade LM4 ($AlSi_5Cu_3$) is carried out in this work. In the experiment conducted, six values of cutting speed, three values of depth of cut, six values of feed and two values of tool nose radius are used. The experimentation was carried out using a three factor experiment principle from design of experiment. The chemical composition of the work material was tested using arc spectrometer and verified to be of grade LM 4. The values of parameters like cutting speed, feed rate and depth of cut were selected from the recommended ranges from the tool manufacturer catalogue. The test pieces were turned on a center lathe machine under different levels of these parameters. The surface roughness of the machined surface was measured using surface measurement tester. From the analysis of results the relationship between surface roughness and equivalent stress is established.

1. Introduction

Surface finish is a quality specified by customer for machined parts. There are many parameters that affect surface roughness, but most are difficult to quantify adequately. In turning operation, parameters such as cutting speed, depth of cut, feed rate and tool nose radius have great impact on the surface finish [1, 2]. In order to study the effect of cutting parameter selected for turning operation, an accurate model of process must be constructed. There are number of studies carried out to investigate the general effects of feed, cutting speed and depth of cut on the surface roughness [3,4,5]. Thus, in this project, turning operation is carried out to study the effect of cutting parameters on surface roughness by using spindle speed, cutting speed and depth of cut as parameters and to establish covariance between surface roughness and cutting force.

Surface roughness of a product is a very crucial quality parameter in metal cutting industries. Surface roughness is important functionally for mating parts, closing tolerances and appearance also [6,7]. A smooth surface finish reduces the risk of system contamination and facilitates rapid cleaning. Surface roughness of the part surface is affected mainly by the feed rate, tool nose radius and the machinability of the work material along with other parameters [8,9]. The analysis of metal cutting parameters helps in optimizing the process, reduction in cutting forces, improved tool life and improved work piece quality.

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2. Experimental Set Up and Procedure

Aluminum Specimen Piece (LM4) material is selected for experimentation. Before the turning operation, the specimen (LM4 bar dia. 26 mm) has to be cut into desired dimension of 300 mm in length for each piece. There is need for a systematic methodological approach by using experimental methods and statically mathematical models. The design of experiment is an efficient procedure for the purpose of planning experiments [10, 11]. Data obtained from experiments is analyzed to test validity and arrive at conclusions. The experiment was carried out by using design of experiment method [12]. Using design matrix (22 *61 *31) i.e. two values of spindle speeds, three values of depth of cut, six values of feed rate

Table 1
Input parameters.

Sr. No.	Parameters	Value
1	Work piece material	Aluminum alloy (Grade -LM4)
2	Tool material	Tungsten Carbide Coated inserts grade – K10 Specifications a) CCGT Insert 090304 b) CCGT Insert 090308
3	Environment	Without coolant
4	Cutting Speed (m/min)	V_1=51.27,V_2=53.50,V_3=55.73,V_4=80.88,V_5=84.40,V_6=87.92
5	Length of cut (mm)	25 mm
6	Tool nose radius	0.4 mm, 0.8 mm
7	Tool over hang	20 mm

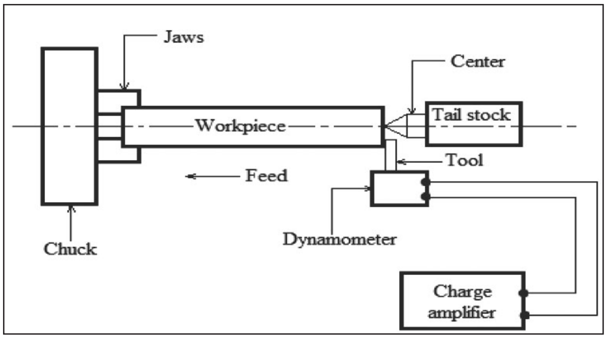

Fig. 1. Experimental setup – schematic diagram.

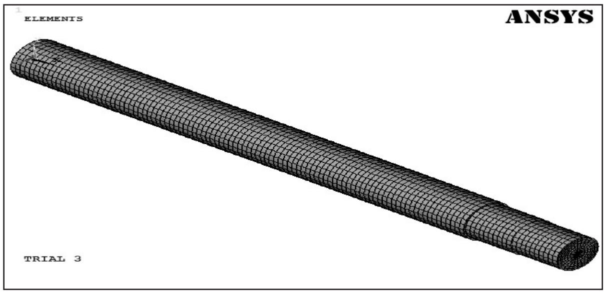

Fig. 2. Meshing.

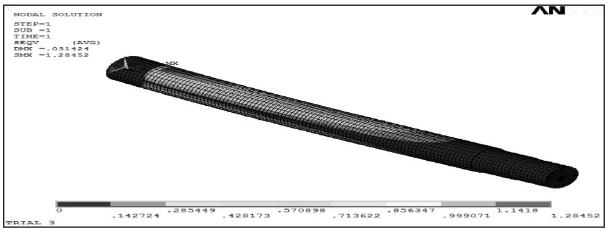

Fig. 3. Equivalent stresses.

and two values of tool nose radius are used. No. of Sets of Experiment = 22 *61 *31 = 72 set.

3. Methodology

The ways, methods and procedures are described which are used to conduct the experiment are discussed step by step.

3.1 Strategy of experimentation

The general approach to planning and conducting the experiment is called strategy of experimentation and following are the steps of experimentation [12,13]. The experimentation was carried out by using input parameters as shown in Table 1.

3.2 Finite element method

The finite element method is the dominant discretization technique in structural mechanics. The basic concept in the physical interpretation of the FEM is the subdivision of the mathematical model into disjoint components of simple geometry called finite elements. The response of each element is expressed in terms of a finite number of degrees of freedom characterized as the value of an unknown function [11].

A typical finite element analysis on a software system requires the following information:

1. Nodal point spatial locations (geometry)
2. Elements connecting the nodal points
3. Mass properties
4. Boundary conditions or restraints.
5. Loading or forcing function details
6. Analysis options

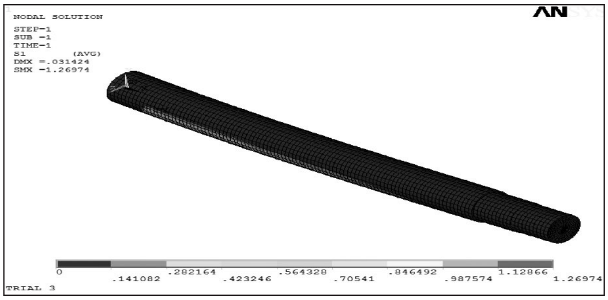

Fig. 4. Major Principle stresses.

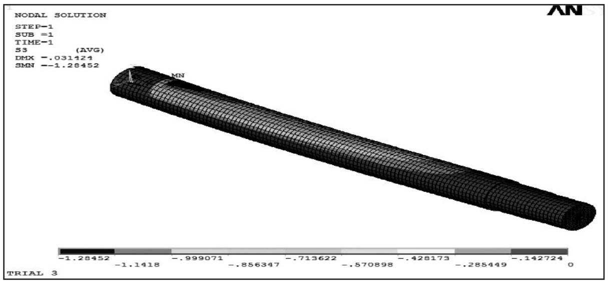

Fig. 5. Minor principle stresses.

Table 2
Equivalent stress and surface Roughness values (Tool nose radius = 0.8 mm).

Cutting speed (V1 = 51.27 m/min.), Depth of cut = 1.5 mm						
Feed Rate (mm/rev.)	0.045	0.05	0.071	0.1	0.2	0.25
Surface Roughness (µm)	1.66	1.93	2.72	3.43	4.12	4.6
Equivalent Stress (N/mm2)	9.44	7.64	12.19	12.5	26.69	20.83
Cutting speed (V2 = 53.50 m/min.), Depth of cut = 1mm						
Feed Rate (mm/rev.)	0.045	0.05	0.071	0.1	0.2	0.25
Surface Roughness (µm)	1.51	1.87	2.33	3.01	3.96	4.42
Equivalent Stress (N/mm2)	5.72	4.45	7.38	7.3	16.18	12.16
Cutting speed (V3 = 55.73 m/min.), Depth of cut = 0.5mm						
Feed Rate (mm/rev.)	0.045	0.05	0.071	0.1	0.2	0.25
Surface Roughness (µm)	1.05	1.78	2	2.88	3.59	4.2
Equivalent Stress (N/mm2)	2.58	1.91	3.32	3.13	7.29	5.32
Cutting speed (V4 = 80.88 m/min.), Depth of cut = 1.5 mm						
Feed Rate (mm/rev.)	0.045	0.05	0.071	0.1	0.2	0.25
Surface Roughness (µm)	2.02	2.8	2.84	3.54	3.9	4.73
Equivalent Stress (N/mm2)	9.44	7.64	12.19	12.5	26.69	20.83
Cutting speed (V5 = 84.40 m/min.), Depth of cut = 1 mm						
Feed Rate (mm/rev.)	0.045	0.05	0.071	0.1	0.2	0.25
Surface Roughness (µm)	2.27	2.42	2.66	3.2	3.83	4.52
Equivalent Stress (N/mm2)	5.72	4.45	7.38	7.3	16.18	12.16
Cutting speed (V6 = 87.9 m/min.), Depth of cut = 0.5mm						
Feed Rate (mm/rev.)	0.045	0.05	0.071	0.1	0.2	0.25
Surface Roughness (µm)	2.2	2.34	2.54	2.64	3.62	4.1
Equivalent Stress (N/mm2)	2.58	1.91	3.32	3.13	7.29	5.32

Table 3
Equivalent stress and surface roughness values (Tool nose radius = 0.4 mm).

Cutting speed (V_1 = 51.27 m/min.), Depth of cut = 1.5 mm						
Feed Rate (mm/rev.)	0.045	0.05	0.071	0.1	0.2	0.25
Surface roughness (µm)	2.34	3.34	3.97	5.61	7.2	8.12
Equivalent Stress (N/mm^2)	1.71	3.82	6.08	6.25	13.35	10.42
Cutting speed (V_2 = 53.50 m/min.), Depth of cut = 1mm						
Feed Rate (mm/rev.)	0.045	0.05	0.071	0.1	0.2	0.25
Surface Roughness (µm)	2.24	2.88	3.5	4.76	6.57	7.3
Equivalent Stress (N/mm^2)	2.86	2.23	3.69	3.65	8.1	6.08
Cutting speed (V_3 = 55.73 m/min.), Depth of cut = 0.5mm						
Feed Rate (mm/rev.)	0.045	0.05	0.071	0.1	0.2	0.25
Surface Roughness (µm)	2.18	2.86	3.12	4.36	6.52	7.14
Equivalent Stress (N/mm^2)	1.28	0.95	1.66	1.55	3.64	2.6
Cutting speed (V_4 = 80.88 m/min.), Depth of cut = 1.5 mm						
Feed Rate (mm/rev.)	0.045	0.05	0.071	0.1	0.2	0.25
Surface Roughness (µm)	2.52	2.69	2.79	4.05	5.65	5.98
Equivalent Stress (N/mm^2)	4.71	3.82	6.08	6.25	13.35	10.42
Cutting speed (V_5 = 84.40 m/min.), Depth of cut = 1 mm						
Feed Rate (mm/rev.)	0.045	0.05	0.071	0.1	0.2	0.25
Surface Roughness (µm)	2.33	2.42	2.49	3.51	4.68	5.36
Equivalent Stress (N/mm^2)	2.86	2.23	3.69	3.65	8.1	6.08
Cutting speed (V_6 = 87.9 m/min.), Depth of cut = 0.5mm						
Feed Rate (mm/rev.)	0.045	0.05	0.071	0.1	0.2	0.25
Surface Roughness (µm)	2.19	2.24	2.3	3.21	4.12	4.92
Equivalent Stress (N/mm^2)	1.28	0.95	1.66	1.55	3.64	2.6

4. Results and Discussion

The various tests are conducted; analyses of experimental results and analytical calculations are described. The finite element analysis technique is applied to construct mathematical model for surface roughness and equivalent stress.

4.1 Finite Element Analysis (F.E.A.) meshing and modeling

The metal cutting process is modeled using ANSYS to estimate equivalent stresses, major and minor principle stresses in the work piece (Aluminum alloy - LM4) during machining. The results are used for establishing relationship between surface roughness and equivalent stress. (Shown in Fig 2, 3, 4, 5)

4.2 Results of F.E.A. Modeling (Tool nose radius = 0.8 mm)

The values of equivalent stress and surface roughness are shown in Table 2.

4.3 Results of F.E.A. Modeling (Tool nose radius = 0.4 mm)

The values of equivalent stress and surface roughness are shown in Table 3.

4.4 Graphical interpretation of finite element analysis result

The findings from the Finite Element Analysis are shown graphically in Figure 6. From figure 6 it is seen that, as the equivalent stresses increases surface roughness value increases. The surface roughness and equivalent stress values having similar tendency for all cutting speeds.

4.5 Equivalent stress and surface roughness (4th order polynomial equation)

Table 4 shows equivalent stress and surface roughness values with tool nose radius 0.4 mm. (Cutting speed (V1 = 51.27 m/min.), Depth of cut = 1.5mm)

Figure 7 shows Equivalent stress Vs Surface roughness (4th order polynomial equation). Therefore, total twelve 4th order polynomial equations are obtained and tabulated in Table 5. Cutting force as a predictor of surface roughness and Table 5 shows equivalent stress (4th order

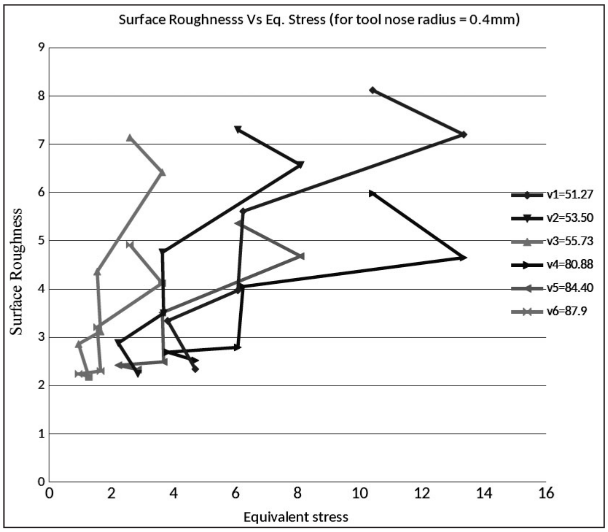

Fig. 6. Surface roughness Vs Equivalent stress (for tool nose radius = 0.4 mm).

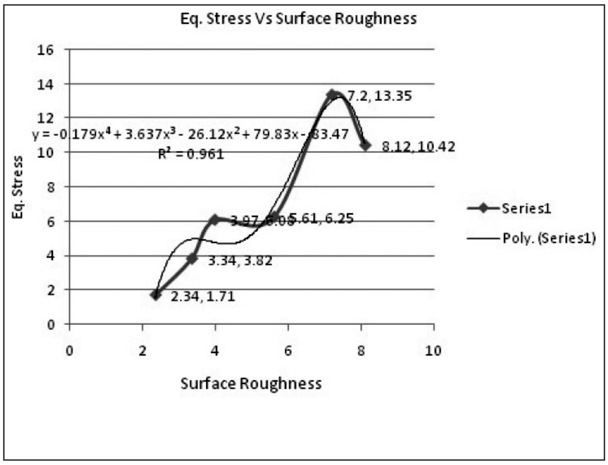

Fig. 7. Equivalent stress Vs Surface roughness.

Table 4
Equivalent stress and surface roughness values.

Cutting speed (V_1 = 51.27 m/min.), Depth of cut = 1.5mm						
Feed rate (mm/rev.)	0.045	0.05	0.071	0.1	0.2	0.25
Equivalent Stress (N/mm^2)	9.44	7.64	12.19	12.5	26.69	20.83
Surface roughness (µm)	1.66	1.93	2.72	3.43	4.12	4.6

Table 5
Equivalent stress (4th order polynomial equation and R2 –values).

Cutting speed (m/min.)	Depth of cut (mm)	Model (4th order polynomial)	R^2 Value
Tool Nose Radius = 0.8 mm			
V_1 =51.27m/min	1.5	$y = -3.745x^4 + 44.33x^3 - 186.6x^2 + 334.7x - 207.5$	$R^2 = 0.895$
V_2 = 53.50 m/min	1	$y = -2.237x^4 + 24.28x^3 - 92.85x^2 + 150.6x - 82.50$	$R^2 = 0.932$
V_3 = 55.73 m/min	0.5	$y = -1.363x^4 + 13.53x^3 - 46.29x^2 + 64.70x - 28.39$	$R^2 = 0.904$
V_4 = 80.88 m/min	1.5	$y = -18.89x^4 + 247.3x^3 - 1174.x^2 + 2400.x - 1771.$	$R^2 = 0.947$
V_5 = 84.40 m/min	1	$y = -8.217x^4 + 104.2x^3 - 483.6x^2 + 979.1x - 726.1$	$R^2 = 0.955$
V_6 = 87.9 m/min	0.5	$y = 3.522x^4 - 47.80x^3 + 235.7x^2 - 498x + 383.6$	$R^2 = 0.979$
Tool Nose Radius = 0.4 mm			
V_1 =51.27m/min	1.5	$y = -0.179x^4 + 3.637x^3 - 26.12x^2 + 79.83x - 83.47$	$R^2 = 0.961$
V_2 = 53.50 m/min	1	$y = -0.123x^4 + 2.141x^3 - 12.91x^2 + 32.79x - 26.96$	$R^2 = 0.940$
V_3 = 55.73 m/min	0.5	$y = -0.060x^4 + 1.007x^3 - 5.786x^2 + 13.95x - 10.75$	$R^2 = 0.943$
V4 = 80.88 m/min	1.5	$y = -0.987x^4 + 15.70x^3 - 90.20x^2 + 223.8x - 198.4$	$R^2 = 0.966$
V_5 = 84.40 m/min	1	$y = -1.230x^4 + 17.92x^3 - 94.90x^2 + 217.9x - 180.4$	$R^2 = 0.964$
V_6 = 87.9 m/min	0.5	$y = -1.312x^4 + 17.83x^3 - 88.26x^2 + 189.5x - 147.6$	$R^2 = 0.962$

Table 6
Equivalent stress (Model No. M1 to M6).

For Tool Nose Radius = 0.8 mm(surface roughness varies from 2.02µm to 4.1µm)							
Surface Rough. (µm)	**Eq.stress (N/mm^2)**	**Cutting Speed (m/min)**					
		V_1= 51.27	**V_2=53.50**	**V_3=55.73**	**V_4=80.88**	**V_5=84.40**	**V_6=87.9**
2.02	M1: $\sigma_{eq.1}$	10.22	5.72	2.24	10.44	0.44	4.04
2.1	M2: $\sigma_{eq.2}$	10.17	5.64	2.13	14.53	2.52	3.057
2.6	M3: $\sigma_{eq.3}$	9.31	5.91	2.42	16.07	6.34	2.94
3.1	M4: $\sigma_{eq.4}$	11.62	8.8	4.52	9.64	7.07	6.13
3.6	M5: $\sigma_{eq.5}$	18.32	13.4	6.93	19.19	12.61	6.87
4.1	M6: $\sigma_{eq.6}$	25.04	15.43	6.09	40.36	18.53	4.72

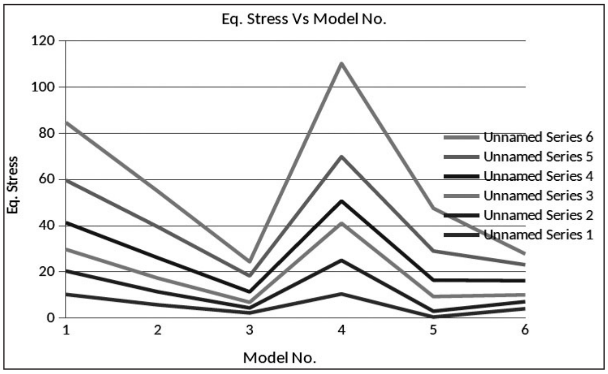

Fig. 8. Equivalent stress Vs Model no.

polynomial and R2 –values) with tool nose radius 0.8 mm and 0.4 mm.

For a target surface roughness value we can select set of cutting parameters to minimize equivalent stress and Table 6 shows values of equivalent stress (Model No. M1 to M6) with tool nose radius 0.8 mm.

Figure 8 shows equivalent stresses for different models. The model can predict the set of cutting parameters resulting in minimum equivalent stress for any given surface roughness value. This can help in optimizing the tool life.

5. Conclusions

The following are the conclusions drawn based on the experiment conducted in turning of aluminum alloy LM4. The inserts used with tool nose radii of 0.4 and 0.8 mm respectively.

- To verify the grade of the raw material (aluminium alloy) a chemical analysis test is conducted on the specimen to identify the grade by using an arc spectrometer. The material is verified to be of grade LM4.
- From result table it is observed that, two different spindle speeds which are 710 rpm and 1120 rpm (Cutting speeds are 51.27 m/min, 53.50 m/min, 55.73 m/min, 80.88 m/min, 84.40 m/min and 87.9 m/min respectively). The work piece diameter is reduced from 26 mm to 23 mm. the surface roughness value decreases from 5.09 µm to 3.16 µm. Thus it is verified that surface roughness value increases as the cutting speed increases.
- Surface roughness values for the same depth of cut have increased when cutting speed reduced in case of insert with 0.4 mm tool nose radius. However for the same depth of cut, the surface roughness values are decreased when the cutting speed increases. This may be due to rubbing of chips on work piece surface or built up edge during turning process. However it needs to be investigated separately.
- The finite element model can predict the set of cutting parameters resulting in minimum equivalent stress for any given surface roughness value. This can help in optimizing the tool life.

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