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Finite Element Analysis of Milling Roller-Burnishing Process on Surface Integrity for Non-Ferrous Metal

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***Abstract:** In today's world, large amount of attention is given to the surface roughness and surface micro hardness of the material as it's mechanical properties are greatly influenced by the surface finish. Surface Roughness is generally a measure of irregularities of the surface. It is essential to analyze the surface roughness of the material in order to avoid the failure of the material. A large number of parameters are involved analyzing the surface roughness such as type of tool, tool material, work piece material, machining operation, cutting parameters and cutting fluids. This paper aims to show that how surface roughness of the material reacts when different cutting parameters are adopted using face milling operation and how it reacts when finishing of the surface is done using roller burnishing operation experimentally and validate the results using FEM analysis using DEFORM 3D.*

***Keywords:** Roller burnishing, Milling, Aluminum, FEM analysis, surface roughness*

I. INTRODUCTION

The experimental approach to investigate any machining processes is expensive and time consuming. There are various parameters included. One should search for alternate method. Amongst the various numerical procedures, the finite-element methods (FEMs) are mostly used. The aim of finite-element analysis is to derive a computational model which is used in predicting the various parameters like deformations, stresses and strains in the work piece, as well as the various loads on the tool working under specific cutting parameters. The FEM simulations results have also been validated by comparisons with the results of experimental investigations.

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II. EXPERIMENTATION FOR MILLING

Aluminum is used as work piece. The material is chosen because of its importance in industry and its susceptibility to degradation through surface. The work material is taken in the form of rectangular block having a cross section of 20 mm × 20 mm with 200 mm length. Work piece is milled on a CNC vertical milling machine with various machining conditions and the surface roughness value is measured using TR200 hand held Roughness Tester.

Table 1 Specification of CNC milling machine

Parts	Specifications
Table size	9 x 49 inch
Longitudinal X travel	34 inch
Lift up/down ram travel	12 inch
Spindle motor	3 HP variable load
Spindle speed type	Step pulley
Spindle speed (rpm)	Up to 5600 with variable spindle speed control

III. DESIGN OF EXPERIMENTAL CONDITION

The effect of various process parameter as feed, depth of cut and speed on surface roughness are studied. The average roughness values are measured from the experiment for milling for various conditions lies in the range from 0.69 to 2.347 µm as shown in Table. 2. The minimum surface roughness is found to be 0.69 µm for speed 350 m/min, feed 0.5 mm/rev and depth of cut 1.8 mm.

Table 2 Experimental result for milling

Number	Speed (m/min)	Feed (mm/rev)	Depth of cut(mm)	Average roughness(µm)
1	240	0.5	2	2.347
2	240	0.6	2.5	2.01
3	240	0.7	3.5	2.194
4	300	0.5	2	0.75
5	330	0.5	1.5	0.96
6	350	0.5	1.8	0.69

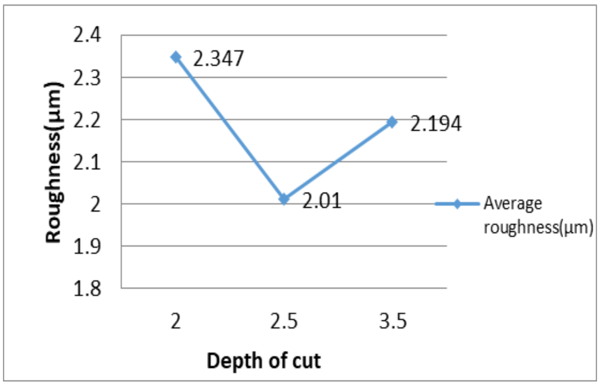

Figure 1 variation between depth of cut and average roughness

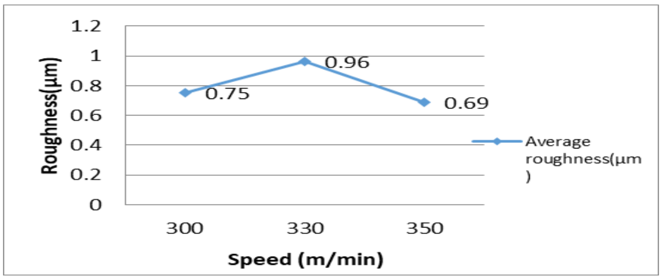

Figure 2 Variation between speed and average roughness

The relation between experimental average surface roughness value and the experiment number is shown in Figure 3.

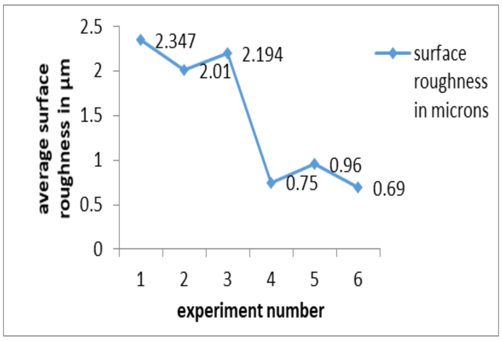

Figure 3 Experimental average surface roughness Vs. Experiment number

IV. MODELING OF EXPERIMENT USING FEM

Deform-3D is used to model the experimental conditions for milling process. Shell mill cutter is modeled using CATIA and is imported in Deform-3D using STL file.

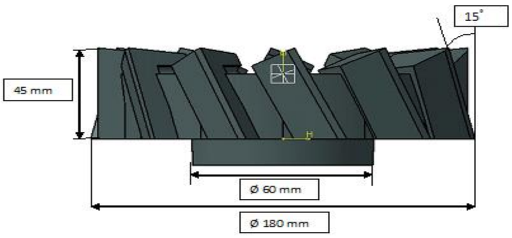

Figure 4 shell Mill cutter

V. PROCESS CONDITIONS

The process condition of milling process for simulation is given in Table 5.

Table 3 Process conditions

Process Parameters	Values
Temperature	20˚c
Convection coefficient	0.02 N/sec/mm/˚c
Shear friction factor	0.6
Heat transfer coefficient	45 N/sec/mm/˚c

VI. FEM SIMULATION OF MILLING PROCESS

The relative mesh size of tool and work piece is 25000. The meshing of tool is shown in Figure 5. FEA results converge toward the exact results as the mesh is continuously refined. To assess improvement, in regions where high stress gradients appear, the structure can be remeshed with a higher mesh density at this location.

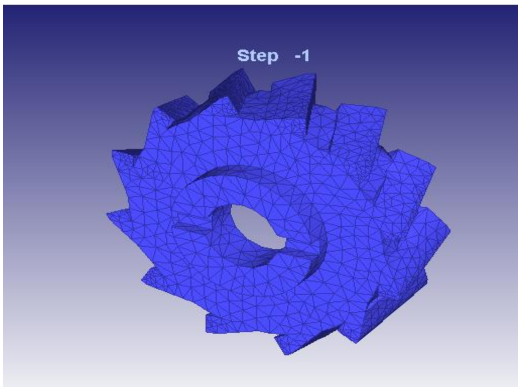

Figure 5 Tool mesh

Number of simulation steps to be performed as 10,000 and Arc angle to be cut 65˚. While the simulation is running, the second most recent saved step can be viewed.

VII. RESULTS FOR MILLING

The surface roughness of the milling process is measured for the specimen and found to be in the range from 2 to 4.5 µm. The result of the 3D FEM model obtained from the simulation in 3D-Deform software for various process conditions are tabulated in Table 4.

Table 4 Simulation result for milling

Serial no.	Speed (m/min)	Feed (mm/rev)	Depth of cut (mm)	Average roughness (µm)
1	240	0.5	2	3.5
2	240	0.6	2.5	2.5
3	240	0.7	3.5	4.5
4	300	0.5	2	1.15
5	330	0.5	1.5	2.2
6	350	0.5	1.8	2

The effects of the speed and the depth of cut on the surface roughness at various feed is shown. Increase in speed cause to decrease in the surface roughness. The decay of the surface roughness in the process at high speed is believed to be caused by the tool chatter that results in variability of the tool across work piece.

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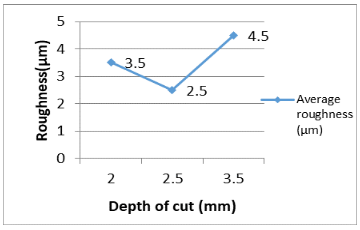

Figure 6 Depth of cut vs roughness graph for simulation

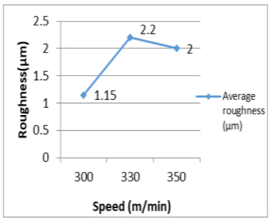

Figure 7 speed vs roughness graph for simulation

Increase in speed leads to decrease in the surface roughness. The minimum surface roughness is obtained as 1.15 microns for speed 300 m/min, feed 0.5 mm/rev and depth of cut 2 mm.

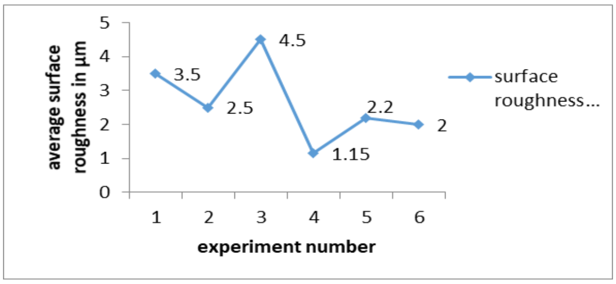

Figure 8 Simulation result of average surface roughness Vs. Experiment number

VIII. TESTING MODEL WITH EXPERIMENT

Table 7 shows the variation between simulation and experimental results.

Table 5 Comparison of results

Experiment no.	Average roughness in µm (simulation)	Average roughness in µm (experimental)	Percentage error in %
1	3.5	2.347	32.9
2	2.5	2.01	19.6
3	4.5	2.194	45.15
4	1.15	0.75	34.78
5	2.2	0.96	54.54
6	2	0.69	32.75

The maximum percentage error between simulation and experimental results is found to be 45.15 whereas minimum percentage error is 19.6.

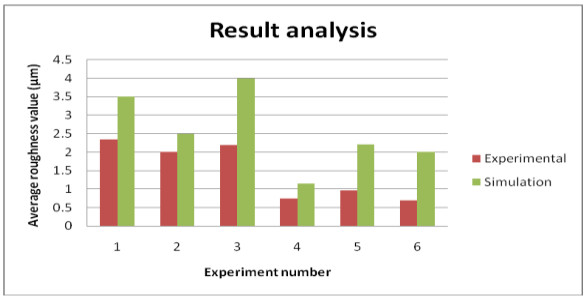

Figure 9 Comparison between simulation and experimental results

IX. CONDUCTING EXPERIMENT FOR BURNISHING

The work piece used for burnishing experiments are four rectangular bars (200 mm length x 20 mm width x 20 mm height), made of aluminum. Burnishing tool used is roller type and is pressurized and loaded on the work piece surface before work piece is rotated. Burnishing process is performed on the machined surface of each work piece. Surface roughness and surface micro hardness is measured on burnished surface of work piece. The surface roughness of the burnishing process found in the range from 0.13 to 1.2 µm (Ra).

X. DESIGN OF EXPERIMENTAL CONDITION FOR ROLLER BURNISHING

Table 6 Summary of burnishing conditions

Code	force (N)	feed (mm/rev)	no. of pass	Step over in m/min
A	900	100	3	2.5
B	1000	100	3	2.5
C	1100	100	3	2.5
D	1200	100	3	2.5
E	1000	100	3	2.5
F	1000	200	3	2.5
G	1000	300	3	2.5
H	1000	400	3	2.5
I	1000	100	1	2.5
J	1000	100	2	2.5
K	1000	100	3	2.5
L	1000	100	4	2.5
M	1000	100	3	1.5
N	1000	100	3	2
O	1000	100	3	2.5
P	1000	100	3	3

XI. STUDYING THE CHARECTERISTIC OF PROCESS PARAMETER

The average arithmetic surface roughness (Ra) for X and Y for each sample is measured with TR-200 hand held roughness tester. Surface micro hardness for each work piece is also measured with micro Vickers hardness tester.

Figure 10 shows the effect of burnishing force on surface roughness and surface micro hardness of roller-burnished aluminum. It can be seen from the curve that the surface roughness decreases with the increase in burnishing force to a minimum value, after which it starts to increase. Also it seems that surface hardness increases with increase in the roller-burnishing force for the material.

Table 7 Experimental result for roller burnishing

Code	Surface roughness in X in µm	Surface roughness in Y in µm	Surface micro hardness in H.V
A	0.7	0.3	97.43
B	0.6	0.132	85.2
C	1	0.457	99.43

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D	0.9	0.543	97.13
E	0.87	0.11	105.4
F	0.99	0.12	104.33
G	1.12	0.23	103.2
H	1.14	0.27	95.866
I	0.86	0.456	88.2
J	0.76	0.342	87.7
K	1.12	0.576	91.63
L	1.23	0.674	96.3
M	0.86	0.156	102.36
N	0.76	0.184	101.43
O	0.65	0.126	103.3
P	0.85	0.155	106.1

The effect of the number of tool passes on surface roughness for roller-burnished aluminum is illustrated in Figure 11. The curve indicates that the surface roughness reaches a minimum value with increase in the number of burnishing tool passes, after which it starts to increase, with further increase in the number of passes. It can be observed from this figure that the surface hardness increases with the increase in the number of tool passes for roller burnished aluminum work piece.

Figure 12 shows the effect of burnishing feed on surface roughness and surface micro hardness of roller-burnished aluminum work piece. It can be seen from the curve that the surface roughness increase with the increase in burnishing feed. Also it seems that surface hardness decrease with increase in the roller-burnishing feed for the material under consideration. Figure 13 depicts that the surface roughness decrease with increase in step over to a minimum value, after which it starts increasing.

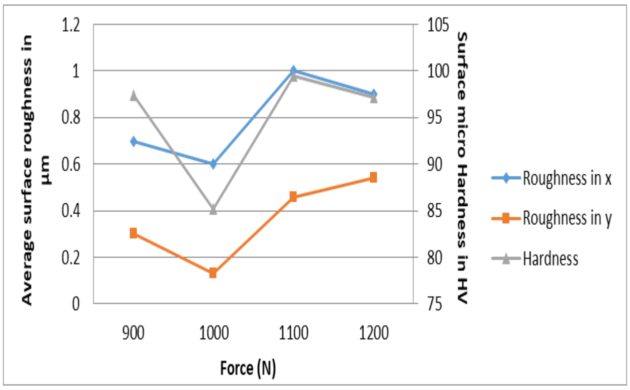

Figure 10 Variation of surface roughness and surface micro hardness with respect to burnishing force

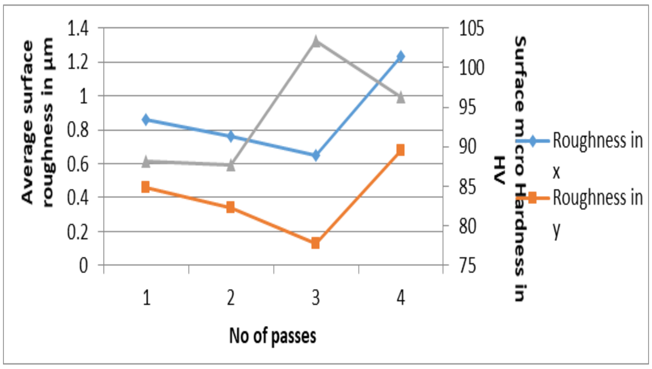

Figure 11 Variation of surface roughness and surface micro hardness with respect to number of pass

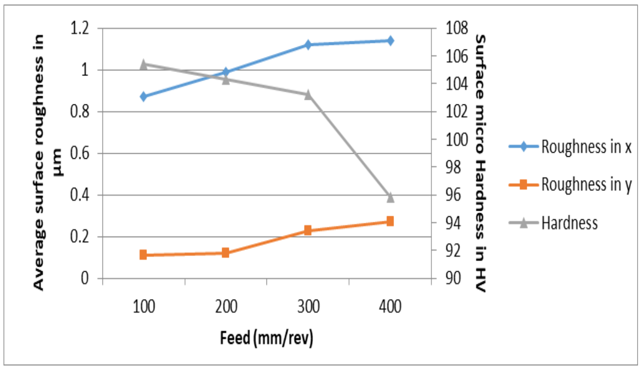

Figure 12 Variation of surface roughness and micro hardness with respect to burnishing feed

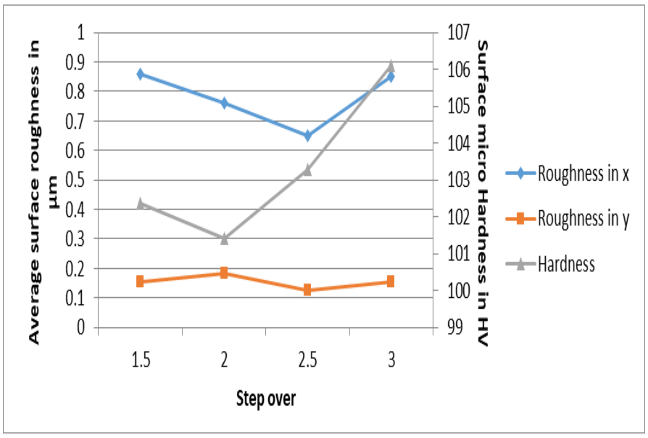

Figure 13 Variation of surface roughness and micro hardness with respect to step over

XII. FEM SIMULATION OF ROLLER BURNISHING PROCESS

Deform-3D is used to model the experiment for roller burnishing process. The roughness of 2 microns is modeled in CATIA. The roughness value is taken as the average of values obtained from milling. Burnishing tool (roller) is modeled using Deform-3D software. The width of roller is taken as 4 mm and diameter of 6 mm Material properties for burnishing tool and work piece are given in Table 10.

Table 8 Material properties for tool and work piece

Tool (roller)	Material = WC (Tungsten carbide), Young's modulus= 2.3 x 5 N/mm2, Poisson's ratio = 0.25
Work piece	Material = Aluminum, Young's modulus = 4.15 x 5 N/mm2, Poisson's ratio = 0.25

Table 9 Setup in the 3D FEM roller burnishing model

Object type	Elastic plastic work piece
	Rigid tool
Work piece size	20 x 6 x 6 mm
Thermal condition	Isothermal
Initial roughness	Determined from experiment as 2 µm
Tool movement	Tool moves toward the work piece + rotates at the same tangential speed
Initial displacement	Calculated by Hertz theory

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Roller and work piece are meshed with 4 noded tetrahedral elements with relative mesh size of 25000. The model and meshing of roller tool are shown in Figure 14.

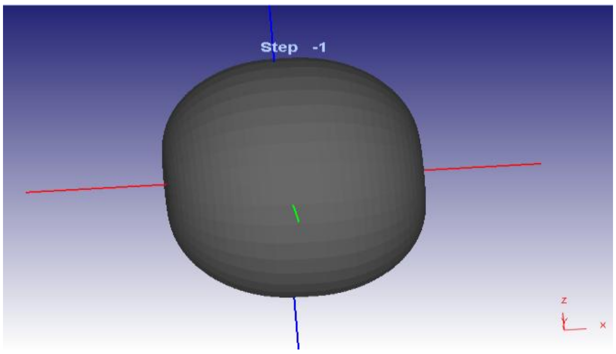


Figure 14 Setup and the meshing of roller burnishing tool

XIII. CALCULATION OF INITIAL DISPLACEMENT

Hertz theory for normal contact of elastic solids is used to predict the normal displacement and area of the contact surface [3].

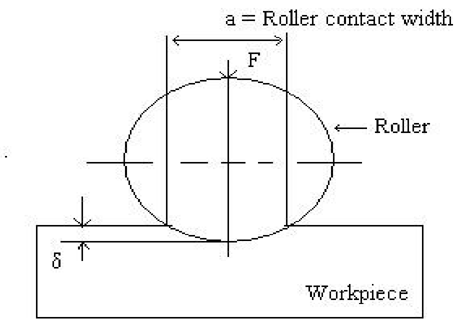
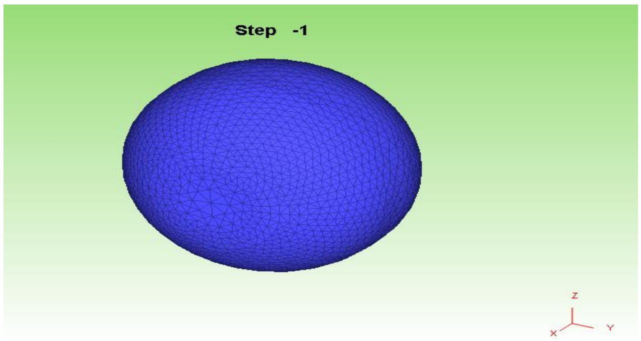


Figure 15 Normal displacement and semi-axis of the contact area

According to this theory, in which both work piece and burnishing ball are supposed to be elastic, the semi axis a and the normal displacement δ are given by equation (3.1) and equation (3.2).
Let F (N) is normal force, δ (μm) is normal displacement, a (mm) is semi-axis of the contact surface assumed to be elliptic, R1, E1 and v1 are respectively the radius, Young modulus and Poisson s ratio of the work piece, R2, E2 and v2 are respectively the radius, Young modulus and Poisson's ratio of the burnishing roller, C1, C1' are maximum and the minimum curvature of the work piece, C2, C2' are maximum and the minimum curvature of the burnishing roller. Then

$$a = \left(\frac{3\pi(K1 + K2)F}{2(C1 + C1' + C2 + C2')}\right)^{1/3} \quad (3.1)$$

$$\delta = \frac{0.003\pi r(K1 + K2)F}{4a} \quad (3.2)$$



Where,

$$K1 = \frac{1 - v1}{\pi E1}$$

$$K2 = \frac{1 - v2}{\pi E2}$$

Table 10 Initial displacement

Force	Initial displacement δ in mm
900	0.00097
1000	0.00187
1100	0.00265
1200	0.0046

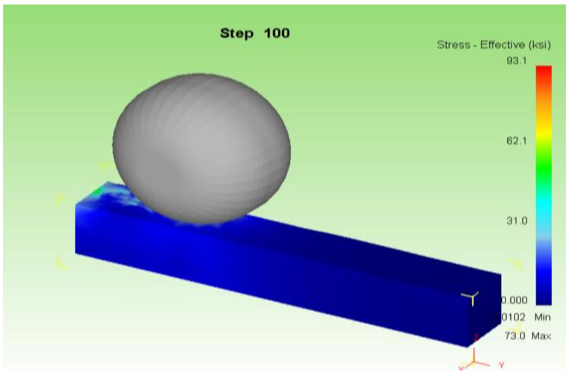


Figure 16 Simulation

XIV. SIMULATION RESULT

In Deform-3D displacement data is used to determine the arithmetic average surface roughness for various conditions. The surface roughness in X and Y for various conditions are shown in Table 3.14.

Table 11 Simulation result for roller burnishing

Code	Surface roughness in X in μm	Surface roughness in Y in μm
A	0.9	0.387
B	0.67	0.145
C	1.24	0.512
D	1.12	0.611
E	0.99	0.18
F	1.23	0.186
G	1.32	0.291
H	1.35	0.31
I	1.01	0.512

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J	0.97	0.397
K	1.23	0.611
L	1.36	0.698
M	1.01	0.201
N	0.97	0.211
O	0.88	0.154
P	0.99	0.189

XV. RESULT AND DISCUSSION

The best results are obtained at burnishing force of 1000 N. Rise in the burnishing force results in rise in surface roughness. Figure 18 shows the effect of burnishing feed rate on the surface roughness. It can be seen that rise in feed rate is not suited in the roller burnishing process. The best results are obtained at the number of burnishing passes 2. Rise in the number of passes decay the surface roughness. The decay of the surface roughness in the burnishing process is believed to be caused by the chatter that results from the impudence of the burnishing tool crossing the work piece surface.

The rise in burnishing force causes rise in the amount of surface deformation as the tool passes along the surface of the work piece. This will lead to an increase in the work hardening of the surface layers, which have been pretentious by plastic deformation. However, the results of the burnished surface roughness show that when burnishing the aluminum work piece, with forces of more than 1000 N, the surface finish is decayed, as can be seen in Figure 17. This may be because high forces cause shear failure in the subsurface layers which, in turn, results in the flaking.

Structural homogeneity found increased when burnishing process is repeated on same work piece, resulting increased in surface roughness. However, in some cases, if number of passes increased more than a certain number decay results because of the over hardening of the surface layers. Figure 20 and Figure 24 show the effect of step over on surface roughness. The best result results were obtained at the step over of 2.5 m/min.

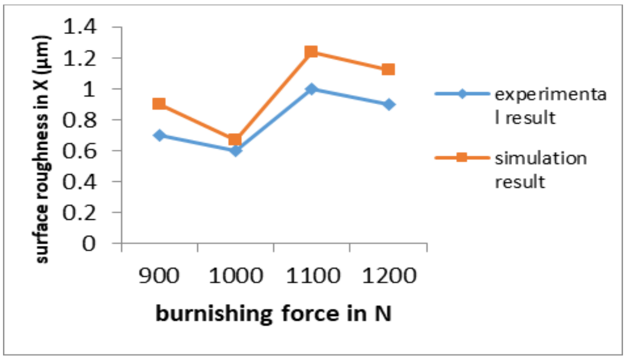

Figure 17 Surface roughness in X Vs. Burnishing force

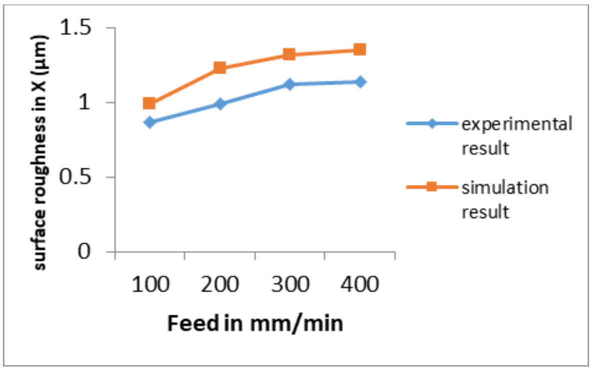

Figure 18 Surface roughness in X Vs. Burnishing feed

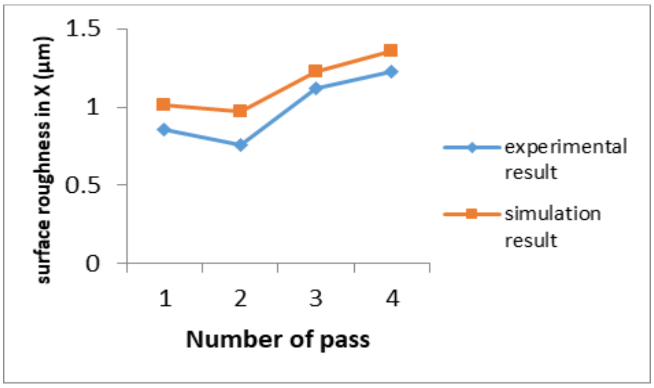

Figure 19 Surface roughness in X Vs. Number of pass

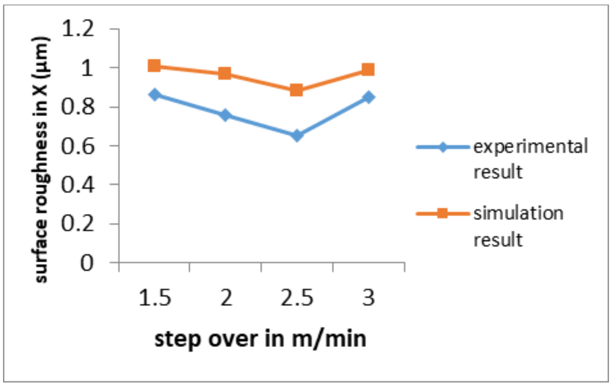

Figure 20 Surface roughness in X Vs. Step over

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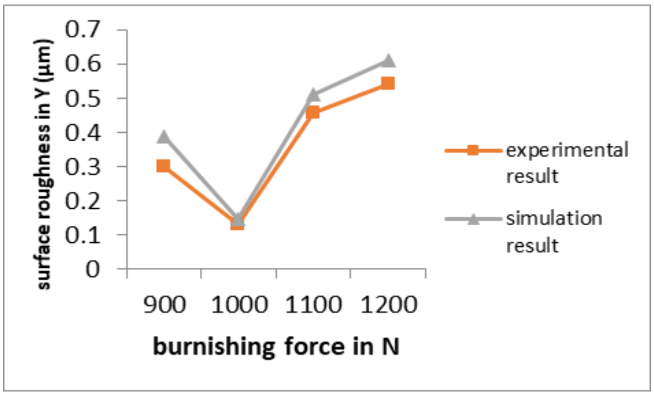

Figure 21 Surface roughness in Y Vs. Burnishing force

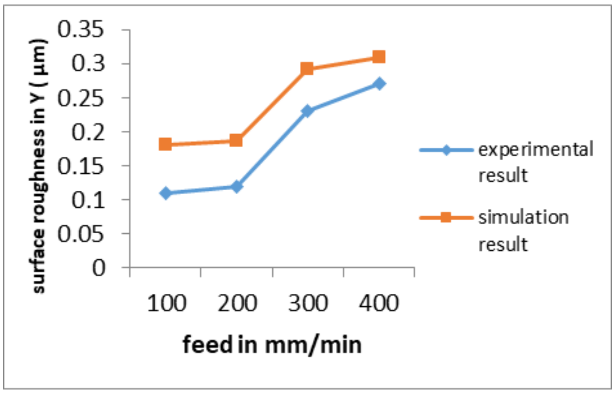

Figure 22 Surface roughness in Y Vs. Burnishing feed

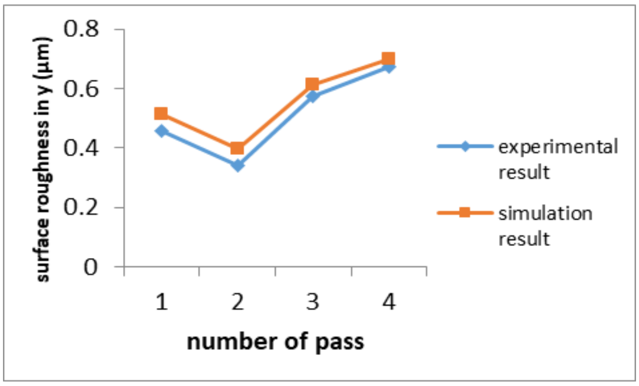

Figure 23 Surface roughness in Y Vs. Number of pass

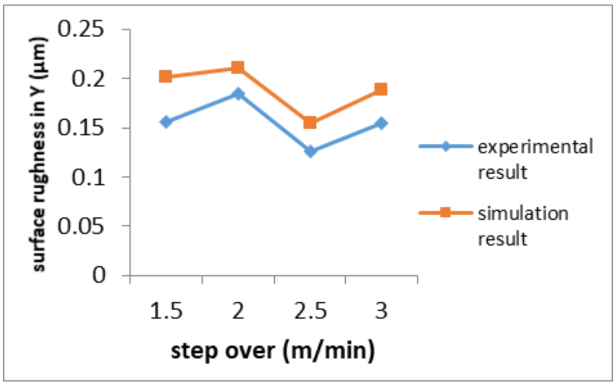

Figure 24 Surface roughness in Y Vs. Step over

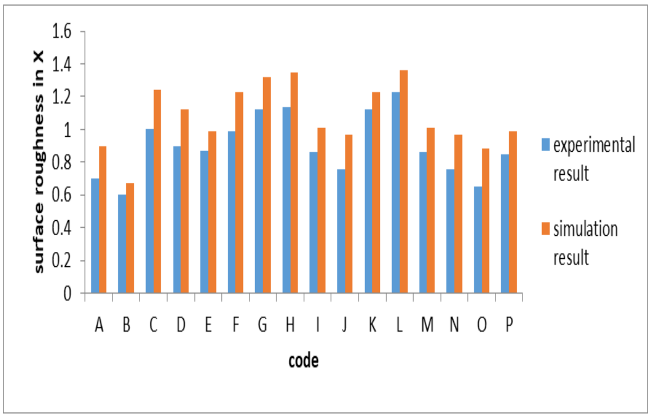

Figure 25 Comparison of result between simulation and experimental burnishing for surface roughness in X

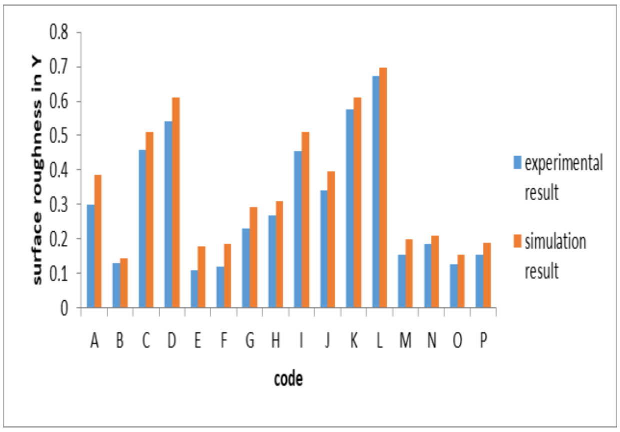

Figure 26 Comparison of result between simulation and experimental burnishing for surface roughness in Y

XVI. CONCLUSION

This research intended to show that by selecting specific process parameters, very good results can be obtained. Different results have shown that burnishing gives good surface quality which improves wear resistance, fatigue, tensile strength and corrosion resistance. This process is having many advantages, such as flexibility, low price and a simple machining range. According to this research, the following conclusions may be drawn which are listed as:

1. The maximum percentage error between simulation and experimental results for face milling is found to be 45.15 where as minimum percentage error is 19.6.
2. The maximum and minimum deviation between experimental and simulations for surface roughness in X are 30.12% and 4.34 % respectively.
3. The maximum and minimum deviation between experimental and simulations for surface roughness in Y are 28.67% and 5.38 % respectively.
4. It was shown that the burnishing force, burnishing feed, step over and number of passes have the most significant effect on surface roughness.
5. The increase of structural homogeneity of the surface layers that occurs when using low burnishing feed.
6. The recommended burnishing force and burnishing feed for good surface roughness is about 1000 N and 100 mm/rev.
7. Surface roughness is found to be good in number of pass 2.

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