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An experimental study on effect of process variables on cutter vibrations and elastic spring back in milling of AISI 316 Austenitic Steel

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Abstract: *In this paper, effect of process variables like cutting speed, feed rate and depth of cut has been studied. The multi variable responses like tool vibrations and elastic spring back effect on CNC end milling operation of AISI 316 Austenitic Steel is analyzed. The AISI 316 Austenitic Steel is taken as a sample for our work. The experiments are performed on a 3 axis CNC vertical milling machine with two flute tungsten carbide end mills at high rotational spindle speeds and optimized the process parameters. The elastic spring back is referred to as the change in shape of the work piece after removing the tool. The cutting tool vibrations are measured by Laser Doppler Vibrometer (LDV). The elastic spring back is calculated as the difference between any two corresponding points in metal cutting and the value is measured by using Scanning Electron Microscope (SEM). Based on the experimental data from the specified instruments, the process variables have been optimized. This paper shows the influence of process parameters on the spring back and amplitude of the cutting tool vibrations. In online tool condition monitoring, the optimized process parameters would give better tool life, maintain good machining time and gives higher machining efficiency.*

Key words: *AISI 316 Austenitic Steel, CNC milling, Elastic spring back, Laser Doppler Vibrometer and Tool vibrations.*

1. Introduction

AISI 316 Austenitic Steel has wide applications include pumps, valves, marine fittings, fasteners, paper and pulp machinery, petro chemical equipment and surgical implants. The material has a good combination of high strength, corrosion resistance and low stress. The mechanical properties lead to challenges in machining operations such as high process temperature as well as rapidly increasing tool wear. In this work, tungsten carbide end mills have been used in machining of AISI 316 Austenitic Steel. The vibrations and elastic spring back have been experimentally investigated and put into relationship with the process parameters under dry machining condition. The quality of the machined surfaces has been evaluated by measuring the roughness of the machined surfaces. Finally the correlation among vibrations, surface roughness and elastic spring back has been analyzed and discussed. Literature to date has shown that limited work has been carried out to analyze the consequence of machining process variables on cutting of AISI 316

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Austenitic Steel. Vibration is defined as the relative motion of an object or objects relative to a stationary frame referred to as the equilibrium of the vibration.

Since the vibration of mill cutter is a result of relative motion between work piece and tool, it is required to measure vibration of cutter as close as to machining. We used LDV to measure vibration of mill cutter the LDV's are used as non-contact methods to measure vibrations of cutting tool or work piece accurately. The LDV is capable of giving reliable information of tool vibration.

Venkatarao et al [1] have used LDV to measure vibration of rotating work piece in boring of steels on horizontal computer numerical control (CNC) lathe machine. LDV was developed by Yeh and Cummins [2] as the measuring process involves measuring the Doppler's shift of the laser radiation that is scattered by the moving particles. Later the technique was developed as LDV. Response surface methodology (RSM), artificial neural networks and support vector regression were used by Amit Kumar [3] to develop the empirical models for prediction of surface roughness, tool wear and power consumption in turning process. RSM was used to optimize cutting parameters for minimum surface roughness and amplitude of cutter vibration. RSM shows effect of individual factors and two factors interaction on the responses and it also identifies significant factors. In RSM, the quantitative relationship between input and output variables is presented as follows [4]

$$y = f(x_1, x_2, x_3, \ldots, x_n) \pm e_r \qquad -(1)$$

where "y" is the desired response; "f" is the response function, dependent variable; x_1, x_2, x_3, ., x_n are independent variables; and "e_r" is the fitting error.

Increased feed rate in any machining process will lead to generation of heat and therefore contributes high surface roughness. Maiyar et al [5] stated that increased cutting speed and feed rate will remove high amount of material, but it leads to wear on cutting edges due to abrasion between cutting edges and work piece. Pettersson et al [6] also proved that the cutting speed has significant effect on the cutter vibration. Newmann et al [7] stated that 6%-40% of energy savings can be achieved in metal cutting with optimum cutting parameters. Albrecht.P [8] stated that the desirability function was introduced in 1980 to optimize cutting parameters. The desirability function uses a gradient algorithm and it finds desirability with maximum value between 0 and 1. If the desirability value closes to 0, then the response is completely unaccepted and if the desirability value is 1 or close to 1, then the response is accepted. Spring back energy density is proposed by Zhu et al [9] for evaluation of the amount and direction of spring back. Spring back in the present context refers to the elastically driven change of shape that occurs following a metal cutting operation when loads are removed from the work piece. N. Schaal et al [10] explained the spring back in metal cutting with high cutting speeds. He proved the influence of the cutting speed on the spring back is significant. Spring back involves small strains, similar in magnitude to other elastic deformation of metals. As such it was formally considered a simple phenomenon relative to the large strain deformation required for forming. Spring back is inevitable during the process of metal cutting. It can cause the shape and size of the final part to be in discordance with the shape and size of the end mill. The factors that affect the spring back generally include the mechanical parameters of AISI 316 Austenitic Steel, anisotropy, grain arrangement, process conditions, work hardening phenomenon etc. A large no of studies on the spring back have been conducted by scholars and various solutions and simulation algorithms have been presented. Due to the diversity the materials used as sheets, structures and sizes of work pieces, different metal sheets have different spring back rules. According to the essence nature of mechanics, spring back is caused by non-uniform stress distribution along the metal thickness direction and the spring back amount is decided by spring back energy.

The main objective of this work is to experimentally investigate the elastic spring back effect and vibrations during milling of AISI 316 Austenitic Steel with carbide end mills under dry machining condition. The quality of the machined surfaces has been evaluated by means of amplitude of cutter vibration and elastic spring back.

Material and Methods

The experiments have been carried out on Chandra BFW CNC milling machine as shown in the Figure 1. The following sequential procedure was used to carry out the experiment under dry condition.

1. Each trail was started with a new end mill with one new test condition (trail) and machining was stopped at the end of each pass.
2. An LDV was placed in front of the machine and the LDV produces a laser beam to the rotating mill cutter to measure vibration signals and the setup of experiment is shown in the Figure 1.
3. After each pass, the work piece was removed and its spring back effect was measured.
4. The above steps were repeated and remained the same in the experiment with a new end mill.
5. Experimental data of 27 experiments, the vibrations along x direction and spring back effect are shown in the Table.1

The Vibrations of the work piece are measured by Laser Doppler Vibrometer (LDV) and the elastic spring back effect is measured by Scanning Electron Microscope (SEM).

Figure 1: 3-axis CNC vertical milling machine with Laser Doppler Vibrometer (LDV) arrangement

Figure 2: The machined AISI 316 Austenitic Steel work piece

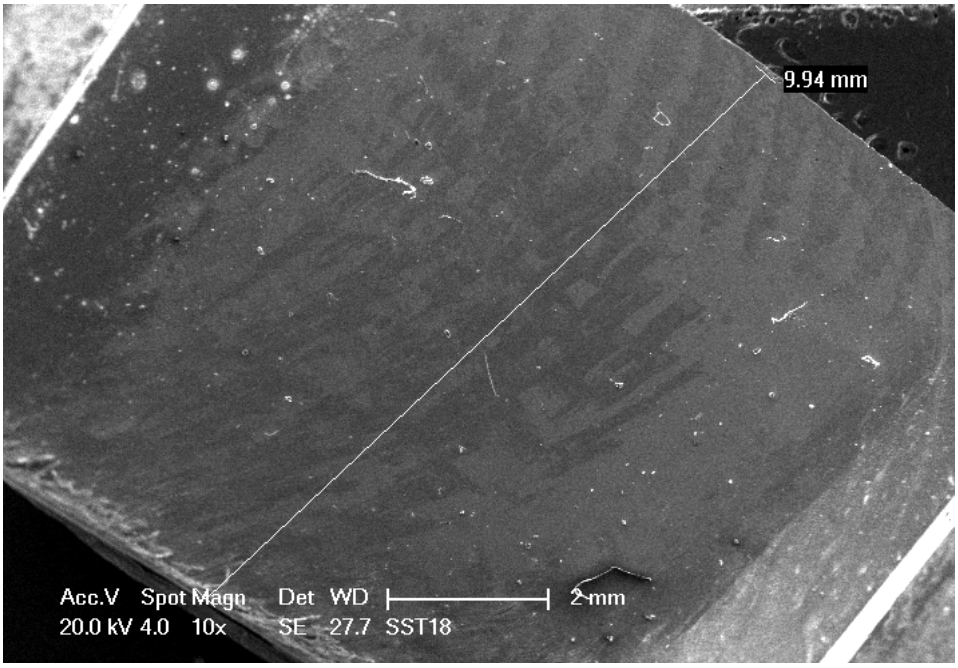

Figure 3: Measurement of spring back of a AISI 316 Austenitic steel sample using Scanning electron Microscope (SEM)

A Sample of AISI 316 Austenitic Steel with dimensions of 150mm X 120mm X 15mm has been tested. Three levels of Cutting Speed CS (95, 110 and 126 m/min), three levels of Feed Rates FR (0.1, 0.2 and 0.3mm/rev) and three levels of Depth of Cut DOC(0.3, 0.6 and 1mm) have been taken into account.

Results and Discussion

The experimental tests have been performed on CNC milling machine in random sequence, in order to reduce the effect of any possible systematic error. The AISI 316 sample is fixed in a vice and the Laser Doppler Vibrometer (LDV) is used to measure vibrations through data logger. As per Taguchi design of experiments (DOE), total 27 experiments have been performed on a CNC milling machine follows and experimental results shown in the Table 1(a) and 1(b).

No	Design of experiments			Cutter vibration in X direction (μm)				
	C S	F R	DOC	V_{x1}	V_{x2}	V_{x3}	V_{x4}	V_x Avg
1	95	0.1	1.0	9.93	10.0	9.3	9.61	9.71
2	95	0.2	1.0	9.91	10.2	10.3	9.94	10.
3	95	0.3	1.0	9.01	9.88	10.1	9.94	9.74
4	95	0.1	0.6	9.73	8.20	8.93	10.4	9.31
5	95	0.2	0.6	9.62	9.39	9.41	10.2	9.67
6	95	0.3	0.6	8.45	9.85	9.33	9.19	9.21
7	95	0.1	0.3	8.21	8.58	10.3	10.4	9.38
8	95	0.2	0.3	8.57	8.37	10.0	10.4	9.33
9	95	0.3	0.3	8.33	8.27	8.92	10.1	8.89
10	110	0.1	1.0	9.92	9.69	8.22	8.52	9.09
11	110	0.2	1.0	9.9	9.5	9.27	10.1	9.69
12	110	0.3	1.0	9.15	8.52	9.69	10.3	9.42
13	110	0.1	0.6	9.88	8.42	8.21	10.2	9.19
14	110	0.2	0.6	9.88	9.23	8.76	10.1	9.5
15	110	0.3	0.6	8.93	8.64	9.32	9.25	9.04
16	110	0.1	0.3	8.71	8.15	10.4	10.4	9.4

17	110	0.2	0.3	9.54	8.36	10.2	10.3	9.59
18	110	0.3	0.3	8.61	8.86	8.57	8.54	8.65
19	126	0.1	1.0	9.91	9.48	8.67	8.12	9.05
20	126	0.2	1.0	9.87	9.34	9.13	8.64	9.25
21	126	0.3	1.0	9.62	9.01	8.92	10.2	9.43
22	126	0.1	0.6	9.89	8.84	8.11	10.1	9.24
23	126	0.2	0.6	9.90	9.28	8.25	10.2	9.41
24	126	0.3	0.6	9.63	8.91	9.85	9.74	9.53
25	126	0.1	0.3	9.12	8.12	9.8	10.4	9.36
26	126	0.2	0.3	9.80	8.22	10.1	10.4	9.61
27	126	0.3	0.3	9.53	8.98	9.76	9.59	9.47

Table 1(a): DOE and experimental results of cutter vibration in X direction

No	Design of experiments			Elastic spring back S (µm)				
	C S	F R	DOC	S_1	S_2	S_3	S_4	SAvg
1	95	0.1	1.0	0.13	0.13	0.13	0.13	0.13
2	95	0.2	1.0	0.13	0.13	0.13	0.14	0.133
3	95	0.3	1.0	0.15	0.16	0.16	0.17	0.159
4	95	0.1	0.6	0.13	0.13	0.14	0.15	0.137
5	95	0.2	0.6	0.13	0.13	0.14	0.16	0.142
6	95	0.3	0.6	0.17	0.15	0.18	0.18	0.169

7	95	0.1	0.3	0.15	0.14	0.18	0.18	0.164
8	95	0.2	0.3	0.14	0.14	0.18	0.18	0.179
9	95	0.3	0.3	0.17	0.18	0.18	0.18	0.179
10	110	0.1	1.0	0.13	0.13	0.15	0.14	0.138
11	110	0.2	1.0	0.13	0.14	0.15	0.13	0.137
12	110	0.3	1.0	0.14	0.17	0.17	0.15	0.157
13	110	0.1	0.6	0.13	0.13	0.14	0.14	0.137
14	110	0.2	0.6	0.13	0.14	0.14	0.14	0.137
15	110	0.3	0.6	0.14	0.17	0.18	0.18	0.167
16	110	0.1	0.3	0.17	0.15	0.17	0.18	0.165
17	110	0.2	0.3	0.13	0.13	0.16	0.18	0.151
18	110	0.3	0.3	0.16	0.17	0.18	0.18	0.172
19	126	0.1	1.0	0.13	0.14	0.15	0.15	0.144
20	126	0.2	1.0	0.13	0.15	0.15	0.14	0.142
21	126	0.3	1.0	0.13	0.16	0.16	0.15	0.151
22	126	0.1	0.6	0.13	0.14	0.16	0.14	0.142
23	126	0.2	0.6	0.13	0.14	0.15	0.14	0.139
24	126	0.3	0.6	0.13	0.16	0.15	0.17	0.153
25	126	0.1	0.3	0.18	0.18	0.17	0.17	0.174
26	126	0.2	0.3	0.13	0.14	0.14	0.15	0.143

27	126	0.3	0.3	0.13	0.16	0.17	0.17	0.157

Table 1(b): DOE and experimental results of elastic spring back of AISI 316

The input variables in the table as CS cutting speed in m/min, feed rate FR in mm/rev and depth of cut DOC in mm. The output responses like cutter vibration V_x in µm and elastic spring back effect is denoted by S in µm. The tool vibrations along feed direction are measured by Laser Doppler Vibrometer (LDV) for four passes of 1, 2, 3 and 4 are $V_{x\ 1}$, $V_{x\ 2}$, $V_{x\ 3}$ and $V_{x\ 4}$. The average of the four passes V_x Avg is calculated and tabulated for each and every experiment. Similarly the spring back effect of the four passes for each tool of a AISI 316 specimen has been measured by Scanning Electron Microscope (SEM) and the average value is taken as the spring back effect of a work piece has been tabulated for each and every experiment. Later the optimum analysis is done by response surface methodology in Design expert software 10. The LDV measures the vibrations of a milling cutter in the laser beam direction. In this work, LDV was used for online acquisition of cutter vibration data in the form of AOE signals as shown in the Figure 4.

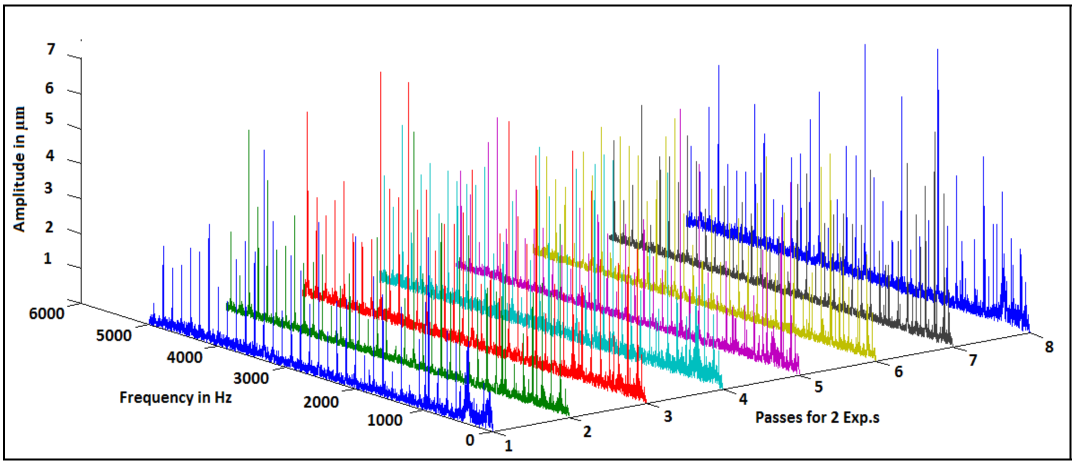

Figure 4: Frequency domains for the experiment 1 and 2

The trends of effect of these machining parameters help to identify which parameter and interaction of parameters are significant on the cutting tool vibrations and elastic spring back.

Based on the experimental results and experimental parameters shown in Table 1(a) and 1(b), two factor interaction response function for amplitude of cutter vibrations and elastic spring back effect can be expressed as function of process parameters. The quadratic model for the elastic spring back is given by the following equation (2).

$$S = 0.27847 - 9.20921E - 004v + 0.017955f - 0.24799d - 3.94475E - 003vf + 9.21643E - 004vd + 0.10360fd + 4.30108E - 006v^2 + 1.06111f^2 + 0.073280d^2 \quad --(2)$$

The interaction effect of cutting speed, feed rate and depth of cut on the elastic spring back effect is shown in the Figure 5. Figure 5 (a) represents normal probability plot of the residuals for the elastic spring back effect, most of the residuals are almost close to the straight line. That indicates that there is normal distribution of errors for the elastic spring back effect. As per the Figure 5 (b), the feed rate of 0.3 mm/rev and cutting speed of 95m/min the elastic spring back effect is very high. At the feed rate of 0.1mm/rev and cutting speed of 95m/min, the elastic spring back is very low. As per the Figure 5 (c) and (d), the depth of cut of 1mm and cutting speed of 95m/min, the lower elastic spring back is noticed. At the feed rate of 0.3mm/rev and depth of cut of 0.3 mm, the elastic spring back is very high. The cutting speed and depth of cut have a significant contribution in high elastic spring back of the material AISI 316.

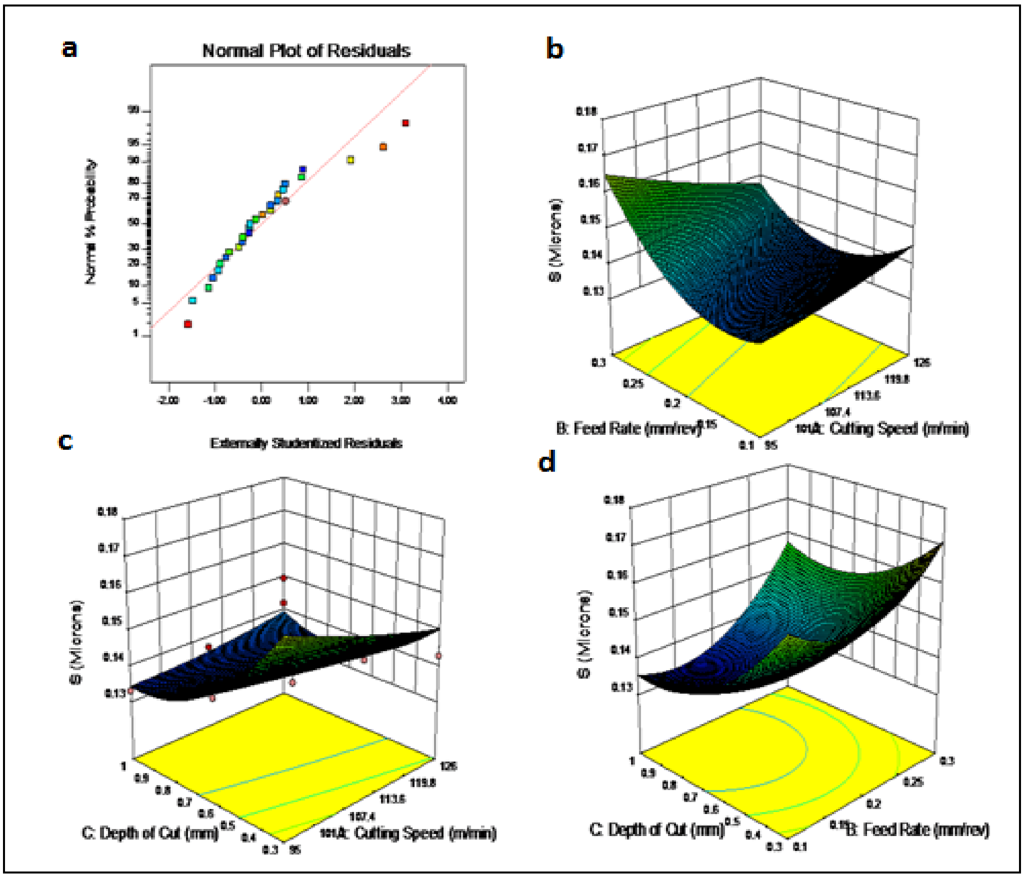

Figure 5: (a) Normal probabilities of residuals for ‘S’ (b) Effect of feed and cutting speed on ‘S’, (c) effect of depth of cut and cutting speed on ‘S’, and (d) effect of depth of cut and feed rate on ‘S’

Conclusions:

The optimization of cutting parameters to improve surface quality and production rate at low power consumption was found using multi objective optimization technique. The milling experiments were conducted on AISI 316 Austenitic Steel with two flute carbide end mill on three axis milling machine. Response Surface Methodology (RSM) approach in Design Expert Version 10 is used to identify significant parameters where which affects amplitude of cutter vibration and elastic spring back effect of the material. The following conclusions can be drawn from this study:

1. Effect of cutting parameters on amplitude of mill cutter vibration was measured with LDV by focusing optic signal on rotating cutter. Changes in the amplitude of cutter vibration due to tool wear can be used for online tool condition monitoring.

2. The AOE signals are very sensitive and they identify changes in cutting zone due to vibrations.

3. The amplitude of cutter vibration and elastic spring back were analyzed by using RSM. The cutting speed, feed rate and depth of cut were found to be significant cutting parameters on the amplitude of cutter vibration and elastic spring back has been proved.

4.The multi objective optimization technique shows at a particular cutting speed, feed rate and depth of cut are the optimal combination of milling parameters for minimum cutter displacement V_x and maximum elastic spring back effect(S) has been proved in our study. This data can help to improve simulation result of cutting processes and to understand the importance of elastic-plastic effects of materials.

In this study, smaller the better function was used for cutter displacement and larger the better function for elastic spring back because these responses should be optimum for any product to obtain good product quality and tool life. The amount of spring back during unloading depends on the Young's modulus of the material. Based on the experimental and numerical analysis, it is concluded that the amplitude 'V_x' has a lower value at cutting speed of 95m/min, feed rate of 0.1mm/rev and at depth of cut of 0.3mm. The elastic spring back 'S' has higher value at cutting speed of 95m/min, feed rate of 0.3 mm/rev and at depth of cut of 1mm.

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