AN EXPERIMENTAL STUDY ON EFFECT OF PROCESS VARIABLES ON SURFACE ROUGHNESS, TOOL VIBRATIONS AND ELASTIC SPRING BACK IN MILLING OF AISI 316 STAINLESS 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 surface roughness, tool vibrations and elastic spring back effect on CNC end milling operation of AISI 316 Stainless Steel is analyzed. The AISI 316 Stainless 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 surface roughness is measured by diamond point stylus and 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 on surface roughness and 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 stainless steel, surface roughness, tool vibrations, elastic spring back and CNC milling

Eksperimentalna studija uticaja promenljivih procesa na hrapavost površine, vibracije alata i elastične deformacije prilikom glodanja AISI 316 nerđajućeg čelika. U ovom radu je ispitivan, efekat više varijabli procesa kao što su brzina rezanja, pomak i dubina rezanja. Više promenljivih utiče na hrapavost površine, vibracije alata i elastično pomeranje delova pri CNC vretenastom glodanju nerđajućeg čelika AISI 316. Od nerđajućeg čelika AISI 316 su pravljeni uzorci za ispitivanje. Eksperimenti se izvode na 3 osnoj CNC vertikalnoj glodalici sa visokim brzinama obrtanja vretena sa alatom od tvrdog metala sa dva žljeba i optimizirani su parametri procesa. Elastična deformacija nazad, naziva se promena u obliku obradka nakon vađenja alata. Površinska hrapavost je merena dijamantskim vrhom alata a vibracije se mere pomoću Laser Doppler Vibrometera (LDV). Elastična deformacija se izračunava kao razlika između bilo koje dve tačke pri rezanju metala i vrednost se meri pomoću elektronskog mikroskopa (SEM). Na osnovu eksperimentalnih podataka iz navedenih instrumenata, varijable procesa su optimizovane. Ovaj rad pokazuje uticaj parametara procesa na elastične deformacije, na hrapavost površine i vibracije. U online praćenju stanja alata, optimizovani parametri procesa će dati bolju postojanost alata, održavati dobro vreme obrade i dati veću efikasnost mašinske obrade.

Ključne reči: AISI 316 nerđajući čelik, hrapavost površine, vibracije alata, elastične deformacije i CNC glodanje

1. INTRODUCTION

AISI 316 Stainless Steel has wide applications include pumps, valves, marine fittings, fasteners, paper and pulp machinery, petro chemical equipment and surgical implants that demand a good combination of high strength, good 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 Stainless Steel. The surface roughness, 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 Stainless 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.

Among the online tool wear monitoring methods, the vibrations are a tool wear indicator during automated manufacturing because the measurement of vibration is fairly simple. With the widely used CNC machine tools together with high performance computer aided design and computer aided

manufacturing systems, HSM has demonstrated advantages over traditional machining techniques such as increased productivity, high quality surface, burr-free edges and virtually stress free components. The increasing demand for higher machining efficiency has led to a much more reliable monitoring condition of the machining process. A recent study shows that a coated carbide tools may be used to machine AISI 316 Stainless Steel for a wide range of cutting conditions by producing variation in chip morphologies.

Alberti et al. [1] developed an algorithm based system to select optimal cutting parameters in conventional as well as high speed milling process. They have used the algorithm based system to select optimum parameters for reduction in production time in both conventional milling and high speed milling operations while ensuring optimal finishing conditions. Optimization of cutting parameters helps to improve production rate by reducing production time with improved tool life and less power consumption. This gives less production time and maximum profit in manufacturing. Albrecht. P [2] 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.

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. Baskar et al. [4] have developed optimization strategy with hill climbing algorithm and genetic algorithm for the optimization of parameters in face milling, corner milling, pocket milling and slot milling. They have obtained maximum profit with the help of developed strategy through optimization of cutting parameters. Production cost of a unit is affected by direct and indirect costs. Bhardwaj et al. [5] have used RSM with center composite rotatable design in turning of AISI 1019 steel to find out influence parameter on surface roughness. Prediction models were also developed for accurate prediction of surface roughness. Feed rate was found as significant parameter on surface roughness, while the depth of cut has no significant effect. In RSM, the quantitative relationship between input and output variables is presented as follows

$$y = f(x_1, x_2, x_3, \dots, x_n) \pm e_r \quad (1)$$

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

The increased feed rate in any machining process will lead to generation of heat and therefore it contributes high surface roughness. A prediction model was developed by Choudhuri and El-Baradie [6] using RSM for prediction of surface roughness in machining of EN 24T steel. They have conducted dry machining

with uncoated carbide inserts and studied the effect of cutting speed, feed and depth of cut on surface roughness. RSM shows effect of individual factors and two factors interaction on the responses and it also identifies significant factors. The RSM combined with factorial design of experiments is a better alternative to the traditional one variable at a time approach for studying the effects of cutting variables on responses such as surface roughness and tool life. Karagu'zel et al. [7] analyzed turn milling process is a new technology that combines two conventional machining processes like turning and milling. This new technology is an alternative process that gives improved productivity especially in machining of hard and large diameter work pieces. Many authors reported that there is a correlation between surface roughness and vibrations of cutter in any machining process. Kirby et al. [8] and Lin SC et al. [9] found a strong correlation between vibrations and surface roughness in turning process. In metal cutting, there is a relative motion between work piece and cutting tool. The cutting tool is getting dynamic excitation due to deformation of metal that results in vibration of tool. The relative motion and vibration of tool affect the surface quality of the product. These vibrations are to be maintained minimum to reduce surface roughness and tool wear. Vibration is defined as the repetitive motion of an object or objects relative to a stationary frame referred to as the equilibrium of the vibration. Vibrations are measured in terms of displacement, velocity or acceleration. Maiyar et al. [10] 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. Muthukrishnan et al. [11] studied the surface roughness, the ANOVA has been used to find out significant cutting parameters and interaction of cutting parameter on the amplitude of cutter vibration. The ANOVA was performed at the confidence level of 95%, and the cutting parameters which are having ‘p’ value less than 0.05 are significant. There is no significant effect of depth of cut on surface roughness. Previous researchers have also claimed the similar results that cutting speed and feed rate have more effect on the surface roughness. Newmann et al. [12] stated that 6%-40% of energy savings can be achieved in metal cutting with optimum cutting parameters. Pettersson et al. [13] also proved that the cutting speed has significant effect on the cutter vibration. Prasad et al. [14] have used LDV's to measure vibration of mill cutter in milling process. Fast Fourier Transformation (FFT) is used for generating features from an outline Acousto Optic Emission (AOE) signals to develop a data base for appropriate decisions. The FFT transforms the AOE signals into time domain with different time frequency zones. In this work, the LDV was adopted for online data acquisition of mill cutter vibration and a high speed FFT analyzer was used to process the AOE signals obtained from LDV. Prasad babu GHV et al. [15] analyzed tool vibration and surface roughness in orthogonal turn milling of ASTM B139 Phosphorous Bronze as per Taguchi design of experiments. Total 16 experiments were conducted on

four axes CNC milling machine and experimental results of tool vibration and surface roughness were collected. Response surface methodology (RSM) was used to find out the effect of process parameters such as cutting speed, feed and depth of cut on responses. A multi response optimization technique was used to optimize process parameters for minimum surface roughness and tool vibration. They have concluded that vibration increases with increase of feed. At the same time the surface roughness has found to be increased as speed was increased. Rantatalo et al. [16] have used the LDV in milling process to measure vibrations of rotating arbor in horizontal milling machine. Sahin. [17] has prepared design of experiments with cutting parameters and experiments were conducted according to design of experiments. Signal to noise ratios of experimental results were calculated by Taguchi method and analysis of variance (ANOVA) was used to analyze the ratios to identify cutting parameters which having more influence on tool life. Sahin and Motorcu [18] studied the effect of cutting parameters such as cutting speed, feed rate and depth of cut on turning of hard material with cubic boron nitride tool. They used RSM to predict surface roughness and a good correlation was found between them. Savas and Ozay [19] have used genetic algorithms for optimization of cutting parameters to get good surface quality in tangential milling. Different optimization strategies were developed by different researchers using algorithms to optimize cutting parameters. Schaal N. et al. [20] explained the spring back in metal cutting with high cutting speeds. They proved the influence of the cutting speed on the spring back is significant. Senthil Kumar et al. [21] have used genetic algorithms to select optimum cutting parameters in order to reduce production cost by improving tool life. They found that the Zirconia toughened alumina ceramic cutting tool has more life and it is able to machine at lower production cost. Sriram et al. [22] discussed the use of LDV's in the field of light weight structures. Frequency domain of LDV output signal is scanned to obtain deflection shape of the vibrating structure. Tatar and Gren[23] stated that the measurement of spindle and tool vibration is more important for tool condition monitoring in high speed milling process. 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. They have used Laser Doppler Vibrometers (LDVs) to measure vibration of mill cutter. In recent applications, LDVs are used as non contact methods to measure vibration of cutting tool or work piece accurately. Venkatarao et al. [24] 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 [25] 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. Spring back energy density is proposed by Zhu et al. [26] 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. 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 Stainless 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 during milling of AISI 316 Stainless Steel with carbide end mills under dry machining condition. The quality of the machined surfaces has been evaluated by means of roughness. Finally the correlation among spring back effect, vibrations and surface roughness has been analyzed and discussed.

2. MATERIAL AND CUTTER

The work piece material used in the experiment was AISI 316 Stainless Steel with chemical composition shown in Table 1. Its mechanical properties are shown in Table 2.

Elements	Percentage (%)
C	0.08 Max
Mn	2.0
Si	0.75
P	0.045
S	0.03
Cr	16-18
Ni	10-14
N	0.1
Fe	Balance

Table. 1 Chemical composition of AISI 316 Stainless Steel

Mechanical Properties	Value
Ultimate Tensile strength (MPa)	620-795
Yield strength (MPa)	206
Elongation at Break (%)	30
Modulus of Elasticity (GPa)	164
Hardness(BHN)	146

Table 2. Mechanical properties of AISI 316 Stainless Steel

The tungsten carbide end mill cutters were used for milling of AISI 316 Stainless Steel. The tools have

been rapidly fixed to a tool holder with a nominal diameter of 10mm. Geometric parameters of the tools are given in Table 3.

Diameter (mm)	10
Rake angle (°)	10
Clearance angle (°)	10
No of tooth	2
Helix angle (°)	30

Table 3. Geometric parameters of end mills

3. EXPERIMENTAL PROCEDURE

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 surface roughness 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, surface roughness R_a and vibrations along x and y directions and spring back effect are shown in the Table.4

Fig. 1. Three axis CNC vertical milling machine with Laser Doppler Vibrometer (LDV)

The surface roughness of the work piece was measured by a stylus instrument. To measure roughness of the surface of the work piece, the cut off length was taken as 100mm and the sampling length as 150mm.

Samples of AISI 316 Stainless Steel with dimensions of 150mm X 120mm X 15mm have been tested. Three levels of cutting speed (95, 110 and 126 m/min), three levels of feed rates (0.1, 0.2 and 0.3mm/rev) and three levels of depth of cut (0.3, 0.6 and 1mm) have been taken into account. The machined sample of work piece is shown in Figure 2.

Fig. 2. The machined AISI 316 Stainless Steel work piece

4. RESULTS AND DISCUSSION

The experimental cuts have been performed in random sequence, in order to reduce the effect of any possible systematic error. The titanium 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 machine follows and experimental results shown in the Table 4(a) and (b).

In each experiment, cutter vibration, surface roughness and elastic spring back effect on machined surface were measured in microns. The analysis is done by response surface methodology in Design expert software 10. Laser Doppler Vibrometer (LDV) measures vibrations in ways that other sensors cannot. 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 3.

Exp. No.	Design of experiments			Surface roughness (μm)					Cutter displacement in X direction (μm)				
	C S m/min	FR mm/rev	DOC mm	R_a 1	R_a 2	R_a 3	R_a 4	R_a Avg	V_x 1	V_x 2	V_x 3	V_x 4	V_x Avg
1	95	0.1	1.0	0.21	0.19	0.17	1.60	0.54	9.93	10.0	9.30	9.61	9.71
2	95	0.2	1.0	0.22	0.17	0.37	1.65	0.60	9.91	10.2	10.32	9.94	10.00
3	95	0.3	1.0	0.65	0.22	1.76	1.74	1.09	9.01	9.88	10.11	9.94	9.74
4	95	0.1	0.6	0.22	0.25	0.78	0.76	0.49	9.73	8.20	8.93	10.37	9.31
5	95	0.2	0.6	0.24	0.31	1.60	1.33	0.87	9.62	9.39	9.41	10.20	9.67
6	95	0.3	0.6	1.15	1.66	1.74	1.72	1.57	8.45	9.85	9.33	9.19	9.21
7	95	0.1	0.3	0.26	0.31	1.36	1.08	0.75	8.21	8.58	10.33	10.39	9.38
8	95	0.2	0.3	0.28	0.92	1.69	1.47	1.09	8.57	8.37	10.02	10.37	9.33
9	95	0.3	0.3	1.41	1.76	1.74	1.72	1.66	8.33	8.27	8.92	10.04	8.89
10	110	0.1	1.0	0.21	0.22	0.27	0.23	0.23	9.92	9.69	8.22	8.52	9.09
11	110	0.2	1.0	0.22	0.23	0.24	0.17	0.21	9.90	9.50	9.27	10.08	9.69
12	110	0.3	1.0	0.49	0.80	0.58	0.32	0.55	9.15	8.52	9.69	10.32	9.42
13	110	0.1	0.6	0.22	0.24	0.31	0.16	0.23	9.88	8.42	8.21	10.23	9.19
14	110	0.2	0.6	0.22	0.24	0.23	0.21	0.22	9.88	9.23	8.76	10.12	9.50

15	110	0.3	0.6	0.67	1.09	0.45	1.71	0.98	8.93	8.64	9.32	9.25	9.04
16	110	0.1	0.3	0.31	0.29	0.16	0.18	0.24	8.71	8.15	10.35	10.39	9.40
17	110	0.2	0.3	0.22	0.27	0.17	1.56	0.55	9.54	8.36	10.15	10.29	9.59
18	110	0.3	0.3	0.84	0.89	0.60	1.76	1.03	8.61	8.86	8.57	8.54	8.65
19	126	0.1	1.0	0.21	0.23	0.26	0.34	0.24	9.91	9.48	8.67	8.12	9.05
20	126	0.2	1.0	0.22	0.25	0.26	0.29	0.25	9.87	9.34	9.13	8.64	9.25
21	126	0.3	1.0	0.25	0.32	0.40	0.27	0.31	9.62	9.01	8.92	10.17	9.43
22	126	0.1	0.6	0.22	0.24	0.32	0.16	0.23	9.89	8.84	8.11	10.10	9.24
23	126	0.2	0.6	0.22	0.24	0.27	0.17	0.22	9.90	9.28	8.25	10.20	9.41
24	126	0.3	0.6	0.27	0.38	0.30	0.18	0.28	9.63	8.91	9.85	9.74	9.53
25	126	0.1	0.3	0.43	0.40	0.17	0.16	0.29	9.12	8.12	9.80	10.39	9.36
26	126	0.2	0.3	0.23	0.26	0.17	0.16	0.21	9.80	8.22	10.10	10.33	9.61
27	126	0.3	0.3	0.30	0.40	0.17	0.18	0.26	9.53	8.98	9.76	9.59	9.47

Table 4 (a). DOE and experimental results of surface roughness and cutter displacement

Exp. No.	Cutter displacement in Y direction (μm)					Elastic spring back (μm)				
	V _y 1	V _y 2	V _y 3	V _y 4	V _y Avg	S 1	S 2	S 3	S 4	S Avg
1	6.11	5.81	5.72	6.58	6.06	0.131	0.131	0.132	0.132	0.132
2	6.03	5.06	5.03	6.52	5.66	0.131	0.131	0.132	0.137	0.133
3	5.44	4.89	5.21	5.69	5.31	0.150	0.155	0.16	0.171	0.159
4	6.32	6.59	6.59	6.55	6.51	0.131	0.133	0.135	0.147	0.137
5	6.27	6.48	6.58	6.49	6.46	0.132	0.132	0.144	0.158	0.142
6	6.07	5.59	6.36	6.45	6.12	0.166	0.152	0.177	0.179	0.169
7	6.59	6.59	6.59	6.60	6.59	0.152	0.144	0.179	0.180	0.164
8	6.58	6.60	6.60	6.60	6.60	0.141	0.143	0.180	0.181	0.179
9	6.50	6.60	6.58	6.59	6.57	0.174	0.178	0.181	0.181	0.179
10	6.10	5.65	5.99	6.42	6.04	0.131	0.133	0.152	0.136	0.138
11	6.07	5.27	5.07	5.28	5.28	0.131	0.138	0.146	0.132	0.137
12	5.84	5.01	4.89	4.89	5.16	0.139	0.174	0.166	0.150	0.157
13	6.15	6.57	6.55	5.16	6.10	0.131	0.133	0.142	0.143	0.137
14	6.12	5.98	6.23	5.65	6.00	0.131	0.135	0.14	0.143	0.137
15	5.91	5.08	4.95	6.14	5.52	0.144	0.172	0.175	0.176	0.167
16	6.53	6.6	6.08	6.50	6.43	0.169	0.145	0.168	0.179	0.165
17	6.39	6.59	5.59	6.59	6.29	0.132	0.134	0.159	0.179	0.151
18	6.21	5.78	5.69	6.59	6.07	0.155	0.170	0.180	0.181	0.172
19	6.07	5.25	5.35	6.57	5.81	0.131	0.139	0.152	0.154	0.144
20	5.98	5.09	5.06	6.16	5.57	0.131	0.145	0.15	0.140	0.142
21	5.70	5.03	4.99	4.91	5.16	0.134	0.157	0.163	0.148	0.151
22	6.09	6.22	6.58	5.11	6.00	0.132	0.136	0.159	0.140	0.142
23	6.06	5.32	6.41	5.03	5.71	0.131	0.14	0.148	0.139	0.139
24	5.90	5.05	4.95	4.96	5.22	0.133	0.159	0.153	0.165	0.153
25	6.13	6.6	5.78	5.43	5.99	0.181	0.176	0.165	0.172	0.174
26	6.13	6.55	5.17	5.18	5.76	0.133	0.142	0.142	0.154	0.143
27	6.00	5.23	4.98	5.04	5.31	0.134	0.156	0.165	0.174	0.157

Table 4 (b). Experimental results of cutter displacement and elastic spring back

Fig. 3. Frequency domains for the experiment 1 and 2

FFT analyzer was used for generating features from online AOE signals to develop a data base for appropriate decisions. The trends of effect of these machining parameters help to identify which parameter and interaction of parameters are significant on the surface roughness and mill cutter vibration.

Based on the experimental results and experimental parameters shown in Table 4, four factor interaction response function for elastic spring back effect, surface roughness and vibrations along x and y can be expressed as function of process parameters. The quadratic model for the elastic spring back is given by the following equation (2).

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

Effect of parameters on R_a

Interaction effect of cutting speed, feed rate and depth of cut on the amplitude of cutter vibration in feed direction is shown in the Figure 4. Figure 4 (a)

represents normal probability plot of the residuals for the surface roughness, most of the residuals are almost close to the straight line. That indicates that there is normal distribution of errors for the surface roughness. As per the Figures 4 (b), the surface roughness is found to be low at 113.6m/min of cutting speed and 0.25 mm/rev of feed rate. If feed rate increases, the surface roughness will also increase. If the cutting speed increases, the surface roughness will also increase. When the cutting speed increases from 113.6m/min, the surface roughness will also increase. When the feed rate increases from 0.25mm/rev the surface roughness will also increase. As per the Figure 4 (c and d), it is observed that when the feed rate at 0.18mm/rev and depth of cut at 0.6 mm, the surface roughness is low. When the depth of cut is above 0.6 mm and feed rate is 0.3mm/rev the surface roughness is high. When the cutting speed increases from 113.6m/min the surface roughness will also increase. The feed rate has a significant parameter on surface roughness.

Fig. 4. (a) Normal probabilities of residuals for R_a , (b) Effect of feed and cutting speed on R_a , (c) effect of depth of cut and cutting speed on R_a , and (d) effect of depth of cut and feed rate on R_a

Effect of parameters on V_x

Interaction effect of cutting speed, feed rate and depth of cut on the amplitude of cutter vibration in feed direction is shown in the Figure 5. Figure 5 (a) represents normal probability plot of the residuals for the amplitude in feed direction, most of the residuals are almost close to the straight line. That indicates that there is normal distribution of errors for the amplitude in feed direction. As per the Figures 5 (b), when the feed rate and cutting speed increases, the amplitude of cutter vibration will increase. It is also observed that at high feed rates and low cutting speeds, the amplitude of cutter vibration is very high. As per the Figure 5 (c and d), the amplitude is found to be high at 1mm of depth of

cut and cutting speed at 95 m/min. The amplitude of cutter vibration is getting reduced when the depth of cut is decreased. When the depth of cut is 0.3 mm and cutting speed is 95m/min and the feed rate is 0.1mm/rev, the amplitude of cutter vibration is very low.

When the depth of cut is at 1mm, it gives higher amplitude of cutter vibration. The higher depth of cuts is a significant parameter on cutter vibrations. There is no significant of cutting speed and feed rate on the amplitude of cutter vibration in feed direction. Among the cutting speed and feed rate, the feed rate has significant effect on the vibration.

Fig. 5. (a) Normal probabilities of residuals for V_x , (b) Effect of feed and cutting speed on V_x , (c) effect of depth of cut and cutting speed on V_x , and (d) effect of depth of cut and feed rate on V_x

Effect of Parameters on V_y

Interaction effect of cutting speed, feed rate and depth of cut on the amplitude of cutter vibration in depth of cut direction is shown in the Figure 6. Figure 6 (a) represents normal probability plot of the residuals for the amplitude of cutter vibration in depth of cut direction, most of the residuals are almost close to the straight line. This indicates that there is normal distribution of errors for the amplitude of cutter vibration along y direction. As per the Figures 6 (b,c,d), When the feed rate is 0.3mm/rev and at cutting speed 95

m/min the V_y is very high. At same time it is observed that at feed rate of 0.3mm/rev and cutting speed 95m/min, the V_y is very low. At the depth of cut of 1mm and cutting speed at 95m/min the V_y is high. At depth of cut at 1mm and feed rate 0.1 mm/rev, the V_y is very high. At the depth of cut of 0.3mm and feed rate of 0.3mm/rev, the V_y is high. There is no much variation in the amplitude of cutter vibration for further changes in the cutting speed and feed rate.

Fig. 6. (a) Normal probabilities of residuals for V_y , (b) Effect of feed and cutting speed on V_y , (c) effect of depth of cut and cutting speed on V_y , and (d) effect of depth of cut and feed rate on V_y

Effect of Parameters on ‘S’

Interaction effect of cutting speed, feed rate and depth of cut on the elastic spring back effect is shown in the Figure 7. Figure 7 (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 7 (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 7 (c and d), the depth of cut of 1mm and cutting speed of 95m/min, the lower elastic recovery is noticed. At the feed rate of 0.3mm/rev and depth of cut of 0.3 mm, the elastic recovery is very high. The cutting speed and depth of cut have a significant contribution in high elastic recovery of the materials.

Fig. 7. (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’

Optimum values of multi objective function

The objective of this work is to find out optimum cutting parameters to achieve less surface roughness and amplitude of cutter vibration in order to reduce power consumption, production time and to improve tool life.

Optimum values for multi objective of surface

roughness and amplitude of cutter vibrations were done using response surface methodology and spring back effect is being measured by Scanning Electron Microscope (SEM) and the results are shown in the figure 8.

Fig. 8. Measurement of spring back of a AISI 316 Stainless steel sample using Scanning electron Microscope (SEM)

In this study, smaller the better function was used for surface roughness and amplitude of cutter vibration 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 ' R_a ' has a lower value at cutting speed of 113m/min, feed rate of 0.25mm/rev and depth of cut of 0.6 mm. 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 amplitude ' V_y ' is also lower at cutting speed of 126m/min, feed rate of 0.3 mm/rev and depth of cut of 0.6 mm. 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.

5. CONCLUSIONS

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 Stainless Steel with two flute carbide end mill on three axis milling machine. Response Surface Methodology (RSM) approach Design Expert Version 10 is used to identify significant parameters where affecting surface roughness, amplitude of cutter vibration and 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. Surface roughness, 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 surface roughness, amplitude and elastic spring back has been proved.

4. The multi objective technique shows at a particular cutting speed, feed rate and depth of cut are the optimal combination of milling parameters for minimum surface roughness (R_a), amplitude of cutter vibration along feed and depth of cut directions (V_x, V_y) 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.

6. REFERENCES

- [1] Alberti M, Ciurana J and Casadesu's M. A system for optimizing cutting parameters when planning milling operations in high-speed machining. *J Mater Process Tech* 2005; 168(1): 25–35.
- [2] Albrecht.P. New developments in the theory of the metal cutting process part 1, the ploughing process in metal cutting, *ASME journal of engineering for industry*, Vol 81; 1960:348-358
- [3] Amit Kumar G. Predictive modeling of turning operations using response surface methodology, artificial neural networks and support vector regression. *Int J Prod Res* 2010; 48(3): 763–778.
- [4] Baskar N, Asokan P, Saravanan R, et al. Selection of optimal machining parameters for multi-tool milling operations using a memetic algorithm. *J Mater Process Tech* 2006; 174(1–3): 239–249.
- [5] Bhardwaj B, Kumar R and Singh PK. Surface roughness prediction model for turning of AISI 1019 steel using response surface methodology and Box–Cox transformation. *Proc I Mech E, Part B: J Engineering Manufacture* 2014; 228(2): 223–232.
- [6] Choudhuri IA and El-Baradie MA. Surface roughness prediction in the turning of high-strength steel by factor-ial design of experiments. *J Mater Process Tech* 1997; 67(1–3): 55–61.
- [7] Karagu'zel U, Uysal E, Budak E, et al. Analytical modeling of turn-milling process geometry, kinematics and mechanics. *Int J Mach Tool Manu* 2014; 91: 24–33, <http://www.sciencedirect.com/science/article/pii/S0890695514001618>
- [8] Kirby ED, Chen JC, Zhang JZ, et al. Development of a fuzzy-nets-based in process surface roughness adaptive control system in turning operations. *Expert Syst Appl* 2006; 30(4): 592–604.
- [9] Lin SC and Chang MF. A study on the effects of vibrations on the surface finish using a surface topography simulation model for turning. *Int J Mach Tool Manu* 1998; 38(7): 763–782.
- [10] Maiyar LM, Ramanujam R, Venkatesan K, et al. Optimization of machining parameters for end milling of Inconel 718 super alloy using Taguchi based grey relational analysis. *Proc Eng* 2013; 64: 1276–1282.
- [11] Muthukrishnan N and Davim JP. Optimization of machining parameters of Al/SiC-MMC with ANOVA and ANN analysis. *J Mater Process Tech* 2009; 209: 225–232.
- [12] Newman ST, Nassehi A, Imani-Asrai R, et al. Energy efficient process planning for CNC machining. *CIRP J Manuf Sci Techn* 2012; 5(2): 127–136.
- [13] Pettersson L, Hakansson L, Claessonans I, et al. Active control of machine-tool vibration in a CNC lathe based on an active tool holder shank with embedded piezo ceramic actuators. In: *Proceedings of the 8th international Congress on Sound and Vibration*, Hong Kong SAR, China, 2–6 July 2001. IIAV Publisher.
- [14] Prasad BS, Sarcas MMM, Satish Ben BB, et al. Surface textural analysis using acousto optic emission- and vision-based 3D surface topography—a base for online tool condition monitoring in face turning. *Int J Adv Manuf Tech* 2011; 55(9–12): 1025–1035.
- [15] Prasad Babu GHV, BSN Murthy, K Venkatarao

- and Ch Ratnam. Multi response optimization in orthogonal turn milling by analyzing tool vibration and surface roughness using response surface methodology, Proc I Mech E Part B: J Engineering Manufacture 1–10 I Mech E 2016
- [16] Rantatalo M, Tatar K, Norman P, et al. Laser Doppler vibrometry measurement of a rotating milling machine spindle. In: Proceedings of the international conference on vibrations in rotating machinery—I Mech E conference transactions, Swansea, 7–9 September 2004, pp.231–240. Professional Engineering Publishing Ltd.
- [17] Sahin Y. Comparison of tool life between ceramic and cubic boron nitride (CBN) cutting tools when machining hardened steels. J Mater Process Tech 2009; 209(7): 3478–3489.
- [18] Sahin Y and Motorcu AR. Surface roughness model in machining hardened steel with cubic boron nitride cutting tool. Int J Refract Met H 2008; 26(2): 284–290.
- [19] Savas V and Ozay C. The optimization of the surface roughness in the process of tangential turn-milling using genetic algorithm. Int J Adv Manuf Tech 2008; 37: 335–340.
- [20] Schaal N. et al, spring back in metal cutting with high cutting speeds, 15th CIRP conference on modeling of machining operations, Zurich, Switzerland, 2015.
- [21] Senthil Kumar A, Adam Khan M, Thiraviam R, et al. Machining parameters optimization for alumina based ceramic cutting tools using genetic algorithm. Mach Sci Technol 2006; 10(4): 471–489.
- [22] Sriram P, Hanagud S, Craig J, et al. A new laser Doppler technique for velocity profile sensing. Appl Optics 1990; 29(16): 2409–2417.
- [23] Tatar K and Gren P. Measurement of milling tool vibrations during cutting using laser vibrometry. Int J Mach Tool Manu 2014; 48(3–4): 380–387.
- [24] Venkatarao K, Murthy BSN, Mohanrao N, et al. Cutting tool condition monitoring by analyzing surface roughness, work piece vibration and volume of metal removed for AISI 1040 steel in boring. Measurement 2013; 46: 4075–4084.
- [25] Yeh Y and Cummins HZ. Localized fluid flow measurements with a He-Ne laser spectrometer. Appl Phys Lett 1964; 4: 176.
- [26] Zhu D.B, L. Ma, D.C. Li, B.H. Lu On spring back evaluation for 3-D sheet metal stamping parts Mech. Sci. Technol.,19 (2000),pp.953-955
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