Investigation on the correlation between surface roughness and acoustic emission characteristics in turning process*

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ABSTRACT

Keywords:
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One of the most significant feature for monitoring in machining processes is tool wear. It has a direct influence on the quality of machined surfaces. In-order to maintain the product quality and to reduce material wastage, online tool wear monitoring has become a regular practice. With the progress in tool wear, surface roughness changes accordingly and this change can be used to assess the tool condition. However, it is difficult to measure the surface roughness online. It is well known that interaction of tool and workpiece results in high frequency stress waves known as Acoustic Emissions (AE), which can be used as an indirect online method to monitor the surface roughness and in-turn tool wear. The analysis of AE signals which received significant attention in structural and machine health monitoring opens wide opportunities to monitor the machining process. Hence, in the present work an attempt has been made to explore the correlation between the acoustic emission characteristics and workpiece surface roughness during the high speed turning operation using AISI 4340 alloy steel workpiece with the help of Zirconia Toughened Alumina (ZTA) tool on a lathe machine. Experiments has been designed as per Central Composite Design (CCD) of Response Surface Methodology (RSM) with varying 3 levels of 3 parameters such as cutting speed, feed rate and depth of cut. For each experiment, AE signals are acquired and surface roughness is measured using Surtronic 25 portable surface roughness meter. Analysis of variance (ANOVA) is used to study the effect of control parameters on output responses and a model is prepared using regression analysis. It is observed from the ANOVA analysis that feed rate and cutting speed have profound influence on surface roughness and RMS respectively. The optimum condition is found at Cutting speed of 300 m/min with feed rate of 0.12 mm/rev and depth of cut of 1.5 mm with 97.15% desirability for minimum surface roughness and nominal RMS value. From the parametric study, it is observed that AE characteristic (RMS) shows good correlation with surface roughness which can be used for further analysis in online monitoring of tool wear.

1. Introduction

Application of process automation or smart manufacturing in industries is rapidly growing due to the demand in increased productivity, better product quality and efficient utilization of resources. Tool wear is one of the most important factor that limits the productivity in most of machining processes. Since the tool wear has a direct influence on the product quality, its condition monitoring is very much essential to reduce the material wastage. The term wear is used to explain the deterioration of the edge, surface quality, any type of fracture of the tool or the degradation of mechanical properties by temperature, friction and other physical properties[1]. Several investigations reported in literature indicates that the surface roughness of machined components deteriorates with increase in tool wear [2][3]. In order to achieve the higher surface quality along with minimum

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amount of material wastage, the online tool condition monitoring system becomes a primary requirement, especially in conventional machining environments. As online tool wear monitoring as well as online surface roughness measurement is a difficult task, the changes occurred in surface roughness due to the effect of tool wear can be used to assess the tool condition during machining.

The methods which are used to monitor the tool conditions can be categorized into two major groups: direct methods and indirect methods. Generally direct methods of tool wear monitoring include radioactive, optical, electrical resistance or visionary system, etc. A brief review on using optical methods for online flank wear monitoring during turning operation was presented by Teti et. al., [4] in which some advantages of this kind of process such as capturing original geometric feature changes during the machining had been mentioned. Contradictorily, Kurada et. al., [5] reported that large inaccessible cutting region and continuous contact between the tool and the workpiece can be considered as two major obstacles of this kind of process. Ahmet Cakan[6] designed a real time monitoring system by using optical fiber and laser beam, Cook [7] reported different radioactive techniques applied for tool wear measurement along with their advantages and gaps [8]. Based on earlier works, it can be summarized that direct methods are not very suitable for practical applications especially radioactive and current proximity sensor based methods [9] due to their slow speed and safety issue. In order to address the issues, research tried to employ various indirect methods to monitor the tool condition. These methods are commonly based on the measurement of different parameters during machining that can be correlated to flank wear [10]. These indirect methods involve the use of force, acoustics signals, vibration, temperature, current, torque, sound, etc. to assess the tool condition. Ambhore et. al.,[11] presented a brief review on a wide variety of indirect tool wear monitoring system.

Among all the suitable methods for indirect supervising of tool wear, cutting force, vibration and Acoustic Emission (AE) signals analysis are found to fit for the industrial environments. Acoustic Emission (AE) is commonly described as a transient of elastic waves in solids that happens when a material experiences some irreversible changes in its internal architecture, for example as a result of any crack formation or plastic deformation due to temperature gradients, aging or any external mechanical forces [12]. Henceforth, the analysis based on AE signals gaining significant attention in structural health monitoring [13][14] and machining condition with wide opportunities to monitor the machining process. The key advantage of using AE for monitoring the tool state is that the frequency range of AE signal is much higher than that of the machine vibrations and environmental noises [12]. Ferrari et. al., demonstrated a real time acoustic emission sensor based system for monitoring and controlling the tool wear in drilling process [15]. Söffker et. al., applied the AE system to detect and quantify the sliding error [16]. The correlation between cutting phenomena and AE in a turning process was evaluated experimentally by using cermet tool and a steel workpiece in a numerically controlled turning machine by Allan Hase et. al.,[17]. A concise review on Acoustic Emission method for tool condition monitoring during turning operation had been published by Xiaoli Li [13]. Afore mentioned literature review revealed that acoustic emission signal has immense potential in the field of tool wear monitoring during turning process but most of the work were done in low speed using carbide tool, on the other hand application of AE characteristic analysis for tool condition monitoring during high speed turning process using ceramic tool is almost an unexplored area.

Hence, in the present work an attempt has been made to explore the correlation between the acoustic emission characteristics and surface roughness of workpiece during the high-speed turning operation where experiments are carried out using AISI 4340 alloy steel workpiece with the help of Zirconia Toughened Alumina (ZTA) tool on a conventional lathe machine. During the turning process, acoustic emission signals are acquired using AE sensor with the frequency range of 100 kHz to 1MHz. These signals are further processed to obtain the acoustic emission characteristics.

2. Experimental Details

2.1. Design of experiment

In order to study the correlation between the AE features and surface roughness, response surface methodology (RSM) had been used in which the correlation among unlike parameters with different responses can be obtained. It is a very powerful tool for finding out the impact of each process parameter and the extent of each on the individual responses. The experiments were selected on the basis of Response Surface Methodology (RSM) based on Central Composite Design (CCD). A three-level, three-factor central composite design (CCD) had been employed to understand the significant process parameter such as cutting speed, feed rate and depth of cut on the responses like surface roughness of machined surface and RMS value of the AE sensor signal. The value of the different control parameters of the experiments are portrayed in Table 1.

Table 1
Process parameters and their levels.

Sl No.	Level	Cutting Speed (m/min) (A)	Feed Rate (mm/rev) (B)	Depth of Cut (mm) (C)
1.	Low (1)	100	0.12	0.5
2.	Middle (2)	200	0.16	1.0
3.	High (3)	300	0.2	1.5

Table 2
Desing layout of the experiment.

Sl. No.	Cutting Speed (m/min)	Feed Rate (mm/rev)	Depth of Cut (mm)	Surface Roughness (μm)	RMS (V)
1	300	0.2	0.5	1.361	3.08155
2	100	0.2	1.5	1.874	0.33385
3	200	0.2	1	1.872	1.0506
4	300	0.16	1	1.149	3.5301
5	300	0.12	1.5	0.948	2
6	200	0.16	1	1.0955	0.57265
7	300	0.2	1.5	1.49	3.81965
8	200	0.16	0.5	1.0025	0.4393
9	200	0.12	1	0.925	0.59715
10	100	0.16	1	1.202	0.4989
11	200	0.16	1.5	1.172	0.6216
12	200	0.16	1	1.1	0.58
13	100	0.2	0.5	1.6915	0.2986
14	100	0.12	1.5	1.235	0.5312
15	100	0.12	0.5	0.934	0.26125
16	300	0.12	0.5	0.837	1.8783

In this study cutting speed, feed rate and depth of cut were chosen as process parameters which can affect the responses significantly. The value of the different parameters were selected depending on the capability of machine as well as according to some previous literatures [18]. The consequences of different parameters on the responses were examined through a set of planned experiments based on 3 levels 3-factor central composite design (CCD) for mapping it in the quadratic response surfaces. The design layout of the experimentsare depicted in Table 2.

2.2. Materials and methodology

In this experimental study, turning experiments were executed by using three jaw central chuck Lathe Machine, model no: N26 made by HMT powered by 11kW power motor with the speed range 47rpm – 1210rpm. AISI 4340 Steel (0.43% carbon)bar was used as job for the operation. The bar used for experiments was 140mm in diameter and 450mm in length. In order to execute the high speed operation ceramic tools named Zirconia toughened alumina (ZTA) were used. To acquire the acoustic emission characteristics AE sensor of frequency range 100kHz to 1MHz had been mounted to the nearest point of the tool holder. As the signal obtained from AE sensor was very weak, to amplify this for further analysis the acquired signal from sensor was fed into a pre amplifier in differential mode with 40 dB gain. "Micro II Digital AE" system was used to digitize the signal as well as analyze the characteristics. The

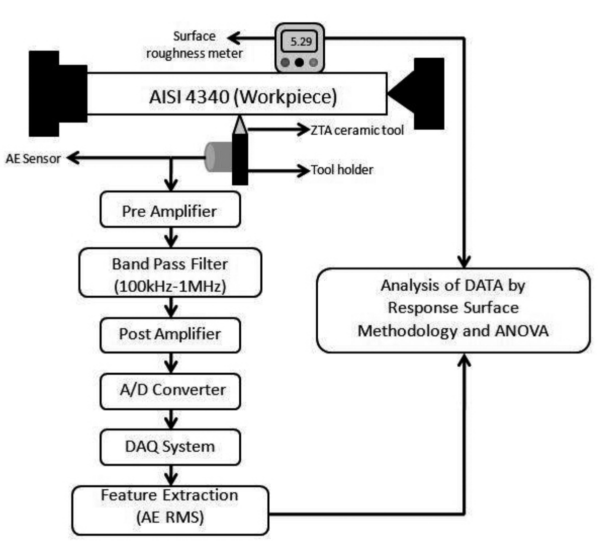

Fig. 1. Experimental Setup.

sampling rate was selected as 10Mega samples per second (MSPS). Each experiment was repeated twice keeping all the parameters unaffected. After the turning operation the surface roughness of the job was measured using "Surtonic25" a portable surface roughness meter.

3. Results and Discussion

Design Expert software (Version 8.0.1) was employed to know the coefficients of polynomial of equation for each response. Through ANOVA the adequacy of the model were checked to understand the statistical significance of the each contributing parameters on the responses. The significance test of each process parameters was carried out with 95% confidence level by comparing “Prob>F” to 0.05. The ANOVA results for surface roughness are shown in Table 3. From Table 3, it can be concluded that the Model F-value was 36.84, which shows developed model is significant. There is very minimum chances (0.01%) to get higher value of “Model F-value” due to noise factor. The conclusion made from Table 3 clearly indicates that the major contribution is shown by feed rate nearly 76.93% inthe developed model of surface roughness. Further more, the contribution of cutting speed is limited to 9.456% followed by depth of cut which was 5.19%. The model also shows significant contribution of square of feed rate of 9.71%. This result is mainly attributed to the non machined material left per revolution on the work piece due to increase in feed rate. The significant effect of feed rate on surface roughness is also illustrated by various researchers like Singh et al., [19]. The value of R^2 is 0.93 with “Pred. R-Squared” and “Adj R-Squared” were 0.91 and 0.86 respectively. The “Adequate Precision” is calculated as 19.21 (more than 4) justified that the developed model is ready to navigate in the design space.

The developed model for RMS shown in Table 4, clearly signifies that the model is significant having “Model F-value” 32.71. The ANOVA shows that all process parameters have their contribution on the developed model of RMS. The note worthy contribution is noted for

Table 3
ANOVA for surface roughness.

Source	Sum of Squares	df	Mean Square	F Value	p-value Prob> F	Remarks
Model	1.515410401	4	0.3788526	36.83913	2.60776E-06	significant
A-cutting Speed	0.134676025	1	0.134676025	13.09572	0.004034921	
B-Feed Rate	1.156340025	1	1.156340025	112.441	4.1027E-07	
C-Depth of Cut	0.0781456	1	0.0781456	7.598775	0.018669446	
B^2	0.146248751	1	0.146248751	14.22104	0.00309459	
Residual	0.113123708	11	0.010283973			
Lack of Fit	0.113113583	10	0.011311358	1117.171	0.023279275	significant
Pure Error	1.0125E-05	1	1.0125E-05			
Cor Total	1.628534109	15	R-Squared	0.930536		
Std. Dev.	0.101409928		Adj R-Squared	0.905277		
Mean	1.24359375		Pred R- Squared	0.857948		
C.V. %	8.154586491		Adeq Precision	19.20978		

Table 4
ANOVA for RMS.

Source	Sum of Squares	df	Mean Square	F Value	p-value Prob> F	Remarks
Model	21.89571157	9	2.432856842	32.70974	0.000203	significant
A-cutting Speed	15.340804	1	15.34080416	206.257	7.13E-06	
B-Feed Rate	1.0998177	1	1.099817732	14.78704	0.008505	
C-Depth of Cut	0.1815217	1	0.181521729	2.440558	0.169261	
AB	1.2663566	1	1.266356551	17.02615	0.006173	
AC	0.0384476	1	0.038447645	0.516928	0.499186	
BC	0.0182119	1	0.018211861	0.244858	0.638314	
A^2	3.5011536	1	3.501153584	47.07297	0.000472	
B^2	0.0038523	1	0.003852298	0.051794	0.827527	
C^2	0.2899797	1	0.289979685	3.898774	0.095747	
Residual	0.4462629	6	0.074377149			
Lack of Fit	0.4462359	5	0.089247177	3304.074	0.013207	significant
Pure Error	2.701E-05	1	2.70113E-05			
Cor Total	22.341974	15	R-Squared	0.980026		
Std. Dev.	0.2727217		Adj R-Squared	0.950065		
Mean	1.2559188		Pred R-Squared	0.797016		
C.V. %	21.714919		Adeq Precision	16.87235		

Table 5
Table for confirmation run.

Sl. No.	Parameters			Experimental Value		Predicted Value		% Error	
	Cutting Speed	Feed Rate	Depth of Cut	Surface Roughness	RMS	Surface Roughness	RMS	Surface Roughness	RMS
1	200	0.16	1.5	1.172	0.6216	1.208566665	0.569924733	3.12002263	8.31326694
2	300	0.12	0.5	0.837	1.8783	0.773149999	1.90211227	7.628435	1.267756461
3	300	0.2	1.5	1.49	3.81965	1.630049998	3.769217271	9.39932872	1.32034949
4	100	0.2	1.5	1.874	0.33385	1.862149998	0.357675471	0.6323374	7.136579512
5	200	0.2	1.5	1.856	0.86485	1.746099998	0.911046371	5.921336315	5.34154717

cutting speed as 66.05%. The effect of feed rate and combined effect of cutting speed and feed rate have also shown valuable effect as 4.74% and 5.45%, respectively. The effect of depth of cut is minimum only 0.78% while the square of cutting speed have 15.07% of contribution on whole. The value of R^2 approximately equal to 1 which fulfill the desirability. The values of "Pred. R-Squared" and "Adj R-Squared" are noted as 0.95 and 0.797. The "Adequate Precision" is noted as 16.87 (more than 4) which signifies that the developed model is suitable for navigation in the design space.

4. Confirmation Run

The adequacy of the developed model was checked by considering five confirmation run of experiments shown in Table 5. The first four conditions were selected from the previously experiments and next one run were performed outside the range of operating condition. Using Design Expert software, the result were predicted within 95% confidence level. The predicted value were calculated for surface roughness and RMS using Eqn 1 and Eqn 2. The maximum percentage error for surface roughness and RMS were calculated as 9.39932872 and 8.31326694 respectively. Therefore it can be concluded that the predicting capability of the models are very well for this application. From the statistical modeling two equations for surface roughness and RMS had been got which are as follows

$$\text{Surface Roughness} = 2.975 - 0.0011605 * A - 30.99541667 * B + 0.1768 * C + 123.4270833 * B^2 \text{ ....(eqn1)}$$

$$\text{RMS} = 3.206961552 - 0.051011166 * A - 6.342702586 * B + 2.263666897 * C + 0.099465625 * A * B + 0.0013865 * A * C + 2.385625 * B * C + 0.00011524 * A^2 - 23.89116379 * B^2 - 1.326603448 * C^2 \text{..(eqn2)}$$

Where A = cutting speed, B = Feed rate, C = depth of cut

5. Conclusion

1. Based on the ANOVA outcome for RMS value AE signal, it has been summarized that feed rate dominates the cutting speed with nearly 76.93% contribution where the contribution of cutting speed is limited to with 9.456% followed by depth of cut which is 5.19%. The model also shows significant contribution of square of feed rate of 9.71%. So from the above result it can be easily concluded that feed rate and cutting speed of turning operation have significant influence on RMS whereas the influence of depth of cut is almost negligible.
2. Based on the ANOVA result for surface roughness of the workpiece, it has been observed that cutting speed prevailed the rest two factors with almost 66.05% contribution where the effect of depth of cut was minimum only 0.78 %. The effect of feed rate and combined effect of cutting speed and feed rate have also show valuable effect as 4.74% and 5.45%, respectively while square of cutting speed have 15.07%.
3. The models developed for surface roughness and RMS value using regression analysis also provide good results where predicted values of the same are very close to the actual or experimental values. From the confirmation run table it is observed that the predicted values of surface roughness and RMS are maximum deviated by 8.3% and 9.4% respectively.
4. The cutting speed of 300 m/min, feed rate of 0.12 mm/rev and depth of cut of 1.5 mm is the optimum condition with 97% as desirability level for minimum surface roughness and nominal range of RMS such as 2.1 to 2.3 V.

From the above statements it can be concluded that AE RMS has the significant response against the surface roughness i.e. indirectly with tool wear. This relationship can be judicially applied for the development of indirect tool condition monitoring system in future.

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