Applied Mechanics and Materials Vol. 315 (2013) pp 749-754
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doi:10.4028/www.scientific.net/AMM.315.749

Dimensional Deviation Affected by Cutting Parameters and Machine Tool Rigidity in Dry Turning of S45C Steel

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Keywords: dimensional deviation; vibration; dry turning; machine tool rigidity

Abstract. Performance of machining processes is assessed by dimensional and geometrical accuracy which is mentioned in this paper as dimensional deviation. A part quality does not depend solely on the depth of cut, feed rate and cutting speed. Other variable such as excessive machine tool vibration due to insufficient dynamic rigidity can be deleterious to the desired results. The focus of the present study is to find a correlation between dimensional deviation against cutting parameters and machine tool vibration in dry turning. Hence cutting parameters and vibration-based regression model can be established for predicting the part dimensional deviation. Experiments are conducted using a Computerized Numerical Control (CNC) lathe with carbide insert cutting tool. Vibration data are collected through a data acquisition system, then tested and analyzed through statistical analysis. The analysis revealed that machine tool vibration has significant effect on dimensional deviation where statistical analysis of individual regression coefficients showed $p<0.05$. The developed regression model has been validated through experimental tests and found to be reliable to predict dimensional deviation.

Introduction

In this study, among factors should be taken into consideration is vibration of machine tool including force vibration and chatter [1]. In the case of turning, aggressive cutting conditions are often employed in order to obtain high material removal rates in production machining environment. Use of such aggressive cutting conditions leads to chatter, wherein intense vibrations and excessive forces occurs at the cutting point. The occurrence of chatter thus resulting numerous adverse effects which include reduction in tool life, poor dimensional accuracy, poor surface finish, and brings damage to machine tool itself if the case prolong.

In most cases of practical interest, the chatter monitoring in turning operation is useful in predicting dimensional deviation of machined parts. The dimensional deviation is the difference between expected product dimension based on CNC machine program and actual dimension measured from finished product. Based on previous studies [2-9], the dimensional deviation is strongly dependent on cutting parameters and cutting forces. El-Karamany [2] claimed that inaccuracy of cut diameter is due to cutting forces while turning between centers. He presented a mathematical model to predict dimensional deviation of slender workpiece as a prerequisite to develop Adaptive Control System. However, this model does not take into account the vibrations in transverse direction and the change in radial force due to dynamic effect. Other studies are assuming that the dimensional errors are caused by bending of the workpiece and tool. This assumption leads to several investigations [3-6], where analytical formulations from mechanics and finite element analysis have been used to calculate the workpiece deflection. However, a study by Zhou [7] proved that not only deflection contributes to diameter errors in workpiece, particularly for short workpiece. Feed rate and depth of cut are the most influencing parameters on residual stresses and in turn on dimensional stability [8]. In a recent study, neural network was utilized to develop a model to predict dimensional deviation using the radial component of cutting force and acceleration of radial vibration as a feedback [9]. In [10], an intelligent sensor fusion approach based on statistical tools and neural network is proposed to estimate surface finish and dimensional deviation. It is found that the feed rate, depth of cut and two components of the cutting force provided the best average effect on surface quality. The present study explores the influence of machine rigidity and cutting parameters on dimensional accuracy which in this paper is named dimensional deviation and this value is used as the machine dimensional accuracy indicator.

Methodology

This study presented an empirical approach for assessing dimensional deviation in cylindrical turning operation based on the cutting parameters (cutting speed, feed rate and depth of cut) and machine tool rigidity (vibration amplitude in x, y and z direction). Experiments have been conducted by carrying out dry turning cutting of commercially available steel bar S45C using carbide insert PVD coated cutting tool. The analysis of variance (ANOVA) and regression analysis are employed to study the effect of the cutting parameters and vibration on dimensional deviation values. Validation test with different levels of machining parameters are implemented in order to illustrate the reliability of developed regression model. As shown in Fig. 1 the experiment was performed by using a CNC Turning machine (HAAS, Germany). Samples of medium carbon steel S45C with raw material diameter of 13.0 mm are used due to its commercial availability. The 3-jaw chuck held a sample with 15.0 mm extending out. The VBMT 160404 carbide turning insert was used as a cutting tool. Experiments are conducted without cutting fluid and a range of cutting parameters are selected according to the tool manufacturer's recommendation and industrial applications. 96 samples are used in this study which involves 2 replications for each set of independent factors (cutting speed, feed rate, and depth of cut). An accelerometer is attached on the lathe chuck based on cutting axis. The vibration signals generated by accelerometer are sent to a multifunction data acquisition software vibDAQ (National Instrument, USA) for storing purpose.The independent factors levels are then varied as summarized in Table 1. For convenience of recording and processing the experimental data, each variable are coded as A, B, C, D and E.

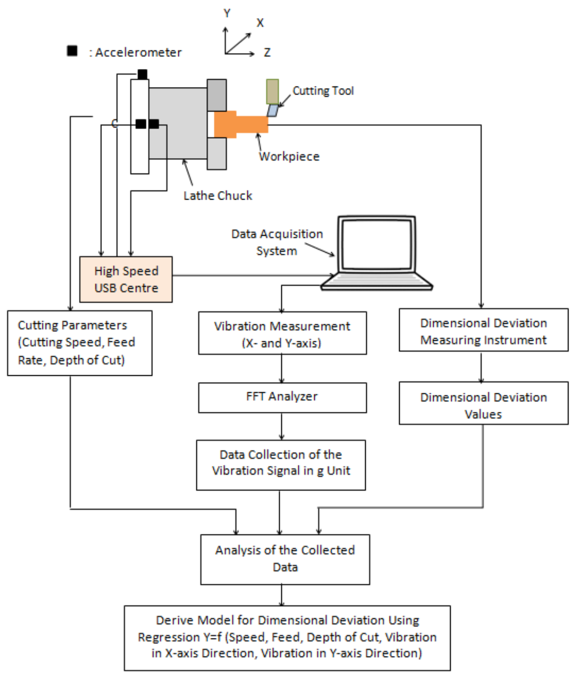

Fig.1. Schematic diagram of the hardware setup

Table 1. Summary of experiment design

Summary of the experiment design				
Tools	VBMT 160404 (Carbide Insert PVD Coated)			
Work material	S 45C Medium carbon steel (Ø 13 mm)			
Independent Variables				
A - Feed rate (mm/min)	f1 = 0.1	f2 = 0.2	f3 = 0.3	f4 = 0.4
B - Cutting speed (rpm)	c1 = 1958	c2 = 2450	c3 = 2940	
C - Depth of cut	d1 = 0.2	d2 = 0.3	d3 = 0.4	d4 = 0.5
Dependent Variables				
D – Ave. vibration y-axis	measured in g(RMS) units.			
E – Ave. vibration x-axis	measured in g(RMS) units.			
Responses				
Diameter accuracy	mm			

An experimental was designed in such a way to get the output data uniformly distributed all over the ranges of the input parameters. Through this, 96 runs were carried out with different combinations of levels of the parameters. MINITAB software was employed to analyze the experimental data. Based on 95% confidence interval ($\alpha=0.05$), the samples data were computed and analyzed. In addition to the main effects of these variables, effects of the interactions of them were also taken into account in the analysis. Representing the dimensional deviation of the sample, "Y", the response function could be expressed as:

$$Y=f(A,B,C,D,E) \quad (1)$$

The first regression model chosen includes the main effects and the interaction effects of all factors. Since the higher order interactions (3 and above factor interactions) are considered insignificant [11], the general regression model could be written as:

$$Y= \beta_0+ \beta_1A+ \beta_2B+ \beta_3C+ \beta_4D + \beta_5E+ \beta_6AB+ \beta_7AC+ \beta_8AD+ \beta_9AE+ \beta_{10}BC+ \beta_{11}BD+ \beta_{12}BE+ \beta_{13}CD+ \beta_{14}CE+ \beta_{15}D \quad (2)$$

where β_0 is the intercept of the plane, and parameters $\beta_1,i=1,2,3....15$ are called the regression coefficient. The original terms are used in each model and then each interaction term kept if it appears significant individually. For finding the significant factors, analysis of variance (ANOVA) is used.

Results and Discussion

After doing statistical analysis of data, the regression model is established as shown in the following model:

$$Y=76.600-0.580(A)-0.310(B)+0.968(C)-12.900(D)+17.800(E) \quad (3)$$

The test of significance of regression model involved the null hypotheses of $H_0= \beta_i=0$ where $H_1= \beta_i\neq0$ *for at least one i*. Table 2 and Table 3 summarize the results of statistical analysis of the regression model. The p-value in Table 2 is less than α, so it can be concluded that null hypothesis $\beta_i=0$ is rejected. In other words, there is significant difference among the parameters under studied (speed, feed rate, depth of cut, amplitude of vibration in x and y-axis direction in dimensional deviation as verified by p-value< 0.001. Alternatively, F_0 can be used to determine the significance of regression model. Here, the computed value of $F_0=2082.530 > F_{\alpha,k,n-k-1} = 2.330$ indicated that the estimated value is adequate.

Table 2. Analysis of variance of fitted model

Source	DF	SS	MS	F_0	P
Regression	5	1260231	252046	2082.53	<0.001
Error	90	10893	121		
Total	95	1271124			

Table 3. Statistical analysis of individual regression coefficients

Predictor	Coef	SE Coef	T	P
Constant	76.63	19.82	3.87	<0.000
v (A)	-0.5797	0.1367	-4.24	<0.000
f (B)	-0.3100	0.01033	-30.01	<0.000
doc (C)	0.96818	0.0101	95.84	<0.000
vib y (D)	-12.864	6.996	-1.84	0.0690
vib x (E)	17.809	7.987	2.23	0.0280
S =	11.0013			
R-Sq =	0.991			
R-Sq (adj) =	0.991			

This *study* calculates the value of R^2 or adjusted R^2 to measure the percentage of variation of response. The estimated R^2 for the fitted model is 0.991, indicating that the parameters explain 99.1% is the closeness of the data with respect to fitted line. This finding shows the regression equation is reliable for predicting the dimensional deviation. The p-values for vibration in y- and x-axis are 0.0690 and 0.0280 respectively. These values are considered as highly and moderately significant. The coefficients had the largest effect on dimensional deviation as their values are 17.809 and -12.864, which accords with common chatter theory [12]. The other main effects; depth of cut, feed rate and cutting speed are found to be slightly significant. Their relative degree of influence in decreasing order is cutting speed, feed rate and depth of cut with -0.5797, -0.3100 and 0.96818 respectively. This showed that adjustment of depth of cut helps in improving the diameter accuracy [8], whereas increased cutting speed and feed rate would not much affecting the dimensional deviation.

Fig. 2 shows the main effect plot for various level depth of cut, cutting speed and feed rate. At the bottom of left side is depth of cut. It indicates that with increase in depth of cut, there is a continuous increase in dimensional deviation. Depth of cut of 200 μm produces the lowest dimensional deviation, whereas the depth of cut 500 μm produces the highest dimensional deviation. The top left side is cutting speed. It shows that with the rise in speed, there is a slight decrease in dimensional deviation. At the right side is the feed rate. It illustrates that the dimensional deviation start to decrease significantly after feed rate of 200 μm/rev. All three cutting parameters cutting speed v(A), feed rate f mac(B), and depth of cut doc mac(C) show they had significant effect with depth of cut is the highest while cutting speed is the lowest. Do take note that it is unable to check the main effect of vibration since it could not be fixed as cutting speed, feed rate and depth of cut. To perform the parametric study using the regression models, the relationships have been drawn between experimental results, *DVe* and predicted results, *DVr* of dimensional deviation. It is found that maximum error in the prediction is 16.43%, which considered that reasonable (< 20% error). Details of this are shown in validation test.

Validation Test

After identifying the significant parameters and the fitted regression model was obtained, the final step is to verify this developed model using the experimental tests with different levels of parameters. The predicted value versus actual value of dimensional deviation is recorded. The predicted dimensional deviation obtained from equation (3) is compared with the actual dimensional deviation using Pearson correlation and a good agreement existed between these values. The correlation is 99.7% and the average error is 7.61%, which mean that the model can practically recall the data with minimal error. According to above analysis, the developed regression model is found to be reliable and provided good results of prediction. A t-test was carried out to validate if the actual value of dimensional deviation taken from difference set of cutting condition differed significantly from the data calculated from model. The result is shown in Table 5.

Table 5. Two-sample t-test for dimensional deviation

DEVIATION	N	Mean	StDev	SE Mean
ACTUAL	27	186	122	23
MODEL	27	209	104	20

Difference = mu (ACTUAL) - mu (MODEL)
Estimate for difference: -23.8
95% CI for difference: (-85.5, 37.9)
T-Test of difference = 0 (vs not =): T-Value = -0.77 P-Value = 0.442 DF = 52
Both use Pooled StDev = 112.9531

In this example, a 95% confidence interval is (-85.5, 37.9) which includes zero, thus suggesting that there is no significant difference between both data. Next is the hypothesis test result. The test statistics is -0.77, with p-value of 0.442, and 52 degrees of freedom. Since the p-value is greater than commonly chosen α-levels, there is no evidence for a difference in deviation of actual laboratory data versus data calculated from model.

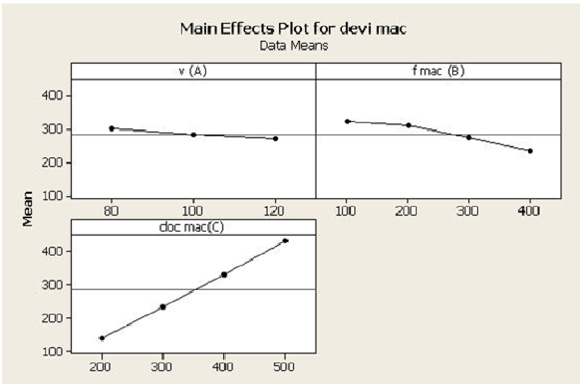

Fig. 2. Main effect plot between cutting parameters and dimensional deviation

Conclusion

The present study explores the influence of machine rigidity and cutting parameters on dimensional deviation. The study concluded that machine rigidity associated with vibration amplitude in x and y-axis direction and depth of cut are the significant factors that affecting the dimensional deviation of part. Additionally a regression model is established and proved to be reliable for providing prediction value of dimensional deviation in CNC turning process. The model hence could be used for helping in predicting process capability of machine tool without having to start the development of new product with a great uncertainty as practiced by some industrial practitioners.

Acknowledgment

The authors gratefully acknowledge the financial support from the Ministry of Higher Education under Fundamental Research Grant Scheme (FRGS/1/12011/FKP/TK03/1-F00116). The authors would like to acknowledge the Universiti Teknikal Malaysia Melaka (UTeM) for technical supports.

References

[1] S. Kalpakjian, S.R. Schmid, Manufacturing Engineering and Technology. Prentice Hall Pearson, 2010.

[2] Y. El-Karamany, Turning long work-pieces by changing the machining parameters, International Journal of Machine Tool Design, 24/1 (1984), 1-10.

[3] L. Kops, M. Gould, M. Mizrach, Improved analysis of the workpiece accuracy in turning based on the emerging diameter. Transactions of the ASME, Journal of Engineering for Industry, 115 (1993), 253-257.

[4] W.H. Yang, Y.S. Tarng, Design optimization of cutting parameters for turning operations based on the Taguchi method, Journal of Materials Processing Technology, 84 (1998), 122-129.

[5] S. Yang, J. Yuan, J. Ni, Real-time cutting force induced error compensation on a turning center. International Journal of Machine Tools and Manufacture, 37 (1997), 1597-1610.

[6] A.V. Phang, G. Cloutier, J.R.R. Mayer, A finite element model with closed-form solutions to workpiece deflections in turning. International Journal of Production Research, 37/17 (1999), 4039-4051.

[7] B. Zhou, Set-up planning optimization for semi-finished rotational parts in a feature-based CAD environment. Master Thesis. 1999, Manhattan, KS: Kansas State University.

[8] B.K.Subhash, R. Bhat, K. Ramchandran, H.K. Balkrishna, Simultaneous optimizations of machining parameters for dimensional instability control in Aero Gas Turbine components made of Inconel 718 alloy. Transaction of ASME, 122 (2000), 586-590.

[9] K.A. Risboo, U.S. Dixit, A.D. Sahasrabudhe, Prediction of surface roughness and dimensional deviation by measuring cutting forces and vibrations in turning process. Journal of Materials Processing Technology, 132 (2003), 203-214.

[10] R. Azouzi, M. Guillot,On-line prediction of surface finish and dimensional deviation in turning using neural network based sensor fusion. International Journal of Machine Tools and Manufacture, 37/9 (1997), 1201-1217.

[11] D.C. Montgomery, Design and Analysis of Experiments. 7th Edition. John Wiley & Sons Inc. (2007)

[12] Y. Altintas, M. Weck, Chatter Stability of Metal Cutting and Grinding. CIRP Annals - Manufacturing Technology, 53/2 (2004), 619-642.