DIMENSIONAL ACCURACY AS A RESULT OF CUTTING PARAMETERS AND MACHINE TOOL RIGIDITY IN DRY TURNING OF MEDIUM CARBON STEEL

Rahman, M.A., Elfi, R.I.F., Dan, M.M.P., Baharudin, A.B., Azureen, M.N.

Faculty of Manufacturing Engineering
Universiti Teknikal Malaysia Melaka (UTeM)
Durian Tunggal, 76100 Melaka, Malaysia

Email: abrahman@utem.edu.my

ABSTRACT: Capability of machining processes is assessed by dimensional accuracy which is mentioned in main part of this paper as dimensional deviation. Part quality does not depend solely on the depth of cut (doc), feed rate (f) and cutting speed (v). Other variable such as excessive machine tool vibration due to low rigidity of machine tool can also affect the dimensional accuracy. The focus of the present study is to find a correlation between dimensional deviation against cutting parameters and machine tool vibration in a turning process. Hence cutting parameters and vibration-based regression model can be established for predicting the component dimensional accuracy. Experiments are conducted using a Computerized Numerical Control (CNC) lathe with carbide coated cutting tool insert. Vibration data is collected through a data acquisition system and then analyzed using statistical data 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 predicting dimensional accuracy in dry turning process.

KEYWORDS: Dimensional accuracy, dimensional deviation, vibration, dry turning, rigidity.

1.0 INTRODUCTION

Machine tool is generally made of cast iron of heavy or light weight structure. Some are made of combination of cast iron and steel structure. The physical property of material contribute to magnitude of vibration, the structure made of steel is higher in terms of strain compared to structure made of cast iron, thus create different magnitude of vibration. Wylde, J., (1999), claimed it is found that the frequency increases with increasing strain. Thus thin structure will produce more strain compared to thich structure and subsequently will give different value of vibration.

When considering high quality products or fulfilling customer requirements, dimensional accuracy played importance role. Dimensional accuracy in this study is measured by dimensional deviation. Among factor should be taken into consideration is vibration of machine tool including force vibration and chatter Kalpakjian, S., Steven, S.R., (2001). In the case of turning, aggressive cutting conditions for 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 obtained from finished product.

Based on previous studies, shown that the dimensional deviation is strongly dependent on cutting parameters and cutting forces. El-Karamany, Y., (1984), claimed that inaccuracy of 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, where analytical formulations from mechanics and finite element analysis have been used to calculate the workpiece deflection. However, a study by Zhou, B., (1999), proves that, not only deflection contributes to diameter errors in workpiece, particularly for short workpiece. Subhash, B. K., R. Bhat, K. Ramchandran, and H. K. Balkrishna, (2000), found out that feed rate and depth of cut are the most influencing parameters on residual stresses and in turn on dimensional stability. In a recent study, Risbood *et.al* [9] utilized a neural network to develop a model to predict dimensional deviation using the radial component of cutting force and acceleration of radial vibration as a feedback. Azouzi, R. and M. Guillot, (1997), 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.

This paper presents 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 vibration measurement. Experiments have been conducted by carrying out dry turning cutting of commercially available steel S45C using carbide insert Physical Vapor Deposition(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.

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.

2.0 METHODOLOGY

As shown in Figure 1, the experiment is performed using a CNC Turning machine (HAAS, Germany).

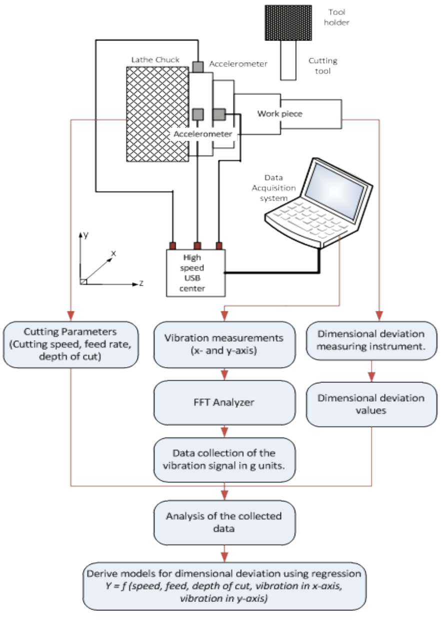

Fig.1. Schematic diagram of the hardware setup

To clearly visualize the setup of equipment a close up view of accelerometer and USB centre are shown in fig 2a and 2b respectively.

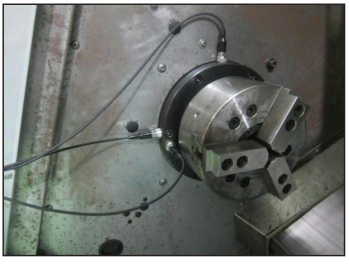

Fig. 2a. Accelerometer in 3 axes location

Fig. 2b: The high speed USB centre connecting the accelerometer and PC

The samples of medium carbon steel S45C with raw material diameter of 13.0 mm are used due to its commercial availability. A 3-jaw chuck held this sample with 15.0 mm extending out. In order to eliminate variation in raw material size, each work piece is primarily turned and reduced its diameter by 0.60 mm. The VBMT 160404 carbide turning insert is used as cutting tool. Experiments are conducted without the presence of 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 is coded as A, B, C, D and E as shown in Table 1.

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			

The aim of this study is to determine the dependency of dimensional accuracy (in this case dimensional deviation) to vibration and other selected machining parameters. An experimental design is designed in such a way to get the output data uniformly distributed all over the ranges of the input parameters. Through this, 96 runs are carried out with different combinations of levels of the parameters. A standard package of statistical software MINITAB is employed to analyze the experimental results. Based on 95% confidence interval (α=0.05), the samples data are computed and analyzed. In addition to the main effects of these variables, effects of the interactions of them are also taken into account in the analysis. Representing the dimensional deviation of the sample, "Y", the response function could be expressed as:

$$Y=f(A,B,C,D,E) \quad \text{.................................(1)}$$

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, Montgomery, D. C., (2009). The general regression model could be written as:

$$Y = \beta_0 + \beta_1 A + \beta_2 B + \beta_3 C + \beta_4 D + \beta_5 E + \beta_6 AB + \beta_7 AC + \beta_8 AD + \beta_9 AE + \beta_{10} BC + \beta_{11} BD + \beta_{12} BE + \beta_{13} CD + \beta_{14} CE + \beta_{15} DE \quad \ldots\ldots(2)$$

Where β_0 is the intercept of the plane, and parameters $\beta_1, i=1,2,3\ldots.15$ 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.

3.0 RESULTS AND DISCUSSION

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

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

The test of significance of regression model involved the null hypotheses of $H_0 = \beta_i = 0$ where $H_1 = \beta_i \neq 0$ for at least one i. Table 2 and 3 summarized the result 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 is rejected. Alternatively, F_0 can be used to determine the significance of regression model. Here, the computed value of $F_0 = 2082.530 > F_{\alpha,k,n-k-1} = 2.330$ which 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			

It is also calculated the value of R_2 or adjusted R_2 to measure the percentage of variation of dimensional deviation. The estimated R_2 for the fitted model is 0.991. It indicates that closeness of dimensional deviation data against fitted line of model is 99.1%. High R_2 values for the regression equation reveal reliable estimation for predicted dimensional deviation. According to the fitted regression equation in Equation 3, the p-values (refer Table 3) 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 have 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.

Figure 2 showed the main effect plot for various depth of cut, cutting speed and feed rate. At the bottom of left side is for the depth of cut and 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 figure is for the cutting speed, and it shows that with the rise in speed, there is a slight decrease in dimensional deviation. At the right side of Figure 3 is for the feed rate plot and it illustrates that the dimensional deviation start to decrease significantly after feed rate of 200 μm/rev. All three cutting parameters v, f, doc showed they have significant effect with doc(C) the highest while v(A) the lowest. Do take note that it is unable to check the main effect of vibration since it couldn't be fixed as v, f and doc.

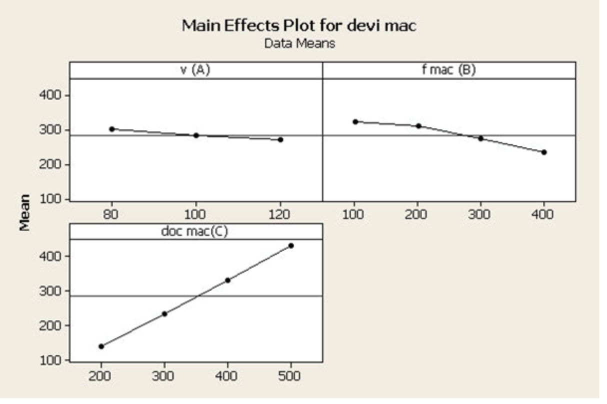

Fig. 3. Main effect plot between cutting parameters and dimensional deviation

To perform the parametric study using the regression models, the relationships have been drawn between experimental result and predicted result. The error between the regression model and experimental values are calculated as following Equation 4:

$$Error = \frac{|DV_e - DV_r|}{DV_e} \times 100 \qquad \text{.....(4)}$$

Where *DVe* is the experimentally measured dimensional deviation and DVr is the predicted dimensional deviation from fitted regression model. 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 topic.

4.0 VALIDATION TEST

After identifying the significant parameters and the fitted regression model is 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 graph of correlation is plotted as shown in Figure 4. It is discovered that most of the points are close to the correlation line, thus it could be concluded that this regression model provided reliable prediction.

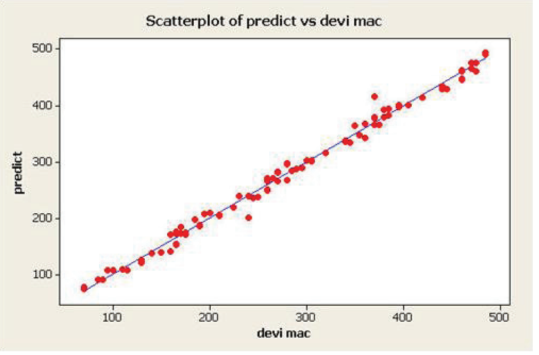

Fig. 4. Predicted value versus actual dimensional deviation in turning.

The predicted dimensional deviation obtained from equation 3 is compared with the actual dimensional deviation using Pearson correlation and 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 is also 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 showed in Table 4. MINITAB displayed a table of the sample sizes, sample means, standard deviations, and standard errors for the two samples. For this example, a 95% confidence interval is (-85.5, 37.9) which includes zero, thus suggesting that there is no difference between both data. Next is the hypothesis test result. The t-test statistic 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 dimensional deviation of actual laboratory data versus data calculated from model.

Table 4. Two-sample t-test for 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

5.0 CONCLUSION

The study successfully explores dimensional accuracy as a result of cutting parameters and machine tool rigidity in dry turning of medium carbon steel. It is found that predictors of vibration in x- and y-axis direction which is closely related to machine tool rigidity and doc (depth of cut) are the influential factors affecting the dimensional accuracy (dimensional deviation) in dry turning. The Regression model developed from this study is proved to be reliable for providing prediction value of dimensional accuracy in CNC turning of the medium carbon steel using carbide coated cutting tool insert. The rigidity of machine tool plays an important role in determining the capability of the machine to produce quality product. Any new product development requires right choice of capable machine tool. The regression model in this study can be used to estimate the dimensional accuracy of machine tool prior to developing a new product.

6.0 ACKNOWLEDGMENT

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