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The Effect of Feed Rate and Cutting Speed to Surface Roughness

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Abstract: In this study, a sensitivity analysis method was used to identify the optimal machining conditions with respect to surface quality. Presently, programming Turbo C++ is used to evaluate the properties of machined surfaces with cutting parameters using arbitrary sets of experimental values. Based on the proposed equations and its differentiated function, the quality of surface roughness can be known clearly through the sensitivities of proper local deviations. This method shows the sensitivity of each surface roughness to the machining parameters. The variables investigated were cutting speed (Vc), depth of cut (d), feed rate (fr) and the surface roughness (Ra). The result indicates that machining parameter that had the highest influence on surface roughness is the feed rate followed by the cutting speed and the depth of cut. Finally experiment analysis was carried out to verify the analytical results.

Key words: Machining parameter, surface roughness, sensitivity analysis

INTRODUCTION

Cold forging can be described as a process in which a piece of metal is shaped to the desired form by plastic deformation of a simple starting form such as bar, billet, bloom or ingot at room temperature (Altan *et al*., 2005). Initially forging operation has various advantages compared to other metal manufacturing including little loss of material, improve strength, geometrical precision of components and high production rates (www.forging.org). There are variety of processes that can be classified as forging such as open die, impression die, ring rolling, warm forging and cold forging. Currently in practice forging process design (maiuly die) repeatedly carries out trial and error based on skills and experience of the designer who is familiar with the forging problem. Currently most of the companies still rely on formulas, standards and experience to aid their die design. Several machining processes can be used to fabricate the forging die. The behavior of machined components under fatigue is highly influenced by the residual stress and surface roughness (Gurgel *et al*., 2006). The quality of the surface plays a very important role in the performance of milling as a good-quality milled surface significantly improves fatigne strength, corrosion resistance, or creep life. Therefore, the desired finish surface is usually specified and the appropriate processes are selected to reach the required quality (Lou *et al*., 1999). Özel and Karpat (2005) utilized the regression and neural network to study the effect of turning parameter on surface quality and tool wear, while recently Korkut and Donertas (2007) study the effect of feed rate and cutting speed to the cutting force, surface roughness and tool-chip contact length.

The objective of this study is to determine the effect of two machining parameter i.e. feed rate and cutting speed analytically and experimentally. A sensitivity analysis program is then developed to measure level of sensitivity of the surface roughness. The research begins with brief introduction and then followed by research related to the die design process and recent finding in cold forging process.

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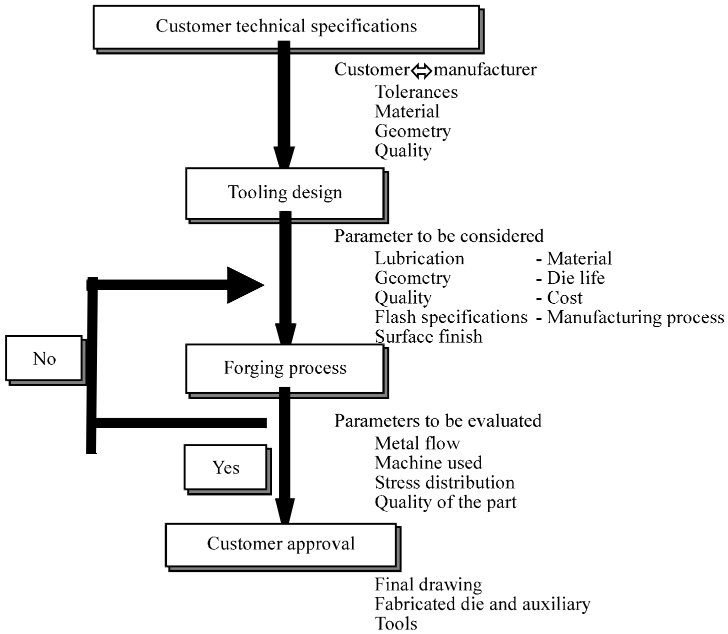

Fig. 1: General forging dies design process (Mynors *et al*., 1997)

After that the machining parameter is explained. Then the methodology of the research is presented. The framework of sensitivity analysis program is then outlined and followed by the verification sections. Before ends, the results of the works are then discussed and concluded

DIE DESIGN PROCESS

In the forging process, performance of the die is measure based on quality of the forged parts and reliability of the die itself. Due to demands for complex part, long life die and accurate tooling recently becomes crucial. The success of cold forging process depends on two main criteria i.e. the selected tool material and dies design (Vazquez *et al*., 2000). Since the process involves huge pressure, selection of material which exhibits the both criteria i.e. high strength and tough is very critical (Destefani, 1994). Commonly material that owns these criteria is very expensive. Compared with the tooling material, the design of die is claimed has bigger influences. This is because choosing in different material may not extend the die life until the die is properly design. In practice the die design process begins upon requirement and specifications from customer and then followed by the tooling design and forging process stage. The process ends upon customer satisfaction in terms of die performance and auxiliary tools required, the general die design process as practice by the industry is as shown in Fig. 1.

MACHINING PARAMETER

The effect of cutting parameters on the fiual surface roughness of machined surface has brought great challenge for engineers and researchers. Some useful techniques of prediction the surface roughness of a product before milling is necessary in order to evaluate the fitness of machining parameters for keeping a desired surface roughness and increasing product quality. It is well known that the prediction technique should be accurate, reliable, low-cost and non-destructive. Surface roughness analytical equation proposed here as in Eq. 1 will be useful to predict of the criterion variable finish surface roughness of work piece depend on variables such as feed rate, spindle speed, or depth of cut as following:

$$R_a = \frac{f^2}{31.2r_n} \tag{1}$$

Where:
r_n = Tool tip radius (mm).
f = The feed (mm tooth^{-1}).

A simple theoretical model was proposed using the cutting speed and the feed rate as major parameters to predict the sensitivity of parameters on surface roughness of work piece. With the help of the experimental analysis, surface roughness of machined surface is measured and compared with predicted values using the theoretical method. In this case, depth of cut has no or little influence on surface roughness and thus it can be neglected. Since the controllable machining parameters are easily measurable input variable, the proposed model is quite efficient in providing a convenient guideline for the estimation of the surface quality in any given cold-forging operation. This method shows the sensitivity of each surface parameter for each input variable. The Eq. 2 defined the function of spindle speed, N (rpm) with respect to cutting speed, Vc (m min^{-1}).

$$N = \frac{1000 \times Vc}{\pi D} \tag{2}$$

Where:
D = Tool diameter (mm).

The functional of feed rate, fr (mm min^{-1}) given in Eq. 3 with respect to feed (mm tooth^{-1}), allowing the determination of parameters as:

$$fr = f \times \eta_t \times N \tag{3}$$

Where:
r_n = No. of teeth.

Thus, from Eq. 3, it can be modified as:

$$f = \frac{fr}{\eta_t \times N} \tag{4}$$

So from Eq. 1 and 4, the functional Ra can be rewritten as:

$$R_a = \frac{fr^2}{{\eta_t}^2 \times N^2 \times 31.2r_n} \tag{5}$$

Fig. 2: Mitutoyo surftest SV-400 measuring instrument

MATERIALS AND METHODS

The case study used in this project is a universal joint, which is model using SolidWork 2006. The model is then converted into CAM file to develop machining code for fabrication purpose using CNC milling machine. Before that a simple CNC program has been generated to run the CNC milling machine on Aluminum plate at various machining parameter. The objective of the experiment analysis is to investigate the affect of machining parameter on the surface roughness. The measurement of surface roughness was done using Mitutoyo Surftest SV-400 Measuring Instrument as shown in Fig. 2. Before that, the machined surface must be examined using Mitutoyo Measuring Flatness Testing Instrument to ensure the flatness of work piece is achieved.

The next step is implementing a parameter sensitivity analysis method to obtain the optimal machining conditions with respect to surface quality. There are two main machining parameters (spindle speed and feed rate) used in the program.

SENSITIVITY ANALYSIS

The framework of machining parameter sensitivity analysis proposed is based on four criteria. The sensitivity program is built using C++ programming. The purpose of program is to help creating a new approach for surface finish prediction in end-milling operations.

Criteria 1

Machining Parameter Sensitivity Surface Roughness Analysis

- Key in No. of flutes (η_t).
- Key in tool tip radius (r_n).
- Key in N value (N = spindle speed/rpm).
- Then key in fr value (fr = feed rate, mm min^{-1}).

Formula used:

$$\frac{\delta Ra}{\delta N} = \frac{2fr}{\eta_t^{2} \times 31.2r_n \times N^3} \qquad \text{Answer: } \frac{\delta Ra}{\delta fr} = \text{let say A (displayed)}$$

$$\frac{\delta Ra}{\delta N} = \frac{2fr^2}{\eta_t^2 \times 31.2r_n \times N^3} \qquad \text{Answer: } \frac{\delta Ra}{\delta N} = \text{let say B (displayed)}$$

- Compare A and B. Program will choose the answer, which has higher value.
- Finally, if $\frac{\delta Ra}{\delta fr}$ has higher value, then display: feed rate has the highest influence on surface roughness.
- Otherwise, if $\frac{\delta Ra}{\delta N}$ has higher value, then display: 'Cutting speed has the highest influence on surface roughness.

Criteria 2

Analytical Calculation of Surface Roughness

$$R_a = \frac{f^2}{31.2r_n}$$

Where:

r_n = Tool tip radius (constant in this case) and f is the feed (mm $tooth^{-1}$)

Criteria 3

Judgment for Accuracy of Parameter Analysis

Percentage deviation is defined as:

$$\phi_i = \frac{\left|Ra_i^{/} - \hat{R}a_i\right|}{Ra_i^{/}} \times 100\%$$

Where:

ϕ = Percentage deviation of single sample data

Ra_i' = Actual Ra measured by a surface texture measuring machine → value obtained from experiment

$\hat{R}a_i$ = Predicted Ra generated by a analytical equation → equation from choice 2

Criteria 4

Average percentage deviation

$$\bar{\phi} = \frac{\sum_{i=1}^{m} \phi_i}{m}$$

Where:

$\bar{\phi}$: = Average percentage deviation of all samples and m represent the size of sample data

The result to date has claimed that the cutting tools are identical in properties and the material of the work piece is similar. The result of sensitivity analysis showed that feed rate was the most significant machining parameter used to predict surface roughness.

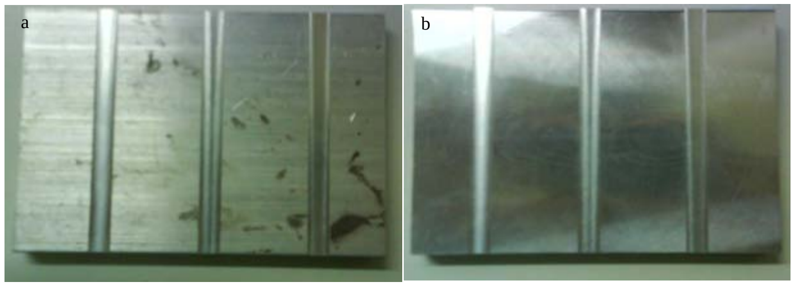

Fig. 3: (a) Machined surface for experiment No. 1 and (b) machined surface for experiment No. 2

RESULT VERIFICATION

The main objective of this experiment is to verify the surface roughness obtained from the developed program. If the comparative result on aluminum is positive (deviation percentage is not more than 10%), that's mean the analytical method can be used to act as benchmark to predict surface roughness. The experiment can be divided into two;

- **The experiment 1:** To determine which machining parameter that gives the highest influence on surface roughness when all parameters are varies. Figure 3a show the machined plate.
- **The experiment 2:** To investigate the effect on the surface roughness when one of the parameter is varies and the others are constant. Figure 3b shows the machined plate.

DISCUSSION

Experiment 1

The predicted result and experimental output indicated similar pattern that the feed rate is the most important parameter to provide smooth surface because the final answer of Ra for both methods has smallest value mean the smoothest surface produced if smaller feed rate value is used. The positive result of experiment shows that the Ra prediction equation can be used to determine parameter sensitivity on surface roughness. It is well recommended that smaller feed rate and higher cutting speed (spindle speed) can help to produce higher quality of surface. Thus, these two parameters are adjusted to the desired value and create two critical parameter sets. First set result (n_1) contains the smallest cutting speed but slowest feed rate value while third result (n_3) has the largest value of cutting speed and highest feed rate. Second set (n_2) is a default value. This method is done to determine which one parameter has the greatest significant influence on surface finish when both of main parameters are set to desired value (Table 1, 2). The average percentage deviation is less than 10% (= 9.963%), the result of experiment analysis in Table 3 is considered to be accepted.

Figure 4 plots the result of surface roughness (Ra) with cutting speed (Vc) using fitted variation data as input while the plots of average surface roughness (Ra) with the feed (fz) is shown in Fig. 5. The continuous line represents experimental data of surface roughness while the dotted line means computational surface roughness. From gradient slope of both lines, there are small difference values between analytical result and experimental data. That's mean the percentage deviation is small and the computational results showed by sensitivity program are accepted. The value of gradient line represents the sensitivity rate value that depicted influence of machining parameter (cutting speed and feed rate) to the surface roughness. For example, the gradient value for experimental data in Fig. 4 is

Table 1: Analytical result for aluminum plate

	Finish cut of aluminum material, D = 6.0 mm No. of flutes = 4, HSS tool cutter		
Input	n_1	n_2 (Default value)	n_3
Cutting speed (V_c) (m min^{-1})	15.24	20.00	30.48
Feed (f_z) (mm $tooth^{-1}$)	0.29	0.50	0.35
Spindle speed (N) (rev min^{-1})	808.51	1061.03	1617.01
Feed rate (f_r) (mm min^{-1})	937.87	2122.07	2263.82
Output			
Surface Roughness (Ra) (μm)	0.90	2.67	1.31

Table 2: Experimental result for aluminum plate

	Experimental		
Surface roughness (Ra) (μm)	n_1	n_2	n_3
Ra_1	1.30	2.63	1.37
Ra_2	1.20	2.63	1.27
Ra_3	1.19	2.63	1.23
Average Ra (μm)	1.23	2.63	1.29

Table 3: Comparison between analytical and experimental result

	Experimental vs. analytical		
Parameters	n_1	n_2	n_3
Percentage deviation (ϕ_i) (%)	26.82	1.52	1.55
Average percentage deviation ($\bar{\phi}$) (%)	$\bar{\phi} = = \frac{26.83 + 1.52 + 1.55}{3} = 9.963\%$		

Table 4: Analytical result for aluminum and sensitivity analysis

	Finish cut of aluminum material, D = 6.0 mm No. of flutes = 4, HSS tool cutter		
Readings	n_1	n_2 (default value)	n_3
Input			
Cutting speed (V_c) (m min^{-1})	16.00	16.00	30.00
Feed (f_z) (mm $tooth^{-1}$)	0.20	0.23	0.23
Spindle speed (N) (rev min^{-1})	848.83	848.83	1591.55
Feed rate (f_r) (mm min^{-1})	679.064	780.92	1464.23
Output			
Surface roughness (Ra) (μm)	0.427	0.565	0.565
Sensitivity output			
$\frac{\delta Ra}{\delta fr}$	1.26×10^{-6}	1.44×10^{-6}	7.71×10^{-7}
$\left\lvert\frac{\delta Ra}{\delta N}\right\rvert$	1.07×10^{-6}	1.33×10^{-6}	7.10×10^{-7}

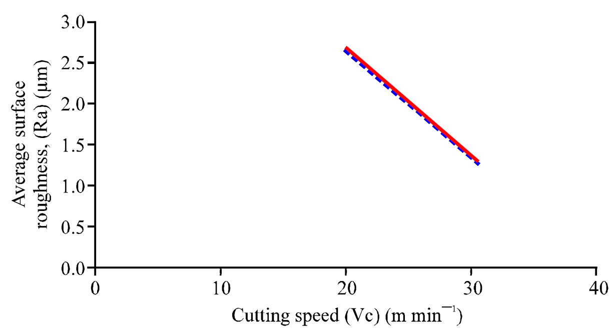

Fig. 4: Chart for average surface roughness, Ra (μm) by cutting speed, Vc (m min^{-1})

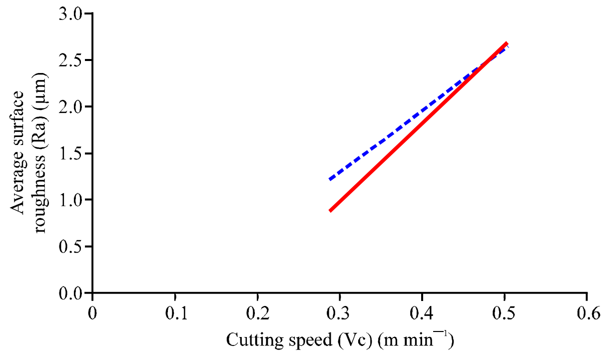

Fig. 5: Chart for average surface roughness (Ra) (µm) by feed (fz) (mm tooth^{-1})

Table 5: Experimental result for aluminum

	Experimental readings		
Surface roughness (Ra) (µm)	n_1	n_2	n_3
Ra_1	0.480	0.570	0.650
Ra_2	0.510	0.590	0.700
Ra_3	0.430	0.590	0.680
Average Ra (µm)	0.473	0.583	0.677

Table 6: Analytical and experimental result for aluminum

	Experimental vs. analytical		
	n_1	n_2	n_3
Percentage deviation (ϕ_i) (%)	9.725	3.087	16.544
Average percentage deviation ($\bar{\phi}$) (%)	$\bar{\phi} = = \frac{9.725 + 3.087 + 16.544}{3} = 9.785\%$		

0.128, which is much smaller value than gradient value in Fig. 5 is 6.667, which means that feed rate has much more influence on surface roughness than spindle speed. The experimental result also show that feed rate has the highest influence on surface roughness in end milling of aluminum platen and then followed by cutting speed and depth of cut. The similar result can be proved by theoretical calculation of surface roughness shown in sensitivity analysis.

Experiment 2

Differ from experiment No. 1, The higher sensitivity value of each machining parameter in term of surface roughness indicates that greater influence on surface finish. From the sensitivity model obtained, feed rate is the most critical parameter compared to cutting speed (Table 4, 5). It shows that the smoothest surface was obtained by using parameter set 1, which based on decreases in feed rate while maintaining the cutting speed value. Decline in feed rate value also has a tendency of improving the surface finish and thus reducing the R_a parameter. Positive R_a sensitivity value means there is proportionality between R_a and feed rate. Since the average percentage deviation is less than 10% i.e., 9.785% (Table 6), the experiment result once again is accepted and theoretical model can be referred as benchmarking to provide a good indication of the influence of machining parameters on surface roughness.

To prove the finding, the same experiment for different material is conducted. Table 7 exhibited the resultant predicted surface roughness for finishing cut of Cast Iron using HSS cutter tool in end milling. The resultant Ra is predicted and the sensitivity value of each parameter variable in term of Ra shows that the feed rate is still become the most significant parameter compared to cutting speed.

Table 7: Analytical result for cast iron and sensitivity analysis

	Finish cut of aluminum material, D = 6.0 mm No. of flutes = 4, HSS tool cutter		
Readings	n_1	n_2 (Default Value)	n_3
Input			
Cutting speed (V_c) (m min^{-1})	15.240	15.240	18.55
Feed (f_z) (mm $tooth^{-1}$)	0.127	0.150	0.15
Spindle speed (N) (rev min^{-1})	808.510	808.510	984.11
Feed rate (f_r) (mm min^{-1})	410.720	485.106	590.466
Output			
Surface roughness (Ra) (μm)	0.172	0.240	0.240
Sensitivity output			
$\frac{\delta Ra}{\delta fr}$	8.39×10^{-7}	9.91×10^{-7}	8.14×10^{-7}
$\left\lvert\frac{\delta Ra}{\delta N}\right\rvert$	4.26×10^{-7}	5.94×10^{-7}	4.88×10^{-7}

The result indicates that by increasing cutting speed, the surface finish can be improved. It is because the occurrence of Built-Up Edge (BUE) when machining multiphase materials at lower cutting speeds. It generates large burr quantity on the machined surface, consequently deteriorating surface finish. This phenomenon may be associated with increase in the cutting forces and the consequent dynamic instability of the cutting process. Hence, increase in the depth of cut increases surface roughness values.

CONCLUSIONS

The purpose of this study is to develop analytical based surface prediction technique which can be more accurate, flexible, reliable and non-destructive and then evaluate its prediction ability. The sensitivity analysis program proposed in this study is a useful computational tool to help analysis of the relationship between the cutting parameters and the surface roughness of machined surfaces without embarking on laborious time consuming and often expensive machining trials. The sensitivity results showed that the feed rate is the most important cutting parameter for determining the machined surface roughness, Ra when end milling aluminum platen. This is followed by the cutting speed and the depth of cut. The sensitivity result was verified by experimental analysis, which was showing result that the percentage deviation between analytical method and experimental is less than 10%. The same result also obtained for different material. This application of this model can be used in predicting the machining condition of die and mold design with some minor modification and upgrading.

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