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Manufacturing Cutting Strategies for Forging Die Manufacturing on CNC Milling Machines

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Abstract

Manufacturing of dies has been presenting greater requirements of geometrical accuracy, dimensional precision and surface quality as well as decrease in costs and manufacturing times. Although proper cutting parameter values are utilized to obtain high geometrical accuracy and surface quality, there may exist geometrical discrepancy between the designed and the manufactured surface profile of the die cavities. In milling process; cutting speed, step over and feed are the main cutting parameters and these parameters affect geometrical accuracy and surface quality of the forging die cavities

In this study, effects of the cutting parameters on geometrical error have been examined on a representative die cavity profile. To remove undesired volume in the die cavities, available cutting strategies are investigated. Feed rate optimization is performed to maintain the constant metal removal rate along the trajectory of the milling cutter during rough cutting process.In the finish cutting process of the die cavities, Design of Experiment Method has been employed to find out the effects of the cutting parameters on the geometrical accuracy of the manufactured cavity profile. Prediction formula is derived to estimate the geometrical error value in terms of the values of the cutting parameters.Validity of the prediction formula has been tested by conducting verification experiments for the representative die geometry and die cavity geometry of a forging part used in industry. Good agreement between the predicted error values and the measured error.

INTRODUCTION

Forging Process

Forging is a metal forming process in which a piece of metal is shaped to the desired form by plastic deformation. The process usually includes sequential deformation steps to the final shape. In forging process, compressive force may be provided by means of manual or power hammers, mechanical, hydraulic or special forging presses. The process is normally but not always, performed hot by preheating the metal to a desired temperature before it is worked.

Compared to all manufacturing processes, forging technology has a special place because it helps to produce parts of superior mechanical properties with minimum waste of material. Forging process gives the opportunity to produce complex parts with desired directional strength, refining the grain structure and developing the optimum grain flow, which imparts desirable directional properties. Forging products are free from undesirable internal voids and have the maximum strength in the vital directions as well as a maximum strength to weight ratio.

The products of net-shape precision forging are used directly without any machining operations. A comparison can be made between a precision forged

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component and a conventionally forged component which are shown in Figure 1.2 to realize the quality of the end products.

Figure 1.1 Precision and conventionally forged components [3]

In close die forging process, die surface characteristics are directly reflected on the forged component. Thus, the geometrical accuracy of the forging die influences the geometrical accuracy of the produced part. Geometrical inaccuracy, poor surface finish can be partially and/or fully eliminated by proper strategies in precision die manufacturing stages. For this reason, cutting parameters of the precision die production must be carefully determined to satisfy desired geometrical accuracy without excessive increase in cutting time.

Geometric Dimensioning And Tolerancing In Forging Dies

In this chapter, [1]brief information about geometric dimensioning and tolerancing has been presented to provide background knowledge for the current study. The design considerations for forging die cavities have been given to relate geometric dimensioning and tolerancing[2]with forging die cavity design. Finally, an experimental cavity profile which is required for the studies conducted in the following chapters has been determined.

Definition of Geometric Dimensioning and Tolerancing

Geometric dimensioning and tolerancing (GD&T)[3] is a symbolic language. It is used to define the nominal geometry of parts and assemblies, to define the allowable variation in form and possibly size of individual features, and to define the allowable variation between features [4]. The features toleranced with GD&T reflect the actual relationship between mating parts. Drawings with properly applied geometric tolerancing provide the best opportunity for uniform interpretation and cost effective assembly [5].

GD&T is a design tool. Before designers can properly apply geometric tolerancing, they must carefully consider the fit and function of each feature of every part. GD&T, in effect, serves as a checklist to remind the designers to consider all aspects of each feature. Properly applied geometric tolerancing insures that every part will assemble every time. Geometric tolerancing allows the designers to specify the maximum available tolerance and consequently, design the most economical parts [23].

Rough Cut Milling Of Experimental Die Cavities

In this chapter, details of rough cut milling have been presented and cutting strategies for the experimental die cavity have been analyzed. Feed rate optimization has been performed to satisfy constant metal removal rate along the tool path trajectory. Finally, optimized rough cut milling codes have been implemented to the die cavities which are required for the finish cut experiments.

Importance of Rough Cutting Operations in Forging Die Manufacturing

Nowadays, current trend in forging die manufacturing is to produce high quality surface with an accurate geometrical properties using high speed machining centers. With the introduction of new developments in CNC milling technology, higher feed rates and cutting speeds are more and more applicable. Advances in feed rate and cutting speed provide great reductions in the production time of forging die cavities. However, obtaining geometrical accuracy in accordance with the product specifications is still primary objective; therefore, the most suitable cutting parameters for each operation must be carefully selected.

Many researchers pay attention to optimizing finish parameters of the cutting operations but this is not completely sufficient to increase the efficiency of manufacturing processes of dies. As expected, a rough cutting operation is performed before each finishing operation. For this reason, proper strategies must be defined and applied for both rough cutting and finish cutting operations. A well done rough cutting operation not only provides a smoother surface before finish cutting but also increases tool life considerably.

Analysis Of The Experiments And Derivation Of Geometrical Error Prediction Formula

In this chapter, effects of the cutting parameters i.e. step over, feed and cutting speed on geometrical accuracy of the surface profile have been examined by utilizing 3^2 factorial design. Geometrical error analysis for the finish cut experiments has been given initially. Then, geometrical error prediction formula and verification analysis for the prediction formula have been presented.

Geometrical Error Analysis of the First Set of Experiments

The design matrix for the first set is shown in Figure 5.1.

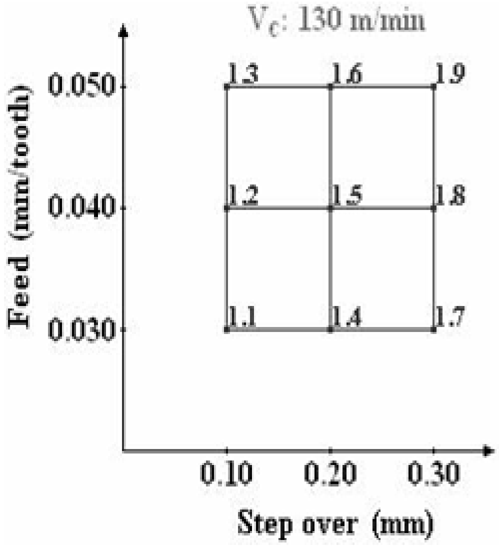

Figure 3.1 Design matrix for the first set of experiments

With the application of the cutting parameter values described in Figure 5.1, experimental die cavities involving surface and geometrical diversities are attained. Manufactured die cavities in the first set of experiments are shown in Figure 5.2.

Figure 3.2 Photograph of the first set of experiments

The procedure for the geometrical error measurement between the CAD profile and the manufactured profile was discussed in Section 4.3.3. According to this procedure, the error measurements are performed and geometrical error variations of the first set are obtained. Results of the geometrical error analysis for the first set of experiments are presented in Table 5.1. The error measurements are performed in two scan directions. Therefore, averages of the geometrical error measurements are also tabulated in Table 5.1.

It can be observed from Table 5.1 that all geometrical error values are lower than 100 μm which is the predefined profile tolerance value for the experimental die cavity. Therefore, all die cavities can be accepted as geometrically accurate in the defined tolerance limits. However, when surface quality is taken into account, die cavities having step over value of 0.10 mm are superior to the others. Depending on visual inspection, these die cavities can be directly utilized for forging applications without any requirement of polishing operation.

Table 3.1 Results of the first set of experiments

	Cutting Parameters			Geometrical Error		
Exper. No	Step Over (mm)	Feed (mm/tooth)	Cutting Speed (m/min)	1st Scan Dir. Error Meas. (μm)	2nd Scan Dir. Error Meas. (μm)	Average Error (μm)
1.1	0.10	0.030	130	22	19	20.5
1.2	0.10	0.040	130	25	29	27.0
1.3	0.10	0.050	130	34	31	32.5
1.4	0.20	0.030	130	34	35	34.5
1.5	0.20	0.040	130	39	39	39.0
1.6	0.20	0.050	130	43	42	42.5
1.7	0.30	0.030	130	44	46	45.0
1.8	0.30	0.040	130	52	47	49.5
1.9	0.30	0.050	130	54	57	55.5

By examining the main effect plots given in Figure 5.3-5.4, one can decide on the parameter having major influence on the geometrical error. These plots are just representation of marginal response averages at the three levels of two factors. Main effects of the step over and

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the feed for the first set of experiments are represented in Figure 5.3-5.4 respectively.

When the main effect of the step over is analyzed, it is realized that change in the input variable from 0.10 mm to 0.30 mm is resulted with a change in the response variable i.e. geometrical error from 26.7 µm to 50.0 µm. Response line characterizes a linear behavior in the range of the step over values. On the other hand, variation in the second input parameter, feed, causes again increase in the response value similar to the step over but rate of increase is milder than the first input parameter. Linear tendency of the response curve of the feed is another point observed in the main effect plot of the second input parameter.

To check for the validity of the prediction formula given in Equation 5.2, additional experiments are performed with different cutting parameter values. Results of the verification experiments are presented in Table 5.5.

Table 3.2 Results of the verification experiments

Exper. No	Cutting Parameters			Geometrical Error		
	Step Over (mm)	Feed (mm/tooth)	Cutting Speed (m/min)	1st Scan Dir. Error Meas. (µm)	2nd Scan Dir. Error Meas. (µm)	Average Error (µm)
3.1.1	0.15	0.030	130	27	28	27.5
3.1.2	0.20	0.035	130	38	36	37.0
3.1.3	0.25	0.050	130	48	49	48.5
3.2.1	0.15	0.030	170	28	29	28.5
3.2.2	0.20	0.045	170	43	43	43.0
3.2.3	0.25	0.050	170	52	48	50.0

Visual diversities of the verification cavities can be examined in Figure 5.13.

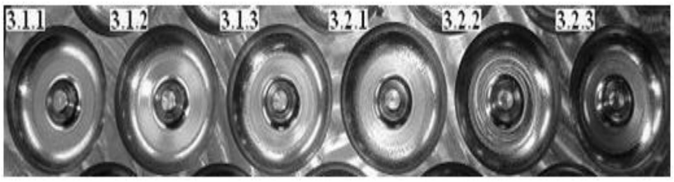

Figure 3.3 Photograph of the verification experiments

Comparison of the real geometrical error value with the predicted geometrical error value indicates conformity of the prediction formula for the various cutting parameters. The deviation between these two error values can be calculated as:

$$\%Error = \frac{Z - Z}{Z} \times 100 \qquad (5.3)$$

where$Z$ is the real geometrical error measured by CMM and Z' is the predicted geometrical error computed by the prediction formula.

The parameters used in the verification experiments are substituted into Equation 5.2 and the geometrical error values for the verification experiments are calculated. The results of the calculations are given in Table 5.6.

It can be observed from Table 5.6 that the maximum error between the measured error value and the predicted one is 2.00% which is an acceptable error percentage for geometrical error prediction on surface profile of forging die cavities. These results verify that the prediction formula is suitable for geometrical error estimation in forging die cavities when Ø6 mm ball nose cutter is used in the defined limits of the cutting parameters i.e. a_e = 0.10-0.30 mm, f_t = 0.030-0.050 mm/tooth and V_c = 130-170 m/min.

Table 3.3 Comparison of predicted error values with measured error values

Exper. No	Average of the Measured Geometrical Error (µm)	Predicted Geometrical Error (µm)	Error %
3.1.1	27.5	27.6	0.36
3.1.2	37.0	36.6	1.08
3.1.3	48.5	49.4	1.86
3.2.1	28.5	29.0	1.75
3.2.2	43.0	43.1	0.24
3.2.3	50.0	51.0	2.00

Case Study

Although the experimental profile is defined to analyze the geometrical error on surface profile of the die cavities, a real case application would be beneficial to evaluate validity of the experimental study. For this reason, a case study is conducted to investigate geometrical error on the surface profile of the forging die for a real part geometry which is taken from Aksan Steel Forging Company. Die and forging part geometries are shown in Figure 5.14.

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To remove the excess volume in the die cavity, available cutting strategies in the Pro/Engineer Wildfire 3 library [10] are again analyzed. It is realized that “Type_Spiral” cutting strategy is better than the other cutting strategies in terms of cycle time and tool-workpiece contact duration. Cycle time of the each cutting strategy for the removal of the same amount of volume can be examined in Table 5.7.

The finish cut experiments indicates that increase in the step over and the feed is resulted in linear advance of the geometrical error. Additionally, it is concluded that influence of the step over on the geometrical error is considerably higher than influence of the feed. Therefore, by considering these facts, step over of 0.10 mm, feed of 0.045 mm/tooth and cutting speed of 130 mm/min are selected as values of the finish cut parameters for the case study.

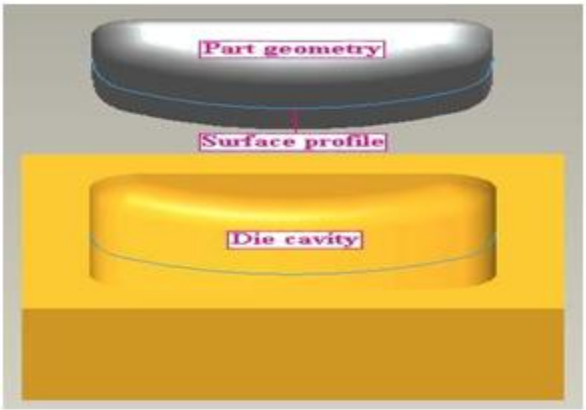

Table 4.1Cutting strategies vs. cycle time

Cutting Strategy	Cycle Time (min)
Type_1	17.92
Type_2	16.73
Type_3	14.00
Type_Spiral	9.92
Type_One_Dir	18.94
Type_1_Connect	18.28
Constant_Load	20.69
Spiral_Maintain_Cut_Direction	12.61
Spiral_Maintain_Cut_Type	12.73
Follow_Hardwalls	11.38

Surface attained after performing finish machining can be visualized in Figure 5.15.

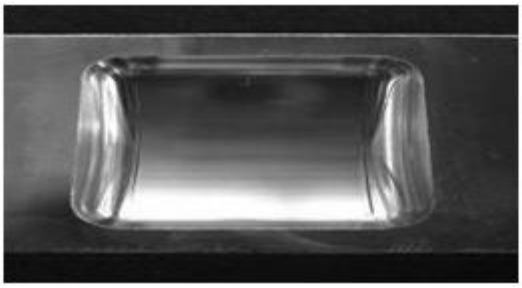

Figure 4.1 Photograph of the case study

The geometrical error measurement is performed in a similar way described in Section 4.3.3. The results of the geometrical error measurements for the case study are presented in Table 5.8.

Table 4.2 Results of the case study

	Cutting Parameters			Geometrical Error		
Experiment	Step Over (mm)	Feed (mm/tooth)	Cutting Speed (m/min)	1st Scan Dir. Error Meas. (µm)	2nd Scan Dir. Error Meas. (µm)	Average Error (µm)
Case_study	0.10	0.045	130	29	32	30.5

When the input parameters are substituted in Equation 5.2, the geometrical error for the case study is computed as 29.4 µm. The error between the predicted geometrical error and the measured geometrical error is given in Table 5.9.

Table 4.3 Comparison of predicted error values with measured error values

Experiment	Average of the Measured Geometrical Error (µm)	Predicted Geometrical Error (µm)	Error %
Case_study	30.5	29.4	3.61

It can be observed from Table 5.9 that the predicted value for the geometrical error is close to the measured average error value. Verification results indicates that the prediction formula is suitable for error estimation on sculptured surfaces of Dievar tool steel when Ø6 mm ball nose cutter is used for finish cut operations of forging die production. As a result, it can be concluded that Equation 5.2 predicts the geometrical error on surface profile of the die cavities well in the range of the cutting parameters.

CONCLUSIONS

Geometrical discrepancies may exist between the CAD model of die cavities and the manufactured die cavities. In this study, it is aimed to find out the effects of the cutting parameters i.e. step over, feed and cutting speed on geometrical accuracy of the surface profile of forging die cavities. For this purpose, a representative die cavity profile involving major design features of the forging die cavities is initially determined. The geometrical discrepancy between CAD model of the representative die cavity profile and the manufactured profile is examined by utilizing design of experiment approach. The factorial design is implemented to investigate the influence of the step over, the feed and the cutting speed on the geometrical error. Then, a methodology is developed for the prediction of geometrical error on sculptured surfaces of forging die cavities. Additionally, feed rate optimization is performed for the rough cutting operation of die cavity production by satisfying metal removal rate constant along the tool path trajectory.

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