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Cutting Strategies for Forging Die Manufacturing on CNC Milling Machines

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ABSTRACT

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 values has been observed.

INTRODUCTION

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.

SCOPE OF THE THESIS

Recent requirements of die and mould manufacturing can be summarized as: maintaining geometrically

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accurate and high quality die surfaces as well as reduction in production time. In order to decrease production time of die manufacturing processes and achieve geometrical accuracy in accordance with product specifications, optimum cutting parameters for rough cutting and finish cutting operations must be accurately selected. By selecting a fixed feed rate based upon the maximum force, tool is saved but very often it results in extra machining time in rough cutting operations, which reduces productivity. By optimizing the feed rate, both objectives of saving the tool and also reducing machining time thereby increase in productivity can be achieved.

For the finish cutting operations, attaining geometrically accurate products with acceptable surface quality in a reasonable production time is the common objective of today's die manufacturers. Therefore, experimental analysis dealing with the effects of the cutting parameters on geometrical error and production time would be beneficial for the determination of these parameters. The main objective of this particular study is to find out geometrical discrepancy between CAD model of a die cavity and a manufactured die cavity by utilizing various cutting parameter values for the finish cut operation of precision forging dies.

GEOMETRIC DIMENSIONING AND TOLERANCING IN FORGING DIES

In this chapter, 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 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) 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 [22]. 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 [23].

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.

FINISH CUT MILLING OF EXPERIMENTAL DIE CAVITIES

In this chapter, three level factorial design for the experimental study has been initially defined. Then, details of the finish cut parameter selection and experimental levels are presented. Finally, geometrical error measurement technique for the manufactured experimental cavity profile has been explained.

Three Level Factorial Design

3^k design is a factorial design, that is, a factorial arrangement with k factors each at three levels. Three levels of the factors are referred as low, intermediate, and high. Each treatment in the 3^k design are denoted by k digits, where the first digit indicates the level of factor A, the second digit indicates the level of factor B and the k^{th} digit indicates the level of factor k. Geometry of 3^2 design is shown in Figure 4.1.

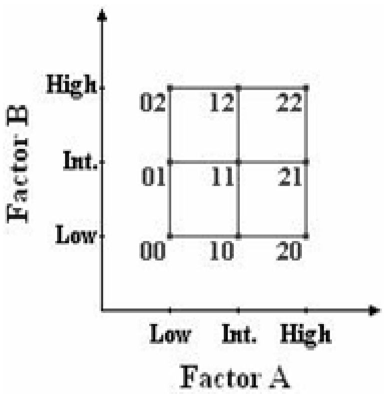

Figure 4.1 Treatment combinations in 3^2 design

Finish Cut Experiments and Experimental Details

In order to examine the effects of the cutting parameters; step over, feed and cutting speed to the geometric error during finish cut of the forging die cavities, the factorial design method has been utilized. The design consists of running tests with all the possible combinations of variables at each of three levels, thereby obtaining most of the information required for a multilevel experiment. In that way, the factorial design does an excellent job relating the experimental effort to the information obtained.

The input parameters; step over, feed and cutting speed are all quantitative factors that level values of each should be properly defined. Improper selection of the level values and/or determination of level limits may result in incompatible results of the response variable which is undesirable.

By considering the recommended ranges of the feed and the cutting speed given in Table C.1 in Appendix C, three levels for the step over and the feed; two levels for the cutting speed are selected. Thus, two sets of 3^2 factorial test have been performed and number of experiments is enhanced from $3^2 = 9$ to $2 \times 3^2 = 18$ by introducing the second level of the cutting speed to the factorial design. The cutting parameter values in Table C.1 are presented in Table 4.1 as a matter of convenience.

Table 4.1 Cutting data recommendations for end milling [34]

Cutting Parameters	Solid Carbide	Carbide Indexable Insert	High Speed Steel
Cutting Speed V_c (m/min)	130-170	120-160	25-30
Feed f_t (mm/tooth)	0.03-0.20	0.08-0.20	0.05-0.35

At that point it should also be kept in mind that radius of the ball cutter must always be less than the radius of any concave surfaces and corners in the die cavity to ensure tool contact throughout the tool path. Since the minimum curved section of the experimental die

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cavity has dimension of R4 mm, ball nose solid carbide end mill having radius of 3 mm is utilized for the finish cutting operations.

Elimination of these formations during finish cut operation is directly related with the defined step over value. For this reason, a systematic approach is implemented to decide on the first input parameter values. The level values of step over are determined by taking a certain percentage of the cutter diameter. The first level of step over value 0.10 mm constitutes 1.67% of the Ø6 mm solid carbide ball nose cutter seeming quite small value for the application. Keeping the step over value low guarantees excellent geometrical accuracy and surface quality but causes substantially longer production time. Therefore, the second level of step over is chosen as 0.20 mm which is 3.33% of the tool diameter and double of the first level. This step over value should present good geometric accuracy and surface quality with a reasonable production time. Finally, third level is selected as 0.30 mm which is triple of low level value and 5.00% of the cutter diameter. Tool paths for the three levels of step over are represented in Figure 4.3-4.5.

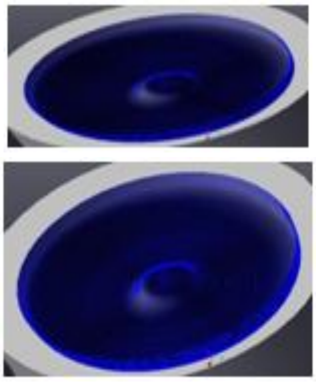

Figure 4.3 Tool path with 0.10 mm step over

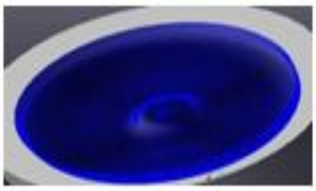

Figure 4.4 Tool path with 0.20 mm step over

Table 4.2 Selected factors and levels for the first set of finish cut experiment

Levels	Step over, a_e (mm)	Feed, f_t (mm/tooth)	Cutting speed, V_c (m/min)
Low Level	0.10	0.030	-
Intermediate Level	0.20	0.040	-
High Level	0.30	0.050	170

Table 4.3 Selected factors and levels for the second set of finish cut experiments

Levels	Step over, a_e (mm)	Feed, f_t (mm/tooth)	Cutting speed, V_c (m/min)
Low Level	0.10	0.030	130
Intermediate Level	0.20	0.040	-
High Level	0.30	0.050	-

Within this setup, 18 experiments are performed to analyze the geometrical discrepancy between the CAD model of the die cavity and the manufactured die cavity. Additionally, 6 verification experiments are held to check out the validity of the prediction formula which will be derived in Chapter 5. All experimental details, levels and factors are presented in Table 4.4.

After determination of the cutting parameters, proper cutting strategies for the generation of finish machining codes are investigated. In finish machining, volume is not removed like in the case of rough machining. Therefore, cutting strategies for finish machining differ from the cutting strategies for rough machining. A strategy suitable for rough machining would be less favorable for finish machining. For the finish machining of the experimental die cavities, it is aimed to obtain the minimum tool path having one directional continuous motion of the tool providing smooth transitions between radial movements.

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.

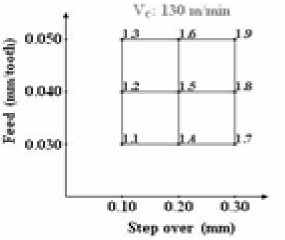

Figure 5.1 Design matrix for the first set of experiments

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.

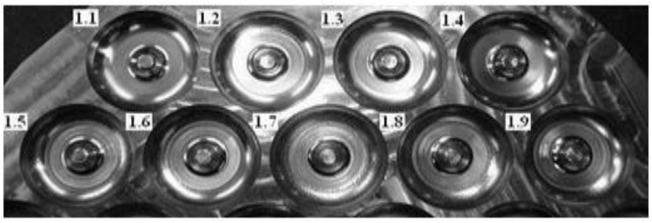

Figure 5.2 Photograph of the first set of experiments

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 5.1 Results of the first set of 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)
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 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

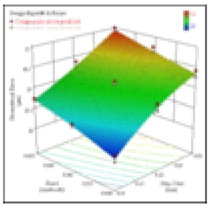

Figure 5.6 Surface plot of the response variable geometrical error [32]

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In Figure 5.12, 3D surface plot for the second set of experiments is presented to relate the cutting parameters with the geometrical error.

Table 5.6 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.

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.

Figure 5.14 Die and forging part geometries for the case s

Table 5.8 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 5.9 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.

Conclusions for the rough cutting process can be summarized as follows:
In order to obtain the minimum tool path and minimize retract and plunge motions of the tool, various cutting strategies available in Pro/Engineer Wildfire 3 library [10] are analyzed and it is realized that a spiral tool path is more favorable than any other strategy for the rough machining of forging die cavities in terms of cycle time and the tool-workpiece contact duration.

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