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CNC Milling Machines Advanced Cutting Strategies for Forging Die Manufacturing

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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 values has been observed.

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 [1].

Precision forging is a kind of closed die forging and normally means “close to final form” or “close tolerance” forging. It is not a special technology, but a refinement of existing techniques to a point where the forged part can be used with little or no subsequent machining. Some examples of precisely forged parts are given in Figure 1.1.

In precision forging process, improvements cover not only the forging method itself but also preheating, lubrication, and temperature control practices. Major advantages of precision forging can be summarized as:

- Reduction in material waste
- More uniform fiber orientation providing superior strength values

Figure 1.1 Precisely forged parts

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.

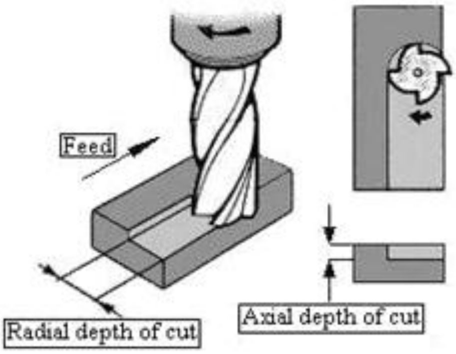


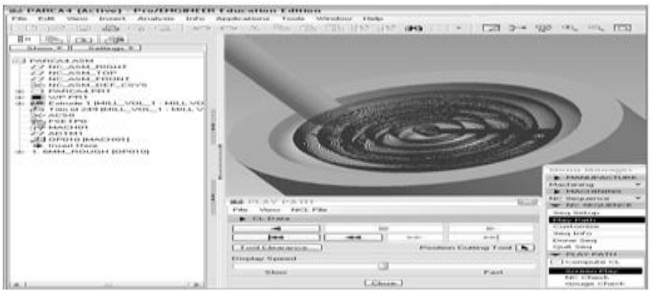
Figure 3.2 Parameters of metal removal rate

Maintaining a constant metal removal rate keeps the cutter at its maximum possible rate of advance into material for the varying cutting conditions. However, to keep material removal rate constant during any kind of operation, either radial depth of cut and feed rate must be kept constant or multiplication term of radial depth of cut and feed rate must be kept constant.

Determining the exact and optimum feed rate selection for sculptured surface is very difficult and requires experience. By selecting a fixed feed rate based upon the maximum force, which is obtained during full length of machining, the tool is saved but it results in extra machining time, which reduces productivity. By optimizing the feed rate, both the objectives of saving the tool (more tool life) and also reducing machining time thereby increasing productivity can be achieved. Since rough machining operations are strongly geometrical feature dependent, feed rate adjustments are usually essential to maintain constant metal removal rate.

Tool Path Generation for Rough Machining

For the generation of rough machining codes of the determined geometry, manufacturing module of Pro/Engineer Wildfire 3 [10] is extensively utilized. Features of the CAM module used throughout the process can be visualized in Figure 3.3.



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

3k 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 3k 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 kth digit indicates the level of factor k. Geometry of 32 design is shown in Figure 4.1

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.

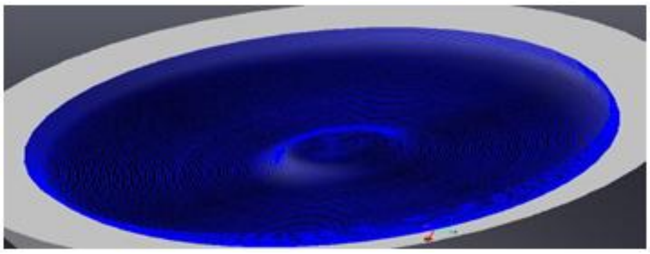


Figure 4.3 Tool path with 0.10 mm step over

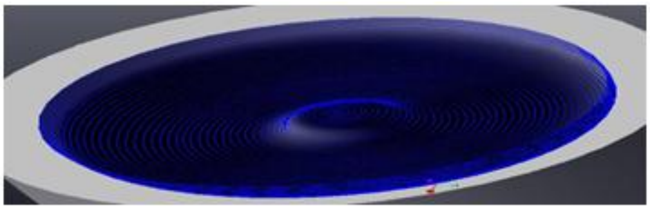


Figure 4.4 Tool path with 0.20 mm step over

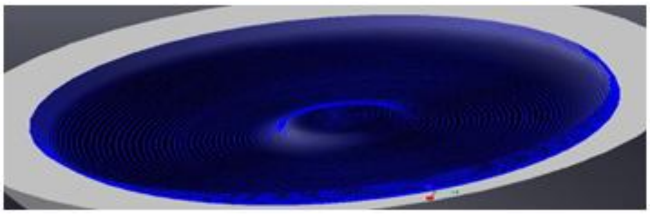


Figure 4.5 Tool path with 0.30 mm step over

The cutting data recommendations of tool steel manufacturer's presented in Table 4.1 have been used to determine low, intermediate and high level values of the second input parameter, the feed. According to the cutting recommendations for solid carbide cutters, level values of the feed are selected as 0.03, 0.04 and 0.05 mm/tooth respectively.

When the reference values for the solid carbide cutters given in Table 4.1 are examined, it is observed that proposed range for the cutting speed is in between 130 m/min and 170 m/min. As mentioned previously, two levels are decided to be practical for the third input parameter. Therefore, low level i.e. 130 m/min and high level i.e. 170 m/min are chosen for the cutting speed. Variable factors considered in the finish cut experiments and the selected levels are summarized in Table 4.2-4.3.

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	-

Table 4.2 Selected factors and levels for the first 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	-
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

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.

Table 4.4 Design matrix for the experiments

	Experiment No	Step Over (mm)	Feed (mm/tooth)	Cutting Speed (m/min)
1^{st} set of experiments	1.1	0.10	0.030	130
	1.2	0.10	0.040	130
	1.3	0.10	0.050	130
	1.4	0.20	0.030	130
	1.5	0.20	0.040	130
	1.6	0.20	0.050	130
	1.7	0.30	0.030	130
	1.8	0.30	0.040	130
	1.9	0.30	0.050	130
2^{nd} set of experiments	2.1	0.10	0.030	170
	2.2	0.10	0.040	170
	2.3	0.10	0.050	170
	2.4	0.20	0.030	170
	2.5	0.20	0.040	170
	2.6	0.20	0.050	170
	2.7	0.30	0.030	170
	2.8	0.30	0.040	170
	2.9	0.30	0.050	170
Verification experiments	3.1.1	0.15	0.030	130
	3.1.2	0.20	0.035	130
	3.1.3	0.25	0.050	130
	3.2.1	0.15	0.030	170
	3.2.2	0.20	0.045	170
	3.2.3	0.25	0.050	170

Geometrical Measurement

Measurement Setup

Precision measurement of the manufactured products in Cartesian coordinate system can be performed by using a coordinate measuring machine (CMM). DEA Brown&Sharpe GLOBALSTATUS777 coordinate measuring machine, which is available at METU-BİLTİR Research and Application Center, is utilized for the dimensional examination of the experimental die cavities. The available CMM at the Center which is presented in Figure 4.6 uses digital readouts, air bearings, computer controls to achieve accuracies in the order of 1 µm over spans of 100 m

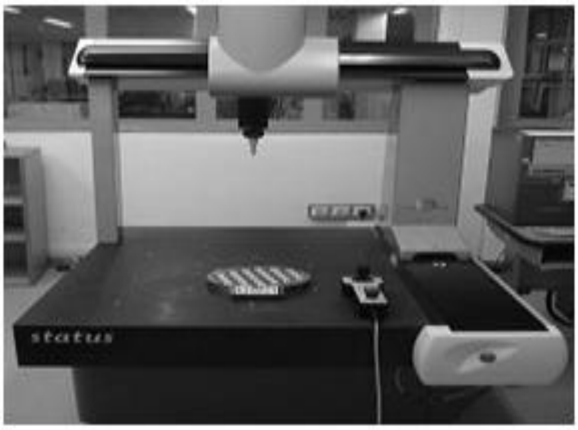
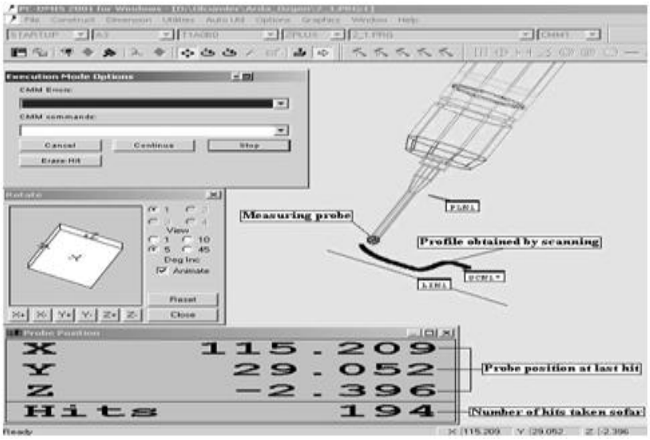


Figure 4.6 CMM used in the study

Scanning Technique on CMM

The dimensions of sculptured surfaces along a directional path can be measured by using scanning technique of CMMs. By introducing boundary points and measurement increments on the directional path, a scanning trajectory for the measurement can be defined. Geometrical variations, positive and negative slopes on the path are taken into account by the computer routines of the CMM. Therefore, there is no need to concern about the diversity of the surface. A sample measurement representing the scanning technique can be visualized in Figure 4.7.

At that point, it should be kept in mind that, values of the measurement increments directly influence the number of points taken on the surface and the fitted curve on these points. As a consequence of this, the measurement interval must be settled to a reasonable value to maintain contact to all surfaces through the trajectory. In this particular study, the maximum incremental value for the measuring probe movement is taken as 0.10 mm since the minimum step over value is predefined as 0.10 mm. The minimum incremental value is chosen as 0.05 mm which is quite safe value for the measurements taken on the curved sections of the surfaces. According to these measurement intervals, measuring probe definitely moves 0.10 mm increments on the flat surfaces of the trajectory; and measuring increments reduce from 0.10 mm to 0.05 mm for the curved regions of the trajectory.



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X                 115.209
Y                  29.052
Z                  -2.396
Hits                  194
```

Figure 4.7 Scanning technique on CMM

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 32 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.

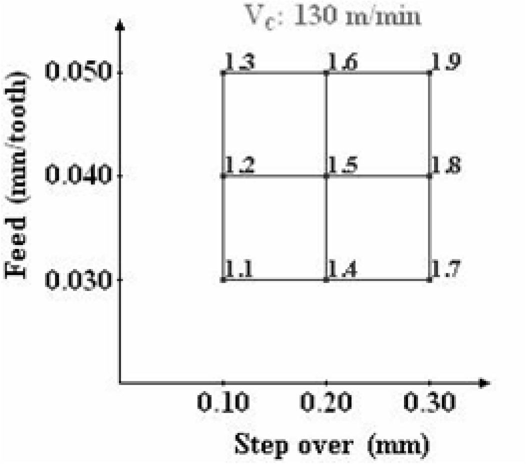

Figure 5.1 Design matrix for the first set of experiments

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.

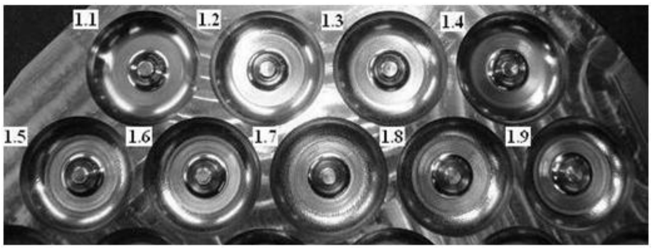

Figure 5.2 Photograph of the first set of experiments

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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

Table 5.1 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

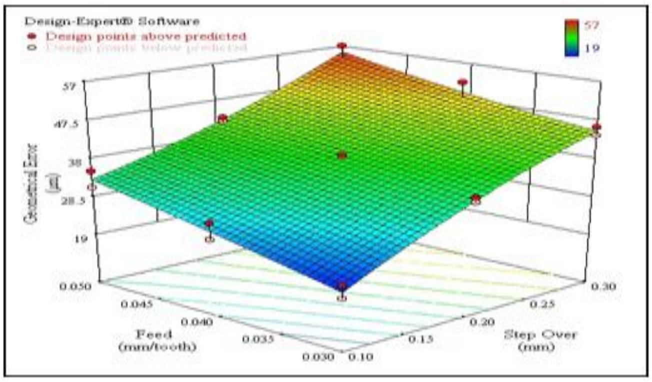

Figure 5.6 Surface plot of the response variable geometrical error

Geometrical Error Prediction Formula

In order to predict geometrical error values for various applications, a prediction formula is derived. Regression analysis is performed and coefficients of linear regression model mentioned in Chapter 4 are computed.

The least square estimate of β is as follows:

$$\beta = (X T X)-1 X T y \quad (5.1)$$

where X is the matrix obtained from the input parameters, step over, feed, cutting speed and y is the vector of the response variable, geometrical error. The variable coefficients are computed by applying the least square method to the experimental data.

Details of the coefficient calculations are presented in Appendix E. For the range of cutting speed of 130-170 m/min, feed of 0.030-0.050 mm/tooth, step over of 0.10-0.30 mm; the geometrical error can be predicted in µm by using the equation:

$$Geom\_error = -19.083 + 156.67ae + 831.25\ ft + 0.0278Vc \quad (5.2)$$

$$-\ 250ae\ ft + 2.016 \cdot 10-13\ aeVc + 0.2083\ ftVc - 75ae\ 2 - 3750\ ft\ 2$$

where ae is the step over in mm, ft is the feed in mm/tooth and Vc is the cutting speed in m/min.

In the regression analysis, quadratic term for the cutting speed is excluded from the prediction formula since only two levels are selected for the cutting speed. As mentioned in Section 4.2, three levels are determined for the step over and the feed. Thus, the prediction formula involves quadratic terms for these parameters.

Verification Analysis for the Finish Cut Experiments
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.

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Table 5.5 Results of the verification 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)
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

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.

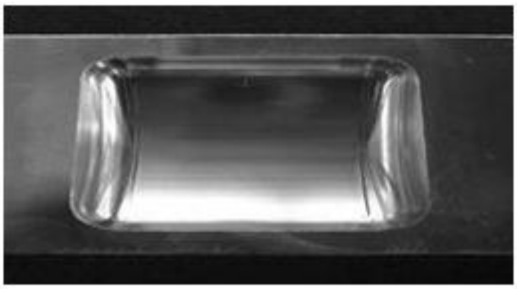

Figure 5.14 Die and forging part geometries for the case study

Table 5.7 Cutting 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.

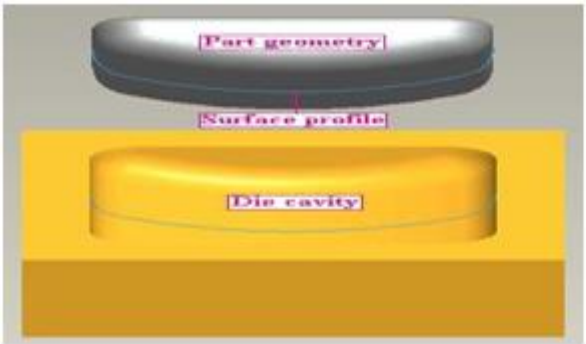

Figure 5.15 Photograph of the case study

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.

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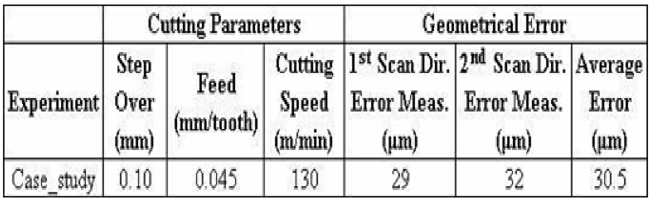
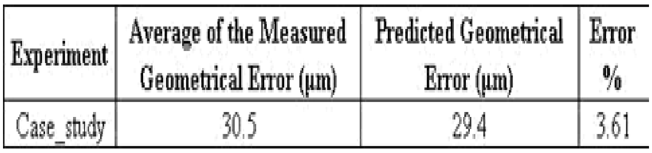
Table 5.8 Results of the case study



	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.

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