Manufacturing Cutting Strategies for Forging Die Manufacturing on Cnc Milling Machines

D.Vikram Deva Narasimha Varma[1], S N S Santosh Kumar[2]
[1]*M.Tech Student,* [2]*Associate Professor*
[12]*Dept of Mechanical Engineering, Hyderabad Institute of Technology And Management, Gowdavalli(V), Medchal (M), R.R District, Telangana , India*

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.

I. INTRODUCTION

A. 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.

B. Precision Forging

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

Fig.1: Precisely forged parts [2]

The decision to apply precision forging techniques depends on the relative economics of additional operations and tooling vs. elimination of machining. Because of higher tooling and development costs, precision forging is usually limited to high quality applications [3].

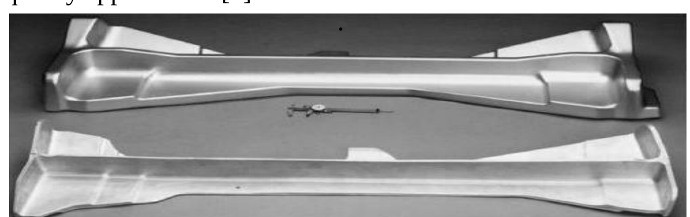

Fig.2: Precision and conventionally forged components

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.

C. Forging Die Manufacturing

Forging die manufacturing requires various affiliated operations that should be separately considered. It would be beneficial to examine real applications of forging die manufacturing to acquire comprehensive information about processes. Thus, Aksan Steel Forging Company in Ankara is chosen as the reference company to investigate current practices in forging die manufacturing [4].

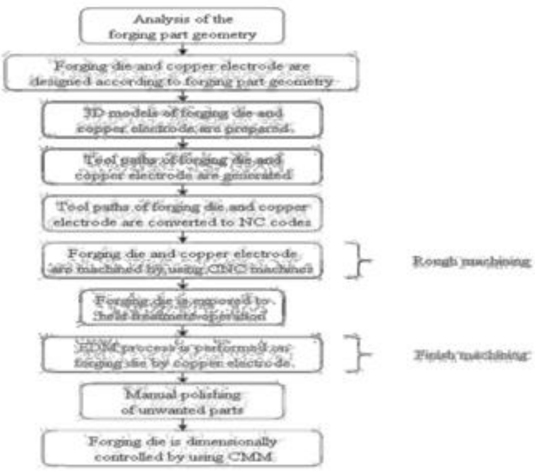

Fig.3: Flow diagram of the die manufacturing processes of Aksan Steel Forging Company

Application of EDM process necessitates manual polishing in the die cavities since micro cracks and nano cracks are formed at the surface layer which is produced by the copper electrode. The formation of these cracks is exactly related with EDM in which electrically conductive material is removed by means of rapid and repetitive spark discharges resulting from local explosion of a dielectric liquid.

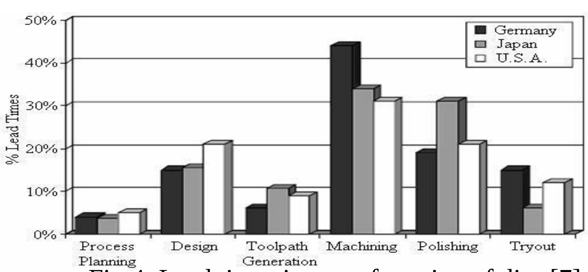

Fig.4: Lead times in manufacturing of dies [7]

It can be concluded from Figure 4 that, polishing time constitutes 20-30% of total manufacturing time of forging die production. It is obvious that reduction in any of the steps of die manufacturing process, will improve efficiency of the whole operation in cost wise and time wise. For this reason, cutting strategies should be developed and numerical codes should be optimized in such a way that no additional application is required in the die cavity after CNC machining operation.

D. CNC Milling vs. EDM Process in Die Manufacturing

Nowadays CNC milling technology is a basic constituent part of every modern tool making company. According to the objective model for cavity manufacturing technology, where milling tool, die and product related parameters are considered, CNC milling technology is prevalently replacing classical die sinking EDM applications. As a consequence of these, for each die cavity, it has to be ascertain, which technology CNC milling plus EDM finishing or CNC milling alone is the most advantageous. In Table 1.1, advantages, disadvantages as well as limits of the EDM and CNC milling are presented.

Table 1.1 Comparison of EDM process with CNC milling application [8]

Criterion	EDM	CNC Milling
Materials	All conductive materials	All cutting materials (steel up to 62 HRc)
Geometry	Free	Limited depth, radius
Sharped inner angles	Radius <0.1 mm reachable	Radius at the bottom >0.3 mm, radius at the wall >0.1 mm
Deep grooves	Depend on manufactured electrode	Up to L/D<10 (L: Length of cutter, D: Diameter of cutter)
Polished surface	Always additional finish machining	Without additional finish machining
Cost of additionional finish machining	High	Low
Geometric accuracy	Good	Better than EDM
Machining tool	Expensive (milled)	Simple, standard product

II. GEOMETRIC DIMENSIONING ANDTOLERANCING 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.

a. 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].

Symbol	Description	Geometry
∠	ANGULARITY	ORIENTATION
◎	CONCENTRICITY	LOCATION
⌭	CYLINDRICITY	FORM
▱	FLATNESS	FORM
∥	PARALLELISM	ORIENTATION
⊥	PERPENDICULARITY	ORIENTATION
⌖	POSITION	LOCATION
⌓	PROFILE	PROFILE
⌒	PROFILE OF A LINE	PROFILE
○	CIRCULARITY	FORM
—	STRAIGHTNESS	FORM
⌯	SYMMETRY	LOCATION
↗	RUNOUT	RUNOUT
⌰	TOTAL RUNOUT	RUNOUT

Table 2.1 Tolerance symbols with their descriptions [22

Geometric tolerances specify the maximum variation that is allowed in form or position from true geometry. The geometric tolerance is, in essence, width or diameter of tolerance zone within which a surface or axis of hole or cylinder can lie which results in resulting feature being acceptable for proper function and interchangeability

b. Feature Control Frame in GD&T

The feature control frame in the GD&T language is like a sentence in any language. All of the geometric tolerancing for a feature, or pattern of features, is contained in one or more feature control frames [23].

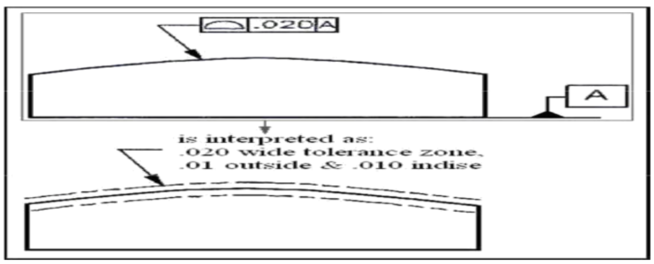

Fig.4: Feature control frame [23]

c. Advantages of GD&T over Coordinate Dimensioning and Tolerancing

Since the middle of the nineteenth century, industry has been using the plus or minus tolerancing system for tolerancing drawings. The system has several limitations [23]. The plus or minus tolerancing system generates rectangular tolerance zones. A tolerance zone, such as the example in Figure 2.2, is a boundary within which the axis of a feature that is in tolerance must lie. Rectangular tolerance zones do not have a uniform distance from the center to the outer edge. In Figure 2.2 from left to right and top to bottom, the tolerance is ±0.005; across the diagonals, the tolerance is ±0.007. Therefore, when designers tolerance features with ±0.005 tolerance, they must tolerance the mating parts to accept ±0.007 tolerance, which exists across the diagonals of the tolerance zones.

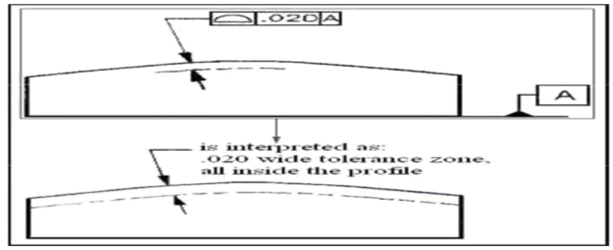

Fig.5: Traditional plus or minus tolerancing system [23]

d. Profile Tolerancing

A profile is the outline of an object. Specifically, the profile of a line is the outline of an object in a plane as the plane passes through the object. The profile of a surface is the result of projecting the profile of an object on a plane or taking cross sections through the object at various intervals.

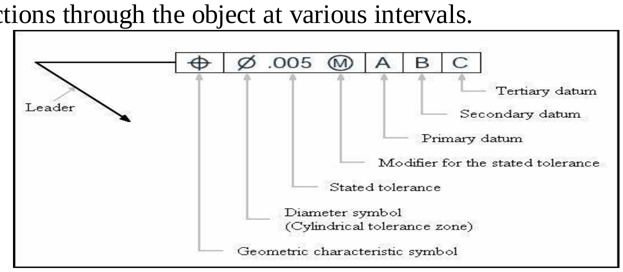

Fig.6: Bilateral tolerance on a profile [23]

If the leader from a profile tolerance points directly to a segment of a phantom line extending, outside or inside, parallel to the true profile, as shown in Figure 2.4-2.5, all the tolerance is outside or inside the true profile [23].

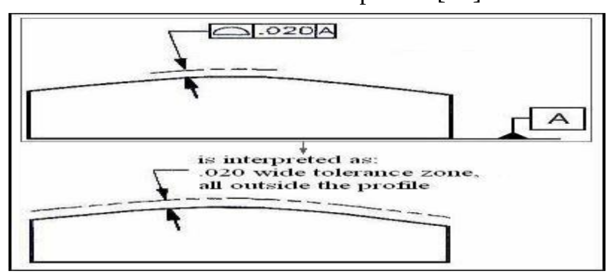

Fig.7: Unilateral tolerance outside on a profile [23]

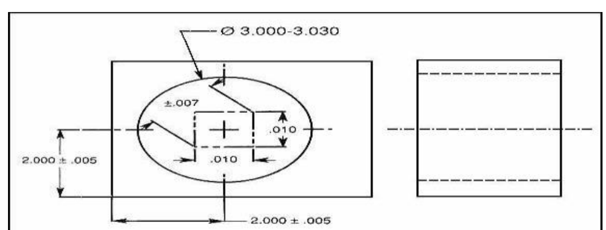

Fig.8: Unilateral tolerance inside on a profile [23]

The tolerance may even be specified as an unequal bilateral tolerance by drawing segments of phantom lines inside and outside parallel to the profile and specifying the outside tolerance with a basic dimension as shown in Figure 2.6 [23].

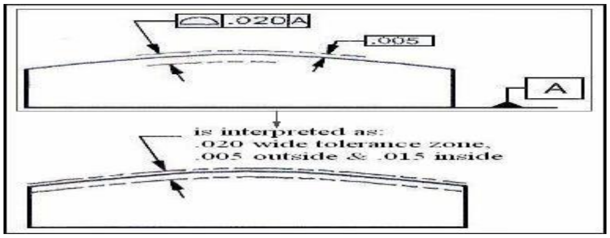

Fig.9: Unequally distributed bilateral tolerance on a profile [23]

Where a profile tolerance applies all around of a pointed feature, the "all around" symbol is specified, as shown in Figure 9 The "all around" symbol is indicated by a circle around the joint in the leader from the feature control frame to the profile.

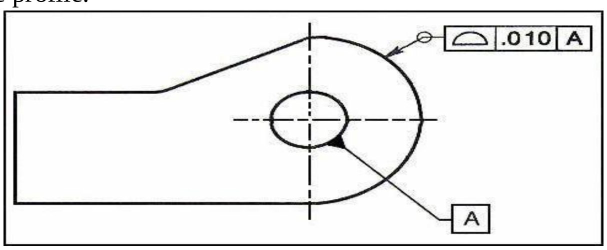

Fig.10: All around tolerance symbol [23]

If the profile is to extend between two points, as shown in Figure 10, the points are labeled, and a note using the "between" symbol is placed beneath the feature control frame. The profile tolerance applies to the portion of the profile between points X and Z where the leader is pointing.

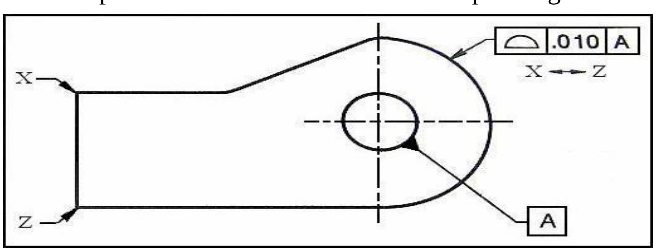

Fig.11: Between tolerance symbol [23]

If a part, such as a casting or forging, is to be controlled with a profile tolerance over its entire surface, the note "all over" is placed beneath the feature control frame, as shown in Figure 11

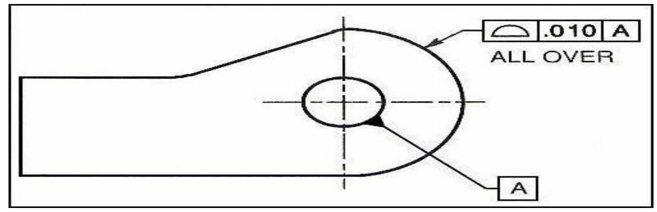

Fig.12: All over tolerance symbol [23]

e. Dimensional Tolerances of Dies

The tolerances of conventional and precision forging dies are related to various kinds of dimension. When the categories of tolerances appearing on forging and precision dies are examined, they can be classified into four groups [25]: Table 2.2 Forging tolerances for length, width, and height [25]

f. Design Considerations of Forging Dies

Since die cavities basically consist of inclined/draft surfaces, corners and radii, a proper consistency between these geometries are always necessary to obtain smooth and continuous surfaces on the produced components. Therefore, values of these geometric entities must be precisely stated in accordance with the desired geometry.

g. Fillet and Corner Radii

One of the most important factor in the design of forging die cavities is the proper selection of fillet and corner radii. On closed die forgings, corners and fillets are the curved surfaces that unite smoothly the converging or intersecting sides of forged elements, such as ribs, bosses and webs

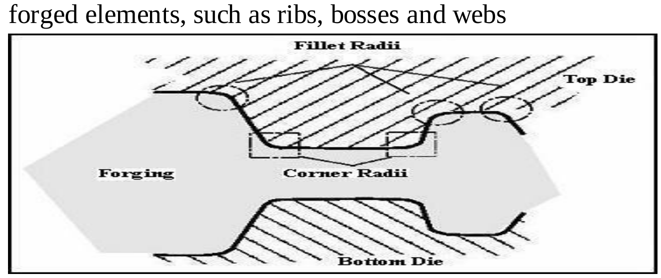

Fig.13: Corner radii and fillet radii in forging dies [26]

Recommended values of fillet and corner radii in forging die cavities are generally based on dominant features of the forged components.

Table 2.3 Recommendations for minimum fillet and corner radii [27]

Forged part height (mm)	Fillet radius (mm)	Corner radius (mm)
25	4	2
40	6	3
63	10	4
100	16	6
160	25	8
250	40	10
400	63	16

h. Draft Angle

Axial projections on forging are usually tapered so that the forged part can be easily removed from the die cavity. This taper is usually called draft. Typical types of drafts existing in forging dies are shown in Figure 13. The most common draft angles are between 5° and 7°. For steel forgings, it is common to apply a smaller draft angles on the outside surface than on the inside because the outer surface will shrink away from die during cooling and permit removal of the forging. Forging designs with zero draft angles require dies with special knockouts [28].

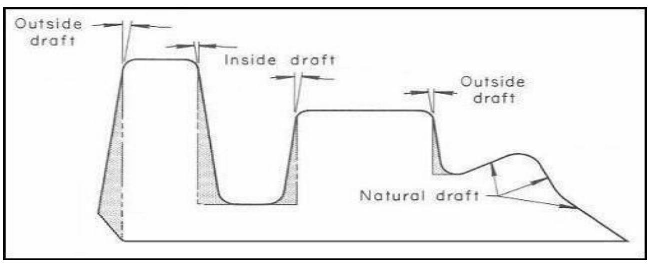

Fig.14: Types of draft angles in forging dies

III. 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.

A. 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.

B. Cutting Parameters for Rough Machining

As cutting tools are varying in terms of number of teeth on the tool tip, feed rate can be related with number of cutting flutes, spindle speed and feed per tooth according to the following equation:

$V_f f_t n_t N$ (3.1)

where f_t is feed in mm per tooth, $n_t =$ is . number . of cutting flutes on the tool, N is spindle speed in rpm.

Cutting speed is the speed difference between cutting tool and surface of the workpiece it is operating on. It depends on tool diameter and spindle speed; and can be calculated according to the following equation:

$v_c = \frac{\pi D N}{1000}$

where D is tool diameter in mm, N is spindle speed in rpm.

In down milling the cutting edge is mainly exposed to compressive stresses, which are much more favorable for the properties of solid carbide cutters compared with the tensile stresses developed in up milling. When the cutting edge goes into cut in down milling, the chip thickness has its maximum value; on the contrary in up milling it has its minimum value. Up milling and down milling process are represented in Figure 15.

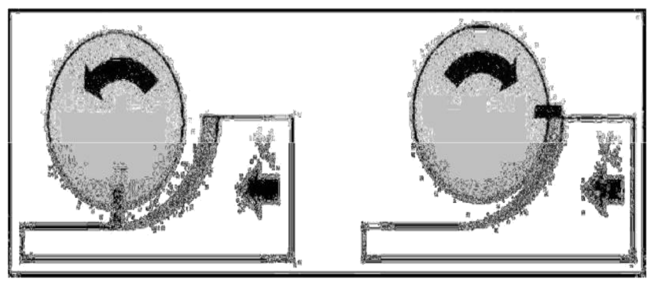

Fig.15: Up and down milling

Additionally, in up milling considerably more heat is generated than in down milling, because of higher friction on cutting edge. Therefore, in modern high speed milling, down milling is in use. It assures low milling tool wear although cutting process is more pretentious because of greater cutting forces. Modern machine tools are more rigid, that is why allowing use of down milling [8].

C. Constant Metal Removal Rate in Rough Cut

In the milling process, material removal rate is defined as the rate at which material is removed from an unfinished part, usually measured in cubic millimeters per minute. The main parameters that determine the metal removal rate are:

Axial depth of cut (a_p) [mm]
Radial depth of cut (a_e) [mm]
Feed rate (V_f) [mm/min]

According to these parameters which are demonstrated in Figure 3.2, metal removal rate, Z_w, can be defined as:
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.

IV. 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.

A. 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 16.

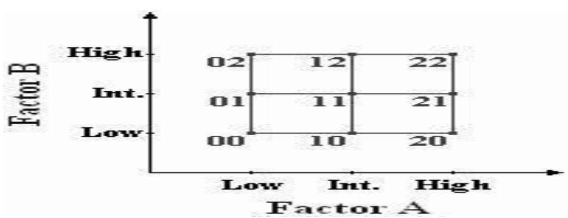

Fig.16: Treatment combinations in 3^2design

In the 3^k system of designs, when the factors are quantitative, low, intermediate, and high levels are denoted by -1, 0, and +1 respectively. This facilitates fitting a regression model relating the response to the factor levels. When 3^2 design in Figure 4.1 is considered and let x_1 represent factor A and x_2 represent factor B, a regression model relating the response y to x_1 and x_2 that is supported by this design is:

$$y = \beta_0 + \beta_1 x_1 + \beta_2 x_2 + \beta_{12} x_1 x_2 + \beta_{11} x_1^2 + \beta_{22} x_2^2 \qquad (4.1)$$

Second order response model in two variables given above can be transformed into linear regression model to evaluate the unknown parameters.

Supposing that $x_3 = x_1 x_2$, $x_4 = x_1^2$, $x_5 = x_2^2$ and $\beta_3=\beta_{12}, \beta_4=\beta_{11}, \beta_5=\beta_{22}$ then Equation 4.1 becomes:

$$y = \beta_0 + \beta_1 x_1 + \beta_2 x_2 + \beta_3 x_3 + \beta_4 x_4 + \beta_5 x_5 \qquad (4.2)$$

In general, any regression model that is linear in the parameters is a linear regression model, regardless of the shape of the response surface that it generates. In this chapter, details of parameter estimation in linear regression models are not derived however all calculations related with the parameter estimation are presented in Appendix E.
In this study, the simplest design in the 3^k system, 3^2design, which has two factors, each at three levels is performed. Since there are 3^2 = 9 treatment combinations, there are eight degrees of freedom between these treatment combinations. Main effects of A and B each have two degrees of freedom, and AB interaction has four degrees of freedom. [31].

V. 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.

A. Geometrical Error Analysis of the First Set of Experiments

The design matrix for the first set is shown in Figure 17.

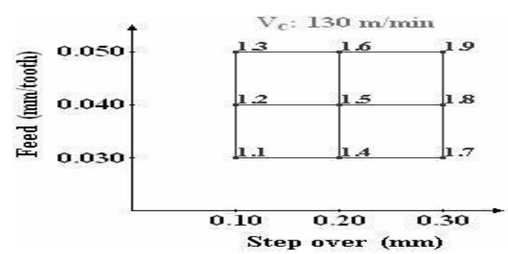

Fig.17: Design matrix for the first set of experiments

With the application of the cutting parameter values described in Figure 17, experimental die cavities involving surface and geometrical diversities are attained. Manufactured die cavities in the first set of experiments are shown in Figure 18.

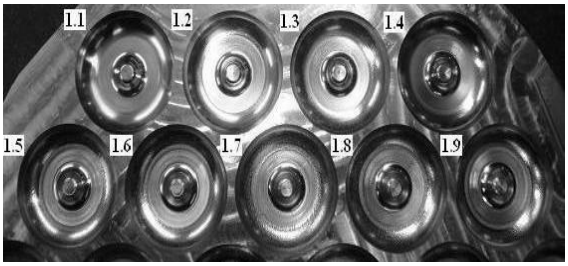

Fig.18: Photograph of the first set of experiments

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 tendency of the response curve of the feed is another point observed in the main effect plot of the second input parameter.

When the interaction effect plot of the input parameters is analyzed, it can be concluded that interaction between the step over and the feed is quite low due to the similar shape of the response curves attained from the three levels of the parameters. The interaction effect plot of the input parameters is shown in Figure 5.5. Since the factors in this factorial experiment are quantitative, a response surface may be used to model the relationship between geometrical error, step over and feed. 3D surface plot for the results of the first set of experiments is presented in Figure 19.

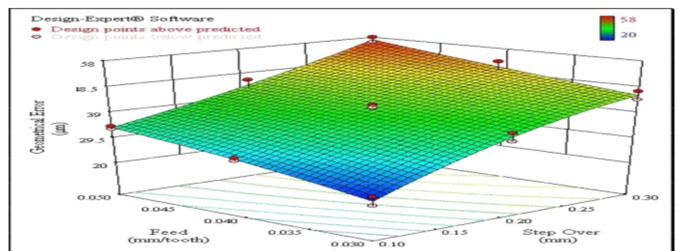

Fig.19: Surface plot of the response variable geometrical error [32]

It is obvious from the first set of experiments that lower step over and feed values provide excellent geometrical accuracy and surface quality; however, lowering these cutting parameters causes higher production time which is undesirable in competitive market conditions. Therefore, a compromise is essential for the determination of cutting parameters by regarding geometrical accuracy and production time together. For this reason, further analysis is performed to clarify the relation between the geometrical error and the production time of the experimental die cavities. Time and error wise comparison of the first set of experiments is given in Table 5.2.

Table 5.2 Comparison of geometrical error values with production time values

Exper. No	Cutting Speed (m/min)	Feed (mm/tooth)	Step Over (mm)	Average Geom. Error (µm)	Production Time (min)
1.1	130	0.030	0.10	20.5	44.4
1.2	130	0.040	0.10	27.0	33.5
1.3	130	0.050	0.10	32.5	26.9
1.4	130	0.030	0.20	34.5	22.8
1.5	130	0.040	0.20	39.0	17.3
1.6	130	0.050	0.20	42.5	14.0
1.7	130	0.030	0.30	45.0	15.6
1.8	130	0.040	0.30	49.5	11.9
1.9	130	0.050	0.30	55.5	9.7

5.2 Geometrical Error Analysis of the Second Set of Experiments

The design matrix for the second set of experiments is given in Figure 20.

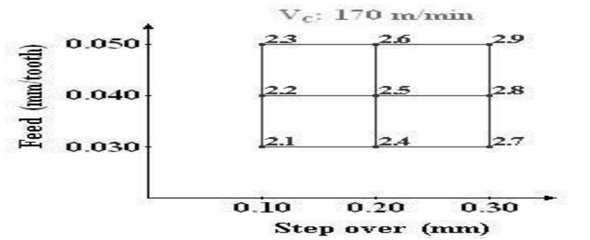

Fig.20: Design matrix for the second set of experiments

By applying the cutting parameter values given in Figure 5.7, die cavities for the second set of experiments are manufactured. Visual diversities of the manufactured die cavities can be observed in Figure 21.

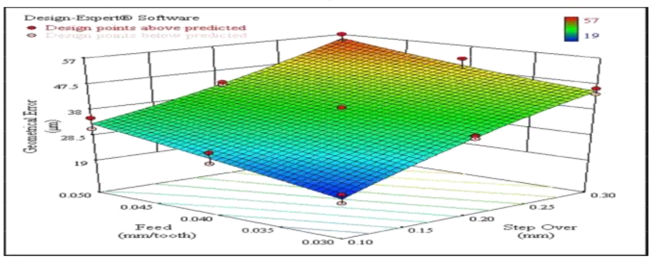

Fig.21: Photograph of the second set of experiments

At that point it should be remembered that main difference between the first and the second set of experiments is the cutting speed of the ball nose cutter. Geometrical error analysis for the second set of experiments is given in Table 5.3.

When the results of the first and the second set of experiments are examined, it can be concluded that increase in the cutting speed causes slightly higher geometrical error values on the surface profile of the die cavities. All of the measured geometrical error values for the second set are again lower than the defined profile tolerance value. Similar with the results of the first set of experiments, die cavities manufactured with step over value of 0.10 mm have better surface properties than the other die cavities.

Table 5.3 Results of the second 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)
2.1	0.10	0.030	170	20	23	21.5
2.2	0.10	0.040	170	29	28	28.5
2.3	0.10	0.050	170	34	33	33.5
2.4	0.20	0.030	170	38	35	36.5
2.5	0.20	0.040	170	41	42	41.5
2.6	0.20	0.050	170	46	42	44.0
2.7	0.30	0.030	170	44	47	45.5
2.8	0.30	0.040	170	49	53	51.0
2.9	0.30	0.050	170	58	56	57.0

By analyzing the main effect plots of the second set of experiments, the input parameters having major influence on the response variable can be found out. Main effects of the step over and the feed on the geometrical error are presented in Figure 5.9-5.10 respectively.

According to the main effect plot of the step over, it can be observed that variation from 0.10 mm to 0.30 mm is resulted with an increase in geometrical error from 27.8 µm to 51.2 µm. Response line characterizes a linear behavior in the range of the step over values. Additionally, variation in the feed induces increase in the geometrical error value similar to the step over but rate of increase is less than the first input parameter. Final observation from the main effect plot of the feed is, response curve has a linear tendency in the range of the second input variable.

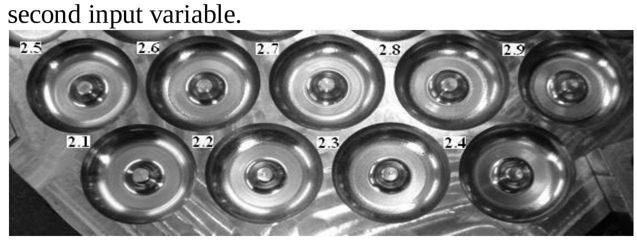

Fig.22: Surface plot of the response variable geometrical error [32]

As a result of these experimental analyses, it is clear that the cutting parameters proportionally influence characteristics of the surface profile in terms of geometrical error and surface quality. Keeping these parameters at lower recommended values provides not only excellent geometrical accuracy and surface quality for the forging die cavities but also elimination of manual polishing utilized in forging die production.

A. 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:

$$\beta = (X^T X)^{-1} X^T y \qquad (5.1)$$

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:

$$Geom\_\ error = -19.083 + 156.67 ae + 831.25\, ft + 0.0278 Vc \qquad (5.2)$$

$-\ 250a_e f_t + 2.016\ 10^{-13} a_e V_c + 0.2083 f_t V_c - 75a_e^2 - 3750 f_t^2$

where a_e is the step over in mm, · f_t is the feed in mm/tooth and V_c 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.

VI. 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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[16]. D.VIKRAM DEVA NARASIMHA VARMA is pursuing M.Tech from Dept of MECHANICAL, Hyderabad Institute of Technology and Management, Gowdavalli(V), Medchal (M), R.R District Telangana, India. She is currently working on project work titled MANUFACTURING CUTTING STRATEGIES FOR FORGING DIE MANUFACTURING ON CNC MILLING MACHINES Under the guidance of S N S Santosh Kumar

[17]. Mr. S N S Santosh Kumar is a Post graduate in MECHANICAL. He is a Assistant Professor of MECHANICAL, , Hyderabad Institute of Technology and Management, Gowdavalli(V), Medchal (M), R.R District Telangana, India.He has 7 Years of UG & PG Level Teaching Experience. Ratified as Assistant Professor by the JNTU- Hydarabad

[18]. Mr K Raghu Ram Mohan Reddy is a Post graduate in MECHANICAL. She is a HOD of MECHANICAL,Hyderabad Institute of Technology and Management, Gowdavalli(V), Medchal (M), R.R District Telangana, India