# Parametric Analysis and Optimization of Closed Die Forging of Gear Blank

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### Abstract

**Objectives**: To analyze the effect of change of input parameters on the forging process using industrial component, a gear blank using the technique of FEM. **Methods/Statistical analysis**: The input parameters of billet shape/size, forging temperature and coefficient of friction between die workpiece interfaces were selected and the simulated experiments were designed using the technique of Response Surface Method (RSM). The simulations were done using Simufact®(MSC Corporation). The results were analyzed on die filling, defects and flash reduction. **Findings**: The deformation process was observed by defining flow lines and flow particles in the workpiece. The quantitative data from the flow particles gave the standard deviations of all the responses i.e. shear and normal stresses, effective plastic strain, effective stress, effective strain rate, material flow rate, load and die wear. These values were analyzed by using ANOVA and the significant parameters were highlighted. It was concluded that the parameters in the decreasing order of significance were billet size, coefficient of friction and temperature of billet. The graphical results were checked for defects, die filling and flash. Based on the simulated analysis and experimental values, mathematical models have been developed for die wear, effective strain rate and material flow rate with error ranging from 4% to 9%. It was concluded that for a defect free forging, a homogenous deformation and proper material flow with increased die life were important. **Application/Improvements:** The experimental production runs have shown remarkable improvement in reduction of rejects. The flash has been reduced by 60%, resulting in the saving of material.

Keywords: Closed Die Forging, Metal Flow, Optimization, RSM, Simulation

## 1. Introduction

The defects like under filling and folding degrade the quality of the forged part. Folds in forging may act as initiation sites for crack propagation during their functioning. The results can be catastrophic as the forged parts are critically loaded in working conditions and the hidden defects can lead to the failure of the component. Efforts have been made to optimize the input parameters to minimize the defects due to incomplete die filling and folding through case studies as the experimental optimization is cumbersome owing to the effort, cost and time involved. Changing of the die parameters on the basis of hit and trial method is not desirable as it may not produce the required results. The process conditions of forging do not allow the precise control of parameters on the shop floor, so, the use of FEA as a tool is very effective approach in design of the forging process<sup>1</sup>. FEM (Finite Element Method) is used to carry out the forging process virtually, giving a better control of the process resulting in saving time, money, ensuring the safety of the worker and increasing the quality of the component<sup>2</sup>. Input parameters affecting the metal flow and deformation pattern can be studied using this technique<sup>3</sup>. The process can be optimized within the virtual environment, reducing the shop floor trials<sup>4</sup>. Effect of various input parameters on micro structural changes<sup>5</sup> and forging defects like folding of metal and cracks can be observed and analyzed graphically<sup>6</sup>. Various techniques like Taguchi and Grey relational analysis have been used by the researchers for the analysis of the forging process<sup>2</sup>.

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Flash formation has also been studied to reduce any wastage of material<sup>8</sup>. Perform design for forging is another vital aspect which defines the ease with which part can be formed, has been dealt by the researchers<sup>9</sup>. FEA is a comprehensive technique which helps in dealing with all the issues in a manufacturing process virtually, making the design process more realistic<sup>10</sup>.

In this paper an industrial component, gear has been taken up to analyze the effect of the change of input parameters on the metal flow defects of folding and under filling of the die and hence improve the quality of the forged component.

# 2. Process Simulation

The details of the gear blank and the raw material required for its manufacturing as used in industry are given in Table 1. The billet initially used currently was RCS with flash allowance of 16% of the volume of finished part.

Table 1. Specifications of forged part

Material of flange	AISI 5120
Weight of part	3.5 Kg
Forging hammer used	1.5 tonne drop hammer
Shape complexity factor	0.75 i.e. S1 category
Current flash allowance	16% of the volume of finished part

Based on the research papers, three important input parameters were considered for the analysis as shown in Table 2. These were varied according to the face centered design of RSM and the experiments were designed. The virtual experimentation of the forging process was done using Simufact 10.0.1 application software. The loading conditions were defined and meshing details of the component are shown in Table 3.

The simulation results were observed for responses viz. normal stresses, shear stresses, effective stress, effective plastic strain, effective strain rate, die wear and material flow rate. The billet was marked with particles using flow particles feature of Simufact. These particles were used to track for the quantitative values of the responses during the deformation process. For every simulation, 1500 points were marked in the cross section of the billet. The variation of the responses was calculated for all the blows of forging from these points. The data was compiled and further used for the analysis. Flow lines were also defined to track the deformation of billet during the forging process. Four sets of 20 simulations in each set were carried out which are given as shown in Table 4.

Table 2.	Parametes	considered	and	their	variatio	n
levels						

Parameters	Levels		
	1	2	3
Coefficient of friction	0.2	0.3	0.4
Temperature (°C)	1150	1200	1250
Billet size (mm)	60	70	80

Table 3. Meshing details

Element size	2
No. of elements	21068
Mesher	SI mesh
Element type	Trias

Table 4. Categories of sets of simulation

Billet shape	Flash allowance as % of volume of finished part
RCS	16%
Cylindrical	16%
RCS	10%
Cylindrical	10%

The detailed stepwise procedure is given below in Figure 1.



Figure 1. Steps in the analysis.

# 3. Discussion

The simulated results yielded graphical and quantitative data. The forging component was checked graphically for under filling and folding defects. The quantitative results revealed the effect of the input parameters on the forging process, which are discussed in the following sections.

## 3.1 Graphical Analysis of Results

From the graphical results, it was observed that with 16% flash allowance the die was completely filled with both RCS and cylindrical billets, but, with folding defects. [Annexure I]. The folding defects are mainly due to improper metal flow during the forging operation. The difference in the metal flow using two different billet shapes can be observed from the flow lines as shown in Figure 2. The die cavity was not deep, so, there was very less flow of material in the longitudinal direction and larger material flow in the lateral direction. So, lateral shear was responsible for the formation of the deformed component.

## 3.2 Quantitative Analysis of Results

The quantitative results of the four sets of simulation were analyzed using ANOVA [Annexure II]. The results reveal the significant parameters that affect the responses. The details are discussed below:

#### 3.2.1 Dimension of Billet

It was found to be the most significant parameter which affected all the responses with RCS billet, except for the

normal stresses with cylindrical billet. When the volume of the billet was reduced, the effective plastic strain, effective stress, effective strain rate, die wear, material flow rate and load were found to be significantly affected by the change of the shape of billet. This implies a reduced billet volume and change of billet shape to cylindrical was showing positive results for the forging process.

#### 3.2.2 Temperature of Billet

This parameter was found significant for material flow rate with RCS billet at both flash allowances. But, it was insignificant when the cylindrical billet was used. It implies that the change of shape was not important for the temperature of billet to affect the process. Nevertheless, die wear was affected using cylindrical billet at 10% flash allowance.

#### 3.2.3 Coefficient of Friction

This parameter was significantly affecting the shear stresses with both billet shapes at 16% flash allowance. When the volume of billet was reduced, there was no significant change in the shear stresses during deformation. The material flow rate was affected with RCS billet, while the die wear was affected by the cylindrical billet at 10% flash allowance.

With the reduction of flash allowance, the volume of material to be handled by the die cavity was reduced. For both billet shapes, it was observed that out of the three input parameters, dimension of billet was found to be the most dominant parameter, followed by coefficient of friction and temperature. The reduced flash volume is reduced as shown in Figure 3.



**Figure 2.** Flowlines showing metal flow for RCS billet (a) 60RCS, (b) 70RCS and (c) 80RCS & cylindrical billet (e) 60DIA, (f) 70DIA and (g) 80DIA



Figure 3. (a) Initial flash volume (b) Reduced flash volume.

It was inferred that the billet dimension and shape is a very important parameter for the forging process design. For finding the optimum shape and dimension, the maximum values of responses from all the cases were compared as shown in Table 5.

Billet t	ype	RCS	RCS	cylindrical	cylindrical
Flash a	llowance	16%	10%	16%	10%
Parame	eters				
tress	X (Mpa)	848	598	839	631
rmal St	Y (Mpa)	833	659	798	694
ž	Z (Mpa)	1006	856	985	818
	XY (Mpa)	36	35	36	37
Stress	YZ (Mpa)	187	174	184	165
Shear	ZX (Mpa)	32	20	31	19
EPS		0.697	0.685	0.679	0.688
ES (Mp	pa)	225	172	234	188
ESR		305	341	252	302
DW (n	nm)	0.413	0.4	0.399	0.376
MFR (1	mm/s)	28020	25380	28310	30740
LOAD	(kN)	47387	32961	47824	46355
MAX. Strokes		7	4	8	4
FLASH (g)		645	257	645	257
EPS-effective plastic strain ESR-effective strain rate MFR-material flow rate				ES-effe DW-d	ective stress ie wear

 Table 5. Comparison of responses on the basis of the shape and size of billets

It can be observed that the maximum variation of normal and shear stresses is found with the RCS billet with 16% flash allowance, while, it was minimum with a reduced flash allowance. The variation of EPS was did not change much in all the cases. The ESR variation was minimum with the cylindrical billet, which indicates the homogenous deformation. The die wear was observed to be minimum when cylindrical billet with 10% flash allowance was used. It can be attributed to the reduced volume of material that has to be managed by the die. The forging load was minimum with RCS billet with 16% flash allowance. The number of strokes required to form the component reduced when the flash allowance was reduced. So, it has been observed that the cylindrical billet with flash allowance of 10% gives best results with optimum metal flow rate, reduced die wear, reduced effective strain rate, reduced number of blows, reduced flash, reduced shear stresses and no folding defect. The predictive models of material flow rate, die wear and effective strain rate for the optimized model were obtained which are given as under:

Material Flow Rate=(5.10e+05)-(3.93e+05)\*Fc-1716.93\*Temp+17349.65\*Billet Size+312.5\*Fc\*Temp+20 5\*Fc\*Billet Size

Die Wear=4.60368+2.42675\*Fc-(1.27e-03) \* Temp - 0.1032 \* Billet Size - (1.73e-03) \* Fc \* Temp - (6.25e-04) \* Fc \* Billet Size + (3.08e-05) \* Temp \* Billet Size - 0.95 \* Fc ^ 2 - (2.00e-07) \* Temp ^ 2 + (4.25e-04) \* Billet Size ^2

Effective Strain Rate= -3408.29 + 613.6814 \* Fc + 7.18027 \* Temp - 21.9844 \* Billet Size - 0.06995 \* Fc \* Temp - 14.8791 \* Fc \* Billet Size - 0.0122 \* Temp \* Billet Size + 721.7913 \* Fc ^ 2 - (2.62e-03) \* Temp ^ 2 + 0.29831 \* Billet Size ^ 2

The predicted and actual simulated values are given below in Table 6.

	· · ·	,	
Response	Effective	Die Wear	Material Flow
	Strain Rate	(mm)	Rate (mm/s)
Predicted	237	0.19	252910
Simulated	252	0.21	242420
Error	6%	9%	4%

**Table 6.** Comparison of predicted and simulated values (0.4 FC, 1200°C, 70mm DIA)

## 4. Validation

For the validation of the optimized process, the parameters from the simulation were used on 1.5tonne gravity drop hammer on the shop floor. The production runs revealed that a defect free part was obtained with complete die filling using a lesser volume of the billet material. The actual part manufactured and the simulated part is shown in Figure 4. Reduced defects and lesser volume of material improved the quality of the forged component and reduced the rejection rate by 10%.



Figure 4. (a) Simulated part (b&c) Actual part after forging.

# 5. Conclusion

The simulated experimentation of the forging process was done using RCS and cylindrical shapes of the billet and flash allowances of 10% and 16 % of the volume of finished forging. The results were compared and it was concluded that all the responses have shown a declining trend with the reduction of flash allowance. It indicates that the deformation has become easier with a reduced volume of material that has to be handled by the die during the forging process. The change of shape of billet from RCS to cylindrical has reduced the variation in strain rate, resulting in homogenous deformation. Another notable change is the increased metal flow rate with reduced die wear, which means that the die would fill up easily with reduced wear. Complete die filling with minimum folding of material was observed with the cylindrical billet with 10% flash allowance. It was also observed that for a completely filled die without any folding of material, a minimum die wear and maximum material flow rate are the ideal requirements, which are fulfilled when the cylindrical billet of 70mm diameter with 10% flash allowance is used. The results of simulation were validated with the production runs in the industry. The use of suggested parameters resulted in reduction in defects as well as flash percentage by 60%. Both the factors result in cost saving and better quality forged components.

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	Desi	gn		Billet type	Flash Allowance	Billet type	Flash Allowance	Billet type	Flash Allowance	Billet type	Flash Allowance
				RCS	16%	RCS	10%	Cyl	16%	Cyl	10%
SN	FC	Temp	Billet size	Die fill	No defect/ Folding/ <b>Underfill</b>	Die fill	No defect/ Folding/ Underfill	Die fill	No defect/ Folding/ Underfill	Die fill	No defect/ Folding/ Underfill
1	0.2	1150	60	Complete	No defect	Incomplete	Underfill	Complete	Folding	Complete	Folding
2	0.2	1200	70	Complete	No defect	Incomplete	Underfill	Complete	Folding	Complete	No defect
3	0.3	1200	70	Complete	No defect	Complete	Folding	Complete	Folding	Complete	No defect
4	0.2	1150	80	Complete	No defect	Complete	No defect	Complete	Folding	Incomplete	Underfill
5	0.3	1150	70	Complete	No defect	Complete	Folding	Complete	Folding	Complete	Folding
6	0.3	1200	80	Complete	No defect	Complete	Folding	Complete	Folding	Complete	Folding
7	0.3	1200	70	Complete	No defect	Complete	Folding	Complete	Folding	Complete	No defect
8	0.3	1200	70	Complete	No defect	Complete	Folding	Complete	Folding	Complete	No defect
9	0.2	1250	60	Complete	No defect	Incomplete	Underfill	Complete	Folding	Complete	Folding
10	0.2	1250	80	Complete	No defect	Complete	Folding	Complete	Folding	Incomplete	Underfill
11	0.3	1200	70	Complete	No defect	Complete	Folding	Complete	Folding	Complete	No defect
12	0.4	1150	60	Complete	No defect	Incomplete	Underfill	Complete	Folding	Incomplete	Underfill
13	0.4	1150	80	Complete	No defect	Complete	No defect	Complete	Folding	Complete	Folding
14	0.3	1250	70	Complete	Folding	Incomplete	Underfill	Complete	Folding	Complete	Folding
15	0.4	1250	80	Complete	No defect	Complete	Folding	Complete	Folding	Complete	Folding
16	0.3	1200	70	Complete	No defect	Complete	Folding	Complete	Folding	Complete	No defect
17	0.4	1250	60	Complete	Folding	Incomplete	Underfill	Complete	Folding	Complete	Folding
18	0.3	1200	60	Complete	Folding	Incomplete	Underfill	Complete	Folding	Incomplete	Underfill
19	0.3	1200	70	Complete	Folding	Incomplete	Underfill	Complete	Folding	Complete	No defect
20	0.4	1200	70	Complete	Folding	Incomplete	Underfill	Complete	Folding	Complete	Folding

**ANNEXURE I** Compiled graphical results from simulations

#### **ANNEXURE II**

(a) ANOVA results of simulations using RCS billet at 16% flash allowance

Responses	Units	Dimension of billet	Temperature of billet	Coefficient of friction
X	MPa			
Y	MPa	$\checkmark$		
Z	MPa	$\checkmark$		
XY	MPa			
YZ	MPa			
ZX	MPa	$\checkmark$		
EPS		$\checkmark$		
ES	MPa			
DW				
MFR	mm/s	$\checkmark$		
LOAD				

Responses	Units	Dimension of billet	Temperature of billet	Coefficient of friction
X	MPa			$\checkmark$
Y	MPa			$\checkmark$
Z	MPa			$\checkmark$
XY	MPa			$\checkmark$
YZ	MPa	$\checkmark$		$\checkmark$
ZX	MPa	$\checkmark$		$\checkmark$
EPS		$\checkmark$		
ES	MPa			$\checkmark$
ESR	MPa	$\checkmark$		
DW		$\checkmark$		
MFR	mm/s			
LOAD				

(b) ANOVA results of simulations using cylindrical billet at 16% flash allowance

(c) ANOVA results of simulations using RCS billet at 10% flash allowance

Responses	Units	Dimension of billet	Temperature of billet	Coefficient of friction
YZ	MPa	$\checkmark$		
EPS		$\checkmark$		
DW		$\checkmark$		
MFR	mm/s		$\checkmark$	

#### (d) ANOVA results of simulations using RCS billet at 10% flash allowance

Responses	Units	Dimension of billet	Temperature of billet	Coefficient of friction
Z	MPa	$\checkmark$		
YZ	MPa			
EPS		$\checkmark$		
ES	MPa	$\checkmark$		
ESR		$\checkmark$		
DW		$\checkmark$		$\checkmark$
MFR	mm/s	$\checkmark$		
LOAD		$\checkmark$		