Selection of optimal parting line for forging in various equipments using numerical analysis

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Abstract. While designing of dies for forging, one of the most important criteria which has to be considered is the selection of parting line/plane. Selection and location of the parting line greatly affect the grain flow direction in the component, load which is coming on the dies and it also determines the location of the burr which is formed in the component after trimming. The main objective of this paper is to select a suitable parting line/plane, for hot forging a circular component in mechanical press and drop hammer. For studying the effect of parting line, four dies are designed with different parting lines (top parting line, bottom parting line, central parting and inverted dies) location for hot forging of an automotive component coupling flange. Two commonly used equipments (mechanical press and drop hammer) are considered for determining the effect of parting line location on load requirement which finally decides the die wear and die life. Numerical analysis is carried out with these dies using a finite element based software DEFORM-3D. Top parting line gave best results with minimum load, minimum effective stress and favourable grain flow in mechanical press. Whereas, in case of hammer, inverted dies yielded in minimum load, minimum effective stress and favourable grain flow.

1. Introduction

In closed die forging the components are manufactured by deforming the raw material between a set of dies in which impression of the component is cut in. Designing of the dies for forging involves various steps namely selection of parting line, adding allowances which include machining allowances, finishing allowances and technological allowances, incorporating draft allowances, adding fillet and corner radii to avoid sharp corners, design of flash and gutter. After incorporating all these allowances, the impression is cut in the dies blocks of suitable dimensions and suitable material. The first and most significant step in the die design is the selection of suitable parting line. Parting line is the plane where the two die halves meet along the forging. The selection and location of parting line affect many parameters like load and energy requirement, grain flow, amount of draft, die sinking, trimming operation, cost of the die, defect formation, die wear and die life. The basic criteria for selection of parting line is to avoid deep impressions, to avoid side thrust, favourable grain flow, maximum periphery [1],[2],[3],[4]. Even after fulfilment of these basic criteria, still there is lot of scope for variation in the selection of parting line. The selection of correct parting line reflects the skill and knowledge of die designer. In closed die forging process mainly two basic equipments are used. First one is drop hammer which is least expensive and very versatile whereas second one is mechanical press which is more costly than hammer but production rate is high and more accurate as compared to
drop hammer. The die design for these two equipments may not be same even though the geometry(component) is same. Earlier practice for production was based on experience and shop floor trial and error which was very time consuming and expensive. Now the manufacturing concept has changed. Industry wants first time right that is they want to minimize the wastage, reduce product development time and ultimately minimize the cost of the forgings with all producing quality forgings from starting of the production. In this case numerical simulation is very useful tool which not only helps in optimum die design but also helps in controlling process parameters as a result of which load on dies are reduced, forging defects are eliminated and wastage of materials in the form of flash is greatly reduced. In this paper it has been shown how numerical simulation helps in selecting correct parting line for same component (same geometry) which are produced in two different forging equipments (drop hammer and mechanical press). This correct parting line helps in reducing forging load and hence die wear. The location of these correct parting lines are different for different equipment used for same forging component. Many researchers have carried out the numerical analysis to predict the effects of variation in die design on output parameters. Zhenchao Qi et.al, [5] proposed a new forming method for manufacturing of bevel gears wherein they used finite element method of simulate the entire process. They also tried to optimize the design parameters using Taguchi method. Doriana M.D Addona et.al, [6] optimized the die shape of a circular forging, in conjugation with Neural Networks. The effect of flash allowances on the load has been studied by F. Fereshteh-Saniee et.al, [7]. Yahui Liu et.al, [8] optimized the forging process for production of two connecting rods using a RSA method and validated experimentally. Xinhai Zhao et.al, [9] optimized the die shape of the preform for reduction of material cost, using numerical analysis where the shape of the die is defined by a B-spline curve. The authors [12] tried to improve the yield in forging of a differential spider using numerical analysis and they have provided complete step by step of die design procedure in forging. Ibrahim Khoury et al., [13] in their work optimized the shape of the turbine engine disc. S.H.Chung et.al., [14] formulated the design problem on by integrating thermo-mechanical finite element process model to optimize the dies shape so that more design variables can be considered for optimization. The fillet radius and draft angle of the rib are varied and simulation is carried out in the finite element package which was developed by mechanical system and concurrent engineering laboratory (LASMIS). From the literature it is evident that most of the researches tried to optimize the shape of the dies for less load or for material saving but the effect of the parting line section in various equipments is least studied. Hence the current study focuses on the effect of parting line selection and its location in forging dies which are used in mechanical press and drop hammer.

In this paper forging of a coupling flange, an automotive component is considered for studying the effect of parting line selection on load, effective-stress and grain flow in two equipments – mechanical press and drop hammer. A three stage (Upsetter, Blocker and finisher) forging process is considered for carrying numerical analysis of coupling flange. For this purpose three different parting lines are selected in flange thickness namely - top parting line, bottom parting line and central parting line. Three die sets are designed with the selected parting lines and numerical analysis is carried out using a FEM based software DEFORM V12.0.2 [10]. The analysis is carried out in two different equipments – mechanical press and drop hammer. Also an inverted die is designed in such a way that the impression is cut completely in the top die.

2. Experimental Procedure

2.1. Forging process design
The first step in designing forging dies is selection of parting line. Selection of parting line affects the load, effective stress and grain flow in the component. In the current study three different parting lines are selected. The three different paring lines are named as top parting line, bottom parting line and central parting line which are shown in the Figure 1.
After selection of parting line various allowances like finish allowance, draft allowance, fillet and corner radii are added to the component on basis of IS-3469[11]. A three stage forging process which includes an upsetter, blocker and finisher is incorporated. Now the flash is designed based on Neuberger & Mockel’s [1] equations 1 and 2. The thickness and width of flash are 2.4mm and 7.8mm respectively.

\[
\text{Flash thickness } t \text{ (mm)} = 0.89\sqrt{W} - 0.017W + 1.13 \quad (1)
\]

\[
\text{Flash width } w \text{ (mm)} = t \left(3 + 1.2 \times e^{-1.09W}\right) \quad (2)
\]

Where \( W \) is weight of forging in kg.

Figure 1. Coupling flange with various parting lines (a) Top parting line, (b) Bottom parting line, (c) Central parting line

The finisher is obtained by scaling the forging by 1.05 times to compensate the contraction which occurs during the cooling of the component from forging temperature to room temperature. The blocker is designed from finisher by reducing each side along the width by 0.3mm and increasing the depth, keeping the volume constant. A cup type upsetter is designed, so that the upsetted billet will sit in the blocker bottom die. For this the cup radius of the upsetter bottom die is kept 0.3mm less than the minimum radius of the blocker. The cross sectional views of upsetter, blocker and finisher die sets with top parting line are shown in the figure 2. Similarly two die sets with bottom parting line and central parting line are designed.

Figure 2. Die sets (a) Upsetter, (b) Blocker with top parting line, (c) Finisher with top parting line

For inverted dies a different approach is used as the placement of the billet will be difficult in such type of dies. Blocker and finisher dies are designed in the same fashion with a difference that the impression is cut completely in the top die instead of bottom dies. The bottom die of the upsetter is kept same as that in the previous case but the top die is given the shape of the blocker bottom die, and
the width vise dimensions are reduced by 0.6mm. The cross sectional views of upsetter, blocker and finisher die sets with inverted dies are shown in the Figure 3.

2.2. Selection of equipment
In the current study two equipments – mechanical press and hammer, are considered for studying the effect of parting on the load, stress and grain flow. Initially required equipment capacity for mechanical press is calculated by using equation 3 and the mass of falling part for drop hammer is calculated by using equation 4.

\[ \text{Capacity of mechanical press } P (\text{kg}) = 8 \left(1 - 0.001 D\right) \left(1.1 + \frac{20}{D}\right)^2 \cdot \sigma \cdot A \]  \hspace{1cm} (3)

\[ \text{Mass of falling part in hammer } M (\text{kg}) = 10 \left(1 - 0.005 D\right) \left(1.1 + \frac{2}{D}\right)^2 \left(0.75 + 0.001 D\right) \times D \times \sigma \]  \hspace{1cm} (4)

Where D is maximum diameter including flash width, A is plan projected area including flash and \( \sigma \) is tensile strength at forging temperature. For medium carbon steel it is 7-8 kg/mm\(^2\). In the present work 7 kg/mm\(^2\) is considered which resulted in a press capacity of 1041.88 Tons. Hence a standard mechanical press of 1500 Tons is considered. Mass of falling part of hammer is 3445.7 kg. Hence a standard drop hammer of 10000lb of falling mass is considered.

![Figure 3](image)

**Figure 3.** Inverted Die set (a)Upsetter, (b) Blocker, (c) Finisher

2.3. Numerical analysis

2.3.1. Rigid-viscoplastic material. The analysis of the material is carried out considering the material to be rigid-viscoplastic material. This is the formulation most commonly used for analysis of a forging process and the finite element based software DEFORM-3D also uses the same formulation in default. The main assumption of this formulation is that there is a linear increase in stress with strain rate till a threshold is reached, this level is referred as the limiting strain rate. The formulation of these materials can be expressed as the following equation.

\[ \phi = \int_V E (\dot{\varepsilon}) \, dV - \int_{S_1} f_i v_i \, ds + K^* \int_{V} \frac{1}{2} \left( \dot{\varepsilon}^2 \right) \, dV \]  \hspace{1cm} (5)

Where, \( K^* \) is a very big penalty constant.

2.3.2. Heat Transfer Equation. The temperature distribution of the component and the dies is governed by the energy balance equation which is shown in the equation 6.

\[ \int_V k \, \delta T \, dV = \int_V \rho c \, \dot{T} \, dV - \int_q k^* \bar{\sigma} \, \dot{\varepsilon} \, dV - \int_{S_q} q_n \, \delta T \, ds = 0 \]  \hspace{1cm} (6)
The equation can be written in matrix form as follows using numerical discretization,

\[ KT + C \ddot{T} - Q = 0 \]  

Lagrangian Incremental method of analysis is adopted for calculation of heat transfer and amount of deformation at each time-step.

2.3.3. Meshing. The size of the element greatly defines the accuracy of the analysis, so it is very important to decide the mesh size before the start of the analysis. Coarser mesh in the places of minute details like fillet and corner radii will result in degradation of mesh, loss in volume and remeshing problems. Finer mesh results in excessive computational time. Mesh size also depends on the output results of concern. If our concern is about die-filling, approximate load, stress and temperature distributions then a moderate mesh size is sufficient. If emphasis is more on folds then the minute details have to be meshed properly. For such cases it is established by the software provider that the size ratio of the element must be 1/3rd of the minimum detailed size. Following these rules the, billet initial elements are 89020, number of nodes are 19377 and surface polygons 16416, for top die - initial elements are 31885, number of nodes are 7247 and surface polygons 6058, for bottom die - initial elements are 52983, number of nodes are 11839 and surface polygons 10832. Further, during simulation if there is any mesh degradation the software has a capability of remeshing. The volume loss permitted while remeshing is 2 percent.

2.3.4. Initial condition. The work piece material considered is AISI 1045 with dimensions ø55mm x 120mm. The top and bottom dies are considered to be of H13 die steel as it is the most commonly used material. The forging range of AISI 1045 is 850°C to 1100°C. So, in all the cases, the maximum forging temperature i.e., 1100°C is considered as the initial billet temperature. The temperature of the dies is considered to be 300°C. Hot forging under lubrication is considered for which the coefficient of friction is 0.3.

The numerical analysis is carried out in DEFORM-3D with the die sets for all the three parting line and inverted die set in both mechanical press and Hammer.

3. Results and discussion

3.1. Load distribution

The load vs stroke curve for the component with bottom parting line when mechanical press is used is shown in the figure 4 and 5 shows the load distribution in mechanical press and hammer with top parting line. The table 5, shows the maximum load in various cases,

![Figure 4. Load distribution in mechanical press with top parting line](image1)

![Figure 5. Load distribution in hammer with top parting line](image2)
From the Table 1, it can be seen that the load is minimum when top parting line is used in mechanical press so it is more suitable to forge coupling flange in mechanical press with a top parting line. All the remaining conditions yielded in a higher load.

While using a hammer, bottom parting line should not be considered as the load in both the blocker and finisher is very high. By comparing blocker loads in top parting and inverted die-set, it can be seen that the top parting line yielded in less load compared to central parting line, but looking into finisher loads it is evident that inverted dies resulted in lesser load. In general as the finisher operation is critical operation, the amount of load coming on to the finisher dies should be kept as minimum as possible. With respect to load, inverted die-set is more suitable for forging a coupling flange in hammer. In a mechanical press the metal flows very easily by forward extrusion process whereas in hammer metal flows by reverse extrusion process easily.

### Table 1. Maximum load in various conditions

|                      | Mechanical press blocker load (tons) | Mechanical press finisher load (tons) | Hammer blocker load (tons) | Hammer finisher load(tons) |
|----------------------|--------------------------------------|--------------------------------------|---------------------------|---------------------------|
| Top Parting Line     | 810                                  | 440                                  | 2578                      | 3365                      |
| Bottom Parting Line  | 1225                                 | 683                                  | 3710                      | 4680                      |
| Central Parting Line | 1256                                 | 628                                  | 3260                      | 2910                      |
| Inverted dies        | 684                                  | 628                                  | 3020                      | 2560                      |

### 3.2. Stress distribution.

The effective stress distribution for blocker and finisher with top parting line are shown in the figure 6 and 7. And the table 2, shows the variation in maximum stress in various cases. From the table 2, it can be seen that the stresses developed in the component is least when top parting line is used in mechanical press so it is more suitable to forge coupling flange in mechanical press with a top parting line. All the other conditions yielded in a higher stress. This is in well agreement with load criteria which is mentioned in the previous section 3.1.

![Figure 6](image1.png) **Figure 6.** Blocker effective-Stress distribution in mechanical press with top parting line

![Figure 7](image2.png) **Figure 7.** Finisher effective-Stress distribution in mechanical press with top parting line

### Table 2. Maximum stress in various conditions
While using a hammer, bottom parting line should not be considered as the effective-stress in both blocker and finisher is very high. The effective stress developed is almost same in the central parting line and inverted die set. But while comparing the stresses developed in the finisher, it can be seen that the stresses in the component forged in inverted dies-set is less compared to that in case of central parting line. Hence according to minimum effective-stress criteria, top parting line has to be selected for forging coupling in hammer. This is in well agreement with the load criteria which is mentioned in the section 3.1. Hence for hammer forging, an inverted die design where the impression is cut completely in the top die should be consider.
3.3. Grain flow
From the figure 8, it can be observed that the grain flow in various cases. There most favourable grain from can be observed in mechanical press with top parting line. We can observe that there is no back flow of flow next hence there is less chance of formations of defects like folds or labs. In the cases of bottom paritng line and central paritng line the grain flow reversal is obsered. Flow reversal is more predominant in bottom paritng line hence it should not be selected in any equipment. For hammer, top paring line and inverted dies have similar flow pattern but there is more dencification of flow net in flange region for top paritng line. Hence for hammer inverted die set can be selected.
Based on the discussions in sections 3.1, 3.2 and 3.3 the most suitable parting line for both mechanical press and hammer is top parting line.

4. Conclusion
- Numerical analysis is carried out for section of optimal parting line in case of mechanical press and hammer forgings.
- The paper describes the effect of selection and location of parting line on load, effective-stress and grain flow.
- The paper also presents most suitable equipment and suitable parting line location for forging of coupling flange.
- Three different parting lines and inverted die design are selected for forging of a coupling flange in mechanical press and hammer.
- The component with top parting line (that is when impression is completely accommodated in bottom die) when forged in mechanical press resulted in minimum load, minimum effective stress and favourable grain flow.
- The most suitable die design for hammer forging is to accommodate coupling flange completely in the top die and it results in minimum load, minimum effective stress and favourable grain flow.
- Bottom parting line should not be selected in any case, as it resulted in high load and high-effective stresses.
- As far as grain flow is concerned top parting line and inverted dies resulted in favourable grain flow.

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