Simulation-Driven Design Approach for Design and Optimization of Blankholder

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Abstract. Reliable design of stamping dies is desired for efficient and safe production. The design of stamping dies are today mostly based on casting feasibility, although it can also be based on criteria for fatigue, stiffness, safety, economy. Current work presents an approach that is built on Simulation Driven Design, enabling Design Optimization to address this issue. A structural finite element model of a stamping die, used to produce doors for Volvo V70/S80 car models, is studied. This die had developed cracks during its usage. To understand the behaviour of stress distribution in the stamping die, structural analysis of the die is conducted and critical regions with high stresses are identified. The results from structural FE-models are compared with analytical calculations pertaining to fatigue properties of the material. To arrive at an optimum design with increased stiffness and lifetime, topology and free-shape optimization are performed. In the optimization routine, identified critical regions of the die are set as design variables. Other optimization variables are set to maintain manufacturability of the resultant stamping die. Thereafter a CAD model is built based on geometrical results from topology and free-shape optimizations. Then the CAD model is subjected to structural analysis to visualize the new stress distribution. This process is iterated until a satisfactory result is obtained. The final results show reduction in stress levels by 70% with a more homogeneous distribution. Even though mass of the die is increased by 17 \%, overall, a stiffer die with better lifetime is obtained. Finally, by reflecting on the entire process, a coordinated approach to handle such situations efficiently is presented.

1. Introduction
Volvo Cars Body Components (VCBC) are very experienced in designing stamping dies and have been producing body components for Volvo cars since the 1920’s. With shortening product lifecycles over the last decades, manufacturing industries have focused to decrease time to market at the same time trying to be efficient and innovative. Companies have begun to realize that gaining competitive advantage and expanding market shares is not achievable purely through continuous technical improvements [1]. This, in addition with continuously changing globalized marketplace calls for a need to develop their capabilities for these scenarios. Hence companies have been forced to radically rethink their strategies.

Today, the structure of the stamping die at VCBC is dimensioned according to Volvo Cars internal standards and guidelines [2]. The standards and guidelines for die dimensions are mostly based on
casting feasibility although it can also be based on broader criteria, such as fatigue, stiffness, economy, safety. Simulation is performed to be able to analyse and test relevant characteristics long before the first prototype has been produced [3]. An approach built on Simulation Driven Design (SDD) can help broaden the criteria for structuring of the stamping die enabling not only design modification and verification of physical properties/behavior but also yield innovative designs that are efficient and manufacturable. Additionally, with such an approach, designers can also explore ‘what if’ scenarios to evaluate different opportunities for innovation.

As defined by Sellgren [4] SDD is “a design process where decisions related to the behavior and the performance of the design in all major phases of the process are significantly supported by computer-based product modeling and simulation”. The meaning of the term in the current work is closely described by this definition. The approach presented in this work builds on SDD in a coordinated manner implementing Design Optimization (DO) with an aim to stimulate new concepts, act as a guidance towards optimal design and support decision making process in the early stages of development in addition to verifying the solution.

2. Research Problem
A stamping die is forms metal sheets to the required shape. A stamping die for a double action press also called double action stamping die, normally consists of three main parts; Punch, Matrix, Blankholder. Figure 1 (a) shows the main parts of a stamping die. Most double action stamping dies at VCBC today have an additional part called blankholder plate attached between the ‘ram’ and ‘blankholder’. The main purpose of the blankholder plate is to fit a ‘small’ die into a ‘large’ press, provide rigidity to the die and prevent the die from bending forces during the stamping operations. The term integrated blankholder, implies unification of the blankholder plate and the blankholder into one structure. This type of integrated design of blankholder is desired at VCBC today as this eliminates costs to manufacture blankholder plates which are usually made of steel, reduces the weight of entire stamping die as blankholder plates are heavy, and renders easy handling i.e., mounting and dismounting of the stamping die.

![Figure 1](image1.png)

**Figure 1.** (a) Simplified CAD model of double action stamping die studied in this work. (b) Crack developed in the studied stamping die during usage.

A major challenge while integrating the stamping die is to be able to produce a design which can withstand high work load even without blankholder plate. Some previous attempts of integrating stamping dies at VCBC have fractured, arising uncertainty regarding their design. It is also uncertain whether the not fractured integrated dies in use today at VCBC are reliable and not close to failure.

In the present work one such failed integrated stamping die that was used to produce outer doors of Volvo V70/S80 car models is studied. This seemed like a suitable case to solve for developing the approach presented in the work. The simplified CAD model of studied integrated stamping die is shown in figure 1 (a) and crack developed is shown in figure 1 (b). The work aims to identify the reason for failure of the die and propose a new optimized design. In the end, an approach to arrive at a reliable, resource efficient design in short span of time should be developed.
Hence, the research aims to address the following question in addition to identifying the reason for failure of the studied integrated stamping die and its design optimization:

*What approach should be adopted to design a new/modify an existing stamping die to produce an optimal design in minimum time?*

Optimal design in the present work implies a stiffer die with less material and longer lifetime. The scope of optimizing design can vary depending on the time availability, costs for manufacturing, main goals of optimization and so on, in accordance with which, the optimization setup will be altered.

To identify the reason for failure, physical investigation of the die, FE analysis and analytical calculations can be carried out. To optimize the design, an optimization setup can be created and run. In the end, the whole process can be reflected upon in addition to relevant literature and practices to develop a coordinated approach for optimal design.

3. **Method**

The first part of the work aims to identify the reason for failure and produce an optimum design of the studied stamping die. The method overview is as shown in figure 2.

![Figure 2](image.png)

**Figure 2.** Method overview followed to address the problem.

The method tree starts with defining the problem and developing an understanding of it. Then virtual modelling and experimental investigations are carried out in parallel. To be able to build trustworthy virtual models and simulation procedures, experimental investigations are necessary since they allow to build the virtual model closer to reality [5]. Then, FE analyses is carried out and the obtained results are checked if they are as desired. Analytical calculations are also carried out to help verify and judge the results. This process is iterated until satisfactory result with desired accuracy is obtained and the reason for failure is established. Next, an optimization simulation is setup with an aim to achieve a stiffer die.
with less material and longer lifetime. The results from optimization simulations is used to re-design the die. This new design is subjected to FE-analyses and checked if the desired stiffness, stress concentration level and lifetime is achieved. The lifetime of the die is predicted using analytical calculations. This process is iterated until satisfactory result with desired accuracy is obtained. The next part of the work aims to build an approach for handling such problems effectively in minimum amount of time. This is done by reflecting on the followed process and the faced problems, by analyzing the traditional way of handling such situations at VCBC and by referring relevant literature dealing with similar problems. The developed approach is shown in figure 6.

4. Modelling & FE Analysis

4.1. Model Setup
The CAD geometry of the stamping die is simplified in Catia V5 by removing various components like screws, rivets, attachments that are of less importance from a simulation perspective. Since the geometry is large, symmetry is utilized to achieve computational efficiency.

4.2. FE Analysis
The simplified CAD model is imported into Hypermesh 13.0 in stp-format to create a structural FE-model and solved with Abaqus 6.14. Only a small part of the ‘matrix’ is considered as its only purpose is to act as a contact to the blankholder. The ‘ram’ is modelled as rigid body with the remaining stamping die modelled as elastic body and solved with a dynamic quasi-static method. The matrix is constrained in all directions whereas the ‘ram’ and ‘blankholder’ is allowed to translate in z-direction. Load is applied on the ‘ram’ through a reference node that is connected to the elements of the ‘ram’ for uniform distribution of load. Rigid bolts are created to fix the ram with blankholder and interaction between them is defined in Hypermesh using control cards. The friction coefficient for the interaction is assumed to be 0.15. ‘Blankholder’ and ‘matrix’ are made of nodular iron and the ‘ram’ is made of steel.

Three load cases are considered for the simulations, two operational loads and one overload limit load. All the parameter values are set such that simulation gets closer to reality. An FE-model for the stamping die with blankholder plate is also analyzed to compare the difference between both cases, that is the case with and without blankholder plate.

To not make high stress concentrations near sharp corners/edges obvious and also build confidence on the accuracy of results, a sub-model of the original stamping die is created and meshed finely to better predict the correct levels of stress in the critical regions. The result from FE analysis for the overload limit case is shown in figure 3 for both FE-models.

![Figure 3](image-url)

**Figure 3.** (a) Von-Mises stress distribution for overload limit load-case. (b) Von-Mises stress distribution for overload limit load-case in FE-sub model.

5. Analytical verification
This section details the analytical calculations carried out to understand and justify the cause for stamping die failure. According to [6], the maximum stress that can be applied on a body without causing any fatigue failure is called the fatigue limit. If the maximum stress generated by the applied load is
greater than the fatigue limit of the material, which is nodular iron for integrated blankholder, it can lead to formation of cracks in the integrated blankholder.

To check whether the die is reliable under these load cases, a Haigh diagram is plotted which is a plot between ‘mean stress’ and ‘alternating stress’ that gives the fatigue limit as a function of the mean stress value [6]. In our analytical model, we do not consider presence of any crack and check whether the stamping die is still safe. First principle major stress (P1 major stress) values corresponding to the three load cases is considered. To estimate the corrected fatigue limit, reduction factors such as κ (kappa) called the surface finish factor, λ (lambda) called the material volume factor and δ (delta) called the loaded volume factor are used.

From the Haigh diagram, it can be noted that, for two operational load-cases, without the blankholder plate and the overload limit load-case with blankholder plate, the point (σ_m, σ_a) that is, the mean stress and the alternating stress, falls under the safety region. But for the overload limit load case without blankholder plate, point (σ_m, σ_a) falls outside the safety region, suggesting that the die is not reliable for this load case. Moreover, there is a drastic reduction in the fatigue strength of the material when a crack has initiated or when the notches present on the surface already act as a crack which makes it highly unpredictable and unreliable. These calculations results are similar to the results from FE analysis which verifies the simulations.

6. Design Optimization

A basic optimization problem can be formulated with four main components, design variables, objective, constraints, and parameters. The main motive behind design optimization is to explore various possibilities that satisfy the optimization problem. This way many design ideas can be tested in less time and the most suitable one can be selected.

In this work, two types of Design Optimization (DO) are implemented. For a concept-level DO, ‘Topology optimization’ is chosen. In a given design space, topology optimization can be used to optimize the material distribution of structure in the entire model for a given set of loads and boundary conditions. For a further fine-tuned DO, free-shape optimization is chosen. For a given structure with features on its boundaries, free-shape optimization modifies the boundary nodes to find a more optimal structure that meets the constraints and objectives. Optimization problem is solved in Optistruct, a standalone solver platform in Hyperworks.

Results from FE analyses indicate high stress regions which are the critical regions for DO and design space for DO is defined based on them. To obtain best results from topology optimization, all big empty cells in the structure are filled. Since, only integrated blankholder part of the stamping die fractured, DO of only that is conducted. To decrease the computational time and complexity, the blankholder is considered to be almost quarterly symmetrical. Other components of the stamping die and press, the matrix and ram respectively, are neglected for DO setup by incorporating their presence using boundary conditions and pressure.

![Figure 4](image)

Figure 4. (a) Suggested element density in design space after topology optimization. (b) Re-design of the integrated blankholder based on topology optimization.
All the optimization parameters are set keeping in mind the manufacturability of stamping die with the objective to minimize compliance or increase stiffness with constraints on the stress levels. It is worth to note here that the correct parameter values rendering reasonably accurate results from the optimization setup are obtained iteratively after several runs. Figure 4 (a) shows the material redistribution obtained in the design spaces as a result of topology optimization. The contour in figure 4 (a) shows the suggested element densities in design space with red colour indicating highest element density. Based on the suggestions from topology optimization the integrated blankholder is re-designed as seen in figure 4 (b) and is subjected to FE analysis. From the results of FE analyses for re-designed stamping die, further critical regions are identified and free-shape optimization of re-designed stamping die is conducted for fine tuning the design in a similar manner as topology optimization.

![Figure 4](image)

**Figure 4.** (a) Design space before free-shape optimization. (b) Design space after free-shape optimization.

The result from free-shape optimization is shown in figure 5. This way the re-design of stamping die, FE-analysis and further optimization of stamping die is carried out iteratively until desired results are obtained. The results from topology and free-shape optimization suggests to have more walls and larger radii fillets in the regions where high stress levels are developed with increased thickness of wall at most critical regions. This paper presents simulation results from [2], additional information and results from the FE-simulations can be found in that publication as well.

7. **Results**

After a final re-design of the stamping die is obtained it is then subjected to FE analysis under different load-cases to know how it behaves. The results show that maximum stress levels in re-designed stamping die has decreased by 70% when compared to the studied integrated stamping die although the mass has increased by 17%. When compared to the stamping die with blankholder plate, the mass of re-designed die has reduced by 26%. The re-designed die is safe for infinite life as per the analytical calculations in addition to being an integrated design eliminating the issues of having a blankholder plate.

The reason for failure of the studied die is acclaimed to fatigue and design of the stamping die. During production, the die is subjected to pulsating type of load. The result from simulations show that the die should not fail under the two-operational load-cases but is unsafe at the overload limit load-case and in the case of latter, cracks can initiate or notches can be created which drastically reduces fatigue limit of the material. The design of the studied stamping die was not equipped for such a scenario which resulted in fatigue failure due to overload. Design of the integrated stamping die should be such that it can even withstand loads higher than the overload limit case without initiating crack or creating notches. Simulations and analytical results show that the new design wouldn’t fail under any of these load-cases with the stress levels quite far away from the fatigue limit of the material, meaning that the die is very safe.

7.1. **Guidelines for safe design of stamping die developed from the current work**

General rules/guidelines for a stiff integrated blankholder with longer lifetime is formulated based on results and learnings from current work. More walls and larger radii fillets should be present in the region of high stress levels with increased thickness of the wall at most critical regions. The walls and
reinforcements should not meet at sharp angles or in such a way that produces stress concentrations. Rather, the walls should be placed in a staggered sequence, for example, as seen in the re-design of the die, to reduce risk of cavities, distortion, and cracking during die casting process since the casting shrinks as it solidifies and draws material from areas that solidify last thus increasing the risk of cavities when more walls meet in the die. To achieve sufficient strength in the die, distance between the cell walls must be suited to the depth of cells such that shallower the cells, shorter the distance between walls. However, it must be noted that these guidelines are developed based on the learnings from the current work and have proved to work for the studied and a few other dies with similar designs. More investigation would be needed to claim a higher level of generalizability of these guidelines.

7.2. Developed SDD approach
In the end, an approach suited to arrive at a reliable, resource efficient design in a short span of time, with a possibility to re-use the gained knowledge/experience for future designs is developed by reflecting on the followed process and problems faced, by analyzing the way of handling such situations at VCBC and by referring relevant literature dealing with similar problems. An overview of suggested approach is shown in figure 6.

![Figure 6](image-url)

**Figure 6.** Overview of the approach suggested in this work.

This framework can be viewed as an iterative loop of problem identification to solution output. In the first phase, the problem to solve is identified, understood and defined. This can come from need for a new stamping die or modification of an existing stamping die. Then the next phase loops in a coordinated manner between modelling, analyses, simulation and optimization, usually in a modern design & simulation system. Modern CAD/CAE system has an advantage of having a higher potential than physical testing (which is highly impractical in the earlier phases of product development) in its ability to support the conceptual phase by exploring many solutions in less time, additionally also guiding reasoning in unexplored directions than the actual goal [4]. Although, to be useful for this, product models, simulations, and optimization procedures must be efficient, pointing towards better solutions while consuming an acceptable amount of time and other resources [7]. The next phase aims at capturing knowledge by outputting lessons learnt in the form of guidelines, rules, support tools. To be effective, the captured knowledge should be well organized, easily interpretable, and
reviewed/revised often. This way, each time the approach is applied on a project, the already captured knowledge can serve as a head-start. At the end of the project, capturing new learnings or reviewing the already present knowledge and updating it with newer learnings can serve to be useful for future projects. This phase is of great importance and can significantly add to reduction in time but is usually neglected [8]. This gradually leads to increase in the knowledge index during initial stages of product development, as a consequence of which reduction in lead time and increased competitiveness can be achieved [8].

8. Discussion, Conclusions and future work

The ability to design a reliable structure of a stamping die in less time is of great importance for a manufacturing industry. One example of an efficient approach to achieve this is demonstrated in the paper with good results. With proper understanding of problem, good knowledge of simulation setup tools and re-use of previously captured knowledge, the process will be less time consuming and more accurate. However, to achieve prominent lead-time reduction through knowledge re-use, there needs to be a consistent way of capturing product and design-process knowledge with the ability to revise the knowledge in less time. One such system called MOKA, which is ‘Methodology and software tools Oriented to Knowledge based engineering Applications ‘provides a framework both for representing and storing knowledge [9]. The main focus of present work is to show the potential of such a coordinated approach through a case study. More investigation is needed in the aspect of knowledge capture and re-use for generalizing the approach.

On a broader scale, the approach holds a potential to initiate development of new concepts, act as a guidance towards optimum solutions, support decision making process mainly in early stages of product development, for verifying solutions and most importantly reduce the time to market.

With engineering technologies changing more rapidly than ever before, new scenario demands new capabilities and expectations. As a future work, the capabilities from Multidisciplinary Design Optimization (MDO) coupled with Knowledge Based engineering (KBE) can be explored and used to build on the current approach making it more robust. More ways to clearly represent and store knowledge, in addition to MOKA can be explored.

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