Optimization of forming machine stiffness for increased production accuracy

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Abstract. This paper deals with the use of topology optimization in the design of mechanical forming machines. This worldwide industry sector has not seen any significant developments or changes in a long time. Yet, there is a constant effort to reduce the weight of machines. Unfortunately, significant design changes are less common in new mechanical presses than in other production machines. In this paper, topology optimization was employed to minimize the weight and maximize the stiffness of an entire 80 MN mechanical forming press. The frame of this press consists of two crossbeams and four preloaded columns. The results of the optimization were translated into new welded and cast frame designs. The main focus was on the upper and lower crossbeams. The optimization theory and parameters (the design space, objectives and variables) are presented from the computational viewpoint. The compliance objective was employed, considering the entire assembly of the press. Submodeling was used to refine the results. The loading cases considered center and off-center loads. Based on the results obtained, new designs of the crossbeams were developed. The comparison between the conventional and optimized designs demonstrates the feasibility of weight reduction and stiffness improvement (depending on the manufacturing method of the crossbeams). The new designs are more economical, environmentally-sound and suitable for production.

1. Introduction
Designs of forming machines have not undergone any significant changes over a long time. Frames continue to be manufactured as cast or welded parts, having total heights of up to 10 meters. Today, advanced computational methods, including the finite element method, are available to designers as tools for improving the characteristics of machines. Topology optimization (TO) is one of such methods. In this paper, the use of TO for improving the overall design of a mechanical forming press is presented. Generally, the optimized designs of crossbeams may possess new and innovative shapes (in both welded and cast versions), which have not been used up to now. [1]

In forming machines, stiffness is one of the most important characteristics. Higher stiffness translates into better production accuracy. To achieve the required accuracy, forming presses are generally provided with tooling guides on their frames. The moving top die is guided in the frame, whereas the bottom die is fixed to the frame. As this guidance is often insufficient, additional guides must be provided in both dies. This study aimed to improve the design of a forming machine in order to improve its production accuracy. If successful, the need for the additional guides in tooling can be eliminated (thanks to sufficient accuracy of the machine alone), delivering obvious economic benefits.
2. Theory of topology optimization

Topology optimization is a mathematical method for optimizing material layout in a structure with respect to boundary conditions, which may include loads, weight constraints, maximal stresses and strains, and other constraints.

To achieve the goal, it generally involves minimization of an objective function. In the present case, the compliance objective function was used. It maximizes the stiffness of a structure within a desired weight range.

The objective function is expressed as follows:

$$ \text{Min}(C(x)) = (u(x))^T f(x) = (u(x))^T K(x) u(x) $$

Where:
- $f$ - global load vector containing the nodal forces
- $u$ - global displacement vector
- $K$ - global stiffness matrix
- $V(x)$ - volume of the structure, which is formed according to input variables "x".
- $V(o)$ - total volume of structure
- $Vr$ - limiting value for the volume. This value can be between 0 and 1. [2]

3. Optimization workflow

Topology optimization was performed on a 80 MN force mechanical forming press (Figure 1) according to [3]. It focused on both crossbeams, as these belong to the core elements of the structure. The initial crossbeams were designed as welded parts. The design space for optimization was defined while taking into account the spaces required for the other assemblies of the machine. In addition, only submodels of each crossbeam were chosen for the TO exercise because modelling the entire assemblies would be impossible due to computational limitations. Topology optimization is a mathematical process based on iterations. Dealing with contact problems adds another level of iterations. Combining these approaches would lead to enormous and time-consuming iteration loops. This is why only certain individual parts of the assembly were considered and subjected to relevant constraints and boundary conditions [4, 5]. The nominal force of the press of 80 MN was applied to the surfaces of bearings (in the upper crossbeam) and the bottom platen (on the lower crossbeam). The upper crossbeam is described in more detail below.

![Figure 1. Mechanical forming press before optimization. The simulation model is shown on the left and the entire plant with manipulators on the right](image)

NX Nastran and Frustum optimization tools were used for modeling the machine members. A hybrid mesh was employed because it allowed the largest proportion of brick elements to be used. These elements are more robust and provide better accuracy than the other element types. The interior of the
design space was meshed using CHEXA 20 brick elements. It was enveloped in a transition layer of CPYRAM13 pyramid elements. The surface region was then meshed using CTETRA10 tetrahedral elements. [6, 7] The basic approach to topology optimization is illustrated in Figure 2. [8, 9]

![Workflow of topology optimization](image)

Figure 2. Workflow of topology optimization

Results of TO using the two tools are compared in the following figure. The material distributions generated by the two finite-element (FE) solvers are almost identical.

![Results of topology optimization](image)

Figure 3. Results of topology optimization of the upper crossbeam obtained using the Frustum solver (left) and the NX Nastran solver (right)

4. Findings from the optimization
The results of TO of both crossbeams are summarized below. They apply to any forming machine under both center and off-center load conditions.

- The ribs extending from the central bearing to the corners of the crossbeam must be X-shaped. Both center and off-center forces can be transmitted by this design. This X-shape can be produced in cast as well as in welded designs.
- The preloaded corner units (where anchors are placed) should have a variable round cross-section instead of the initial rectangular shape.
5. Redesign of crossbeams
The results of topology optimization cannot be translated directly into a CAD assembly model. Instead, both crossbeams need to be redesigned with respect to the relevant production method. The cast and welded designs are shown in Figure 4.

Figure 4. The initial (left), welded (middle) and cast (right) designs of the upper crossbeam

6. Comparison of stress and deformation levels
Static analysis of all the designs was performed to compare their maximal displacement and von Mises stress under loading. Only the upper crossbeam is discussed here but the results for the lower one were comparable. The objective of the optimization was to minimize the maximum displacement in the members.

6.1. Vertical stiffness
The value which was compared between the designs was the displacement at the central bearing. It was found that at an almost identical crossbeam weight, the displacement may drop by almost 40% when an alternative design is used (see Table 1 and Figure 5). The additional guides for forming tools therefore become unnecessary, thanks to the sufficient stiffness of the machine, although this may depend on the exact type of the forming process and the accuracy required. The following table shows the results for center loads, i.e. where the maximal working force acts on the center of the tooling. However, improved results were also found for off-center loads. Von Mises stress levels have not changed significantly after the optimization (Table 1 and Figure 6).

Table 1. Performance of all three designs under center loading

|                | Weight [t] | Weight difference | Displacement [mm] | Displacement difference | Avg. stress [MPa] | Stress difference |
|----------------|------------|-------------------|-------------------|-------------------------|-------------------|------------------|
| Initial design | 106        |                   | 1.04              |                         | 50.3              |                  |
| Welded design  | 103        | -3%               | 0.92              | -12%                    | 52.2              | +4%              |
| Cast design    | 108        | +2%               | 0.61              | -42%                    | 45.8              | -9%              |
6.2. **Horizontal stiffness**

The horizontal stiffness under off-center loading is another important parameter in a forming press. FE analysis showed that deformation of the initial design can be up to 4 mm in the horizontal direction (Figure 7). Both topology-optimized designs exhibit horizontal deformations of about 2 mm. The improvement is therefore approximately 50%.

**Figure 5.** Maximal vertical displacements for the initial (left), welded (middle) and cast (right) designs of the upper crossbeam [mm]

**Figure 6.** Maximal von Mises stresses for the initial (left), welded (middle) and cast (right) designs of the upper crossbeam [MPa]

**Figure 7.** Maximal horizontal displacements for the initial (left), welded (middle) and cast designs of the upper crossbeam [mm]
7. Conclusion
This research demonstrated some benefits of using topology optimization in the design of forming machines. The optimization involved a mechanical forming press with a capacity of 80 MN. The stiffness of its crossbeam in the vertical and horizontal directions can be improved by up to 50%, while using a comparable amount of material. The solution identified the optimal layout of material to support loads in the loading cases chosen for analysis (center and off-center forming operations).

Thanks to this improvement, the vertical guiding elements in the forming tools can be made more slender or even removed altogether, which would deliver clear economic benefits. The resulting changes in the stress distribution are much smaller and therefore less significant than the improvement in stiffness. Two FE solvers, NX Nastran and Frustum, were used for this optimization task. Pre and post-processing was carried out using Siemens NX 12 CAx tool. As topology optimization is usually a time-consuming exercise, only the upper and lower crossbeams of the machine were considered in this study. Nevertheless, the same approach can be applied to other machine parts and units.

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