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ORIGINAL ARTICLE

Structural design of stamping die components using bi-directional evolutionary structural optimization method

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Abstract Nowadays, the casting structure of stamping dies is designed according to die design standards. These standards are usually not based on a structural optimization algorithm and often rely on high safety factors which cause the weight of die components to be more than required. This in turn calls for higher prices of dies and production energy required per part. Therefore, alternative methods to reduce the weight of these components are required. In this paper, a software package is presented which can design an improved structure of stamping dies with a substantial reduction in weight. This package implements Abaqus software and uses the bi-directional evolutionary structural optimization (BESO) method to create a new lighter structure which resembles the shape of the sheet metal part and applied forces in the operation. It obtains the desired optimum design by removing from and adding material to the die component structure. This method involves adding material to that part of the component where the structure is overstressed and simultaneously removing material where the structure is understressed. This procedure is carried out again and again until the objective function is minimized. Finally, the proposed structure can also be reconstructed by the designer to accommodate for a simpler casting method. The operation of the software is demonstrated by an example where the dies for a sheet metal part are studied. The die components are initially designed, analyzed, and compared with the standard die (the die which is in general use today). The final results show a reduction of 31 % of volume while the maximum displacement and stress of the die do not change approximately. This software package is developed in a Microsoft Visual C# programming environment with a link to Abaqus software to analyze finite element simulation processes.

Keywords Structural optimization · Stamping die components · FE analysis · BESO method

1 Introduction

Stamping dies are used in automotive industry to produce large sheet metal parts. The main components of these dies, including die, punch, and blank holder, are large in size and weight. In most cases, forming forces applied to these components are not great enough to cause a noticeable displacement and stress. So in order to overcome these forces, a totally solid part is not required, and uniformly distributed ribs are generally designed for supporting the die face. The structure of these dies is designed in accordance with the rules used by the experts and the existing standards. However, in some cases, the pressure distribution of the die face is ignored by the designer [1]. This design thus leads to the increase of the size and weight of these dies, which results in excessive costs as well as difficulties in transportation and installation and operation [2]. On the other hand, die design with fewer structural ribs can save energy consumption in transportation and operation and the cost of material of die but may have the problem of die failure. Therefore, the light-weight design of the large-scaled stamping die with structural optimization methods is certainly important.

In the last three decades, structural optimization methods were applied to generate an appropriate structural configuration by redistributing the material in the design space with the boundary conditions and prescribed loads. In the final design,

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a light-weight structure is obtained with the required structural strength and stiffness [3–5]. The distribution of the material is generally described with some different methods. Up to now, considerable research and several structural optimization methods such as homogenization methods [6, 7], level set methods (LSM) [8, 9], evolutionary structural optimization (ESO) methods [10, 11], bi-directional evolutionary structural optimization (BESO) methods [12–14], solid isotropic material with penalization (SIMP) methods [15–18], genetic algorithms (GAs) [19, 20], particle swarm optimization (PSO) algorithm [21, 22], cuckoo search algorithm [23, 24], artificial bee colony (ABC) algorithm [25], and harmony search (HS) algorithm [26, 27] have been proposed. Among these methods, the ESO and SIMP methods are more popular and used widely in both engineering optimization and academic research [28].

For instance, Xie and Steven [29] presented a simple method for structural optimization with frequency constraints. The structure is modeled by finite elements. At the end of each analysis, part of the material is removed from the structure so that the frequencies of the resulting structure shifted towards a desired direction. Wang [30] presented a numerical method for structural shape and topology optimization. The method relies on a novel approach for the representation of the design boundaries with level set models. A structural optimization is formulated as a mathematical programming problem with a design objective and a set of constraints, utilizing the level set models for the incremental shape changes. Huang and Xie [31] demonstrated the effectiveness and efficiency of the BESO method on the minimization compliance problem with fixed external loads. They considered the minimization of mean compliance for continuum structure subjected to design-dependent self-weight loads. Tcherniak [32] studied on the layout optimization of resonating actuators using the SIMP topology optimization method. The goal of the optimization is maximization of the magnitude of steady-state vibrations for a given excitation frequency. Yildiz and Saitou [20] developed a novel approach for multi-component topology optimization of continuum structures using a multi-objective genetic algorithm to obtain Pareto optimal solutions that exhibits trade-offs among stiffness, weight, manufacturability, and assembly ability. Fourie and Groenwold [21] applied PSO algorithm to shape optimization of a torque arm and to size optimization of truss structures. In their PSO algorithm, the concept of craziness is redefined, and elitism operator borrowed by GA was used. Their results showed that PSO algorithms were better than GA and the gradient-based recursive quadratic programming algorithm. Perez and Behdinan [22] proposed a particle swarm approach for structural design optimization. The effectiveness of the improved PSO algorithm on structural optimization is shown through the use of four classical truss optimization examples. Results from the three tested cases using an improved PSO illustrate the ability of the algorithm to find optimal results which are better than, or at the same level of, other structural optimization methods. Yildiz [25] developed a novel hybrid optimization method (HRABC) based on the artificial bee colony algorithm and Taguchi method. The proposed approach is applied to structural design optimization of a vehicle component and a multi-tool milling optimization problem. Mahdavi [26] developed an improved harmony search (IHS) algorithm for solving optimization problems. IHS employs a novel method for generating new solution vectors that enhances accuracy and convergence rate of harmony search algorithm.

Most of the existing research work on sheet metal forming is concentrated on the numerical simulation of different kinds of forming processes to improve the precision of produced parts [33]. For example, Wang et al. [34] accomplished a series of numerical simulations concerning the influence of shape error and non-uniformity in thickness distribution of sheet metal parts. Farsi and Arezoo [35] developed a system for operation sequencing sheet metal part that includes bending and stamping operation. They used classification and fuzzy rules for determination of the sequence of the bending operations. Yan and Klappka [36] studied the spring-back behavior of panel forming using multi-point stretch forming technique. Fazli and Arezoo [37] presented an analytical method for estimating the limiting drawing ratio (LDR) of the redrawing stages in deep drawing process of axisymmetric components.

As mentioned, many research works were carried out to develop the forming conditions of sheet metal forming operations. However, there has been a small number of research works in die structural optimization, from which a few are the optimization of the structure of stamping and stretch forming dies. These are presented as follows:

The conversion of the surface loads was simulated by Nilsson and Birath [38] during the stamping process by means of time integration, where the process of lifting and stamping are taken into account. Structural optimization was then applied to reduce the weight by keeping the structure strength and rigidity. In a similar manner, Xu and Tang [39] developed the inner structure of the stamping die with the structural optimization method based on the LS-Dyna platform and Hyperworks software. Using the finite element method, Sheu and Yang [1] tried to predict the pressure on the die face of stamping dies. Then, with the size and shape optimization methods, the inner structure was designed. The optimal results are completely different from a uniform distribution of the ribs which can be seen in usual designs. Zhu et al. [2] used Abaqus software to simulate the process of skin stretch forming numerically. Then, structural optimization was performed to maximize the structural stiffness with the boundary conditions and the material properties properly defined. Finally, the comparison of usual design and the numerical results shows that the structural design can meaningfully improve the strength and stiffness of the stretch forming die. A SIMP-based topology optimization methodology for stamping die was proposed by Xu and Chen [40]. Topology optimization results in this study showed that 28.1 % mass reduction was achieved with a slight difference of the die structure performance and blank forming quality. Stamping tool design was conducted using FE simulation and topology optimization techniques to increase its rigidity by Hamasaki [41]. In the first step of the procedure, stamping simulation was carried out with rigid tools, and contact pressure (nodal forces) was extracted. Topology optimization with the obtained nodal force boundary condition successfully determined the stiffest structure under the given volume fraction constraint in the next step. Based on thus optimized die structure, new CAD model was redesigned. Azamirad and Arezoo developed a software package which can design an appropriate topology of body structure of stamping die components with a reduced weight. This is done by implementing the ESO algorithm, and the results show that the optimal die structure is completely different from a uniform distribution of the ribs which can be seen in standard die design [42].

Despite these researches in literature, there is still not an effective and efficient method which can automatically optimize the structure of stamping dies according to boundary conditions and prescribed loads. In this paper, a software package based on structural optimization is presented. This software implements BESO algorithm to reduce the volume of the main components of the stamping dies, including die, punch, and blank holder, while maintaining the forces applied in sheet metal forming operations. So the main contribution of the present work to this field is the automation of structural design of stamping die components where the most popular topology optimization (BESO) method is used for the first time. This can be a novelty in theory, and the reconstruction of die components with respect to manufacturing constraints and accommodating for a simpler casting method could also be classed as novelty in manufacturing techniques.

2 Method

Structural optimization has attracted notable attention in the last three decades, and several methods have been developed based on the finite element analysis [3–18, 28]. The ESO and the SIMP are two commonly used methods [28]. In the SIMP method, a density of material is defined for each element which varies between 0 and 1. The elastic property for each element is stated in terms of its density [18]. The ESO method is based on the simple idea that by progressively removing inefficient material from a part, the topology of the remaining design will evolve towards an optimum structure [10, 11]. BESO is an improvement of the ESO method which allows for efficient material to be added to the structure at the same time as the inefficient one is removed [12–14].

2.1 Bi-directional evolutionary structural optimization method

The BESO method allows the material of part to be removed and added simultaneously. The initial research on BESO for stiffness optimization was conducted by Yang et al. [12]. In their study, the sensitivity numbers of the void elements are estimated after the finite element analysis by a linear extrapolation of the displacement field. Afterward, the solid elements with the lowest sensitivity numbers are removed from the structure, and simultaneously, the void elements with the highest sensitivity numbers are changed into solid elements. The numbers of added and removed elements in each iteration are determined by two independent parameters, namely: the inclusion ratio (IR) and the rejection ratio (RR) respectively.

In this paper, the modified BESO algorithm by Huang and Xie [43] is used for the structural optimization of stamping dies. In this method, many problems related to structural optimization of continuum structures such as a proper statement of the optimization problem, mesh-dependency, checkerboard pattern, and convergence of solution are resolved.

2.2 Sensitivity number

The purpose of structural optimization is searching for the stiffest structure with a given volume of material. In the BESO method, a structure is optimized by removing and adding elements. The optimization problem with the constraint of volume is stated as Eq. 1 [43]:

$$\begin{aligned} &\text{Minimize } C = \frac{1}{2} f^T u \\ &\text{Subject to : } V^{*} - \sum_{i=1}^{N} V_i x_i = 0 \\ &x_i = 0 \;\; or \;\; 1 \end{aligned} \tag{1}$$

Where f and u are the applied load and displacement vectors and C is known as the mean compliance. V_i is the element volume, and V^* is the prescribed total structural volume. N is the total number of elements in the model of part. The binary design variable (x) expresses the absence (0) or presence (1) of an element.

When a solid element is removed from a structure, the change of total strain energy or the mean compliance is equal to the elemental strain energy [44]. This change is defined as the elemental sensitivity number. When the mesh of part is not homogeneous, the sensitivity number should consider the effect of element volume. In such a case, the sensitivity number can be replaced with the strain energy density of element as Eq. 2 [43]:

$$\alpha_i^e = e_i = \left(\frac{1}{2} u_i^T K_i u_i\right) / V_i \tag{2}$$

Where K_i is the elemental stiffness matrix, and u_i is the nodal displacement vector of the ith element.

2.3 Filter scheme and improved sensitivity number

A filter scheme is used to obtain the sensitivity number for the void elements to add material into the design space and to smooth the sensitivity number in the whole design space. More importantly, by using the filter scheme, the problems of mesh dependency and checkerboard pattern will be resolved at once. Nodal sensitivity numbers are defined before applying the filter scheme by averaging the elemental sensitivity numbers as Eqs. 3 and 4 [43]:

$$\alpha_j^n = \sum_{i=1}^{M} \omega_i \alpha_i^e \tag{3}$$

$$\omega_i = \frac{1}{M-1}\left(1 - \frac{r_{ij}}{\sum_{i=1}^{M} r_{ij}}\right) \tag{4}$$

Where ω_i is the weight factor of the ith element, M is the total number of elements connected to the jth node and the distance between the center of the ith element, and the jth node is r_{ij}. Then, the mentioned nodal sensitivity numbers is converted into smoothed elemental sensitivity numbers. This conversion occurs through projecting nodal sensitivity numbers to the design space. Here, the mentioned filter scheme is used to perform this process. The filter scheme has a length scale r_{min} that determines the nodes that will influence the sensitivity of the ith element and does not change with mesh refinement. This can be visualized by drawing a sphere of radius r_{min} centered at the center of ith element, thus generating the spherical sub-domain Ω_i. Nodes located inside Ω_i contribute to the calculation of the improved sensitivity number of the ith element as Eqs. 5 and 6 [43].

$$\alpha_i = \frac{\sum_{j=1}^{K} \omega(r_{ij}) \alpha_j^n}{\sum_{j=1}^{K} \omega(r_{ij})} \tag{5}$$

$$\omega(r_{ij}) = r_{\min} - r_{ij} (j = 1, 2, \ldots, K) \tag{6}$$

where K is the total number of nodes in the sub-domain Ω_i. The sensitivity numbers of void elements are automatically obtained. They may have high values due to high-sensitivity numbers of solid elements within the sub-domain Ω_i. Consequently, in the next iteration, some of the void elements may be changed to solid ones.

2.4 Stabilizing the evolutionary process

This filter scheme can effectively resolve the mesh dependency problem. But the corresponding structure and the objective function may not be convergent. Huang and Xie found that the effective way to solve this problem is averaging the sensitivity number with its historical information [43]. The simple averaging scheme is given as Eq. 7.

$$\alpha_i = \frac{\alpha_i^k + \alpha_i^{k-1}}{2} \tag{7}$$

Where k is the existing iteration number. Therefore, the new sensitivity number contains all of the history of the sensitivity data in the previous iterations.

2.5 Element removal/addition and convergence criterion

The target volume for the next iteration (V_{k+1}) is given, and some elements are removed from or added to the existing design. The evolution of the volume can be defined by Eq. 8 [43].

$$V_{k+1} = V_k (1 \pm ER) (\mathrm{k} = 1, 2, 3 \cdots) \tag{8}$$

Fig. 1 Algorithm for topology optimization using the BESO method

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1: Discretise the design space of the problem.
2: Initialize Evolutionary Ratio (EV), maximum volume Addition Ratio ($AR_{max}$) and upper limit
   of material volume ($V^*$).
3: Repeat
    3-1: Perform FE analysis
    3-2: Calculate the elemental sensitivity numbers ($\alpha_i^e$) for all elements.
    3-3: Calculate the nodal sensitivity numbers ($\alpha_j^n$) for all nodes.
    3-4: Improve the elemental sensitivity numbers by the filter scheme.
    3-5: Stabilize the evolutionary process by averaging the sensitivity numbers.
    3-6: Add and remove elements based on the mentioned algorithm.
4: Until convergence criterion is satisfied
5: Display the results
6: End
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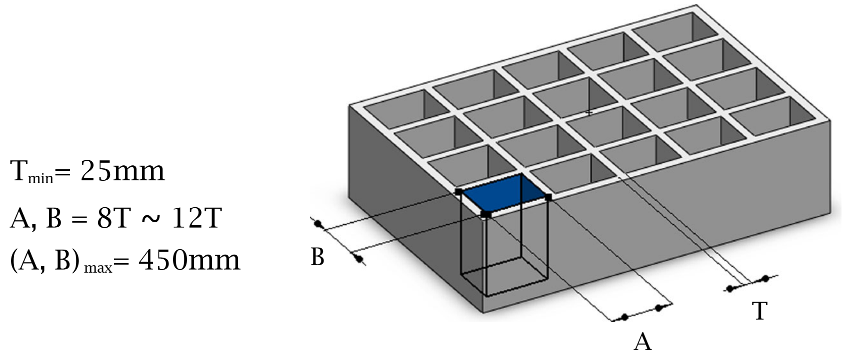

Fig. 2 Rib thickness and distances between them in back view of a die component [46]

Where evolutionary ratio (ER) determines the ratio of volume reduction of the part to its volume in the previous iteration. Once the volume constraint is satisfied, the volume of structure is kept constant and equal to V^* for the next iterations. Then, the sensitivity numbers of all elements, both solid and void, are calculated and sorted from the highest to the lowest value. If $\alpha_i \le \alpha_{del}^{th}$, then solid elements are removed (switched from 1 to 0), and if $\alpha_i \ge \alpha_{add}^{th}$, then void elements are added (switched from 0 to 1). α_{del}^{th} and α_{add}^{th} are the threshold sensitivity numbers for removing and adding elements, and α_{del}^{th} is always less than or equal to α_{add}^{th}.

The cycle of analysis in finite element software and element removal/addition continues until the objective volume (V^*) is reached and the convergence criterion (Eq. 9 [43]) defined in terms of the change in the objective function is satisfied.

$$\text{error} = \frac{\left|\sum_{i=1}^{N} C_{k-i+1} - \sum_{i=1}^{N} C_{k-N-i+1}\right|}{\sum_{i=1}^{N} C_{k-i+1}} \le \tau \qquad (9)$$

In Eq. 10, k is the existing iteration number, τ is an allowable convergence tolerance and N is an integer number [45]. The BESO algorithm can be briefly summarized as shown in Fig. 1.

3 Design of die components based on standards

Using die design standards usually leads to dies with regular shape and structure. To support the die face, these standards usually recommend rectangular ribs as shown in Fig. 3 that represents a back view of a typical die component. This design is totally independent of the shape and forming forces of sheet metal part. This method commonly leads to an overdesign and a non-uniform safety factor in different points of the die. The rib thickness and the distance between them in IKCO DESIGN STANDARD [46] which are defined as a multiple of the rib thickness are shown in Fig. 2.

Where T, A, and B are the rib thickness, the longitudinal, and the transverse distance between two ribs, respectively.

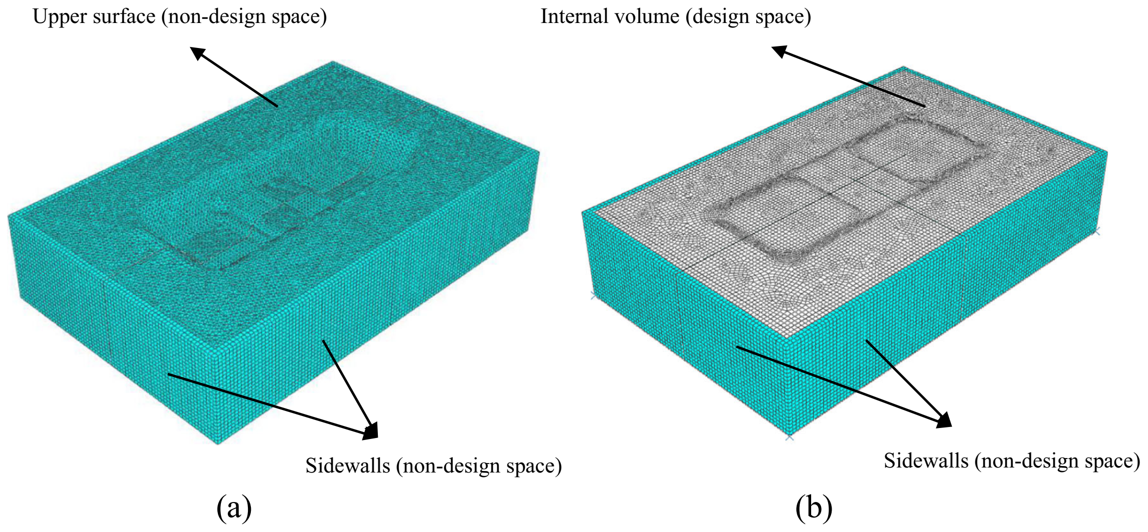

Fig. 3 Design and non-design space of the die component in **a** upper view and **b** reverse view

4 Optimal design algorithm of die structure

The presented software package is developed in Microsoft Visual C# programming environment and uses Abaqus software to analyze the finite element simulation process automatically. The input to the software is the 3-D solid model of the die components and 3-D surface model of sheet metal part. The main components of dies including punch, die, and blank holder are modeled as rigid parts in most forming analysis. However, in the present work, these are modeled as deformable solid parts to perform the optimization algorithm regarding their volumes. These parts are then transferred to Abaqus software, and the design space, boundary conditions, loads, and FE mesh are defined by the designer.

According to the limitations of the structure of components, their volume requires to be divided into a design and non-design space (Fig. 4). Since the purpose is finding the optimal distribution of material without changing the outer design of the part, the material in contact with the sheet metal part is set as a non-design space. It means, during the process of structural optimization, no material should be removed from or add to this area. In addition the sidewalls of the die are also set as non-design space so the die dimension are kept constant and the same press can be used in stamping operations. The whole volume below the non-design space is set as available design space to allow the structural optimization to find the optimal material distribution. The design and non-design spaces are shown in Fig. 3a, b in the upper and reverse view of the die part respectively.

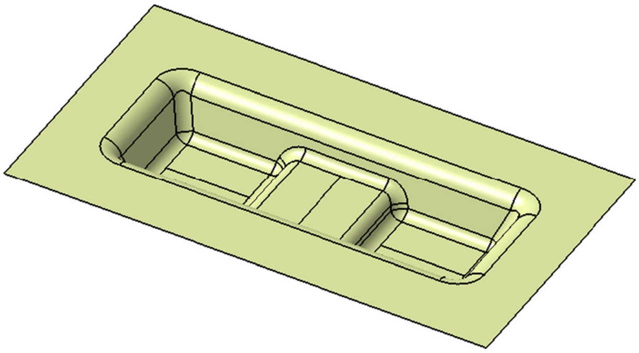

Fig. 5 3-D model of the rectangular part

After defining the design and non-design spaces and the parameters of simulation by designer, the software is capable of analyzing the stamping operations and generating the required results. In the next step, the obtained results are extracted by python script and saved in a file which is then input in a Sql server database to become easier and faster to search and use. Then BESO algorithm is applied on the database. In this step according to this algorithm the solid elements with the lowest sensitivity numbers are removed from the structure of the part, and the void elements with the highest sensitivity numbers are changed into solid elements and a new part is created. The software creates a new input file with the new part. This procedure is carried out again and again for the new parts until the objective volume is reached, the convergence criterion is satisfied, and the final structure of the part is

Fig. 4 Software package structure

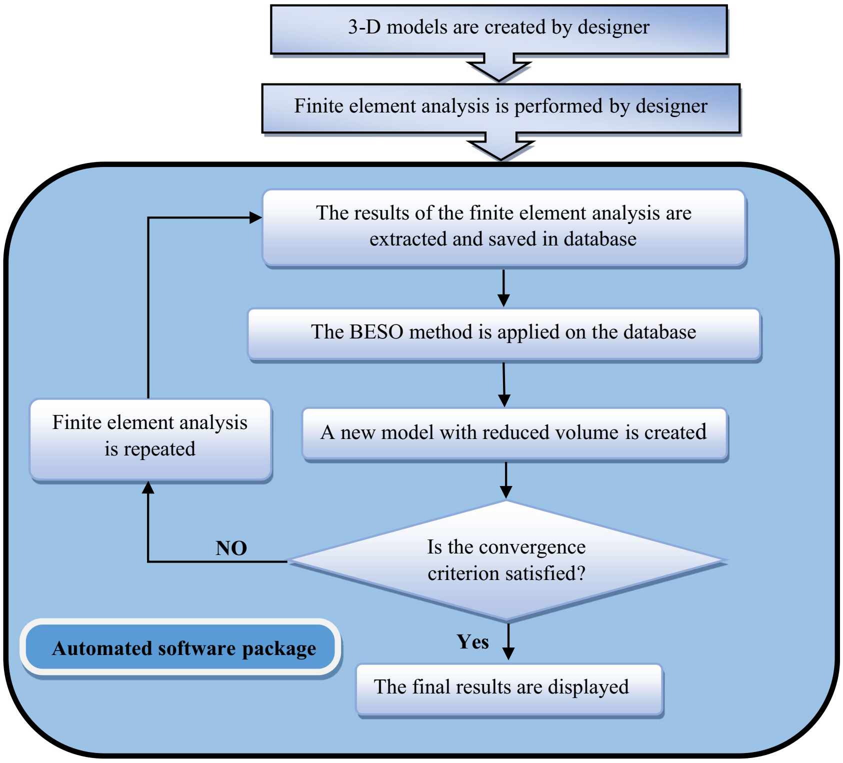

Table 1 Material properties of the sheet metal blank

Sheet metal blank material properties	Value
Young modulus, E (GPa)	207
Poisson's ratio, v	0.3
Yield stress, σ_y (MPa)	220
Stress constant, K (MPa)	500
Strain hardening exponent, n	0.27
Density, $\rho\left(\frac{Kg}{m^3}\right)$	7800

created. All these steps are performed automatically and without any user interactions. The software package structure is shown in Fig. 4.

The structure is free to take any shape within the given design space in structural optimization according to the applied forces in the forming operation. The developed design is often not easy to manufacture which is a concern in structural optimization procedure. However, the designer can modify this structure to simplify the casting conditions as well as the manufacturing procedures and reduce the cost.

5 Numerical simulation

A rectangular sheet metal part (Fig. 5) is adopted in the present research to show the results of the proposed software package. The size of the blank is 1800 × 1000 × 1 mm. The blank is located on the die face. The punch is core and the die is cavity. The die component dimensions are 2000 × 1200 × 400 mm. The BESO method is carried out on the die component. This procedure can also be applied to any other components of the die. The structure of the die is divided into fine hexahedron solid elements with the average size of 10 mm. However, the sheet metal blank is divided into quadrangular shell elements with the size of 10 mm. The material of the die and the sheet metal blank are set to be cast iron GGG60 and st14, respectively. The material properties of the sheet metal blank and die are considered to be as Tables 1 and 2. For the convenience of the FEM simulation, the material law obeying the Ludwik–Hollomon strain hardening law is assumed in the present work and is given as Eq. 10.

Table 2 Material properties of the die

Die material properties	Value
Young modulus, E (GPa)	170
Poisson's ratio, v	0.28
Yield stress, σ_y (MPa)	360
Stress constant, K (MPa)	1585
Strain hardening exponent, n	0.19
Density, $\rho\left(\frac{Kg}{m^3}\right)$	7200

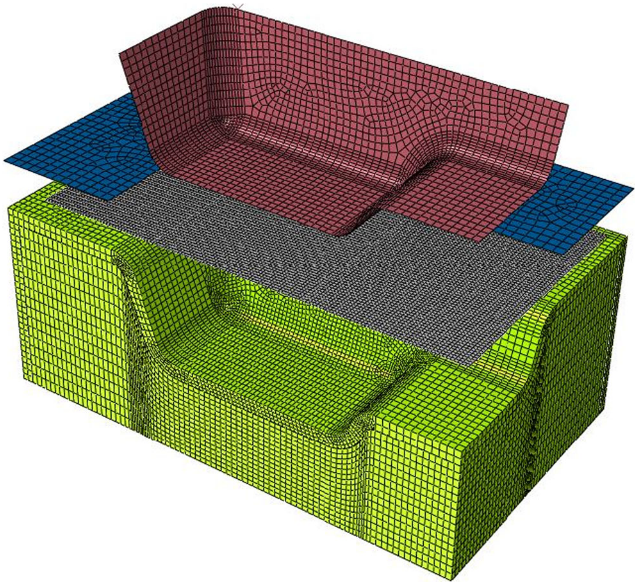
Fig. 6 FEM model of the forming process

$$\sigma = K\varepsilon^n \tag{10}$$

Where K is stress constant and n is the strain hardening exponent.

The friction contact between sheet metal blank and die components follows Coulomb's law (Eq. (11)):

$$\tau_f = \mu\sigma_n \tag{11}$$

Where τ_f is friction shear stress, σ_n is normal stress at interface, and μ is the friction coefficient assigned as 0.15.

The simulation of the process is implemented in Abaqus/explicit environment. The forming process is carried out in three main following steps:

– The sheet metal deformation due to its gravity when placed on the die,

Table 3 Sheet metal forming process parameters

Process setting	Value
Thickness of blank	1 mm
Punch stroke	200 mm
Punch velocity	500 mm/s
Friction coefficient	0.15
Element type of the blank	Quadrangular shell elements
Element type of the die	Hexahedron solid elements
Element type of the punch and blank holder	Rigid body

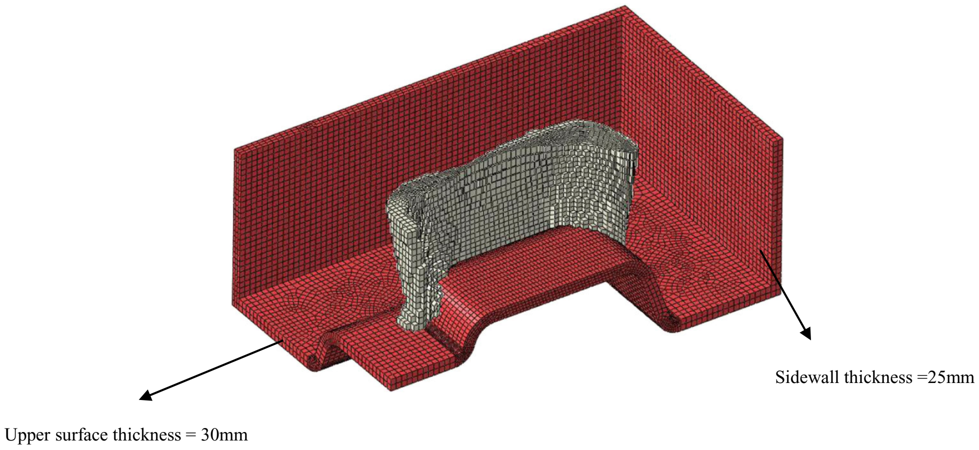

Fig. 7 BESO-based die structure

- The fixing of the sheet metal on the die face by the blank holder,
- The final movement of the punch for forming the sheet metal part.

The die is modeled as a deformable solid part. The punch and blank holders are modeled as rigid surface parts, and the sheet metal part is modeled as deformable shell part. The die is constrained in both displacement and rotation in all directions in the global coordinates, while the punch and blank holders are allowed to be translated in the press movement direction.

Because of the symmetry in the part and die components the finite element simulation is conducted on quarter of the CAD model. The FEM geometrical model is shown in Fig. 6 and the specific settings is listed in Table 3.

6 Results and discussion

The pattern resulted from the software system can be viewed in Fig. 7. This figure is the determined die structure by means of topology optimization named BESO-based die structure. This is the results for the model at iteration number 65. It was found from the optimized structure that elements in the lower area of bending are essential to stand the forming loads. This is the final result which satisfies the convergence criterion and the problem constraints. Based on the standard die (Fig. 8), the 30-mm thickness of upper surface and 25-mm thickness of sidewalls of the die is assigned as the non-design space in this model. Therefore, it will remain unchanged through the structural optimization.

6.1 Displacement and stress analysis of the BESO-based die

To analyze the results of BESO-based die structure, the displacements and Von Mises stresses in this structure and standard die structure are compared. The comparison shows the weight of the BESO-based die is 29 % lighter than the standard die. Also, its maximum displacement and stress on the elements of the die are 10 and 28 % smaller than the standard die, respectively.

In BESO-based die, the mean stress is increased. The mean stress is calculated by averaging the Von Mises stress of all

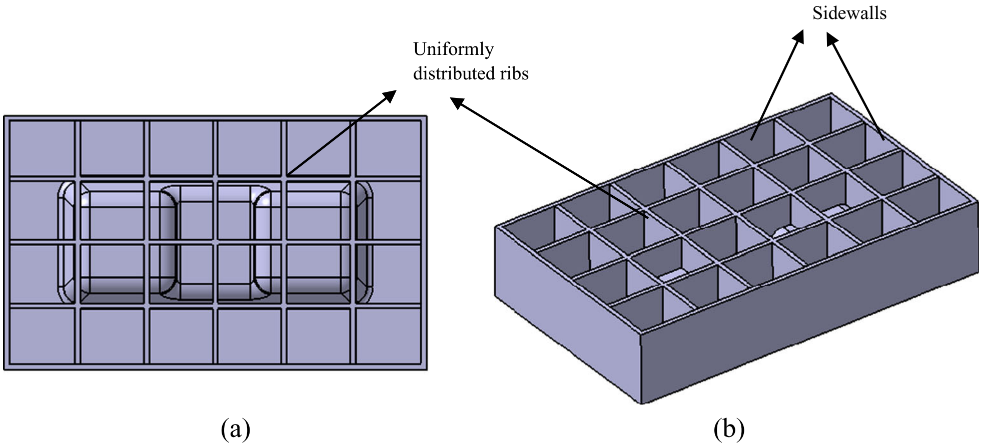

Fig. 8 Standard die structure: **a** bottom view, **b** 3-D reverse view

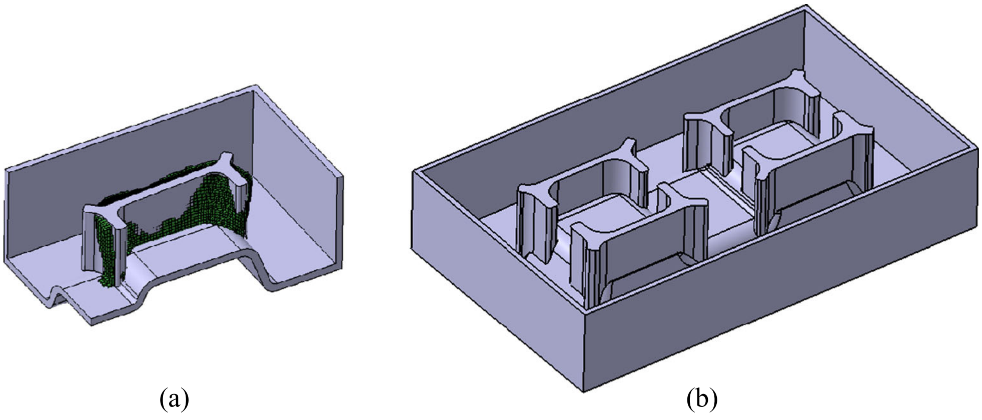

Fig. 9 **a** Reconstruction of the BESO-based die, **b** final reconstructed die

elements. This value in standard die is 50 % smaller than BESO-based die. This shows that the elements of the die component which withstand less stress are removed, and remained elements play a more active role in withstanding the forces. This represents a proper material distribution in the die.

6.2 Reconstruction of the die

It should be noted that the BESO-based die consists of non-smooth surface, therefore, in this step with respect to manufacturing constraints the structure is changed and reconstructed. The created CAD model from the BESO-based die is seen in Fig. 9. As it can be seen in this model, the non-design surfaces are maintained and the new rib structures are created over the volume of maintained elements in the CAD model. This step is carried out by a designer to accommodate for a simpler casting method.

6.3 Displacement and stress analysis of the reconstructed die

To inspect the effect of structural optimization and reconstruction of the die, three different dies are analyzed and compared in this research. These are the following:

(1) The standard die as shown in Fig. 8.
(2) The BESO-based die as shown in Fig. 7.
(3) The reconstructed die as shown in Fig. 9.

Table 4 shows the maximum displacements, Von Mises stresses and weight of these dies.

Compared with the standard die, the BESO-based die can significantly reduce the maximum stress of the die and somewhat reduce the maximum displacement.

In the reconstructed die, the maximum stress and displacement of the structure is bigger than the BESO-based die. This is the cost which has to be paid to reach a die with simplified manufacturing process. However, in this die, there is 31 % weight reduction compared to standard die, and the maximum stress and strain are nearly the same as the standard die. This means that a significant weight loss can be achieved with the same strength. The average stress in the reconstructed die is higher than the standard die. This shows that the material in high pressure areas are remained and in low pressure areas are removed, while the structure of the die is modified in such a way that is easier to be manufactured by casting method.

7 Conclusion

The structural optimization of stamping die components is studied in this paper. A software package is developed based on the BESO method. In this method, the material in low-pressure areas are gradually removed, and efficient material is added to the structure at the same time. The maximum allowable load capacity of the components is maintained at all times. Finally, a proper structure of the components with a lighter weight is created.

To show the capabilities of the developed package, an example is given, and the whole optimization and reconstruction

Table 4 Comparison between standard, BESO-based and reconstructed dies

	Reconstructed die	BESO-based die	Standard die
Weight (kg)	1444 (−31 %)	1484 (−29 %)	2092
Maximum Von Mises stress (MPa)	420 (−0 %)	301 (−28 %)	420
Maximum displacement (mm)	0.59 (+3 %)	0.51 (−10 %)	0.57

procedure is shown. To do so, three different dies, namely the standard die, the BESO-based die, and the reconstructed die, are designed and compared.

The BESO-based die can significantly reduce the maximum stress of the die and to some extent reduce the maximum displacement compared with the standard die.

The final results show a reduction of 31 % of volume while the maximum displacement and stress of the die do not change approximately, but are bigger than the BESO-based die. However, a die with simplified manufacturing process is produced.

The software package is developed in MS visual C# environment. Also, a subroutine in Python is developed and used for data extraction form Abaqus output files. Using MS visual C# environment and Python scripts proved to be suitable development tools for the present work.

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