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Development of a new concrete pipe molding machine using topology optimization †

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Abstract

Sulfur polymer concrete (SPC) is a relatively new material used to replace Portland cement for manufacturing sewer pipes. The objective of this work is to develop an efficient molding machine with an inner rotating die to mix, compress and shape the SPC pipe. First, the alternative concepts were generated based on the TRIZ principles to overcome the drawbacks of existing machines. Then, the concept scoring technique was used to identify the best design in terms of machine structure and product quality. Finally, topology optimization was applied with the support of the density method to reduce mass and to displace the inner die. Results showed that the die volume can be reduced by approximately 9% and the displacement can be decreased by approximately 3% when compared with the initial design. This work is expected to improve the manufacturing efficiency of the concrete pipe molding machine.

Keywords: Sulfur polymer concrete; Molding machine; TRIZ principles; Concept scoring technique; Topology optimization; Product design

1. Introduction

Sulfur polymer concrete (SPC) is an emerging material made of sulfur, binder, and a variety of aggregates to improve hardness. This new concrete mixture has remarkable advantages over the traditional mixture, including a short setting time, high ultimate strength, low permeability, and good resistance to acids and saline solutions. Although Portland cement concrete has been widely used in the past, its strength deteriorates rapidly because of various chemical, mechanical and biological reactions. Thus, the demand for SPC is rapidly increasing given its broad range of benefits. This material can be used effectively for the production of sewer pipes because of its capability to provide extreme durability in harsh environments.

Our practical analysis indicates that the working efficiency of concrete pipes is influenced by several factors, such as strength at an early age, surface texture, density, permeability, sulfate resistance and consistency. High strength in manufactured pipes can be achieved via fast curing time; material compression and the removal of air voids are necessary to obtain a dense and consistent product. In addition, corrosion in concrete pipes is an existing problem in sewer systems throughout the world. Sewer pipes are attacked by sulfuric acid derived from biogenic activity or the direct oxidation of hydrogen sulfide from sewerage.

Concrete pipe manufacturing technology has changed throughout the years in an effort to ensure a dense, strong and durable product. As the demand for concrete pipes continued to grow, so did the need to increase productivity and achieve uniform concrete particle distribution. The traditional approaches, such as horizontal spun, center core vibration, and packer heads technology, have not fully met the needs of pipe manufacturers in terms of fast production rates and high product quality [1]. The development of a new machine with an effective manufacturing method is extremely necessary and is an important area of research to overcome the aforementioned challenges.

Physical experimental studies of concrete pipe molding machines can be time consuming and expensive. Therefore, an effective approach that develops and optimizes the machine structure can significantly contribute to reducing the cost and time required for hardware testing and iterative improvements of the physical prototype [2]. Thus, the aim of this work is to design the best machine model among various generated concepts with the help of the TRIZ principles and a scoring technique. Subsequently, topology optimization using the density method is applied to reduce the mass and displacement of the inner die.

The remainder of the paper is organized as follows: Sec. 2 introduces the primary issue regarding machine development. We propose a scientific methodology to resolve the problem. Then, the machine conceptual design and topology optimization results are discussed. Finally, the conclusions are drawn, and future research is suggested.

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Fig. 1. Existing horizontal spun machine [3].

2. Problem description

Conventional technologies, such as horizontal spun, center core vibration, and packer heads, have been used to produce concrete pipes of various shapes and sizes. Among these technologies, spun technology has been widely applied and is based on incorporating a mechanism of outer core rotation in a horizontal centrifugal machine. This machine operates at a high speed to feed the concrete into the rotating mold. However, this manufacturing operation is time consuming, noisy, and inefficient. Moreover, the light materials settle inside during the operating time, whereas the heavier particles are thrown outside via centrifugal force. Therefore, the strength of the pipes is weak because of the nonuniform density variation and the uneven distribution of product thickness. The addition of vibration technology and a vertical machine layout are considered effective solutions to improve manufacturing efficiency and product quality to overcome the aforementioned drawbacks.

In this study, a new molding machine is designed to produce SPC pipes at the E-entech Company in South Korea, as shown in Fig. 2. Based on an investigation at the partner project, the design requirements of the machine in terms of stable structure, operating parameters, and functions were derived based on five criteria, as shown in Table 1.

3. Design procedure

Fig. 3 outlines the systematic procedure for developing the conceptual design and topology optimization of the new concrete pipe molding machine. First, relevant design information was collected and a feasibility study was performed to identify the engineering issues clearly. An investigation of existing technologies and patents was conducted to obtain an overview of conventional machines. Then, various concepts were created and achieved in terms of performance, cost, and manufacturability with the support of a 3D CAD model to verify the machine functionalities. The developed models were visualized to verify the kinematic behavior and manufacturing steps of the PC pipe. All of the innovative concepts were examined by means of the evaluation criteria to determine the best design. At the end of the first stage, the entire system model was achieved with detailed information on the machine components.

In the second stage, topology optimization of a key component, that is, the inner die, was implemented to improve the design efficiency. A combination of the Hyper software package and Optistruct was used to determine the mass-saving potential and decrease the displacement of the inner die. Subsequently, the CAD data of the entire machine and its components were derived for optimal results. Finally, the prototype

Table 1. Molding machine design requirements.

No.	Criteria name	Specifications
1	Machine layout	Vertical structure
2	Cycle time	$\leq$ 9 min/pipe
3	Rotation speed	$\leq$ 200 rpm
4	Simultaneous motion	Rotation and vibration
5	Machine function	Circular and vertical pipes
		Uniformity density
		High strength
		Low liquid permeability

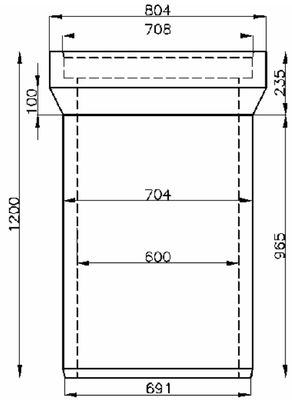


Fig. 2. Dimensions of the desired SPC pipe.

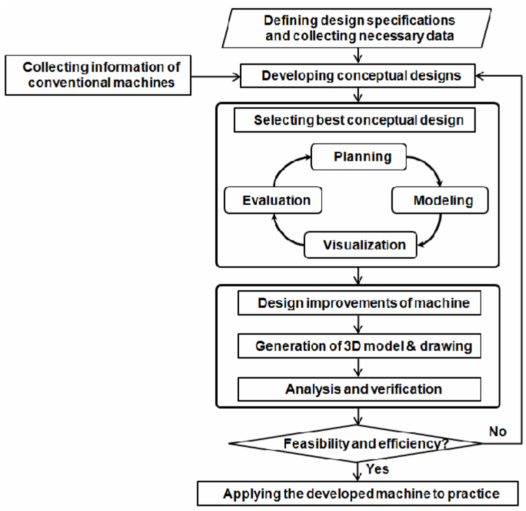
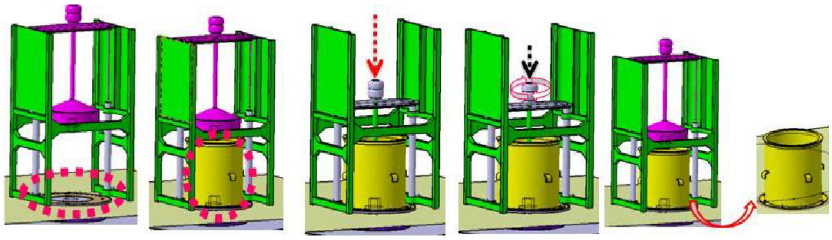
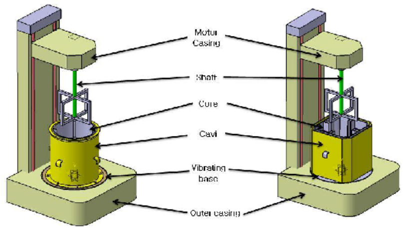


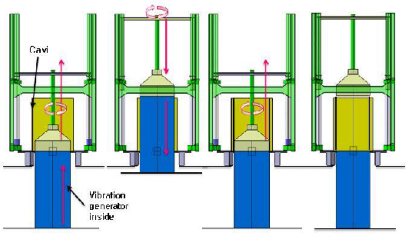
Fig. 3. Schematic of the design process.



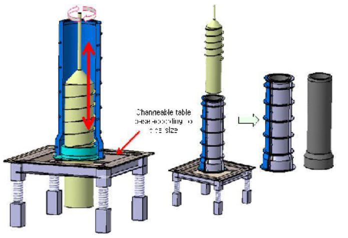
(a) Process chain of the first concept



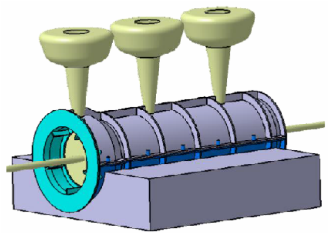
(b) Overview of the second concept



(c) Manufacturing process of the third concept



(d) The fourth concept



(e) Overview of the fifth concept

Fig. 4. Conceptual CAD models of the SPC pipe molding machine.

machine was manufactured to validate the functionalities in real conditions.

4. Development of machine concepts

In this study, the TRIZ principles are used to overcome the problems encountered by the pipe manufacturing machines [4]. This approach is based on four steps, namely, identifying the problems, formulating the problem: The prism of TRIZ, searching for a previously well-solved problem, and looking for analogous solutions and adapting to a solution. According to the TRIZ principle, object-oriented design is used to prevent technical uncertainties at the conceptual phase. Moreover, the appearance and aesthetics of the product were also considered to provide efficient models that meet customer needs. Many researchers have demonstrated that the TRIZ method is a powerful technique to create competitive and innovative ideas [5, 6].

In this work, the manufacturability of a machine and the pipe shape and durability are considered the key factors in terms of developing robust concepts. Based on the inventive principles of TRIZ, specific solutions are established to generate an efficient pipe molding machine, as presented in Table 2. The developed designs of the new machine are shown in Fig. 4.

Concept 1:

The machine model uses a movable base to provide vibration energy to the freshly inserted concrete, as shown in Fig. 4(a). The vibration base is equipped with a motor capable of generating various amplitudes and frequencies for pipes of various sizes [7]. The motion of the rotating part is produced by an electric motor mounted at the top to provide more compressive force and concrete shaping. The process chain of the first conceptual machine is listed as follows:

Step 1: The rotating part is mounted at the topmost position, and the outer die is fixed at the vibration base.

Step 2: The rotating part is moved to the lowermost position.

Step 3: The material is fed, and the rotating part starts to rotate and move upward in slow motion.

Step 4: The rotating part returns to the initial position, and the product is taken out along with the die.

Concept 2:

The second conceptual design of the molding machine is shown in Fig. 4(b) and produces circular and rectangular pipes. Similar to the first concept, the outer die is fixed in the vibration base and the inner die is movable through the rotation of a shaft equipped with an electric motor mounted at the top. The torque of the shaft is transmitted to the inner die through the coupling slots.

Concept 3:

A unique concept using an inner die equipped with a vibrating motor is illustrated in Fig. 4(c). First, the vibration of the inner die is used in conjunction with the rotation to remove air voids and compact the material. Subsequently, the vibration is stopped and the inner die is rotated to obtain a smooth surface on the manufactured pipe to ensure low water permeability. The motion of the inner die and rotating part is produced via a hydraulic mechanism and an electric motor, respectively.

Concept 4:

This concept uses an inner die with a spiral-shaped screw to distribute uniform pressure, as shown in Fig. 4(d). The base-mounted electric vibrator is designed to adapt quickly to changes in the size of the manufactured pipes. The outer die and spigot end are fixed to the table in the first step. Then, the inner die is moved into position and concrete is fed into the inner zone. The inner die begins to move in an upward direction to compact the concrete. The outer core can be adjusted to slide up and down through the small clearance hole at the table center. The balanced distribution of vibration allows the concrete to consolidate in the optimum manner and ensures a uniform distribution of particles. The novel benefits of this

Table 2. Changing TRIZ principles to a specific solution.

Principle no.	TRIZ principles	Specific solution
4	Asymmetry	– Stable design of product – Flexibility in manufacturing operations
5	Merging	– Combining vibration and rotation motion for efficient machine structure
8	Anti-weight	– Saving energy and less material consumption
14	Spheroidicity	– Making a smooth cylindrical shape – Equal circulation of plastic concrete
17	Another dimension	– The vertical machine replaces the horizontal machine to save working floor
18	Mechanical vibration	– Mixing the concrete particles and removing unnecessary voids to make a durable product
20	Continuity of useful action	– Can be able to produce varieties of products
28	Mechanical substitution	– Minimization of operating noise through the vertical machine structure
29	Pneumatics and hydraulics	– Use hydraulic or pneumatic damper for the vibration base to obtain a stable operation

Table 3. Scoring table for the identification of the best concept.

Concepts											
		Concept 1		Concept 2		Concept 3		Concept 4		Concept 5	
Selection criteria	Weight	Rating	Weighted score	Rating	Weighted score	Rating	Weighted score	Rating	Weighted score	Rating	Weighted score
Product variety	8	2	16	5	40	3	24	5	40	3	24
No penetration of liquids	9	4	36	4	36	4	36	4	36	4	36
Ease in manufacturing	6	3	18	4	24	3	18	3	18	5	30
Uniform density of the product	7	3	21	3	21	4	28	5	35	4	28
Ease of handling	6	4	24	3	17	3	18	3	18	5	30
Durable product	9	3	27	3	27	3	27	5	45	4	36
			142		166		151		192		184
			No		No		No		No		No

concept are the vibration, compaction, and centrifugal rotation achieved through the use of a vibratory table and screw core.

4.1 Concept selection

In this stage, the developed concepts are analyzed and sequentially eliminated to identify the most promising design. The evaluation criteria and objective weight can be determined subjectively via team consensus or through the rational intent of the designer. Representative ratings are valued from 1 to 5, representing design quality from worst to best [8]. Once all concepts are rated, a total weighted score for each design is calculated using the following formula:

$$S_j = \sum_{1}^{n} r_{ij} w_i \,, \tag{1}$$

where S_j, n, r_{ij}, and w_i are the total score of concept j, number of selection criteria, raw rating of concept j for the ith criterion, and weighting of the ith criterion, respectively.

The relative strengths and weaknesses of alternative molding machine designs can be identified by investigating the concept scoring matrix, as shown in Table 3. The overall performances of the various solutions are ranked based on their total score. Concept 4 has the highest score. Therefore, its design using an inner die with a spiral-shaped screw can be considered the best.

The concept scoring method can help designers to identify the strengths and weaknesses of alternative designs. The best choice is derived through the combination of the advantages of different concepts to satisfy the functional requirements. This technique is also an efficient approach because, when design requirements are changed, only the weighting information needs to be adjusted to reflect the variations, and most of the scoring information can still be used.

4.2 System improvement and realization

The target requirements of the developed machine are revisited based on the concept selected to investigate mechanical behavior and structure. The configured system is depicted in Fig. 5, and its key components are listed in Table 4. The vibration table, inner die, outer die, and support structures were fabricated in a CAD environment to achieve viability of the system. This vertically oriented design is a semiautomatic operating machine that produces reinforced and non-reinforced circular pipes. Furthermore, the current developed model is a highly flexible machine with a vibration base

Table 4. Machine components.

Number	Name	Number	Name
1	Motor	11	Locking mechanism
2	Gear	12	Fixing hole
3	Bearing	13	Vibration base
4	Chain	14	Vibration motor
5	Frame	15	Base plate
6	Conveying system	16	Sliding area
7	Paddle	17	Coupling
8	Drum for shaping	18	Shaft
9	Support plate	19	Upper panel
10	Outer die	20	Thrust bearing

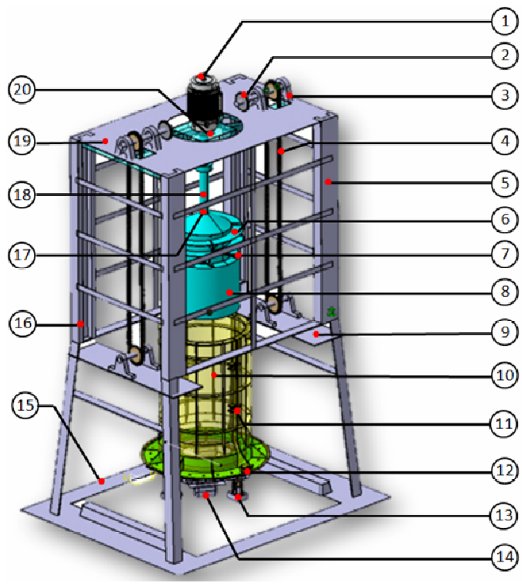


Fig. 5. Design improvement of the concept system.

equipped with a controllable switch to manufacture various pipe sizes. The process chain can be divided into the following steps:

Step 1: The inner die is mounted at the topmost position, and the outer die is fixed at the vibration base.

Step 2: The inner die is moved to the lowermost position, and fresh concrete is fed from the topside.

Step 3: The inner die is rotated, and the machine base is vibrated. Then, the inner die starts to rotate and move upward in slow motion. Vibration is continuous to remove air voids in concrete.

Step 4: The manufactured pipe is taken out. The inner die and outer die are returned to the initial position for the next cycle.

5. Topology optimization of the inner die

5.1 Research method

In the developed machine, the inner die accounts for a large volume compared with the other components and is driven by the rotation-powered motor. The weight reduction of the inner die has a substantial effect on machine stability and energy efficiency. Weight savings can be divided into two branches, namely, material improvements and structural optimization [9]. For the first approach, manufacturing machine components with lighter material assures certain mass reductions. However, this method is capital intensive. By contrast, structural optimization, such as topology optimization [10], shape optimization, size optimization, and topography [11], is inexpensive. Therefore, reducing die volume based on topology optimization can be considered a positive method to improve machine efficiency.

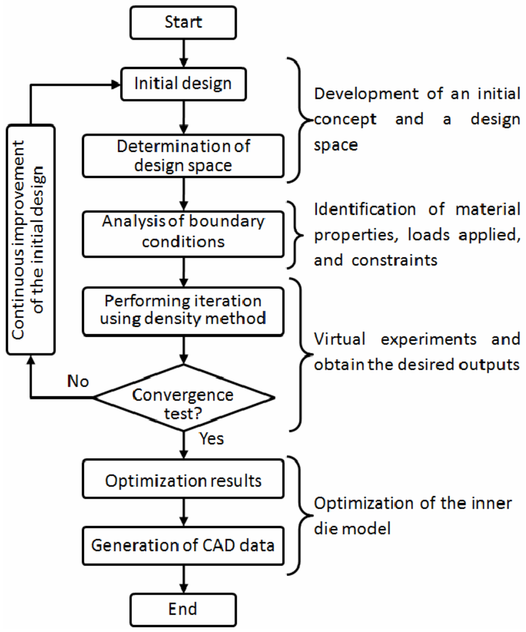


Fig. 6. Topology optimization procedure.

The systematic procedure for topology optimization of the ribs of the inner die is shown in Fig. 6. First, the initial concept of the inner die model was designed with the help of CATIA V5R20. The design space, material properties, applied loads, and constraints were determined to define the correct inputs. Then, a finite element-based inner die model was developed using HyperMesh with the defined constraints [12]. Subsequently, the solver Optistruct 10.0 was used to derive the optimal solution through convergence values [13]. A hypergraph was used to display and plot the optimal data for the interpretation of the results. Finally, the optimization results were exported to CAD data for a 3D representation of the structure.

Topology optimization is a powerful technique widely used in industrial applications to improve design efficiency. Through an iterative process, the material distributes within a given design space considering defined objectives and boundary conditions. The density method is considered an effective approach among topology optimization techniques and assumes that the stiffness of the material is linearly dependent on its density. Thus, the topology optimization problem can be written as follows:

$$\text{Minimize } f(x) \tag{2a}$$

Subject to:

$$g_j(x) - g_j^U \le 0;\ j = 1, 2, ..., m, \tag{2b}$$

$$X_i^L \le X_i \le X_i^U;\ i = 1, 2, ..., m, \tag{2c}$$

where $f(x)$, $g_i(x)$ and g_j^U denote the objective function, jth constraint response, and its upper bound, respectively. $f(x)$ and $g_i(x)$ are the structural responses, including mass volume fraction, compliance, frequency and displacement. X_i and m represent the number of constraints and the normalized material density of the ith element, respectively. The material density of each element is used as a design variable that varies between 0 and 1 to represent void or solid states, respectively. A penalization method is used to track the stiffness values of elements with intermediate densities to force the design to be close to a 0/1 solution. For the solid isotropic material with penalization approach, the penalization method is achieved using the following power laws:

$$\rho_i = x_i \rho_0, \tag{3}$$

$$E_i = (x_i)^p E_0, \tag{4}$$

where ρ_i, ρ_0, E_i, E_0 and p are the actual density, original density, actual Young's modulus, original Young's modulus and penalization power, respectively.

5.2 Optimization problem

Simplifying the geometric structure of the inner die is necessary to save simulation time and cost. In this work, the total volume of the inner die and an upper attachment area for coupling to the drive shaft are considered the design space, as shown in Fig. 7(a). In this way, the upper part was fixed and a rib thickness of 5 mm was maintained during iteration.

During the analysis, the worst scenario with the maximum load applied on the inner die is considered. The total acting force is the sum of four components, namely, frictional force, centrifugal effect, pressure loads and drag force. These forces can be classified into five main categories, namely, resistance force at area 1 (F_1), resistance force at area 2 (F_2), drag force at area 3 (F_3), drag force at area 4 (F_4), and centrifugal force (F_c), as shown in Fig. 7(b); these forces are defined by Eqs. (5)-(9), respectively, as follows:

$$F_1 = P_1 \times A_1, \tag{5}$$

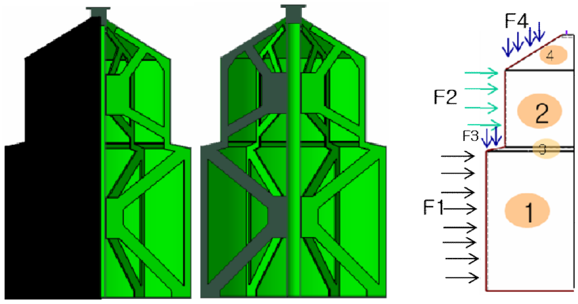
$$F_2 = P_2 \times A_2, \tag{6}$$

$$F_3 = 0.5 C_d \rho A_3 V^2, \tag{7}$$

$$F_4 = 0.5 C_d \rho A_4 V^2, \tag{8}$$

$$F_c = ma, \tag{9}$$

where P_1 and P_2 denote the pressure at areas 1 and 2, respectively. A_1, A_2, A_3 and A_4 represent reference areas 1, 2, 3 and 4, respectively. C_d, ρ, V, m and a denote the drag coefficient, density of fluid, speed of the object relative to the fluid, mass of concrete, and acceleration of the inner die in the upward direction, respectively.



(a) Inner die design space (b) Load conditions

Fig. 7. Inner die model for topology optimization.

A finite element-based inner die was developed in the commercial explicit software HyperMesh to investigate the structural responses of the initial design. A 3D tetrahedral meshing element was used for each analysis with curvature and proximity adaptation enabled to obtain reliable results. The die material was specified as steel and defined as linear isotropic (MAT1). The Young's modulus and Poisson's ratio used were 2.1×10^5 N/mm^2 and 0.3, respectively. The preventative outputs of a numerical experiment of an initial concept, including a Von Mises stress of 1.87×10^7 N/m^2 and displacement of 0.0357 mm, are presented in Fig. 8. The purpose of this optimization is to minimize the die volume such that the Von Mises stress and displacement are smaller than the material yield stress and the analysis result of the initial design, respectively. Accordingly, the optimization problem can be formulated with the following expression:

Minimize compliance $(C) = F^T C$

Subject to: $V = fV_0 = \sum_{\rho=1}^{n} (x^e v^e) \le V$

Von Mises stress $\le 2.5 \times 10^8$ N/m^2

Displacement ≤ 0.0357 mm .

The design sensitivity with respect to the variable (normalized density) and objective (compliance) can be expressed as Eq. (10) to save iterative time and increase optimization accuracy. This expression can be written in another form as Eq. (11):

$$\begin{aligned} \frac{\partial \varphi}{\partial \rho_i} &= \frac{\partial (F^T U)}{\partial \rho_i} = \frac{\partial}{\partial \rho_i}(U^T K U) \\ &= \frac{\partial (U^T K)}{\partial \rho_i} U + \frac{(U^T K)\partial U}{\partial \rho_i} \\ &= U^T \frac{\partial K}{\partial \rho_i} U + K \frac{\partial U^T}{\partial \rho_i} U + \frac{(U^T K)\partial U}{\partial \rho_i} \\ &= U^T \frac{\partial K}{\partial \rho_i} U + \frac{(KU)\partial U^T + (U^T K)\partial U}{\partial \rho_i} \end{aligned}, \tag{10}$$

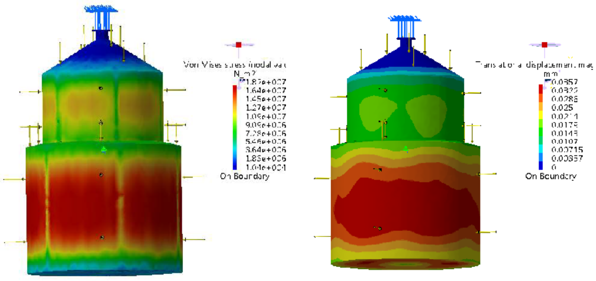


Fig. 8. Stress and displacement counters of the initial model.

$$= U^{\mathrm{T}} \frac{\partial K}{\partial \rho_{\mathrm{i}}} U + \frac{K(U \partial U^{\mathrm{T}} + U^{\mathrm{T}} \partial U)}{\partial \rho_{\mathrm{i}}}$$

$$= U^{\mathrm{T}} \frac{\partial K}{\partial \rho_{\mathrm{i}}} U + 2U^{\mathrm{T}} K \frac{\partial U}{\partial \rho_{\mathrm{i}}} = -U^{\mathrm{T}} \frac{\partial K}{\partial \rho_{\mathrm{i}}} U$$

$$-u_i^T \frac{\partial k_i}{\partial \rho_i} u_i \,, \tag{11}$$

where φ, K, k_i and u_i are the compliance, global stiffness matrix, ith element stiffness matrix, and ith element displacement vector, respectively [14]. Based on the sensitivity formulas, the convergence of the optimal topology was examined as follows:

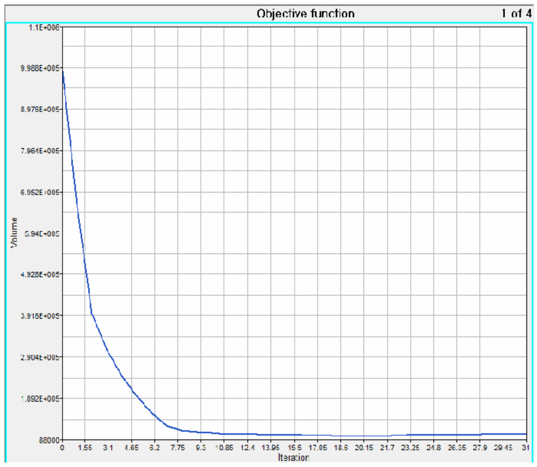
$$\left| \frac{C_{K+1} - C_K}{C_K} \right| < \varepsilon, \tag{12}$$

$$\left| \frac{\max(x_{K+1}) - \max(x_K)}{\max(x_K)} \right| < \varepsilon. \tag{13}$$

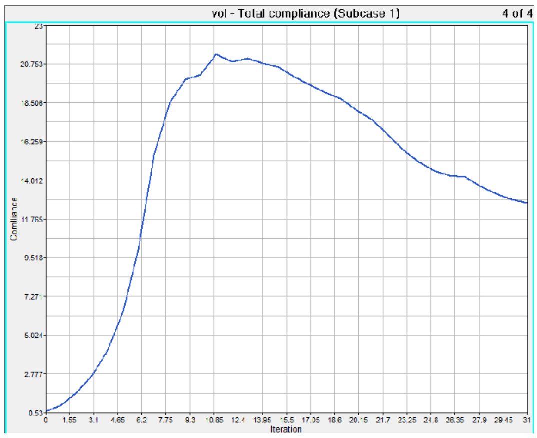
The relative difference among the design variables and objectives can be used as the judgment condition of a convergent result [15].

During the simulation time, the initial model was adjusted for a series of steps until convergence was reached. After several iteration steps, the target criteria is obtained when the values become stable. The history optimization is shown in Fig. 9, which illustrates the convergence value in each level of iteration to determine volume-saving potentials. The volume was observed to converge following 31 iterations to obtain a feasible geometry for the inner die. Although the topology results appear reasonable, the design is not ready for fabrication by the machine shop. Therefore, the interpretations were performed to create the final design by merging rough geometry. Then, the optimized rib shape was created with the support of CATIA V5R20 based on an IGES file exported from OptiStruct (Fig. 10).

The optimization results depicted in Fig. 11 show that the inner die volume exhibited an approximate reduction of 9.5% compared with the initial values; the displacement decreased by approximately 3%. Consequently, the final design retains the optimized features and outperforms the initial concepts.

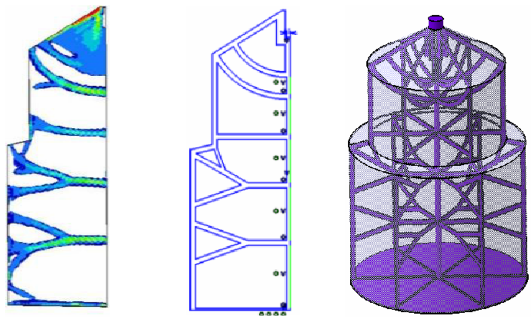


(a) Iteration convergence graph



(b) Compliance graph in each iteration step

Fig. 9. History optimization of the inner die.

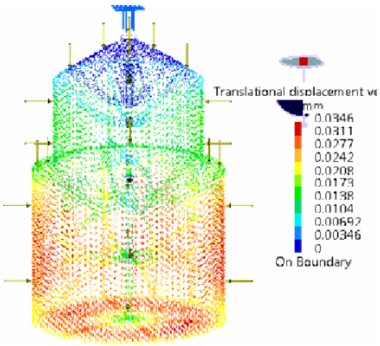


(a) Rough geometry (b) Final design of the inner die

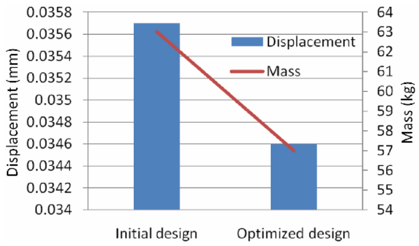
Fig. 10. Optimal machine structure.

6. Conclusions

In this study, a robust approach for the development and optimization of a molding machine of the SPC pipe has been presented through the TRIZ principles, concept scoring technique and topology optimization. The TRIZ method was employed to generate reliable concepts with respect to machine structure and product quality. The most efficient design and entire system configuration were recognized based on the



(a) Optimal displacement value



(b) Comparisons between initial design and optimal design

Fig. 11. Topology optimization results.

effective support of the concept scoring approach. The optimal solution for mass saving and displacement reduction of the inner die was determined by adopting topology optimization with the density method. The following conclusions can be drawn from this investigation:

(1) The most promising solution to improve manufacturing efficiency and pipe quality was a design using an inner core containing a spiral-shaped screw and a vibration base equipped with electric vibrators.

(2) The topology optimization resulted in approximately 9% reduction in mass and 3% decrease in displacement compared with the initial design.

Therefore, the proposed approach can help design engineers to effectively identify optimal structures for pipe manufacturing machines. Although attempts were made using simulation models, physical experiments are necessary and indispensable to verify the selected design and optimization results. Real experimentation and verification should be the subject of further work to enhance this study. In addition, a holistic optimization process that considers not only the inner die but also the outer die should be implemented in future studies.

Acknowledgments

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