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Optimum Shape Design of Axisymmetric Extrusion Die by using Hybrid Meta-Heuristic Optimization (ICACO)

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Abstract

The present study investigates the optimal design of the die shape in the metal forming process using extrusion. Due to the large deformations that occur during the forming process and the resulting entry into the plastic deformation zone, the finite element method is used to analyze the problem in this area, and the modeling is performed in the Eulerian system. The objective function of this study is to minimize the total energy required for deformation in the extrusion process. The design variable is the die shape, and spline curves with multiple control points are used to generate the die shape. Due to the nonlinear nature of the forming problem, the complexity, and the large amount of computation required during the analysis, a powerful combination of two metaheuristic optimization methods, the Imperialist Competitive Algorithm and Ant Colony Algorithm (ICACO), has been inspired for the optimal design of the die shape. To validate the obtained results for the die geometry, they are compared with the results presented in previous studies, the error was less than 2%, showing a good agreement. The results obtained have led to a significant reduction in the total energy consumption during deformation by approximately 12% compared to the conventional linear mode.

Keywords: Hybrid metaheuristic Method; Finite element analysis; Shape optimization; Spline; Imperialist competitive algorithm; Ant colony Optimization.

1. Introduction

In the past two decades, the use of optimization methods, particularly metaheuristic algorithms, has significantly increased in solving engineering problems [1]. Researchers have been able to invent hybrid optimization methods by integrating metaheuristic optimization approaches, which have shown promising efficiency in problem-solving [1 and 2]. Although metaheuristic optimization methods have been widely employed in structural optimization and solving engineering problems, their application in shape optimization and tool design problems has been limited. This is despite the fact that shape optimization in forming processes poses a common challenge [3 and 4].Lee et al. [5] have focused on the optimal design of a symmetric die for the extrusion process. In this study, the problem analysis in the plastic region is performed using the rigid-thermo-viscoplastic finite element method, and the die shape is modeled using the Bezier curves.

The achievement of an optimal design for an extrusion die with an asymmetric cross-section in the L-shape has been carried out by Yan and Xia [6]. In this research, the objective function considers the material flow velocity, which is estimated using an artificial neural network, and then the optimal design variables are calculated using a genetic algorithm. Gordona et al. [7] have successfully reached an optimal die shape design to minimize the average extrusion pressure using the upper-bound method and considering multiple velocity fields for the symmetric extrusion die.

One of the advantage of the current research compared to previous studies is the use of an Eulerian mesh for analyzing the extrusion process. The Eulerian mesh remains fixed in space, unlike Lagrangian meshing, and eliminates the issues associated with element distortion. In this study, the optimal design of a symmetric die for extruding a rod has been carried out to minimize energy consumption during shaping.

In this study, an optimal shape for the forming process has been achieved by starting with a set of random designs and utilizing the ICACO (Improved Combinatorial Ant Colony Optimization) metaheuristic method. The use of this optimization method has not been previously applied to the problem of achieving an optimal shape in metal forming processes. The ICACO method can converge to an overall optimal solution by striking a suitable balance between the extraction and exploration phases. To implement the proposed method, a computer program has been developed in the MATLAB software environment, and all computational stages, including curve generation, finite element analysis, objective function determination, and ultimately shape optimization, have been integrated into it.

2. Process Modeling

Eulerian modeling is suitable for forming processes such as rolling, deep drawing, and extrusion, where material deformation is large and continuous (similar to fluid flow analysis) and enters the plastic deformation zone. In this formulation, equations are considered for a fixed region in space called the control volume, and the material is analyzed as a fluid passing through and undergoing examination within the control volume. In this case, finite element discretization can be applied in the deformation zone. In the present study, the finite element method has been used to analyze the problem, and the following matrix equation is used to obtain nodal velocities, employing the general finite element solution.

3. Numerical Results

In the current research, the objective is to determine the optimal shape of the die curve in a way that minimizes the energy consumption rate required for the deformation of aluminum in the extrusion process. Splines with five control points have been used to design the die shape.

Table 1 presents the input specifications of the die and details of the extrusion process, which will remain constant throughout the analysis.

Table 1. Die Input Specifications in the Extrusion Process

Process Parameters	Input Data
Initial Diameter (mm)	36
Final Diameter in the First State (mm)	20.78
Die Length (mm)	20
Inlet Velocity (mm/s)	2
Friction Factor	0.5

In the extrusion process, energy consumption is one of the critical factors, and minimizing it can significantly reduce production costs. Table 2 provides the coordinates of control points and the energy consumption rate in the optimal state. The energy consumption rate for a die with a conical shape was determined to be 375.27 J/s using analytical methods. As presented in Table 2, for the optimized die shape designed with the proposed method, the energy consumption rate is 333.87 J/s. Therefore, the energy consumption in the optimal state compared to the conical state shows a reduction of approximately 12%.

In Figure 1, a convergence plot for the optimal die shape using the hybrid metaheuristic optimization method of Imperialist Competitive Algorithm-Ant Colony Optimization (ICA-ACO) and the Imperialist Competitive Algorithm (ICA) is depicted.

Table 2 - Values of Control Point Coordinates and Energy Consumption Rate in the Optimal State

Point Number	x-coordinates (mm)	y-coordinates (mm)
1	18.00	0.00
2	16.94	-5.00
3	14.99	-10.00
4	12.35	-15.00
5	10.39	-20.00
Energy Consumption Rate (J/s)		333.87

As observed, in the first iteration, the energy consumption rate is approximately 365 J/s. The mentioned algorithm was able to converge in fewer than 10 iterations, reducing the energy consumption rate by approximately 10% compared to the initial die shape, bringing it to about 333.87 J/s. This is in contrast to the competitive swarm optimization method, which converged after 19 iterations. Meanwhile, the final optimal solution obtained with this method converged to 333.98 J/s within the maximum specified number of iterations in the algorithm.

These results demonstrate the efficiency of the proposed optimization algorithm in achieving a significant reduction in energy consumption in a relatively short number of iterations, outperforming the competitive swarm optimization approach.

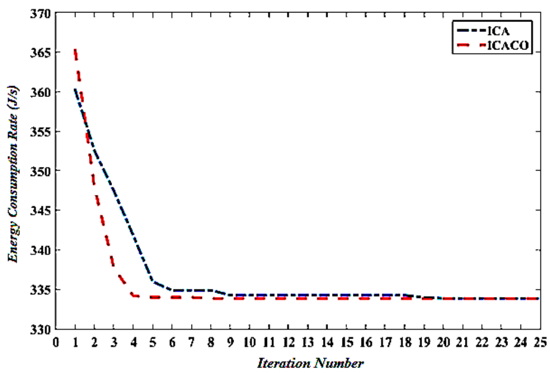

Figure 1 - Convergence Plot for Optimal Die Shape using Hybrid Imperialist Competitive Algorithm-Ant Colony Optimization (ICA-ACO) and Imperialist Competitive Algorithm (ICA) Methods

In Figure 2, the distribution of various stress components in a cylindrical coordinate system, including the equivalent von Mises stress, is presented in MPa in the optimal state.

4. Conclusion

In the present research, a novel design method for optimizing the die profile to achieve the minimum energy consumption during deformation in the extrusion process has been proposed. Finite element analysis was used for simulating the forming process, employing the flow formulation in the Eulerian system. Given that the problem analysis in this study requires time-consuming and complex calculations for each desired design in the optimization algorithm, a powerful hybrid metaheuristic optimization method called Imperialist Competitive Algorithm-Ant Colony Optimization (ICA-ACO) was utilized. This approach significantly reduces the need for analyzing the objective function for various designs.

The results indicate that the proposed method was able to reduce energy consumption by approximately 10% compared to the initial design and approximately 12% compared to the conventional conical shape.

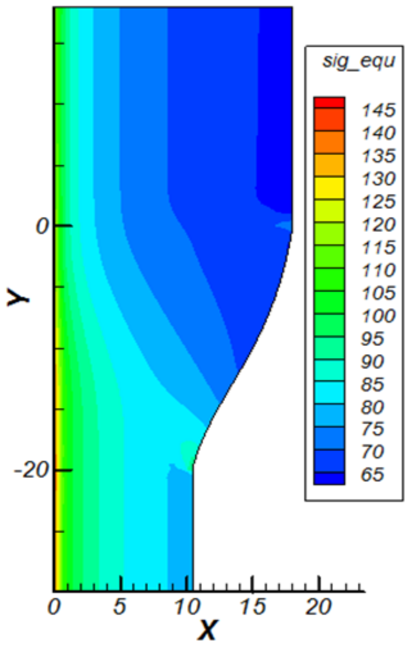

Figure 2 - Distribution of Von Mises Stress in MPa during Material Extrusion in the Optimal Die Shape

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