# Thermal optimisation of the squeeze-forming process using genetic algorithms

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## Abstract

The paper deals with a thermal optimisation of the squeeze-forming process using a genetic algorithm. The objective function is evaluated using the finite element method for the transient thermal system in which the die cooling design is explored. The objective function is nonlinear with respect to coolant channel position. The objective is to achieve near simultaneous solidification in a cast part by varying the position of coolant channels in the die. This shape optimisation is done automatically by integrating finite element analysis with remeshing and a genetic algorithm program. The achievement of a design that achieves near simultaneous solidification is demonstrated.

*Keywords:* Squeeze forming process; Nonlinear optimisation; Genetic algorithms; Finite element method; Remeshing; Die cooling design

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## 1. Introduction

The squeeze-forming process has significant benefits over other forming processes. These include near net shape manufacture, refined grain structure, improved mechanical properties, virtual elimination of all shrinkage and gaseous porosity and also a high process yield. Although there are many benefits in the squeeze-forming process, the process cannot avoid thermal residual stress build-up because of a non-uniform solidification pattern. Thus the cooling process has a dominant role in achieving components that are free of defects and the achievement of near-uniform solidification and cooling may have a significant benefit in minimizing such residual stress buildup.

The squeeze-forming process incorporates the following important stages: mold filling (metered pouring) and metal displacement, and pressurisation and solidification. From the stages mentioned, pressurisation and solidification account for about 50% of the cooling cycle time [1]. This work also suggests that, when shrinkage effects are excluded, the applied pressure has negligible effect on the solidification rate of the cast part. It is likely that this will not be the case when mechanical contact pressure falls as a consequence of the development of mechanical strength and subsequent differential shrinkage between the part and die.

This paper deals with a thermal optimisation of the squeeze-forming process by varying the position of coolant channels in order to obtain near simultaneous solidification in the cast part. This paper explores the use of a genetic algorithm and a stochastic approach to find the optimum value of the objective function. To do so has involved an integration of thermal analysis with remeshing and optimisation through a genetic algorithm code.

## 2. Finite element model

Simulation of all forming processes is particularly demanding since they are inherently complex and nonlinear. In the direct squeeze-forming process, subsequent to the filling and metal displacement stage, pressure is applied by the upper punch during solidification. Because of this no air gap is created at the casting–die interface during the early stages of the solidification process. Thus perfect thermal contact is assumed and

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hence the interfacial heat transfer coefficient is high and independent of the air gap evolution.

The cooling and solidification cycle in the casting process can be described by the heat conduction equation written in discretised form as [2]

$$\mathbf{C}(\mathbf{T})\{\dot{\mathbf{T}}\} + \mathbf{K}(\mathbf{T})\{\mathbf{T}\} = \mathbf{F}$$

where **K** and **C** are the conductivity and heat capacity matrices and **F** is the thermal loading vector.

Thermal resistance will be present when two separate bodies are in contact and for a strategy in which thermal contact will be important, specifically when differential thermal shrinkage occurs and interface pressure falls there will be a need to account for this. There are a number of ways of modelling the thermal interface between the die and cast part. In this work, the heat transfer at the die–cast interface is modelled as a convection heat transfer mechanism [3]. This has been done to deal with the situation where nodes in the die and cast part are not constrained to be coincident, hence simplifying the finite element meshing requirements.

## 3. Nonlinear optimisation

There are a number of process parameters that may be explored to optimise the squeeze-forming process. For a prescribed part shape these include overall die dimensions and the cooling system position and size. The current work focuses on the latter and will investigate a method whereby coolant channel position may be optimised, subject to a prescribed heat transfer coefficient that is determined by the flow regime within the coolant channel. Mathematically, nonlinear optimisation of the coolant channel system can be defined as follows:

Min $f(\mathbf{x})$

Subject to $\mathbf{x} \in \Omega$

$\mathbf{x} = [\mathbf{x}_1, \mathbf{x}_2, \cdots, \mathbf{x}_s]^T$

where $f(\mathbf{x})$ is a nonlinear objective function, $\mathbf{x}$ the design variables and $\Omega$ the feasible decision space.

### 3.1. Objective function

There are a number of objective functions that may be defined to optimise coolant system position. To achieve near simultaneous solidification, the objective function may be defined as minimising the following:

$$F(x) = \frac{1}{\Omega_C} \int_{\Omega c} [(T_{\max} - T_{ave})^2 + (T_{\min} - T_{ave})^2]^{1/2} d\Omega$$

where $\Omega_C$ is the cast part domain. $T_{\max}$ and $T_{\min}$ are the maximum and minimum temperatures in the cast. $T_{\text{ave}}$ is the average temperature in the cast part,

$$T_{\text{ave}} = \frac{\sum_{i=1}^{NC} T_C}{NC}$$

where $T_C$ is the average temperature of the cast element and $NC$ is the total number of elements in the cast. This has been developed to achieve the goal of near-uniform temperature throughout the cast part.

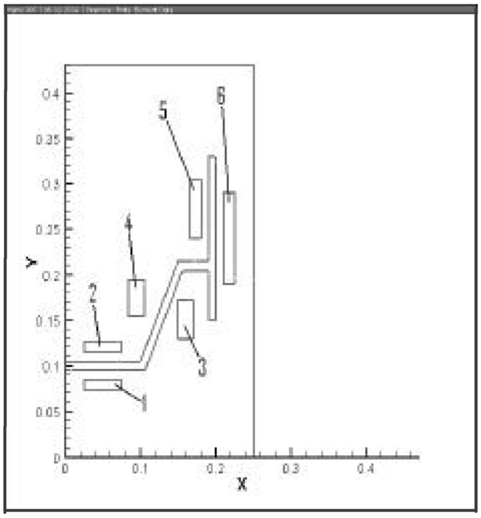

Fig. 1. Coolant channels numbering.

### 3.2. Design variables and constraints

Figure 1 shows the numbering of coolant channels. Design variables for the coolant channels position can be represented as follows and ensures that the coolant channel is located within the die space:

xi = X-coordinates of coolant channel i (i = 1,2,. . .,6)

x(j + 6) = Y-coordinates of coolant channel j (j = 1,2,. . .,6)

Only inequality constraints are applied to the coolant channel position design. These constraints are of the form

$$x_k - x_{\min} \geq 0$$
$$x_{\max} - x_k \geq 0 \qquad (k = 1, 2, \ldots, 12)$$

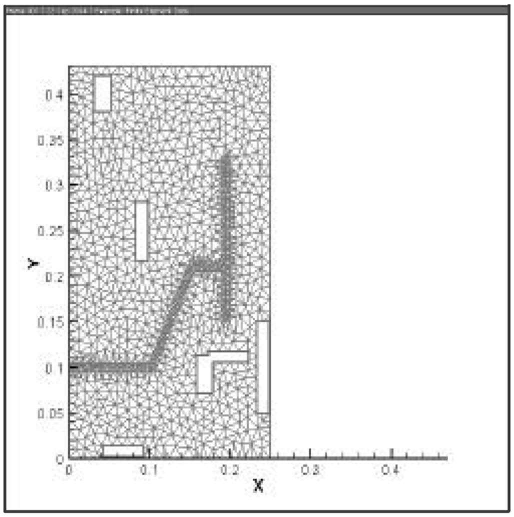

Fig. 2. Finite element mesh in the cast part and die for the optimal solution.

## 4. Numerical example

The thermal optimisation of an axisymmetric squeeze-formed part is presented. The initial temperature of the cast was 700 °C. The cast material is aluminium LM25 whereas the die is steel. This has an initial temperature of 200 °C, the heat transfer conditions in the coolant system correspond to a heat transfer coefficient and reference temperature of 1000 W/m$^2$ °C and 100 °C respectively and heat is removed from the external surfaces in accordance with a heat transfer coefficient to 25 W/m$^2$ °C and an ambient temperature of 30 °C. Perfect contact is assumed at the die and cast interface, hence an interfacial coefficient of 5000 W/m$^2$ °C was applied. The coolant channels have a fixed geometry, only their positions may be varied.

Figure 2 shows a typical finite element mesh in the cast part and die for the optimal solution. The mesh is concentrated in the cast part and the element quality is good. Similar high-quality meshes were generated for other geometric configurations. Figure 3 shows the transient thermal solution at $t = 50$ s for both the initial and optimum position of coolant channels, the latter obtaining near simultaneous solidification in the cast part. The minimum objective function value obtained was 62.8 °C. From Fig. 3 it can be observed that in order to achieve near simultaneous solidification the coolant channels are positioned to control the shape of the zone of high temperature surrounding the cast part.

It is known that genetic algorithms require extended calculation time to converge onto an optimum solution. This case study has taken one day to obtain the optimal solution for near simultaneous solidification using a genetic algorithm. The calculation itself required 1400 minutes and the solution was achieved in 70 generations. This confirms that the approach is practically useful in achieving a result to provide initial design guidance. Also, before implementing the process optimisation as described in this case study, two simple case studies have been explored. These cases involve minimising the square temperature difference between two points inside the cast part, effectively imposing directional

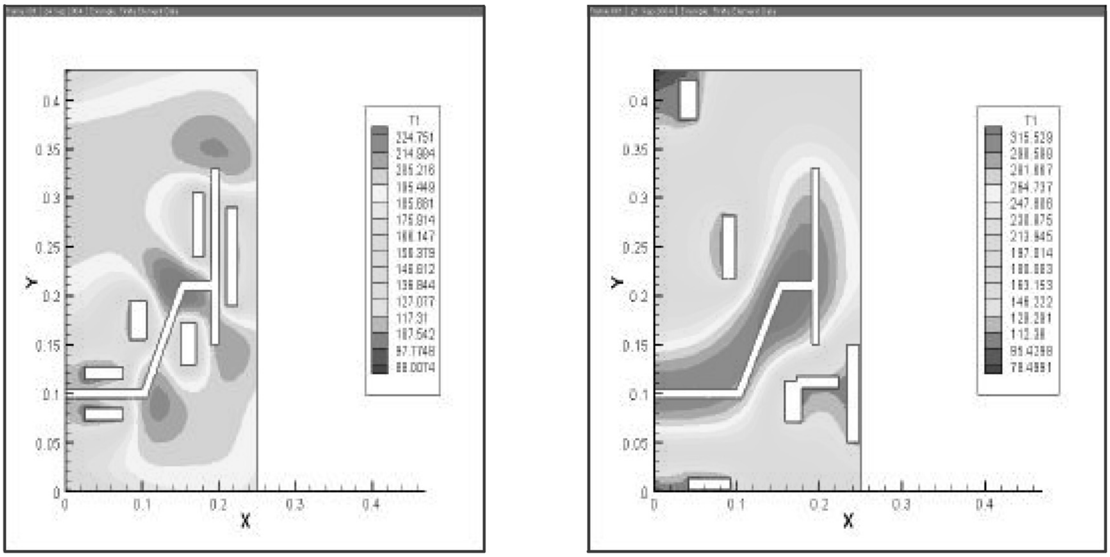

Fig. 3. Temperature distribution in the die at $t = 50$ s for both the initial and optimum position of coolant channels.

solidification. This directionality was observed in the solution, confirming the correct functioning of the approach.

## 5. Conclusions

This paper presents results on using a genetic algorithm to achieve optimisation of cooling channel position to obtain near simultaneous solidification in the cast part. The study confirms that near simultaneous solidification can be achieved through optimal coolant channel position. The next stages of this work will examine optimisation when contact pressure is allowed to relax as a consequence of differential thermal contraction, requiring the integration of nonlinear thermal and mechanical analyses.

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