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A new algorithm for reduction of number of press-forming stages in forging processes using numerical optimization and FE simulation

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Abstract

This study presents a new simulation-based technique for the optimum design of a multi-stage forging process aiming at reduction of the number of press-forming stages. This iterative design technique involves response-surface-based numerical optimization and a finite element analysis of the process. The design procedure starts with an initial process design that is deemed too conservative, i.e. allows to arrive at the desired product but involves an excessive number of stages. To obtain a better process design, one stage of the existing multi-stage process is eliminated using numerical optimization in conjunction with an FE simulation. This is repeated by reducing the number of stages one by one until the minimum possible number of stages is reached. This design technique is applied to stage reduction of a three-stage forging process of an axisymmetric aluminum billet. It is confirmed that a new two-stage process design is obtained successfully and the developed design optimization technique showed its effectiveness in reduction of the number of press-forming stages in a multi-stage forming process.
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Keywords: Multi-stage forging process; Reduction of the number of press-forming stages; Numerical optimization; FE analysis

1. Introduction

Many metal parts of complex shape are formed by a multi-stage forging process. Reduction of the number of press-forming stages is the most efficient approach for the reduction of manufacturing costs and time. Therefore, it is very important to determine the optimum multi-stage process design which has the minimum number of press-forming stages. Optimization of the process design can be achieved by eliminating redundant stages and optimizing working conditions including tool design for every press-forming stage. In current practice such process improvement is performed mainly using a trial and error experimental approach that requires long time and high cost. Nowadays, numerical optimization based on the finite element analysis offers a better choice.

Although several researchers applied numerical design optimization for various plastic forming processes [1–5], such optimization procedures are not applicable to the problem of reduction of the number of stages in a multi-stage process. Another numerical approach to a multi-stage process design is an application of numerical simulation linked to a knowledge-based system [6]. However, such system entirely depends on a sufficient amount of data available in advance.

In this study, we propose a new technique for a multi-stage forging process design specifically aiming at the reduction of the number of stages. It arrives at the optimum process design using response-surface-based numerical optimization and finite element analysis of the process without relying on an existing database. This design technique has been applied to a problem of reduction of the number of stages in a three-stage axisymmetric forging process of aluminum billet [7,8]

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Nomenclature

Optimization

n	number of press-forming stages in initial forging process
p_i	nodal points of tool model
$\boldsymbol{x}$	vector of design variables
x_i	design variable
N	number of design variables
A_i, B_i	lower and upper bounds for design variable x_i
$F_0(\boldsymbol{x})$	objective function
$F_j(\boldsymbol{x})$	constraint functions
C_i	limitation values for constraint functions
M	number of constraint functions
$\tilde{F}_0^k(\boldsymbol{x}, \boldsymbol{a}_0^k)$	mid-range approximation of $F_0(x)$
$\tilde{F}_j^k(\boldsymbol{x}, \boldsymbol{a}_j^k)$	mid-range approximations of $F_j(x)$
$\boldsymbol{a}_j^k$	vector of tuning parameters for approximation
a_i	tuning parameters for approximation
A_i^k, B_i^k	lower and upper bounds for design variable x_i in approximated sub-problem
$\boldsymbol{x}_*^k$	optimum point for approximated sub-problem
$w_p^{(0)}$	weighting coefficient for least square fitting of approximation
P_e	number of points in a design of experiments for least square fitting of approximation

FE analysis

ΔL_l	distance from nodal point on the product contour to target contour (mm)
r_l	radial position of nodal point on the product contour (mm)
n_c	number of nodal points on the product contour
V	volume of target product (mm^3)
P	forming load (kN)
ΔP	load limit tolerance (kN)
$\bar{\varepsilon}$	equivalent plastic strain
ε_f	fracture strain
$\bar{\sigma}$	equivalent stress (MPa)
σ_m	mean stress (MPa)
a, b	material parameters in the Oyane's fracture criterion
Φ	Oyane's ductile fracture integral parameter
H	inner cavity height of product (mm)

demonstrating its effectiveness for the improvement of a multi-stage forging process.

2. Stage reduction algorithm by using numerical optimization

Fig. 1 illustrates the basic idea of stage number reduction technique for obtaining the optimum multi-stage process design. The design procedure starts with an initial process design that is deemed too conservative, i.e. allows to arrive at the desired product but involves an excessive number of press-forming stages (n stages). In order to create the new process design that consists of $n-1$ stages, one stage in the former process is eliminated. The new process design is determined by numerical optimization in conjunction with a finite element analysis of the process. The above procedure is repeated reducing the number of stages one by one until the minimum possible number of stages is achieved.

In optimization, design parameters of tools, billet shape and forming conditions can be described by design variables. The optimization computing effort strongly depends on the number of design variables so it is important to introduce only as few of them as possible. On the other hand, for many products the tool shapes are very complex so the choice of design variables should be capable of adequate description of such shapes. For that purpose, a morphing procedure is suggested. The tool design of the stage i in the new process is generated by morphing the geometry of the tool design of the stage i in the former process onto that of the stage $i+1$. This means that in the morphing procedure the tool designs of the former stages i and $i+1$ are treated as two extremes with a new tool design lying somewhere between them. This new stage i tool design is automatically generated as the intermediate shape which is determined by morphing parameters that are design variables in the optimization procedure. Fig. 2 illustrates this process when only one morphing parameter is used and, therefore, one tool design is described by one design variable. For more dramatic transformations of the tool geometry between individual stages, it may be necessary to introduce several morphing parameters using some advanced morphing tools, e.g. HyperMorph tool in the finite element pre-processor HyperMesh [9] by Altair Engineering Inc.

The objective function (to be minimized) is the error in the shape of the product describing how close the current product is to the desired one. When the optimization for reduction of the number of stages is successful, the shape error approaches zero. In the closed die forging example given below this means that the tool shape of the new final stage becomes the same as that of the original final stage. In order to limit the forming load and avoid material fracture, appropriate constraints have to be introduced in the optimization problem.

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