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Determination of optimal blank holder force trajectories for segmented binders of step rectangle box using PID closed-loop FEM simulation

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Abstract Blank holder force (BHF) is one of the key parameters affecting the process of sheet metal stamping. Numerous researchers have demonstrated two primary failures (wrinkling and tearing) could be avoided if appropriate variable BHF profile was implemented during punch stroke. Several approaches are proposed to determine optimal BHF by experiment or FEM simulation. In this study, new control objective was adopted based on the definition and analysis of BHF formability window. The PID controller was integrated into FEM code to conduct closed-loop forming simulation of step rectangle box, through which the optimal BHF trajectories were determined for each separated binder. The trajectories were verified on a multipoint variable BHF hydraulic press and showed good effect to avoid wrinkling and tearing. The proposed BHF determination approach in this paper can be applied to stamping parts of different geometry due to the application of new objective, which makes it a robust strategy.

Keywords Blank holder force · Closed-loop simulation · PID · Stamping

Abbreviations i: No. i time of forming simulation · j: jth iteration of optimization · BHF: Blank holder force · BHFi,j: BHF after jth iteration for No. i time step of forming simulation · FWHi: Flange wrinkling height · SWHi: Side wrinkling height · FWHi,j: FWH after jth iteration for No. i time step of forming Simulation · SWHi,j: SWH after jth iteration for No. i time step of forming Simulation · FWHi,sr: Safe range of FWH · SWHi,sr: Safe range of SWH · nbst: Nominal blank sheet thickness · Ki: Proportional gain of PID controller · Ki: Integral gain of PID controller · Kd: Differential gain of PID controller · E: Error between desired amplitude and current amplitude · Ai,binder: Area of binder, unit m2 · Bmat: Constant BHF associated with material, Unit: KN · FLC: Formability limit curve

1 Introduction

Sheet metal stamping is one of the primary manufacturing processes for automobile body panels. Obviously, the part quality is affected by many factors, such as part geometry, blank material and lubrication, etc. However, for a given condition of part geometry, material and lubrication, blank holder force (BHF) resulting from binder with or without drawbead, is a key parameter controlling material flow. Typically, a constant BHF is applied throughout the punch stroke. On one hand, too low a BHF will cause excessive material flow into die cavity, which leads to wrinkling. On the other hand, too high a BHF will result in the failure of tearing. Despite that appropriate constant BHF could be gained through a careful experiment design, stamping under constant BHF will be infeasible at all because sometimes the minimum BHF that could suppress wrinkling has already caused tearing. Spatial or/and time variable BHF has demonstrated good effect on this problem [1].

Several approaches have been developed to estimate optimal BHF profiles. One type is through experiment investigation and analysis. Yossifon et al. [2] devised a diagram of BHF as a function of punch stroke through a series of constant BHF tests. Hardt and Fenn [3] presented two closed-loop methods for controlling the blank holder force in-process to ensure optimal forming conditions at all time. Siegert et al. [4] used a special sensor to measure the flow-in of the material into the die and this information was used to set up a closed-loop control system for adjusting blank holder force. Lo and Yang [5] developed a closed-loop control of the blank holding force in sheet metal forming with a new embedded-type displacement sensor. The researchers above were able to establish a BHF scheme based on an experiment system with closed-loop control. The measured BHF profiles obtained from these experiments varied significantly with variations of geometry and
properties of the sheet blank. The closed-loop control experiment system can give real-time control for BHF, but also gives demanding challenge for response speed of sensors and control system.

FEM simulation is another method to obtain optimal BHF. Sim and Boyce [6] conducted FEM analyses of actual closed-loop feedback control laws which had previously applied in experiments of [3]. A PI control strategy to estimate binder force was developed by Cao and Boyce [7]. Krishnan and Cao [8] incorporated an ARMA model into Abaqus/standard FEM codes to estimate the optimal blank holder force for segmented binders of rectangular pan. An adaptive simulation using PI controller was developed by Sheng et al. [9] to predict variable BHF for two conical cup drawing operations. Chengzhi et al. [10] developed an adaptive response surface methodology (ARSM) to determine the optimal spatial variable BHF for a rectangle box. Though all these researchers mentioned above gave effective approaches to optimize the variable BHF through FEM simulation, some issues such as paradox due to the control of multi objectives, still remain unsolved, while a vast number of simulations needed by ARSM to form response function limits its practicability.

In this study, a new control objective was proposed based on the definition and analysis of BHF formability window. Then two PID feedback controllers using new control objective were integrated into dynamic explicit FEM code "LS-DYNA3D", which is used popularly in the simulation of sheet metal forming. The closed-loop simulation model using the proposed PID controller was applied to determine optimal BHF trajectories for six segmented binders of a step rectangle box. The obtained optimal trajectories were tested on a multipoint variable BHF hydraulic press and gave good control of two major failures of sheet stamping, i.e., wrinkling and tearing. The combination of new objective and new PID controller makes the proposed approach in this paper a robust strategy and has a better implementation.

The rest of this paper is organized as follows: In Sect. 2, the BHF formability window will be defined and analyzed, based on which the new control objective will be introduced. Then the model of PID closed-loop FEM simulation will be developed. Section 3 will use FEM code integrating the above model to conduct a closed-loop forming simulation for a step rectangle box, and optimal trajectories are then determined in this section for six segmented binders. The experiment verification will be also conducted in Sect. 3 on a multipoint variable BHF hydraulic press, the results of which will also be compared with those under constant BHF profiles. Section 4 states the conclusion.

2 Closed-loop PID control model

2.1 BHF formability window

In 1983, Doege and Sommer [11] examined the possibility of controlling the BHF with respect to the displacement of the punch as a means of safely avoiding the onset of buckling or tearing, as shown in Fig. 1. Using the concept of “success” in Fig. 1, this working window could be defined as BHF formability window similar to the popular forming limit curve (FLC), which is used to denote the fracture strain limits of a material. And the strip region between the critical wrinkling and the fracture BHF is the safe region (shown in Fig. 2) of BHF formability window. Figure 3 shows four basic types of BHF formability window, in which type a, c, d have forming window, type b has no forming window at all. Moreover, type a could be formed free of wrinkling and tearing under constant BHF if the magnitude of the predefined BHF is between the lowest point of the critical tearing BHF and the highest point of the critical wrinkling BHF. Certainly, this proper constant BHF would be obtained through a careful design of experiment or FEM simulation. However, type c and type d could only be formed successfully under variable BHF.

As stated in the introduction, the BHF plays a key role in affecting the amount of material drawn into the die cavity. From Fig. 3, one important conclusion, which should be drawn, is that the minimum BHF that can suppress wrinkling would never cause tearing in those formable BHF windows, i.e., type a, c and d, thus the critical wrinkling BHF in the BHF formability window is the optimal BHF trajectory during punch stroke. The smaller the BHF, the more material would be drawn in and the less possibility of tearing. Therefore, unlike literature [7–9], in which the control strategy would be switched from a binder

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![Fig. 1 BHF working window of [11]](image1)

![Fig. 2 The definition of BHF formability window](image2)