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Geometrical compensation of deterministic deviations for part finishing in bulk forming

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ABSTRACT

The design and development of bulk forming processes build upon inefficient trial-and-error procedures, especially in industrial practice. Furthermore, manual redesign procedures to transform discrete measurement data or numerical meshes into parametric descriptions cause approximation errors and are not continuously automatable. To achieve the required final accuracy in the part finishing, various iterations consisting of numerical simulations, subsequent real tests and redesign steps have to be carried out. To address these issues, a data-driven numerical strategy to compensate for deterministic deviations of bulk-formed parts is deduced, adapting methods used for springback compensation in sheet metal forming. Due to a parameter-based approach, control points allow for a connection between material points of the part and the tool. As a consequence, a direct mapping between the die and the workpiece in the parametric space is possible. Thus, based on the required part shape the die can be directly adjusted, where any kind of geometrical input data can be provided to determine a systematic compensation. Utilizing the purely geometrical approach takes into account all of the systematic effects causing deterministic deviations. The scope of applications comprises closed-die finishing operations fulfilling the constraint of intimate contact between component and die. The proposed concept is presented and applied to real components. The deviation data of three manufactured industrial bulk forming parts is utilized for validation and verification.

1. Introduction

In many cases, the complex interdependence of the thermo-elastic-plastic material behavior as well as the tool-workpiece system leads to an insufficiently precise numerical modeling of the bulk forming process when the classical approach is used (Zhang et al., 2016). This results in an increased need for prototypic tools, complex reworking and higher control expenditure during manufacturing. Furthermore, the design and development process (computer-aided engineering, CAE) is currently not performed in a holistic environment, but is divided into a design part (computer-aided design, CAD) and a numerical analysis part (for example finite element method, FEM) (Hattangady et al., 1999). This is also reflected through digital or numerical assistance systems dealing with different model representations. CAD usually applies parametric models, whereby numerical analyses are executed on discrete meshes. Due to the separation, a hardly automatable surface reconstruction process of forming tools and components in CAD based on discrete results is required. This has serious potential to significantly increase the efficiency of design and development processes in bulk forming (Herbertz et al., 2013).

To cope with the geometrical accuracy of manufactured components, a careful separation between the deterministic and stochastic portions of geometric deviations is necessary. Stochastic deviations typically arise from variations of the material or the tribology, which use to be focused on process robustness and cannot be directly eliminated by tool compensation. Furthermore, stochastic influences and deviations are handled by prescribing manufacturing tolerances. In contrast, deterministic deviations are unique, unidirectional, and have systematic, identifiable causes and characteristics. Thus, deterministic deviations can be fixed by tool compensation. Fig. 1 illustrates the difference between deterministic and stochastic deviations. To separate the two types of geometrical deviations, a suitable number of measurements depending, for example, on the component shape or the manufacturing process, is necessary.

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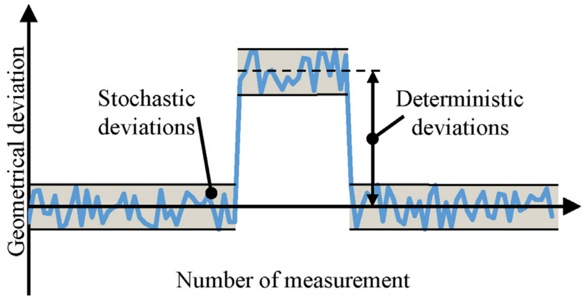

Fig. 1. Schematic illustration of the difference between deterministic and stochastic geometrical deviations. To be able to separate the two types of geometrical deviation, a suitable number of measurements is necessary.

2. State of the art

Two main areas of forming technology are sheet metal forming and bulk forming. Because of different approaches in the design, process layout, numerical modeling and final manufacturing, methods for problem solving evolve in parallel with only a few points of contact. However, geometrical accuracy of the final part is a main objective of both areas. The approach for the geometrical compensation of bulk-formed parts brings together methods from sheet metal forming and bulk forming.

2.1. Springback compensation in sheet metal forming

In sheet metal forming elastic springback is a major problem with regard to geometrical accuracy (Maia et al., 2017). Different methods for the compensation of elastic springback have been proposed. Gan and Wagoner (2004) introduced an iterative approach called "displacement adjustment method" and compared it to the iterative traction-based springforward procedure used by Karafillis and Boyce (1992) for two-dimensional problems. Lingbeek et al. (2005) utilized a parameterized formulation (smooth displacement adjustment and surface controlled overbending) for die geometries and thus could transfer springback compensations strategies into CAD environment. It was found that for successful industrial application, accurate springback prediction, commonly performed by FEM analysis, is crucial. An enhanced method for springback prediction using variable corrective factors for displacement adjustment is utilized by Meiders et al. (2008). Yang and Ruan (2011) take into account the surface normal direction of the die shape and the component geometry by introducing an angle correction for displacement adjustment compensation. In order to ensure feasibility of the die, Livatyali and Ergeldi (2006) implemented an additional step in the compensation routine to correct critical points such as undercuts, for example. The complexity of springback compensation increases significantly for three-dimensional problems. For flanged parts with joggles, Liu et al. (2017) used control surfaces based on cross sections of circular arcs for springback prediction and compensation. The method provided by Mole et al. (2014) generalizes present approaches and enables springback compensation as well as sheet thinning control in three dimensions.

2.2. Shape compensation in bulk forming

Bulk-formed parts vary in their accuracy level due to different factors such as material properties, complexity and size of the part as well as the manufacturing process used (Balendra, 2001b). In general, the component accuracy achieved by conventional bulk forming is IT 14-16 ISO (tolerance range) according to DIN EN ISO 286-1. Regarding the precision hot forging process, a component accuracy of IT 7-9 can be attained (Herbertz et al., 2013). In principle, the accuracy limits depend on the entire system consisting of the workpiece, the die and the forging press used (Behrens et al., 2009). The main influencing factors arising during the forging process are friction conditions and elastic tool deformation, but also material properties, stress state and the prevailing temperature distribution in the tool and the workpiece. Each influencing factor contributes a specific portion of stochastic and deterministic deviation to the bulk forming process, depending on the characteristics of the manufacturing system (Balendra et al., 2000). Further decisive factors for the dimensional deviations of bulk-formed components are secondary flow (Rosochowski and Balendra, 2001), dissipation of plastic forming energy into thermal energy (Long and Balendra, 1998), thermal expansion (Lu and Balendra, 2001), shrinkage (Ou and Armstrong, 2002), the elastic proportion of the component deformation (Lee et al., 2004), volume changes due to structural transformations (Baumgarten, 2002) and subsequent process steps such as heat treatments or machining (Balendra, 2001a).

Due to the high number of interacting variables, influencing factors and the associated complexity, several steps are typically necessary when designing of bulk forming processes. A holistic numerical modeling of the various influencing parameters is usually not possible in detail and thus experience-based trial-and-error is a common method carried out in order to determine a suitable tool geometry for the production of the desired component. In terms of final geometrical accuracy, finishing operations are of main interest.

Fig. 2 shows the typical work flow for tool design in bulk forming, utilizing either numerical analysis or prototypical real tool sets. Originating from a target geometry, a first tool geometry is derived and a first workpiece geometry is manufactured or calculated using FEM, for example. Based on a deviation analysis, a user-dependent, unsystematic tool compensation is derived. After passing through a manual redesign process, the new tool geometry for the next iteration is deduced.

Approaches determining correction values to compensate for the tool geometry are often exclusively based on results of numerical analysis, taking elastic deformation of the die or thermal influences into account. Ou et al. (2004) compensate for aerofoil sections using an elastic compensation based on FEM analysis. A partly automated approach for this type of compensation is presented by Ebert and Awiszus (2006). In order to incorporate the workpiece-tool-machine interaction for elastic compensation, Klocke et al. (2016) use a combined FEM/BEM (boundary element method) numerical shape optimization. Frequently, a coupling of the numerical results with the surface reconstruction is utilized in order to optimize the tool shape (Doege et al., 1996). Lu et al. (2009) utilize variable weighting factors for the coupling and numerical forging error minimization of a B-spline representation. To incorporate systematic and stochastic deviations Ou et al. (2012) include Monte Carlo sampling in a two-step optimization. In the work of Landkammer et al. (2016), an independent and parameter-free geometry updating procedure for metal forming application is presented, where the nodal positions of the discrete shape representation serve as input data. A similar approach is used by (Shao

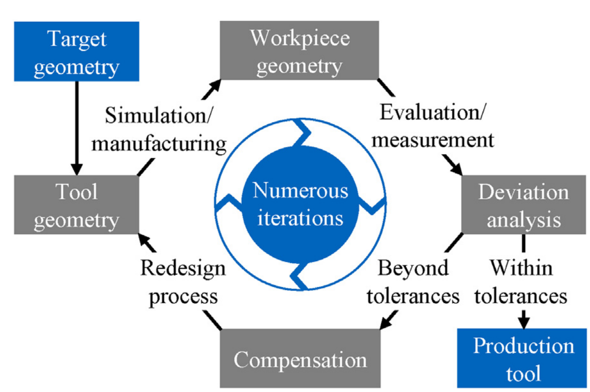

Fig. 2. Flow chart of the design and engineering process for determining of suitable tool geometries for bulk forming.