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DETERMINATION OF SPRINGBACK IN SHEET METAL FORMING

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ABSTRACT

Springback is the partial return of the metal to its original shape when bending forces are removed. The forming of sheet metal requires an understanding of a wide range of technical knowledge, the manufacturing application standard, the interaction of processing and the material properties. In dealing with springback problem, three approaches have been commonly used: Analytical methods, Experimental methods, and Numerical methods. Purely theoretical studies or purely experimental analysis or both of them are encountered. Some researches prepare information just for the sake of analytical analysis of solid mechanics, and some others use available finite element package programs like (ABAQUS, ANSYS, PAM-STAMP, etc.) and perform test-runs for the numerical analysis of the workpiece in hand. Sometimes theoretical and numerical data are compared with experimental data in order to have a proof of the quality of the algorithms, which are prepared to predict the springback. In this research, a survey of the previous research work on springback prediction and compensation in die manufacturing industry has been investigated.

KEYWORDS: sheet metal forming; springback; finite element package programs; analytical methods.

1. INTRODUCTION

In typical sheet metal forming, the shape of the blank obtained at the end of the forming step closely conforms to the tools geometry. However, as soon as the loads are removed, elastically-driven change in the blank shape takes place. This process is termed springback. The deep drawing process is commonly used to manufacture sheet metal products. During the process initially curved or flat blank material is clamped between the die and the blankholder. When the punch is pushed into the die cavity, the blank is plastically deformed and the specific shape of the punch and the die is transferred to it. After the tools are removed, the elastically-driven change of the product shape, or so-called springback, occurs. This phenomenon results into the deviation of the obtained product shape from the design specification and can be the major cause of assembly problems. The quality of the final product depends on the proper tools design, choice of the blank material, blankholder force, lubrication and some other process parameters in sheet metal forming. The Finite element simulation of sheet metal forming is a powerful tool, which allows testing any modifications of the deep drawing process parameters, prior to the actual tools manufacturing. Calculations can be made to predict and compensate for springback and the numerical simulations can be repeated as often as necessary until the product with the desired shape is produced. In FE method, a set of algebraic equations are derived from the space and time discretized form of virtual work expression using the concept of finite elements [1,2]. In recent years, finite element analysis (FEA) has been considered to be an effective tool for simulating the sheet metal forming processes and predicting the springback [3]. To be able to efficiently use a finite element software to predict springback in sheet metal forming, springback needs to be considered as a complex physical phenomenon, which is very sensitive to numerous factors (variation of elastic modulus, material properties, contact parameters, process parameters, sheet geometry, element types, yield function, hardening law, scheme of unloading, contact description, level of discretization, integration scheme).

Currently the numerical analysis is not able to accurately predict the springback of a formed product. There is always a discrepancy between the level of springback obtained in simulations and reality, especially for the products with complicated geometry [4, 5, 6]. The difficulty in simulating the springback and trimming operations was considered by Kawka [7]. One of the reasons for poor springback prediction is that this phenomenon is not accurately represented in finite element formulations. Various assumptions of material behavior - constant elastic properties during forming, simplified elastic-plastic anisotropy and workhardening - introduce the large modeling error. Chosen contact algorithms, the method of unloading, the time integration scheme, the element types and the level of discretization can be other reasons for significant deviation of the numerically predicted springback from that observed in real practice. Furthermore, an analyst plays an important role and substantial discrepancy of the springback results may be caused by unexperienced users.

2. ANALYTICAL METHODS FOR SPRINGBACK IN FORMING

The forming of sheet metal requires an understanding of a wide range of technical knowledge, the geometric difference between the loaded and unloaded configurations, is affected by many factors, such as material properties, sheet thickness, lubrication conditions, tooling geometry and process parameters. It is extremely difficult to develop an analytical model for springback control including all of these factors. The major difficulty with the analytical solution is due to the lack of understanding of the stress distribution throughout the sheet, which limits the analytical approach to simple geometries and simple deformation. In the manufacturing industry, it is still a practical problem to predict the final geometry of the part after springback and to design the appropriate tooling in order to compensate for springback. The understanding and development of bending mechanics are aimed at achieving two kinds of information which are very important for industrial production. One is to predict springback for dies design and compensation in order to obtain high dimension accuracy of bending parts. The other is to determine the limit bending ratio R_i/t_0 for a given sheet thickness and material properties. Different methods such as analytical method, semi-analytical method and finite element method (FEM) have been applied to analyze the bending process [6, 7].For bending mechanics issue; the interested reader may refer to Ref. [7]. Analytical method is a time-saving method and has been widely used for predicting springback of bending parts. Based on plane strain condition, Wang *et al.*[8] established a mathematical model for predicting the springback, By using three rules for material hardening (kinematic hardening, isotropic hardening and directional hardening), Zhang and Hu [9] developed a mathematical model for predicting sheet springback of bending and calculated residual stress distribution through thickness after springback.. Uncomplicated analytical solutions for springback in plane-strain pure bending and plane-strain pure bending with superimposed tension were derived several decades ago. These solutions usually assume elastic-perfectly plastic material behavior [10]. In sheet metal forming, analytical solutions for springback were firstly derived for simple cases, such as: flanging [11, 12, 13, 14], V-bending [15, 16] and U-bending [17]. The methods were extended to more complicated and realistic cases, such as draw bending [18] and stretch bending [19,20,21,22], in which tension was accounted for. Special attention was given to the accurate analytical prediction of sidewall curl caused by bending and unbending deformation at the die shoulder in Refs [17, 18]. Accurate prediction of springback by either finite element analysis or analytical approach depends on the accuracy of the internal stress distribution within the sheet material. The authors [23] have described new techniques for sheet metal forming simulation using a local interpolation for tool surfaces and the effect of tool modeling accuracy on springback simulation. The proposed techniques have the advantage of relatively straightforward numerical implementation.

3. EXPERIMENTAL METHODS & UNDERSTANDING SPRINGBACK PHENOMENON

Springback is a very complicated behavior and not easy to predict through the mathematical models. Therefore, some experiments for understanding springback behavior were conducted and some mathematical models were developed [24, 25]. Various experimental techniques and procedures have been developed to study and characterize springback of sheet metals. The most popular and commonly used techniques are cylindrical bending [26], U-bending [27], V-bending [28, 29] and flanging [12, 14, 30]. These methods are attractive because the level of springback is large and it can easily be measured. Sensitivity of springback to basic parameters, such as R/t ratio (tool radius to sheet thickness), geometric parameters of the tools, mechanical properties of sheet material and friction parameters is usually studied by means of these techniques. The major drawback of these experiments is that they cannot imitate the realistic process conditions that take place during sheet metal forming [31].Stretch bending tests are used to study the importance of tension in minimizing and controlling springback [32]. Carden [10] suggested an alternative experimental procedure to be used to study springback in sheet metals and its sensitivity to various parameters. Several experimental procedures were developed to study the sensitivity of springback to the Bauschinger effect [33]. Accurate modeling of the material behavior under complex deformation conditions with load reversals requires the hardening model to be able to take into account most of the stages of the Bauschinger effect [31,34,35,36,37,38,39,40,41,42]. Based on the framework isotropic/kinematic hardening, the anisotropic hardening models were proposed by various authors, including multi-surface theory by Ref [43], the two-surface model by Ref [44] and the nonlinear kinematic hardening model by Ref [45]. The major difference between these models is the way of defining the generalized plastic modulus [42]. In the two-surface model proposed by Refs [48,49] multi-surface model, the hardening modulus function and the translation direction are defined first, and then the magnitude of the yield surface translation is determined from the consistency condition. In the model proposed by Ref [45], the direction and the magnitude of the yield surface translation are defined first, and then the consistency condition is used to derive the generalized plastic modulus. The hardening models developed by these authors have both advantages and disadvantages. The multi-surface model is able to reproduce the abrupt change of the hardening rate after the load reversal, but at the cost of many material parameters [35]. The major problem of the two-surface model proposed by Ref [44] is related to the updating procedure of the distance between the current stress point and a mapping point on the bounding surface. In a complex loading situation the updating procedure can create significant overshooting problems [46]. The nonlinear kinematic hardening model proposed by Ref [45] is characterized by difficulties in modeling the smooth elastic-plastic transition after the load reversal. Based on the framework of isotropic/kinematic hardening and Mroz's multi-surface model, authors [37] proposed a hardening model that takes into account the Bauschinger effect and is able to accurately predict springback when the sheet material undergoes a complicated deformation path. The authors [42] proposed an anisotropic hardening model based on developments of Frederick and Armstrong [45]. A simple bending-reverse bending experimental method was proposed in Refs [37,38] the experimental procedure consists of several steps: bending, turning the sheet specimen and bending in the opposite direction, turning the specimen again and bending it in the original direction. The uniaxial tension-compression or compression-tension test is the most common experimental procedure [35, 36]; it requires special fixtures to be used to prevent the sheet material from buckling under compression. Yoshida [34] presented the experimental set-up, which can be used to study the elastic-plastic stress-strain responses of sheet material under in-plane cyclic tension-compression under large strain. It is known that Springback depends on Young's modulus of a material. In analysis of sheet metal forming it is a common practice to assume that Young's modulus is constant. Under applied stress the small reversible displacement of dislocations takes place, which builds the non-elastic part of the total strain and ultimately causes the decrease of elastic modulus of a material. Several models were developed to describe this effect quantitatively. Some of the models treat the dislocation as an elastic string, which bows out under the influence of applied stress. Yet another model describes the change of elastic constants caused by the change of width of extended dislocations during loading. Other models take into account the atomic structure of the crystal itself and give relatively good prediction of change of elastic modulus. Variation of Young's modulus in finite element analysis of sheet metal forming can be represented by: simple piecewise linear function [47,48]; power law [49,50] or higher order polynomials [51]. To increase the accuracy of the finite element simulations the yield function should be able to accurately capture all the important anisotropy effects in the material [52, 53]. The plastic anisotropy causes directional dependency of the yield stress and the R-value. Numerous studies were performed to compare the performance of different yield criteria [52, 53, 54, 55, 56].

4. NUMERICAL METHODS

Simulation of springback comprises of two major steps: loading (actual forming) and unloading. In most springback analysis the instantaneous release method is employed. According to this method the change of shape of the drawn product due to the release of the tools is calculated in one increment. Sometimes this increment is subdivided into a number of sub increments to avoid numerical instabilities. An alternative method can be described as inverse forming. This method is less used since it is more computationally costly, it is more realistic because the contact forces are present during the unloading step [9,26,31,57,58,59].Additional difficulties may arise when using the instantaneous unloading during springback step in buckling dominated problems.. The gradual unloading method is commonly used to stabilize the computation stabilization techniques or numerical damping. The main disadvantage of the gradual unloading method comparing to the instantaneous unloading is the computation time. The gradual unloading requires a lot of CPU time and is very often accompanied with bad convergence behavior of the simulation due to the presence of tools sliding with low normal forces. There are two main solution procedures for the simulation of sheet metal forming: the dynamic explicit and the static implicit. The major advantage of the explicit time integration is that it is easy and straightforward. There is no need to generate the stiffness matrix and there are no unbalance forces, since the difference between the external and internal forces determines the values of nodal accelerations at the start of every time increment. Absence of unbalance forces means that the explicit method does not suffer from the convergence problems within the time increment. The major disadvantage of the explicit integration scheme is its conditional stability and prohibitively small maximum allowable time increment. Usually to solve this problem and to decrease the total computation time mass scaling is employed. In this way the critical time increment is enlarged by artificially increasing the mass of the material. The implicit time integration method is unconditionally stable. The sensitivity of springback to explicit/implicit solution procedures was studied by various researchers. The usual procedure is to employ the dynamic explicit method for the simulation of the forming step and the implicit method for the springback analysis [26,57,60]. The reason for that is the critical time step. The explicit method used for springback simulation can take as long as the time spent on the forming step. Furthermore, if the dynamic explicit scheme is used for springback simulation the blank may start to oscillate during unloading and therefore the final static shape of the blank is difficult to find [57]. Simulations of industrial sheet forming processes are usually performed with shell elements. The basic idea of shell elements is that if the thickness of the structure is very small compared to its other dimensions, then its geometry is described by only using variables of the mid-plane [54]. The three major shell deformation theories are Membrane theory, Kirchhoff theory and Mindlin theory. The accuracy of a finite element solution is defined by the modeling error and the discretization error. Both errors need to be controlled in order to perform a reliable simulation. The plate theory assumption is one of the reasons of modeling error in sheet metal forming simulations. All shell element formulations are based on the assumptions that due to geometry of the blank the plane stress state prevails and in-plane strains are linearly distributed across the thickness [61,62,63,64]. Simulations were conducted with several element types: 2D plane stress, 2D plane strain, 3D nonlinear solid and 3D shell elements. The accuracy of a finite element solution is influenced by the discretization error; however, accurate springback simulation requires more nodes on the tool radius than usually recommended for forming analysis [26, 31, 49, 64, 65, 66]. Lagrange multiplier method and penalty method are the main methods used to incorporate the contact conditions into a finite element formulation. An extensive description of both methods, the interested reader may refer to Ref [54]. If finite element modeling is employed for analysis of springback the accuracy of obtained solution is significantly affected by the factors that control the quality of simulation of forming operation. The most important of them include the method of unloading, time integration scheme, choice of element, blank and tool discretization and contact algorithm. Some of the mentioned factors are relatively simple to take into consideration and their influence on predictability of springback is unambiguous. However, there are factors that require careful treatment and extra attention. Material modeling, for example, requires not only a careful selection of an appropriate yield function, but also an extensive analysis of springback characteristics of sheet metal by means of different test procedures.

5. CONTROL SPRINGBACK

The automotive and other manufacturers of sheet metal parts rely on several methodologies to control springback, namely, mechanics-based reduction and geometry-based compensation [5]. The mechanics-based reduction methodology is based on physics of the springback phenomenon. The amount of springback is reduced by changing or constantly varying the process parameters. The mechanics-based reduction methodology relies on the mechanics of sheet metal forming, which becomes the basis for identifying and modifying the critical process parameters at the critical time intervals to control the amount of springback. There are three commonly used methods: Blankholder force control, through thickness deformation and Forming in multiple steps. The geometry-based compensation methodology can guarantee the shape accuracy of the formed product by performing the appropriate modifications of the tools. The bases of modification of the tool geometry are the results of simulations or the measurements of the part after real forming.

Springback compensation often relies on trial-and-error at a great cost and time-consuming or on empirical rules on simple analysis, which is only available to simple shapes based on well-known materials [67, 68, 69].

6. CONCLUSION

The different methods of dealing with springback problem have been discussed in this paper. A survey of literature on analytical methods, experimental methods and numerical methods in the context of springback prediction has been presented. The unloading scheme has an influence on springback prediction. The commonly used instantaneous unloading procedure is proved to produce inaccurate results. During unloading the existing contact forces can cause the additional change of shape of the formed product. Moreover, the instantaneous unloading method is not applicable for predicting springback of buckling dominated problems. Slight variations of a yield stress, R-values, hardening parameters and a sheet thickness -comparable with scatter of material properties due to production process - hardly influence the springback behavior. This influence can become more significant for products with low level of plastic deformation. It is clear that the abilities of analytical methods to predict the level of springback of complex products are limited and the use of finite element method is required. The accuracy of finite element software has a significant influence on the change of shape during unloading. Large modeling and discretization errors, due to the chosen element types, the mesh sizes and the amount of integration points through the thickness, may cause a substantial deviation from the accurate solution. It is suggested in the literature that the solid elements are necessary for describing the fully three dimensional stress state which can occur when the r/t ratio is small. For this situation the underlying assumptions of the shell elements theory are not applicable. However, the use of only solid elements is not feasible, due to unrealistic requirements for CPU power. Alternatively, it is usually suggested to use the mixed solid-shell elements for blank discretization. Unfortunately, this approach has plenty of difficulties related to its implementation. The modification of shell elements - to make them capable of behaving accurately in the regions with fully three-dimensional stress state - can be another interesting approach. Therefore, an additional study is required to investigate the main causes of discrepancy of results for the situations with low r/t ratio. The objective of this present study is to identify the reasons of poor accuracy of prediction of springback phenomenon in sheet metal forming.

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