International Journal of Mechanical Sciences 66 (2013) 192–201

Contents lists available at SciVerse ScienceDirect

International Journal of Mechanical Sciences

journal homepage: www.elsevier.com/locate/ijmecsci

A simple finite strain non-linear visco-plastic model for thermoplastics and its application to the simulation of incremental cold forming of polyvinylchloride (PVC)

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ARTICLE INFO

Article history:
Received 3 July 2012
Received in revised form
25 September 2012
Accepted 8 November 2012
Dedication:
Dedicated to Professor
O.T. Bruhns on the occasion of
his 70th birthday.
Available online 19 November 2012

Keywords:
Incremental forming
Material model
Thermoplastic polymers
Non-linear visco-elasticity
Finite strain
Finite elements

ABSTRACT

This paper introduces a finite strain extension of a non-linear visco-plastic material model, previously proposed by the authors, and its application to the finite element simulation of incremental cold forming processes of thermoplastics, demonstrated on PVC. Preserving the original structure of the model, its finite strain extension does not rely on any presumed kinematic split, either multiplicative or additive, among elastic and inelastic parts. It uses a systematic replacement of the strain and stress tensors and their rates by their respective spatial counterparts. A deviatoric Oldroyd rate is introduced to preserve the objectivity as well as the deviatoricity of the integration of the rate forms of deviatoric tensors. To cope with the incremental loading paths within the process, where through-thickness variations of the variables gain importance, the material model is posed in 3D formulation. The developed model is implemented as an ABAQUS®/UMAT subroutine and used in the simulations following parameter identification studies. The numerical results are compared with analogous experimental ones to evaluate the performance of the material model where PVC sheets of three different thicknesses are formed incrementally with path controlled tool force monitoring. The investigations have the following consequences: the deformation-limited homogeneous stress–strain portion at uni-axial tensile tests, which is generally used in parameter identification of the constitutive model, is not able to reflect the post necking regime and its extrapolation ends up with a stiffer response with much less retained strains. Once a semi-inverse parameter identification is followed by taking into account the overall experimental outputs, one ends up with a considerable improvement in the tool force, geometry and the wall thickness predictions. Nevertheless, these improvements are inversely proportional with the sheet thickness where the local indentation effects (strains and stresses) become larger.

1. Introduction

Incremental forming is stepwise forming in a small forming zone. This process, especially its variation *Single Point Incremental Forming*, introduced in Fig. 1a, is very flexible, since it can be carried out on a standard CNC milling machine without any custom dies. The universal pin-like forming tool moves along a numerically controlled path and forms the part gradually. It can be used for forming different shapes of the final product. Therefore, this process is especially useful for prototyping and small batch production. The incremental cold forming process is an alternative for commonly used forming processes of thermoplastics, which are, because of the tool and energy costs, only economic for large batch production. Thermoplastic polymers, such like polyvinylchloride PVC, polycarbonate PVC and polyethylene PE, have shown their capability to be formed to high strains by the incremental sheet forming process [10,9,21]. The formability of thermoplastics at room temperature makes this process also interesting, because heating and cooling processes are omitted and hence less energy and less equipment are needed. Besides, cold formed parts can show more strength because of polymer molecular chain alignment in forming direction. Exemplary products formed by the incremental forming process are hollow parts with nearly arbitrary contour. Such parts can be used as housings, cups or for decorative and architecture purposes, which have sizes from 10^2 to 10^3 mm at thicknesses from 1 to 3 mm.

The yielding effect during incremental forming is so far not well investigated but has to be understood in order to utilise the potential of the incremental forming process and to obtain the desired mechanical properties of the produced parts or to achieve maximum strains. Consequently, theoretical investigations are

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http://dx.doi.org/10.1016/j.ijmecsci.2012.11.007

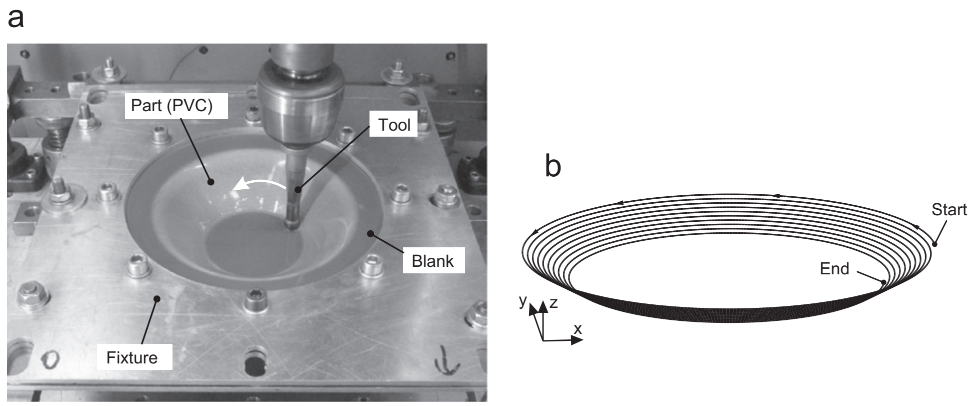

Fig. 1. (a) Experimental set-up of *Single Point Incremental Forming* process, (b) spiral tool path strategy.

needed to support the fundamental research and hence to understand the process.

A first attempt to analytically describe the material behaviour of polymers during single point incremental forming is made by Silva et al. [22] using a modified approach, based on the membrane theory. However, through-thickness shear, which is regarded as a reason for the increased forming limits of metals during incremental forming [3], is not covered in the membrane theory. Therefore an accurate finite element analysis has to be conducted to deliver more detailed information about the material behaviour during incremental forming of thermoplastics.

For the simulation of thermoplastics, which are known to be visco-elastic at small and visco-plastic at finite strains, a proper material model is needed. There are already widely used pragmatic solutions for this problem, which rely on modifying metal-based material models for predicting thermoplastics' behaviour, such like the SAMP model (Mat-187 in LS-DYNA), presented by Haufe et al. [14]. This material model was originally constructed for crash simulations and it applies a modified von Mises (J_2-plasticity) yield surface, which considers hydrostatic pressure dependence of thermoplastics. This can be also achieved with sufficient accuracy by applying the Drucker–Prager yield criterion in which the yield stress depends linearly on the hydrostatic stress. However, SAMP is not viscous. The stress-rate dependence could be considered by supplying the model with stress–strain curves at different strain-rates. However, no relaxation or recovery processes can be covered by this model. Consequently, this material model is less appropriate for simulating incremental forming processes.

Recently, several phenomenological material models, which base on the idea of splitting the total stress into different parts, for instance equilibrium stress and overstress, were developed to describe the mechanical behaviour of thermoplastics in the solid state. Krempl and Ho [20] introduced a material model that includes non-linear strain-rate dependence, non-linear unloading, relaxation and cyclic softening. The predictions of this model for nylon PA66 were sufficient; however, a total of 15 material parameters are needed for it. This model was supplemented by Colak and Dusunceli [6] to enhance the unloading predictions for high density polyethylene. Hartmann [12] and Kaestner et al. [18] presented material models for polyoxymethylene POM and polypolypropylene PP, respectively. Kaestner uses four material parameters to model the equilibrium stress and $3n$ parameters for the overstress, where n is the number of the Maxwell elements in parallel. This model is able to capture the non-linear strain-rate dependence after expanding the overstress with non-linear components [19], and hence two additional parameters. In all the contributions it is obvious that a sufficient number of material parameters should be used to obtain appropriate material behaviour predictions. Accordingly, more parameter identification efforts are necessary. Motivated by the latter examples, Alkas Yonan et al. [2] presented a non-linear visco-plastic material model having only seven material parameters. This simple material model is intended to be used for analysis of incremental forming processes of thermoplastics.

Finite element simulation of incremental forming processes is concerned with numerous local forming zones, which result in long process times and hence is very time-consuming. In addition, the state of stress and strain over the workpiece thickness is essential for understanding this forming process, especially at process parameter configurations, where through-thickness shear in incremental forming is found to be remarkable. This can be achieved for instance by increasing the vertical pitch, increasing the workpiece thickness and decreasing the tool size [17,5]. Therefore, continuum elements are inevitable for the simulation of incremental forming processes, at least for understanding their mechanisms.

Due to the novelity of applying this process on thermoplastics, there has been no numerical studies carried out in the literature to date comparable to those done on metals. The objective of this paper is to show the application and the capabilities of this material model simulating the incremental forming process of thermoplastics. Simulation results, which are calculated in Abaqus®, are opposed to incremental forming experiments regarding tool force, geometry and wall thickness.

2. Behaviour of thermoplastics in solid state

Thermoplastics are known to be viscous, which means that the material behaviour is time-dependent. In the literature, specific characterisation tests are generally used to find out the material behaviour of thermoplastics in the solid state [15,12,18]. These tests have two aims:

1. finding out the equilibrium states,
2. finding out the amount of strain-rate dependence.

Accordingly, two specific characterisation tests are performed by the authors to determine the material behaviour of PVC. Firstly, strain-controlled monotonic tensile tests were conducted at three different strain-rates (Fig. 2a). These tests were carried out until necking in the specimen shaft was observed. In the tested material (PVC) this happened at relatively small strains ($\varepsilon \approx 0.028$). After necking the stress state is not homogeneous due to the locally different reduction of the cross-section. The stress–strain curves show that there is a non-linear stress dependence on the strain-rate. All the curves have the same initial slope.