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# Identifying polymeric constitutive equations for incremental sheet forming modelling

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**Abstract**

Recent publications have revealed an increasing interest in forming polymer materials using Incremental Sheet Forming. Therefore, several constitutive material models are being developed in an attempt to predict the physical response of polymeric materials during the process. This paper discuss several material models that could be used to predict experimental data collected on samples of PVC and PC subjected to simple uniaxial test performed at various temperatures and testing speeds. The results have shown that the Marlow and the rule of mixture material models could be used to describe viscoelastic and softening and permanent set effects, respectively, to predict the behaviour of a part formed by Incremental Sheet Forming.


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*Keywords*: Incremental sheet forming; Thermoplastic materials; Material models; Softening effects

## 1. Introduction

Incremental Sheet Forming is a technology able to manufacture full or scale size prototypes as well as small batch or customized sheet products.

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This technology has been mainly applied in the automotive and aeronautic sectors, either to obtain functional parts or prototypes. However, there are other fields that have a growing interest in this manufacturing process; such has the biomedical one, which requires a technology capable to produce unique parts in a short time and at a reasonable cost. Several works in the literature used Incremental Sheet Forming to produce ankle prosthesis (Ambrogio et al., 2005), cranial implant (Duflou et al., 2005; Gottmann et al., 2012), palate implant (Tanaka et al., 2007), a part for a knee implant (Oleksik et al., 2010) and most recently several maxillofacial implants (Duflou et al., 2013; Araújo et al., 2013). There are also some preliminary studies that use Incremental Sheet Forming for producing medical devices, such as mesoforceps for biopsy (Garcia-Romeu et al., 2012). All of these applications have been manufactured using metallic materials. These biocompatible metallic materials, such as titanium, are very difficult to deform at room temperature. Therefore, it is necessary to use an additional heating system to increase the formability in order to be able to produce the desired part. Nowadays, there are scarce publications dealing with the production of any biomedical device or prosthesis manufactured with Incremental Sheet Forming using biocompatible polymers. Fiorentino et al. (2012) manufactured a plate prosthesis using a titanium alloy and PCL (polycaprolactone). Although they results were promising an optimization of the process parameters should be done in order to increase the accuracy of the part. Thus, a niche market where the use of biocompatible polymers manufactured by Incremental Sheet Forming can provide remarkable advantages in terms of low cost and reduced time to market has been identified.

The first research work in which the feasibility of using Incremental Sheet Forming to produce parts with thermoplastic materials was demonstrated was done by Franzen et al. (2008). They were focused on the evaluation of the performance of PVC (polyvinylchloride) in Single Point Incremental Forming applications. The formability limits and accuracy were characterized and evaluated by varying some process parameters (sheet thickness and tool diameter). The test geometry used was a hyperbolic frustum cone.

Polymers have a drastically different behavior than metals since these are crystalline lattices of atoms all being, more or less, well ordered. In contrast, the molecules of a polymer material consist of carbon atoms bonded into a long chain resembling a tangled collection of yarn scraps. Since the carbon-carbon bond can rotate, the chains can rearrange themselves into infinite different conformations. The rate at which a chain can change its conformation mainly depends on temperature, speed of deformation and stress. At high temperatures, chains can move freely with applied deformation. At low temperatures (below the glass transition temperature), chain mobility decreases drastically and the material virtually “vitrifies” and becomes more fragile, although changes in chain conformation are still possible. Furthermore, as the testing speed increases the maximum stress is higher and the strain at fracture decreases.

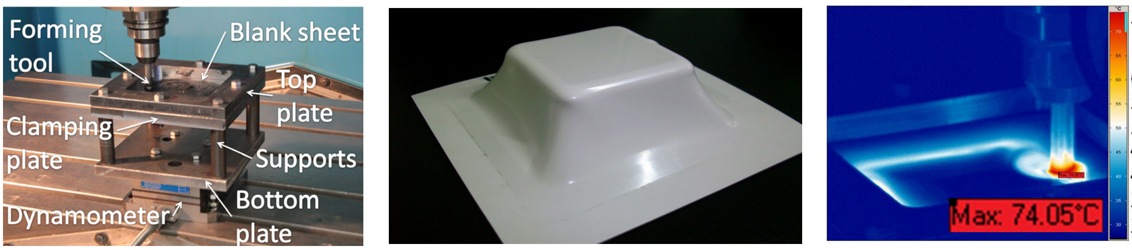
A summary of constitutive material models used to characterize thermoplastic material was presented by Le (2009). He used the viscoplasticity model based on overstress theory developed by Krempl and Ho (2008) to model nonlinear rate sensitivity and unloading, cyclic softening and recovery behavior of Nylon 66. Le (2009) implemented it into finite element computer program to characterize polypropylene material at room temperature during a Single Point Incremental Forming process. The numerical results showed that there exist good agreement between simulation and experimental data for prediction of the sheet thickness but there are some difficulties related to computational time and sheet geometric accuracy.

Recently, several material models are being developed in an attempt to predict the physical response of polymeric materials during Incremental Sheet Forming i.e., there is a tremendous amount of effort put in developing a model that may describe the equilibrium hysteresis and rate-dependence of thermoplastic materials. For instance, Alkas Yonan and co-workers introduced a phenomenological material model to simulate the thermoelastic behavior during cold forming that is based on the existence of an equilibrium stress and a non-linear strain-rate dependant overstress (Alkas Yonan et al., 2011a). Later, they extended their model to characterized three-dimensional deformation state (Alkas Yonan et al., 2011b). However, they only provided theoretical predictions of simple uniaxial deformation test by considering different relaxation times. Therefore, up to now, to the best of our knowledge, only Le (2009) has applied a material model based on overstress theory to model the Incremental Sheet Forming.

This paper will show that by using a small number of material parameters, it is possible to predict experimental data collected on samples of PVC and PC subjected to simple uniaxial test performed at various temperatures and testing speeds and also when applying a cyclic tensile load. This will be done by adjusting material models that are included in the Abaqus 6.13 Dassault Systems software such as: Arruda-Boyce, Marlow, Ogden models, to say a few.

## 2. Materials and methods

The experimental studies have been conducted with PVC (polyvinylchloride) and PC (polycarbonate). Two different thicknesses were available, 1.5 and 2 mm. In previous works of the authors (Bagudanch, 2012), Incremental Sheet Forming parts were done using the aforementioned polymers. The selected geometry was a pyramidal frusta with circular generatrix; meaning a variable wall angle at each depth increment. The length of the pyramid's edges was 105 mm, the initial wall angle was 45º and the generatrix radius was set to 80 mm (Fig. 1b). Incremental Sheet Forming tests were carried out on a Kondia® HS1000 3-axis milling machine equipped with a Fidia® numerical control. A table-type dynamometer Kistler® 9257B was mounted on the machine worktable in order to measure the forming forces that occur during the process. The force data was acquired using a DaqBoard® 505 data acquisition card and the DaqView® 9.0.0 software. A fixture system composed of a bottom plate, four supports, a clamping plate and a top plate was bolted onto the force measurement system. The dimensions of the blank were 150 x 150 mm and the effective working area was 120 x 120 mm (Fig. 1a). The results demonstrated that there was a strong influence of the spindle speed on the analyzed results (maximum forming force, maximum depth and surface roughness). This strong influence was due to the friction between the tool and the blank, which produced a local heating. By using a thermographic camera the maximum temperatures achieved during the process were measured, being 74 ºC (Fig. 1c) in the case of PVC and 50 ºC in the case of PC.




a) b) c)

Fig. 1. a) Experimental setup used on 3 axis CNC milling machine. b) Formed part. c) Image obtained using thermographic camera.

The mechanical properties of both materials have been characterized by means of uniaxial tensile tests carried out in a MTS Insight universal testing machine, using a load cell of 5 kN. The tests have been done until the failure of the specimen at different testing speeds: 50 and 500 mm/min according to the ASTM D 638-02a norm. Furthermore, tests at different temperatures have been carried out in order to acquire knowledge about the behavior of the polymers in those conditions. The temperatures were selected according to the previous results obtained by the authors during the incremental forming process, 60 ºC for PVC and 50 ºC for PC. Notice that the temperature for the tensile test in the case of PVC is lower than the one achieved in ISF, this is due to limitations of the heating chamber mounted on the MTS Insight universal testing machine.

The first numerical tests were carried out using the "Evaluate Material toolbox" in the commercial finite element software Abaqus/CAE 6.12-1. The purpose to use the toolbox was compare the solutions obtained with the experimental data to calibrate the hyperplastic models and identified their mechanical properties and responses. The toolbox was filled out with the experimental data at each temperature test and feed rate to evaluate the available strain energy models in Abaqus as:

- Arruda-Boyce model: it is a physical model based on the molecular chains network, it assumes that the strain energy density is independent of the second invariant of the Cauchy-Green tensor.

- Polynomial model (Poly): based on the first and second invariant of the deviatoric Cauchy-Green tensor.
- Reduced polynomial (R Poly): follows the form of the polynomial model but only considering the first invariant of the deviatoric Cauchy-Green tensor.
- Ogden model: it is described by using the principal stretches.
- Marlow model: it is a general first invariant model, meaning that it is independent of the second invariant and that can be defined with just a single test, therefore, it is easier to use.

These models assume that the material is isotropic and incompressible. They are defined by means of the strain energy density function; a review of these models and the definition of the equations were done in a previous work of the authors (Bagudanch et al., 2013).

The second numerical test was a cyclic tensile loading and unloading to capture the stress softening phenomenon. To calibrate this effect, a uniaxial tension test was implemented for the PC and PVC materials at different extension levels 0.5, 1.0, 1.5 and 2.0 mm. These data showed the monotonic-like material behavior and illustrates stress softening effects (Elías-Zúñiga et al., 2014) that could influence the determination of the manufacturing parameter values that will provide the information needed to define the stress and strain levels for the sets of uniaxial tensile tests. The numerical response was obtained by carrying out a uniaxial loading and unloading tensile test according to the ASTM D 638-02a norm.

## 3. Results and discussion

Some of the models described in the previous section were not able to accurately define the response of the materials in a uniaxial tensile test. As an example, Fig. 2, shows that the Arruda-Boyce, polynomial (order 1 and 2) and reduced polynomial (order 1, 2, 5 and 6) models do not have a good adjustment to the experimental data for the PVC uniaxial tensile test at 500 mm/min and at 60 ºC; therefore, they will not be further discussed because they are not able to predict the necking behavior. While in Fig. 3, are shown the responses with a good agreement with the experimental tests, which are the Marlow and Ogden models. Notice that as the order (N) of the Ogden model is increased, the results present a better agreement compared with the experimental data.

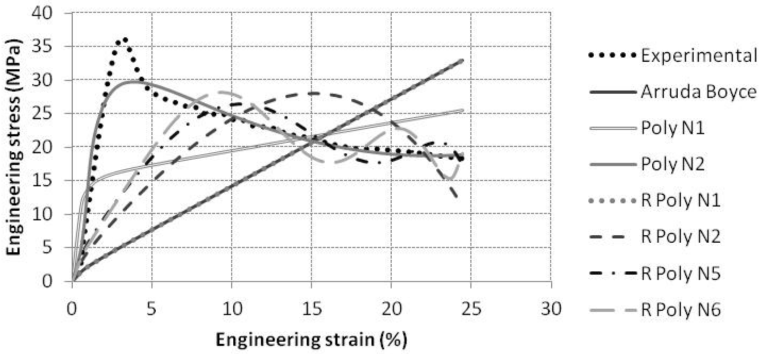



Fig. 2. Example of inaccurate material models evaluation.

The Marlow material model presents the best agreement with the experimental results and successfully describes the viscoelastic behavior of the materials (maximum error of 3%). The Ogden model could provide an acceptable response for the tests done at room temperature when PVC is used (maximum error of 4.5%), however at higher temperatures the maximum error obtained is 17% which would not be acceptable.

Fig. 4 shows the experimental values for the cyclic loading-unloading test for PVC (Fig. 4a) and PC (Fig. 4b) at room temperature compared with the results obtained from the simulation procedure utilizing the rule of mixtures developed by the authors (Elías-Zúñiga et al., 2014) to describe the softening material behavior. It is worth noting that there is a good agreement between both responses. Furthermore, and in accordance with the experimental data, it is evident that besides the springback effects that influence the geometrical accuracy, one must also consider the material softening effects. At present, the authors are engaged in numerical simulation via finite element method in which the inclusion of the material stress softening effects are being considered to accurately describe the polymer Incremental Sheet Forming manufacturing process.

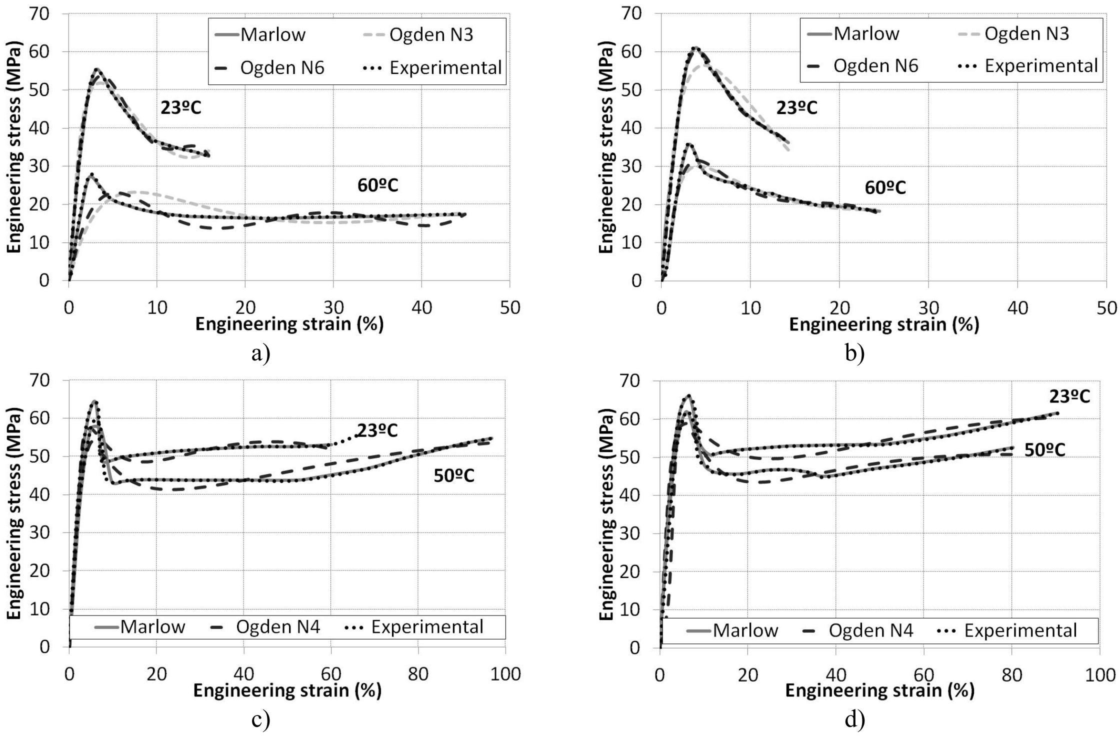



Fig. 3. Experimental results of uniaxial tensile tests and material model evaluation for: a) PVC at 50 mm/min, b) PVC at 500 mm/min, c) PC at 50 mm/min and d) PC at 500 mm/min.

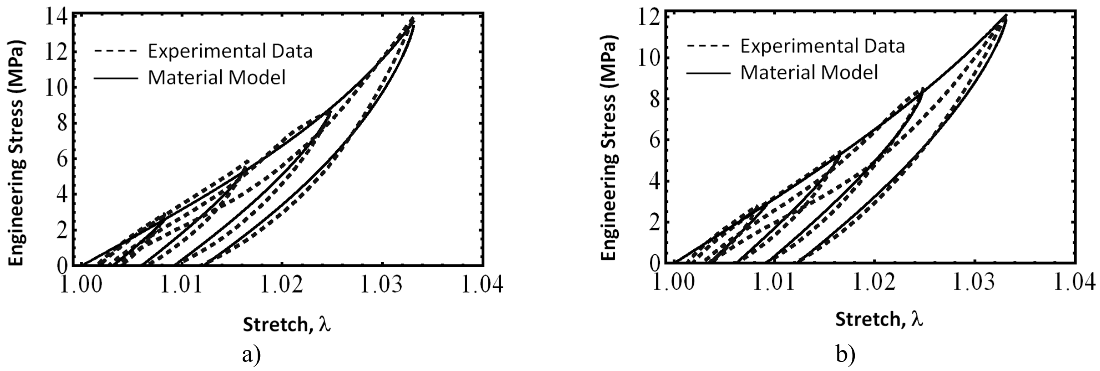



Fig. 4. Experimental and material model adjustment results of cyclic loading-unloading test for PVC (a) and PC (b) at room temperature.

## 4. Conclusions

In the present paper some material models were used to describe polymer material behavior subjected to large stretch deformations in an attempt to provide constitutive equations that would predict its qualitative and quantitative behavior during Incremental Sheet Forming process. These material models are implemented in

Abaqus and it has been found that the material model that best describes experimental uniaxial tensile data in PVC and PC, at different testing speeds and temperatures, is the Marlow model which accurately describes the viscoelastic behavior. Furthermore, cyclic loading and unloading tests have been done in an attempt to have a complete understanding of the polymer material behavior during the SPIF manufacturing process. At present, the authors are implementing a material model, based on the rule of mixtures, in the Abaqus commercial package in order to capture the anisotropic effects (stress softening and permanent set) exhibited by polymeric materials. In future work a combination of both material models will be used in order to predict the material behavior during the Incremental Sheet Forming process.

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