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# Multi-pass deformation design for incremental sheet forming: Analytical modeling, finite element analysis and experimental validation

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ABSTRACT

Incremental sheet forming (ISF) is a promising rapid prototyping technology with high potential to shape complex three-dimensional parts. However, a common technical problem encountered in ISF is the non-uniform thickness distribution of formed parts; particularly excessive thinning on severely sloped regions. This may lead to fracture and limit the process formability. Design of multi-stage deformation passes (intermediate shapes or preforms) before the final part, is a desirable and practical way to control the material flow in order to obtain a more uniform thickness distribution and avoid forming failure. In the present paper, a systematic methodology for designing multi-stage deformation passes considering the predicted thickness strains given the design shape is proposed based on the shear deformation and the strain compensation mechanism. In this methodology, two analytical models (*M*1 and *M*2) are developed by taking into account; the global average thickness strain and only the material in the final part region used in the forming (*M*1), and the local weighted average thickness strain and the additional material around the final part region used in the forming (*M*2), respectively. The feasibility of the proposed design methodology is validated by finite element analysis (FEA) and experimental tests using an Amino ISF machine. The results show that a more uniform thickness strain distribution can be derived using *M*2. The incurrence of the highest strains can be delayed in the intermediate stages and the flow of material is allowed into the deformed region, thereby allowing a compressive stress state to develop and enabling steeper shapes to be formed. Therefore, the process formability can be enhanced via the optimized design of deformation passes.



## 1. Introduction

As a promising technology for rapid prototyping and small-batch production, incremental sheet forming (ISF) has gained great attention in the sheet metal forming community in the past decade. In the ISF process, a forming tool is controlled by a computer numerically controlled (CNC) machine following a prescribed tool path which locally plastically deforms the sheet metal into the desired shape. Thus an infinite variety of 3D shapes can be produced using one tool. This forming process can be categorized into two main types: single point incremental forming (SPIF) without a forming die and two point incremental forming (TPIF) with a partial or a full forming die. The technology of ISF is promising and advantageous by providing higher formability compared with deep drawing or stamping. However, it is still limited by the significant thinning of the deformed sheet metal, forming defects and long forming time induced by the long travel path of the forming tool. A comprehensive review of ISF research is provided by Jeswiet et al. (2005).

Much research in ISF has been performed to investigate the forming limits and increase the formability by adopting multi-stage deformation pass design in the past decade. In particular, Filice et al. (2002) investigated the material formability in ISF under different strain conditions. The results indicated that local stretching is the dominant deformation mode in ISF. On the other hand, Jackson and Allwood (2009) further investigated the mechanics of ISF through an experimental campaign. It was revealed that shear in the tool direction is the most significant strain component and increasing stretching and shear also exist perpendicular to the tool direction. The above discussions show the shear and/or stretching deformation modes lead to material thinning in the ISF process. Failure in ISF is most likely to be caused by the non-uniform thickness distribution and typically the excessive localized thinning of steep walls in a part, which decreases the maximum wall angle that can be achieved in materials formed by ISF in comparison to some other processes.

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This makes it difficult to manufacture complex parts with steep walls. Therefore, the proper allocation of materials during forming is important to uniformly distribute the material thickness on the final parts in order to avoid the occurrence of forming failure. Kim and Yang (2000) proposed a double-pass forming method to improve the formability for the ISF process. This method is based on shear deformation using the predicted thickness strain distribution to design intermediate shapes in order to get a uniform thickness distribution of a final part. Young and Jeswiet (2004) also developed a two-stage strategy to improve the final thickness distribution for the parts with steep areas. The results showed that the occurrence of a thinning band in the single-stage forming process can be delayed in the two-stage process so that complex parts with steep walls can be successfully made. Duflou et al. (2008) explored a multi-step tool path strategy to manufacture parts with vertical walls in order to avoid part failure. The final thinning in the multi-stage forming process can exceed the maximum thickness reductions in the single-stage process, which means a formability increase. In Manco et al. (2011), the effect of the tool trajectory has been studied in terms of the final thickness distribution and the formability. The advantages and disadvantages of single-stage forming and three different multi-stage forming strategies have been compared and analyzed by manufacturing the same shape and evaluating the thickness distributions. It was concluded that formability can be conveniently enhanced with proper multi-stage deformation design by involving as much material as possible from a theoretical point of view. Skjoedt et al. (2010) investigated a multi-stage strategy to produce cylindrical cups with vertical walls. They pointed out that the movement of the forming tool in the multi-stage SPIF has a great influence on the thickness distribution and SPIF is limited by cracking rather than necking. Zhang et al. (2013) proposed an FEM-based multi-stage SPIF method, which treats the SPIF process as hydro-bulging forming. The intermediate surfaces obtained from the FEM results can be used for the tool path generation. Li et al. (2013) used a part regional division idea in the multi-pass deformation design to manufacture a car taillight bracket with nearly straight-wall region and the groove region. They found that an intermediate surface which is geometrically closer to the final part can obtain better forming quality. Liu et al. (2013) proposed three multi-stage deformation pass strategies for forming cups with vertical walls. Those strategies and their combinations have been evaluated in terms of the process formability. The results showed that the forming strategy using more material in the forming as well as the addition of a small amount of bending can greatly improve the formability. However, in most of existing multi-stage forming design in ISF, material flow and thickness strain distribution can still not be quantitatively controlled.

Numerical simulation of sheet metal forming processes is an effective way to design and optimize the process parameters and to evaluate the forming defects such as fracture, springback, wrinkling, geometric deviations and residual stresses. In the past decade, researchers have used the finite element method (FEM) to model the ISF process. In Thibaud et al. (2012), a fully parametric toolbox has been developed to simulate the SPIF process using FEM. The prediction results of geometric deviations, thickness distribution and forming forces showed good agreement with the experimental results. Shanmuganatan and Senthil Kumar (2012) presented an explicit numerical simulation using Abaqus. The stress and thickness distribution have been derived and validated by experimental tests. Dejardin et al. (2010) used a FE model with shell elements to perform the simulation of the SPIF process in order to analyze the shape distortions and spring-back effects. The comparison between experimental and simulated results showed that the developed FE model can predict accurate results. Although FEM is an effective way to model and simulate the multi-stage ISF process, it usually takes long computational hours (several days or even more than a week), and therefore cannot be used effectively for the design of the full multi-stage ISF process.

The above review of recent studies shows that most of the previous work on the multi-stage deformation pass design in ISF is still based on the trial and error method so that material flow cannot be quantitatively controlled. Although there was an analytical model developed by Kim and Yang (2000), it is only suitable for two-stage forming. For the manufacture of more complex parts, more forming stages are needed. This paper proposes a systematic methodology to design multi-stage deformation passes in terms of the predicted thickness strains given a final part based on the shear deformation and the strain compensation mechanism. In this methodology, two analytical models ($M1$ and $M2$) are developed considering; the *global average thickness strain* and only the material in the final part region used in the forming ($M1$), and the *local weighted average thickness strain* and the additional material around the final part region used in the forming ($M2$), respectively. The proposed design methodology is compared with finite element analysis (FEA) and experimental tests using an Amino ISF machine with reference to the process formability and the thickness strain distribution.

## 2. Methodology

The shear-based modeling for deformation pass design in ISF was first proposed in Kim and Yang (2000). However, this model is only suitable for double-pass deformation design. In some cases, multi-stage deformation pass design is necessary for making complex parts, such as examples in Duflou et al. (2008), Skjoedt et al. (2010), Zhang et al. (2013), Li et al. (2013) and Liu et al. (2013). A systematic design methodology for multi-stage deformation pass design is provided in this section. First, the shear-based modeling for single-pass deformation design is briefly reviewed. Then, two analytical models are developed. In addition, a systematic design methodology incorporating the two models is proposed. Finally, the methodology for the FEA and experimental tests is introduced.

It is worth mentioning that the aim of the development of the two models is to improve the process forming limits. The underlying hypothesis of these models can be summarized as follows:

(i) The use of intermediate stages in the forming process will delay the incurrence of the highest strains, and therefore allow steeper shapes to be formed than would be possible by using single-pass forming.
(ii) By forming a wider area than the perimeter of the shape, it is possible to:
- Avoid discontinuities in the intermediate thickness strains, and therefore allow steeper shapes to be formed than would be possible by using single-pass forming;
- Allow the flow of material into the deformed region, thereby allowing a compressive stress state to develop and enabling steeper shapes to be formed than would be possible in single-pass forming.

The first model ($M1$) has been developed to test the first of the above points, whilst the second model ($M2$) has been developed to test all three of the above points.

### 2.1. Single-pass deformation model – shear deformation

An arbitrarily designed part can be discretized by triangular elements. Based on the shear deformation, $x$ and $y$ coordinates are the same for both initial and final configurations. Fig. 1 illustrates the 3D shear deformation for one sheared triangular element in a part.