Published in: Advanced Materials Research (2005), vol. 6/8, pp. 525-532.
Status : Postprint (Author's version)

Finite Element Modeling of Incremental Forming of Aluminum Sheets

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Abstract

Incremental forming is an innovative and flexible sheet metal forming technology for small batch production and prototyping, which does not require any dedicated die or punch to form a complex shape. This paper investigates the process of single point incremental forming of an aluminum cone with a 50-degree wall angle both experimentally and numerically. Finite element models are established to simulate the process. The output of the simulation is given in terms of final geometry, the thickness distribution of the product, the strain history and distribution during the deformation as well as the reaction forces. Comparison between the simulation results and the experimental data is made.

Keywords : Finite element method ; experimentation ; incremental forming

Introduction

The Incremental Sheet Forming (ISF) process has emerged in the past few years as a potential alternative to conventional sheet metal pressing to meet the increasing need to produce prototypes and small batch productions at low cost. The process uses a smooth ended tool under numerical control to create a local indentation in a clamped sheet, and by dragging the point of contact around the sheet according to a programmed tool path, a wide variety of shapes may be formed without the need for specific tooling. The advantage of the ISF approach is that it does not require any specialized tooling, and therefore offers flexibility with short setup times. Two versions of the process have been explored: with and without a supporting post on the reverse side of the workpiece. This paper will focus on the latter approach, so-called 'single point' incremental forming (SPIF).

Recent research work on SPIF has demonstrated that it can be used for low volume production and has explored the forming limits of the process [1-4]. However, this process is still early in its development and requires much more research to better understand the deformation mechanics and the influence of the process parameters. This paper investigates incremental forming of an aluminum cone using the powerful tool of finite element analysis.

Experimental Setup

A 3-axis CNC vertical milling machine is used as the platform for the SPIF process. A cylindrical stylus with a 12.7mm diameter spherical head is mounted on the vertical axis of the machine. A blank sheet with dimensions of 225x225 mm is supported on a four-sided steel fixture and is clamped rigidly to this fixture with a backing plate containing a 182mm diameter orifice (see ref. [5]). A cone with a 50-degree wall angle will be formed inside the orifice and truncated at a 40mm depth. During the deformation, the sheet is not allowed to move into the forming region, only the material available within the 182mm diameter zone can be deformed by the tool. The tool travels along a path that traces the contour of the cone at a feed rate of 2000mm/min. Lubricants are used between the tool and the blank during the process. The material used is annealed aluminum alloy AA3003-O with a thickness of 1.2mm.

The tool travels along a series of contours generated transverse to the radial direction of the cone as shown in Fig. 1. After traveling the entire path of one contour, the tool moves deeper in a stepwise fashion to follow the next contour. This process is repeated like a step like motion until the desired depth is reached. The proportions of the step are controlled by both the vertical step size from one contour to the next and the wall angle of the cone. In the current study, the vertical step size is chosen as 0.5mm, which means that the tool has to follow 80 contours to form the cone with a 40mm depth. During the forming process, the forces acting on the tool are measured. More details about the force measurements are given in ref. [5]. After the experiments, the geometry of the deformed cones is measured by laser scanning, from which the thickness distribution of the cone can be determined.

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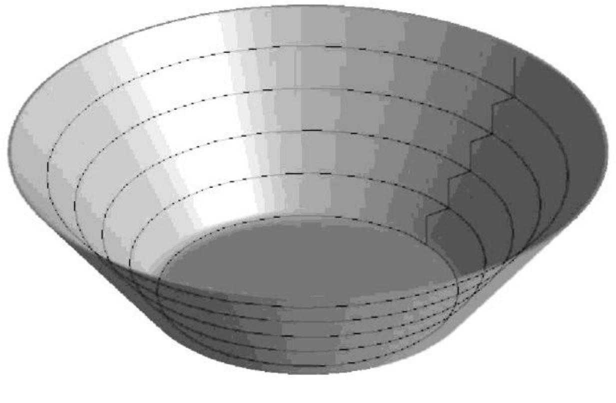
Fig. 1. *Schematic of cone with applied tool path*

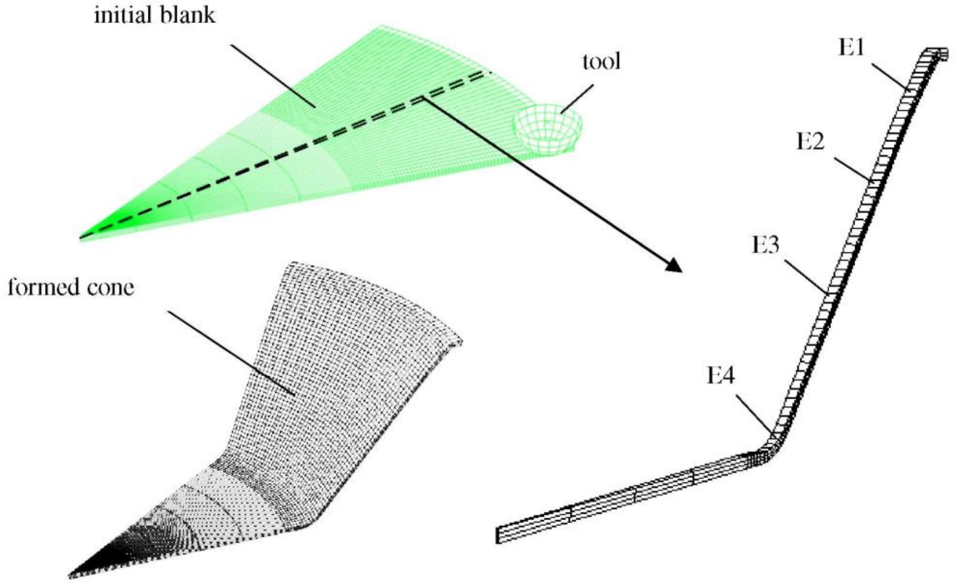


Finite Element Modeling

A three-dimensional, elasto-plastic FE model is set up for the simulation of the SPIF process. The implicit FE package Abaqus/Standard is used in this work. During the deformation, there is no real symmetry and a model for the whole geometry should be established, which is unfortunately very time consuming. Therefore, in the present study, it is assumed that the center of the blank does not move horizontally during the process and a kind of axis-symmetric condition is maintained. As a result, only a 40-degree pie of the blank is considered in order to simplify the numerical model and reduce the computation time. To consider the neighboring material, proper boundary conditions are assigned to the external nodes along the radial edges in such a way that they are not allowed to move in the direction perpendicular to the edges. This means that the angle of the pie will remain unchanged during the process. The 6 and 8-node brick element with reduced number of integration points (element type C3D6 and C3D8R in Abaqus) are utilized for the blank and the mesh for the blank consists of three layers of elements across the thickness and 2640 elements in each layer. Both the tool and the backing plate are modeled as rigid surfaces. Coulomb's friction law is applied with a friction coefficient of 0.05. The flow stress curve of the material obtained by tensile tests is approximated by the Swift law $\sigma=180(\varepsilon+0.00109)^{0.21}$ MPa. It should be mentioned that the anisotropy of the material is not taken into account in the current model and the isotropic von Mises yield criterion is adopted. Fig. 2 shows the utilized FE model for the process.

Besides the FE code Abaqus, another finite element code Lagamine, developed at the University of Liège, is also used for the simulation. The purpose is to compare the accuracy and reliability of these two codes. More details about the comparison are presented in ref. [6]. In this paper, the model for Lagamine makes use of an anisotropic Hill type yield criterion derived from the Lankford coefficients obtained from tensile tests and a friction coefficient of 0.15. Similar mesh is created for the blank, but the mesh density is coarser than that of Abaqus to reduce the computation time.

Fig. 2. *Initial and deformed mesh (E1 to E4: element 1 to element 4 from the blank edge towards the center)*



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Results and Discussions

Final Geometry of Formed Cone

Since there is no die supporting the sheet and the deformation takes place incrementally, the design of the tool path of a SPΓF process is crucial to achieve the desired geometry of the product. Apart from analyzing the material behavior during the process, the FE modeling will also be used to improve the tool path design to obtain the target geometry. In the present study, the simulated final geometry of the cone is compared with experimental results. Fig. 3 shows the inner surface of the cone cross section at 45 degrees with respect to the initial rolling direction. The CAD results show the ideal shape of the formed cone according to the tool path design without taking material behavior into account. It is clear that the agreement between the simulated and experimental shape is rather good for the cone wall except some oscillations of Lagamine results which is due to the coarse mesh. For the cone bottom, the simulated surface from Abaqus is about 1.5mm deeper than the experimental one, whereas, the surface obtained by Lagamine is even deeper. This difference is probably due to the simplified FE model in which only part of the geometry is considered and the applied boundary condition does not represent the real interaction from neighboring materials. Therefore, a full model in which the whole blank is meshed is also established without any imposed boundary conditions along the radial edges existing in the partial model. Fig. 4 shows the comparison between results from the partial model and the full model using Abaqus. Due to the long CPU time for the full model, only the results after the 20th contour are shown in the figure, which means the cone has a depth of 10mm. Apparently the partial model already gives good results for the cone wall region. For the bottom area, in the full model, constrained by the other parts of the materials that are not modeled in the partial model, the material at the central region is less easy to move down as the tool moves deeper from one contour to the next. As a result, the full model gives better prediction than the partial one, especially at the central region of the blank. However, the CPU time increases dramatically if the full model is used, which makes the simulation unfeasible for practical applications.

Fig. 3. *Inner surface of the cross section of formed cone*

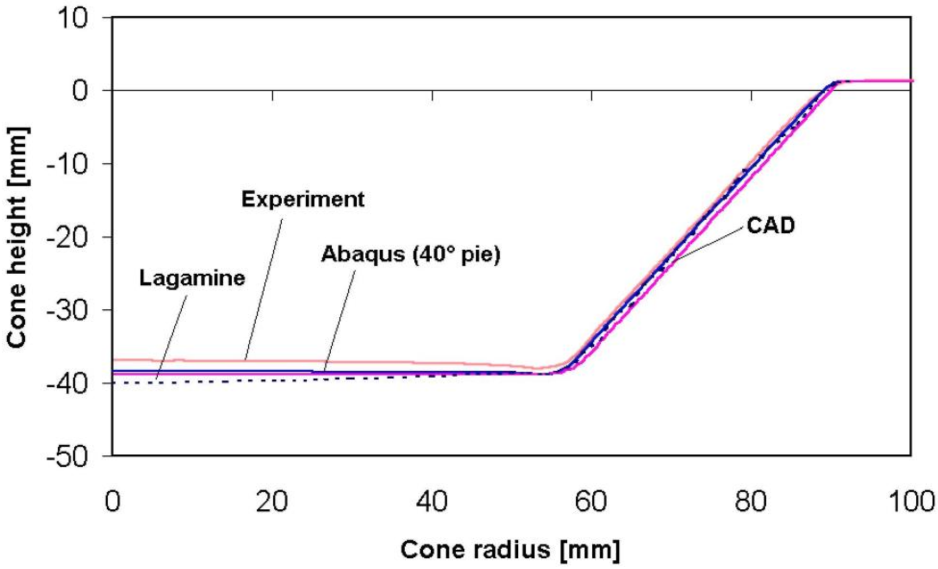
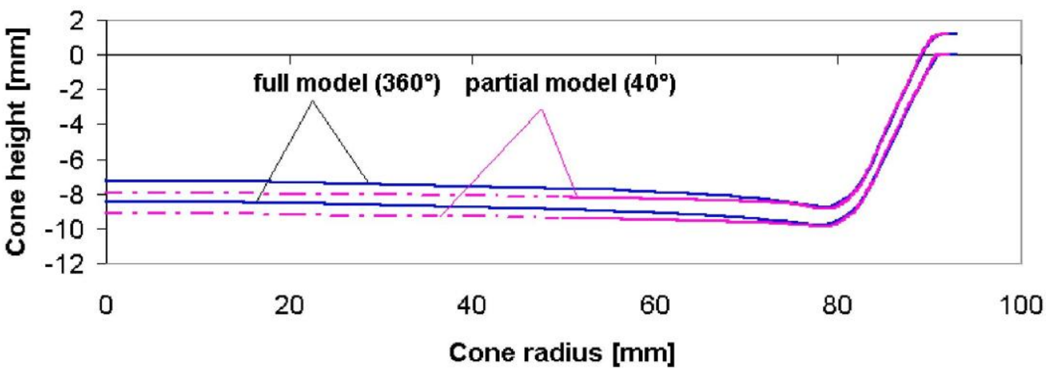


Fig. 4. *Comparison of resulting geometry between partial and full model of Abaqus*



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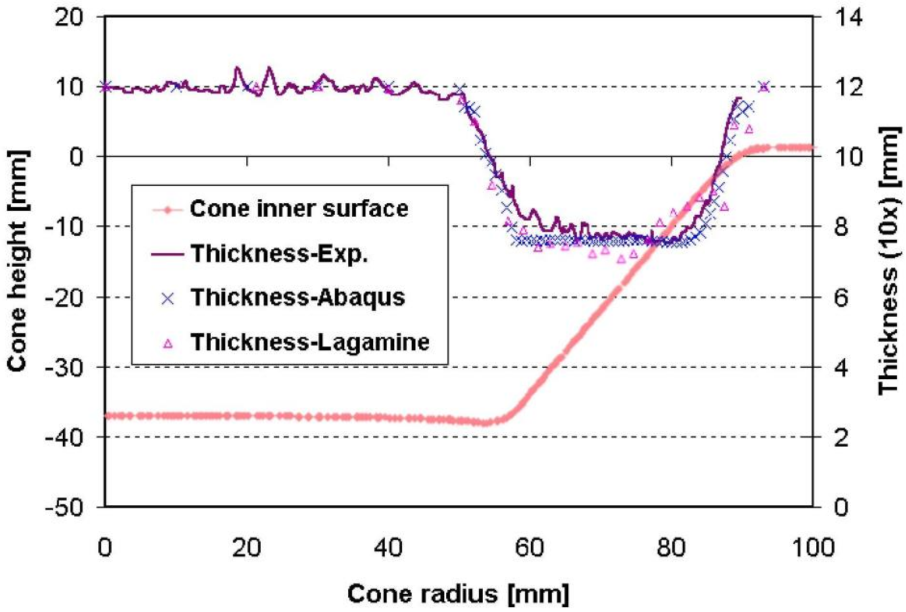
Thickness Distribution

Earlier research has shown that one of the drawbacks of the SPIF process is the excessive thinning which limits the maximum wall angle of the deformed part [7-9]. Therefore, it is important to predict the thickness distribution of the formed part correctly. As shown in Fig. 5, a comparison of the sheet thickness between predicted and measured results shows a quite good agreement with a maximum difference of less than 0.1mm. It is shown that the thickness at the bottom of the cone remains almost unchanged, whereas the thickness in the wall region is reduced drastically from 1.2mm to 0.76mm. This is slightly lower than the thickness of 0.771mm derived from the so-called 'sine law' based on the plane strain condition of the SPIF process.

Fig. 5. *Thickness distribution of formed cone with indication of the corresponding part shape*



Strain History and Distribution

The strain path is analyzed for the elements indicated in Fig. 2 using Abaqus. During the simulation, the four elements are subsequently affected by the movement of the tool: element 1 (E1), which is close to the blank edge, is the former to undergo deformation, but it reaches just a limited strain since it undergoes the tool action just for a few contours. On the contrary, element 4 (E4), which is close to the center of the blank, is not affected by the tool in the former contours and the deformation takes place later in the process. As a result, the deformation there reaches a limited level before the process finishes. Elements 2 (E2) and 3 (E3), lying in between, undergo the tool action for the maximum number of contours and consequently the strains also reach the maximum there. This phenomenon is synthesized in Fig. 6, which shows the evolution of the equivalent plastic strain of mentioned elements.

As mentioned in [10], the strain paths are characterized by a typical step-trend: each strain increment is directly due to the action of the tool as it passes the particular element. In turn, no strain increment occurs when the tool continues its path along the same contour far away from the element. This confirms the feature of localized deformation that characterizes SPIF: a given material point is not affected by the deformation imposed in the nearby area, but undergoes its strain through progressive, small increments. In the studied case, the maximum equivalent strain reaches 0.94. As mentioned above, as the wall angle of the cone increases, the thickness of wall further decreases, resulting in even larger deformation, which might finally lead to fracture at a critical wall angle.

Fig. 6. *Deformation history during the SPIF process (E1 to E4: the same elements shown in Fig. 2)*

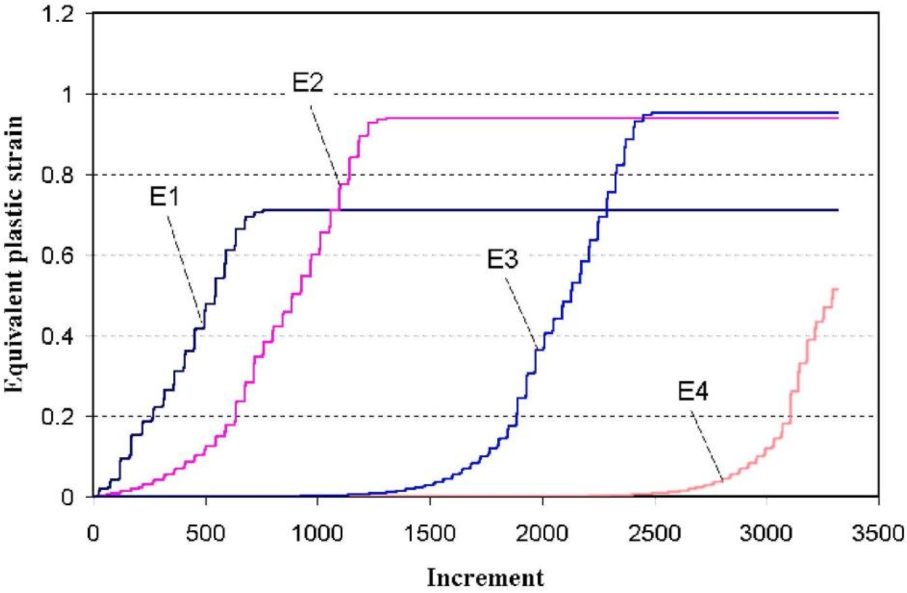
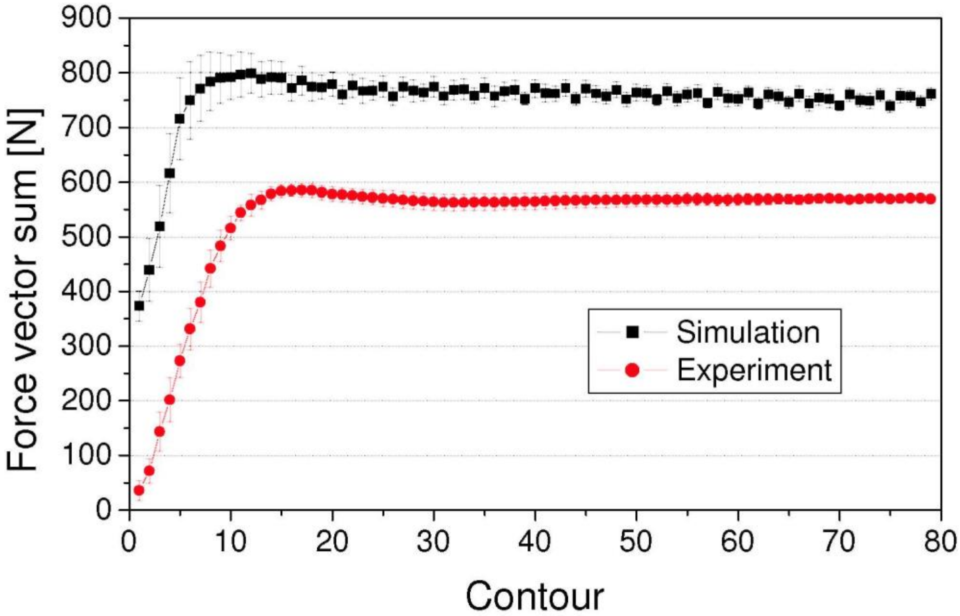


Fig. 7. *Comparison between measured and predicted forces (mean value with standard deviation) through the process*



Reaction Forces

The force required for forming has consequences for the design of tooling and fixtures, and is also critical for the machinery used. As mentioned above, the platform used in the current research is a conventional CNC milling machine, which is not dedicated for the SPIF process. It is of great importance to correctly predict the forces acting on the axis of the machine during the forming in order to avoid any possible damage to the machine. Therefore, an investigation of the forces is also carried out both numerically and experimentally. Fig. 7 presents the comparison of the Abaqus predicted and measured total forces (magnitudes of the force vectors). In this figure, the averaged force during each contour as well as the upper and lower extents of one standard deviation from the mean are shown. Obviously the prediction overestimates the force by about 30%. There might be several reasons for the disagreement. First, the yield criterion employed in the current study is the isotropic von Mises yield criterion. This causes certain error on the calculated stress states because in reality the material presents a certain plastic anisotropy. This can have an effect on the forces. Secondly, the isotropic work hardening law used might not be accurate. The preliminary results of the strain history for individual elements show that the strain path changes as the tool approaches and passes the elements, which means the isotropic work hardening law is not valid anymore. Instead, a law that accounts for these strain path changes (i.e. kinematic hardening) should be used. Finally, the friction description between the tool and the blank might not be accurate in the current study. But since the reaction force introduced by friction is only a small part of the total reaction force, the influence of the friction could be limited. Further investigation on the disagreement is still ongoing [6] and the results will be reported in a follow-up paper.

Despite of the difference in absolute values, the predicted force presents the same trend as the measured one. As shown in the figure, the force starts at zero once forming is initiated and then increases during the first several contours to reach a maximum as the tool pushes deeper into the blank to finally reach a depth where the forces tend to remain approximately constant.

Conclusions

This paper investigates the process of single point incremental forming of a cone with a 50-degree wall angle using the finite element method. By simplifying the numerical model, it is possible to simulate the process so that a better understanding of the deformation mechanism is achieved. Predicted results show good agreement with experimental data for the geometry of the cone, but overestimate the force required in the process.

Acknowledgements

The authors would like to acknowledge financial support from the Institute for the Promotion of Innovation by Science and Technology in Flanders (IWT).

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