FINITE ELEMENT MODELING OF INCREMENTAL SHEET METAL FORMING OF ALUMINUM ALLOY AL 1100

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Abstract: *Incremental sheet metal forming has been well-known as one of the flexible methods of forming metallic sheets, suitable for the production of prototypes or small batch sizes. Apprehending the deformation method in forming processes and selection of route parameters to avoid part failure are of vital importance, because marketing needs standard sound parts in a shortest possible time. This paper presents the study on the use of finite element modeling of incremental sheet metal forming of Al 1100 aluminum alloy to investigate the effect of tool diameter and step over on the forming induced stresses, part thickness distribution and forming forces. The results of finite element analysis are compared with experimental data while producing truncated pyramid parts. It has been shown that the developed finite element model is capable of providing reliable results in the prediction of the final thickness of the part, which matches the experimental results with a maximum discrepancy of 8%.*

Keywords: ALUMINUM ALLOY, INCREMENTAL FORMING, FINITE ELEMENT METHOD, FORMABILITY

1. Introduction

In sheet metal forming industry, the mass production of different parts is usually done by using accurate but expensive punches and dies. In mass production, because of the large quantities of the produced parts, the cost per part becomes significantly small, which makes these processes economically feasible for sheet metal forming industry. However, when small batch sizes or prototypes are required, the cost per part increases drastically. This increased cost makes the conventional methods based on dies and punches not feasible anymore. Therefore, it is necessary to develop and implement new developing techniques to satisfy the requirements imposed by the small batch production industries[1]. Incremental sheet forming (ISF), which originates from hybridization of stretch forming and conventional spinning processes[2], can be considered as a plastic forming process which meets the requirements of individual part or small-batch production, enabling the manufacturing of the desired shape through an incremental localized deformation[3].

In ISF process, the forming of a metal sheet is performed using the movements of a CNC controlled hemispherical head tool, which plastically deforms the blank according to a predefined path. The tool path generated with computer aided manufacturing (CAM) software, makes it possible to obtain complex geometries using a simply shaped tool[1,4,5]. In addition to eliminating a need for sophisticated forming tools, ISF results in an increased forming limit compared to pressing process[4]. Due to its unique advantages such as flexibility, cost effectiveness as well as reduced time-to-market and increased forming limit, ISF has gained a substantial attention from academia and industry as an important research area. According to Jackson & Allwood[4], and Jeswiet et al.[5], the first industrial emergence of ISF which is also called “diless forming”, dates back to 1960s in the USA. This method has been patented by Roux[6] and Leszak[7], while academic research lagging behind industrial application began in the early 1990s in Japan.

Depending on the complexity and desired accuracy of the workpiece, several variations of ISF have been developed in the last decades. In general ISF process can be classified into three groups, i.e. Single-Point Incremental Forming (SPIF), Two-Point Incremental Forming (TPIF), and Hybrid Incremental Forming (HISF).

SPIF, which is the simplest form of ISF, uses a simple tool to form the sheet, without requiring any supporting tool or die. The idea of using a fixed tool as a support has been introduced by Matsubara in 2001[8], where a very straightforward and compact tooling is devised and put on the bed of a CNC machine acting as a support during the forming process. The method which later called as TPIF has been successfully used in the forming of an aluminum sheet into cones and pyramids having an arbitrary number of sides with a minimum half-apex angle of 10°. The TPIF process may use a partial die or a full die. It should be mentioned that due to the reduced forming forces of ISF, it is possible to use soft materials such as plastics as partial or full dies, which can easily be produced by 3D printing techniques[9]. The term Asymmetric Incremental Forming (ASIF) is used to refer to both SPIF and TPIF[5].

Due to the unique advantages of ASIF, recently extensive researches are done to understand the mechanism of forming of ASFI and its potential applications for the fabrication of either prototypes or functional parts. The studies in the literature are mostly concentrated on three important quality measures of the process, namely geometric accuracy, surface quality and formability. Low part accuracy due to spring back and sheet bending has been considered as a limiting factor for the industrial application of ASIF[10], which is directly affected by the tool path generated by CAM software.

Finite element method has been used as an indispensable tool by several researchers to study ISF process. Cerro et al.[1] used FEM modeling of the ISF process of Al 1050-0 sheets during forming of pyramids with a 75° wall angle using the ABAQUS/Explicit software with shell elements. They reported a maximum difference of 5% between the peak values of the measured and predicted forming forces in the Z direction. The compromise between speed and accuracy of SPIF has been investigated by Yamashita et al.[11] using a dynamic explicit finite element code DYNA3D in forming quadrangular pyramids. The TPIF with full die has been studied by Attanasio et al.[12] to understand the effect of tool path type, step depth and scallop values on manufactured part characteristics. They investigated the surface quality, thickness distribution and geometric accuracy of a door handle of a commercial car made of FeP04 steel with a thickness of 0.7 mm. Their results showed that step depth and scallop height significantly influence the characteristics of the manufactured parts. They also presented some preliminary FEM simulations.

In the present paper, deformation behavior of Al 1100 aluminum alloy sheet metal in a single point incremental forming process (SPIF) is numerically simulated using ANSYS software. The effect of tool diameter and step over on the forming induced stresses; part thickness distribution and forming forces are investigated. The results of finite element analysis are compared with experimental data while producing truncated pyramid parts.

2. Materials and Methods

In this study, SPIF of Al 1100 aluminum alloy is well-thought-out. Before conducting SPIF tests, the material properties are obtained using a standard uniaxial tensile test. An annealing process is carried out in the samples at 380 °C for 90 minutes. Fig. 1, illustrates the stress-strain curve for Al 1100 aluminum alloy. The material properties of this alloy are shown in Table 1.

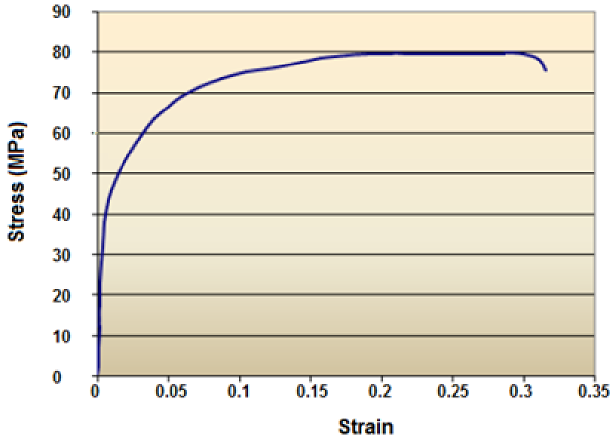

Fig. 1 *Stress-strain curve for aluminum alloy Al 1100*

Table 1: *Material properties of aluminum alloy Al 1100*

Elastic Modulus (GPa)	Poisson's Ratio	Yield Strength (MPa)	Ultimate Tensile Strength (MPa)	Elongation %
84	0.33	41	79.7	31.8

To do single point incremental forming, aluminum sheets with dimensions of 150×150×1 mm are prepared. A forming tool with a diameter of 10 mm with a hemispherical head is fabricated from a Stellite (cobalt-chromium alloy) with a hardness of 54 HRC and mounted on a CNC milling machine (FP4MK-MST). The hemispherical part of the forming tool has been ground and polished to reduce the friction. The aluminum sheet is fixed to the CNC milling machine using a dedicated fixture. Fig. 2 illustrates the forming tool and experimental setup used in this study. A CAM software is used to generate a tool path using parallel spiral outside-in strategy. The tool path is schematically shown in Fig. 3.

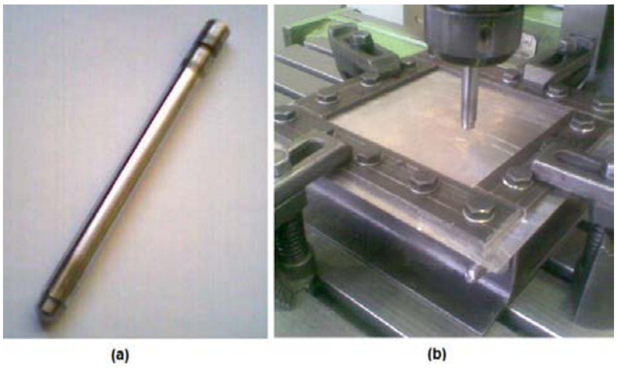

Fig. 2 *(a) Hemispherical tool, (b) Experimental Setup for SPIF*

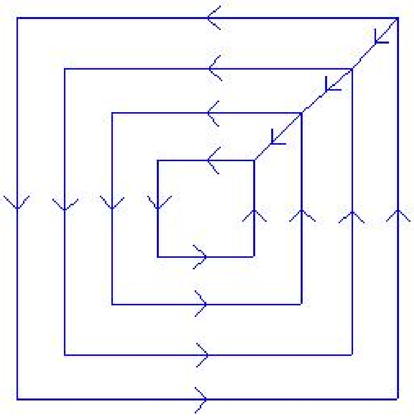

Fig. 3 *The tool path used in the incremental forming process*

The forming operations are performed at a feed rate of 60 mm/min with lubrication to reduce the friction and to avoid tool wear. The rotational speed is taken as 140 RPM. Fig. 4 illustrates a truncated pyramid part produced by SPIF process.

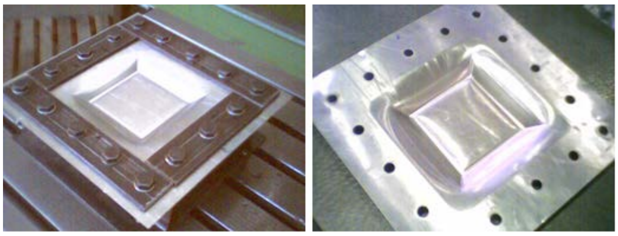

Fig. 4 *(a) Truncated pyramid part fabricated by SPIF process*

3. Finite Element Modeling of SPIF Process

In this study, finite element simulation of single point incremental sheet metal forming is performed using ANSYS software. The geometric model of SPIF process consists of four different parts, including forming tool, blank, blank holder and fixture as depicted in Fig. 5 (a). The fixture and blank holder are meshed using Solid 95 elements. The blank has been modeled using Visco Solid 107 element. The forming tool is modeled as an elastic body with a modulus of elasticity of 207 GPa. The meshed model of the assembly is shown in Fig. 5 (b).

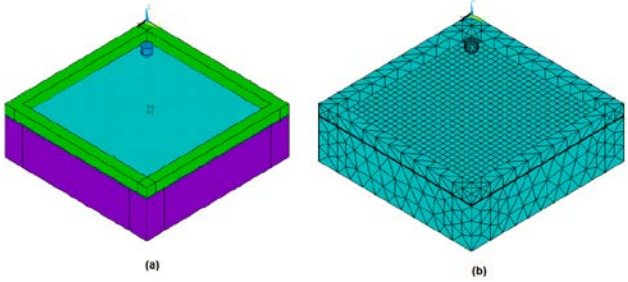

Fig. 5 *(a) Geometric model of the SPIF process, 5(b) Finite element model of the SPIF process*

A rigid-flexible surface-to-surface contact is defined using Target 170 and Contact 174 elements. Since in this process lubricant is used to reduce the friction between sheet and forming tool, a small Coulomb friction factor of 0.04 is used in the simulations. A step over of 10% of tool diameter is considered, meaning that after completing each loop the forming tool moves 1 mm from the current loop towards the center of the part to start the next loop. Fig. 6 illustrates the deformed shape of the sheet at the end of the simulation.

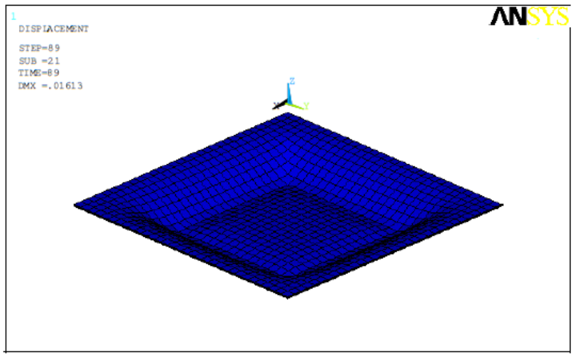

Fig. 6 *Deformed shape of the sheet after SPIF process*

The contours of von Mises stresses and strains are shown in Fig. 7 and Fig. 8, respectively. The results of simulations revealed that as the depth of part increases the level of stresses increases. The maximum stresses occur at the contact region between the forming tool and sheet during deformation.

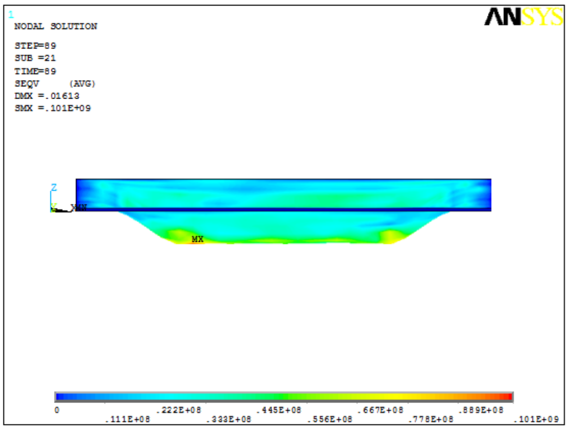

Fig. 7 *Forming induced von Mises stresses in SPIF process*

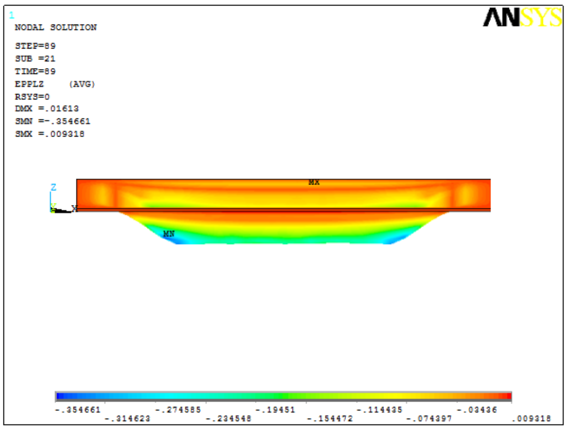

Fig. 8 *Forming induced strains in SPIF process*

The thickness of the part was measured at different positions to compare the results of simulations with experiments. Table 2 shows a comparison between experiments and finite element predictions. As is seen in Table 2, the minimum thickness in FEM predictions is about 0.65 mm, while it is 0.7 mm in experimental one, which shows the capability of the FEM model in the prediction of thickness reduction with a maximum error of 8%.

Table 2: *Measured thicknesses vs. calculated thicknesses*

Thickness FEM [mm]	0.65	0.73	0.81	0.89	0.97	0.99
Thickness Exp. [mm]	0.7	0.77	0.84	0.91	0.96	1

4. Analysis of the Effect of Forming Tool Diameter

The SPIF process was simulated with hemispherical head forming tools having three different diameters of 7 mm, 10 mm and 13 mm to analyze the effect of forming tool diameter in the incremental forming process. For each of forming tools, von Mises stresses, formed thickness and forming forces are obtained at a constant step over/outstep of 1 mm. The simulation results for each tool are shown in Table 3.

Table 3: *Results of simulations for different tool diameters*

Tool Dia. (mm)	Von Mises Stress (MPa)	Thickness (mm)	Maximum Forces (N)	
			F Feed	Fz
7	102	0.64	290	673
10	101	0.65	292	681
13	99	0.66	297	718

As it can be seen in Table 3, the increase in the forming tool diameter results in a decrease in the von Mises stresses and increase in the formed thickness of the workpiece. Therefore, we can conclude that with increasing forming tool diameter the possibility of failure reduces, which makes it possible to produce parts with larger depths. It can also be seen that, by increasing forming tool diameter both in-feed and in-depth forming forces increases.

5. Analysis of the Effect of Step Over

Step over is another important parameter which has a significant influence on the forming induced stresses and formability of the sheets during ISF process. In this study, the effect of step over on forming induced stresses and thickness reduction is considered. Two step over values of 10% and 20% are taken into account for a forming tool of 10 mm diameter, while other conditions are kept similar. The results revealed that by increasing step over from 10% to 20%, von Mises stresses increases from 101 MPa(Fig. 7) to 109 MPa (Fig. 9). The thickness of the part also reduced to 0.62 mm, meaning that as step over enlarges the formability of SIF decreases. Therefore, based on these results, in order to increase the formability, the step over values should be made as small as possible, however by selecting very small step over values, the processing time increases, which in turn reduces the productivity. Hence, the best compromise between step over and the process time is well-thought-out.

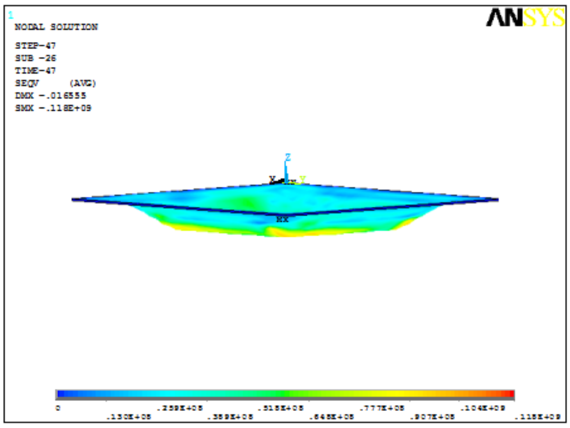

Fig. 9 *Analysis of the Effect of Step over process*

Conclusions

This paper aims at studying the use of finite element modeling of incremental sheet metal forming of Al 1100 aluminum alloy. To investigate the effect of some process parameters on residual stresses and part thickness distributions, the results of the finite element analysis are compared with experimental data while producing truncated pyramid shaped parts. It has been shown that the developed finite element model is capable of providing reliable results in the prediction of the final thickness of the parts, which matches the experimental data with a maximum discrepancy of 8%. The results of FE simulations revealed that with increasing forming tool diameter the possibility of failure reduces, which makes it possible to produce parts with larger depths. It has also found that by increasing forming tool diameter both in-feed and in-depth forming forces increases. The effect of step over on the formability of SPIF process of aluminum alloy Al 1100 has also studied. The results revealed that, as far as the productivity of the process is maintained, small step over values should be preferred to increase the formability and to reduce the forming induced stresses.

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