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An Efficient Force Prediction Strategy in Single Point Incremental Sheet Forming

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Abstract
Incremental sheet forming is a flexible forming process where a tool is programmed to follow a pre-determined tool path to create sheet metal parts. Without using complex tool and die, the process can generate various part geometries directly from CAD models and CNC codes, and is ideal for rapid prototyping and low volume production. Modeling incremental sheet forming and predicting forming forces can significantly benefit product design and process development. Existing force prediction methods are either inaccurate or too time consuming. In this paper, an efficient force prediction strategy was proposed based on experimental observations of forming force patterns. It was found that by creating a near finished part geometry as a starting point of numerical simulation, forming forces can be predicted with satisfactory accuracy and efficiency. The proposed strategy was validated with forming of a truncated pyramid and was further demonstrated in forming of parts having different geometries. As the proposed simulation strategy can be completed in a fraction of the full simulation time, it can be adopted to guide the design and development of incremental sheet forming parts.

Keywords: single point incremental sheet forming, force measurement and prediction

1 Introduction

Incremental sheet forming (ISF) is a flexible sheet forming process that has gained significant interests since early 1990s. ISF is a highly localized deformation process in which a tool is programmed to moved and follow a certain path and create the desired part geometry. A simple incremental sheet forming process to manufacture a truncated cone is depicted in Figure 1 (Ham & Jeswiet, 2006). The workpiece/sheet metal is clamped with a fixture. A pin-like tool is programmed to follow the circumference of a circle. After completing the circle, the tool steps down and towards the

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center to start a new circular pass. After a number of passes, a truncated cone can be generated. Without complex tool and die, the process can form various part geometries directly from CAD models and CNC codes. The process has great potential for rapid prototyping of parts that require small quantity. In addition to the flexibility, it is also known that ISF can significantly increase the formability of the sheet metal workpiece (Shim & Park, 2001) (Filice, Fratini, & Micari, 2002) (Kim & Park, 2002) (Bhattacharya, Maneesh, Reddy & Cao, 2011). A thorough review of the history and development of the incremental forming process has been given by Ham and Jeswiet (Ham & Jeswiet, 2008), and Cao. et.al (Cao, Huang, Reddy, Malhotra & Wang, 2008).

Measuring and predicting the forces acting on the tool during incremental sheet forming is a major research area. Jeswiet and Szekeres (Jeswiet & Szekeres, 2005) discussed the forces developed during forming of pyramid and cone shape parts from aluminum alloy 3003-O. For measuring forces, a cantilever type of sensor was mounted to the spindle of the forming tool. It was seen that the axial force was larger than the combined forces in the plane of the sheet surface. It was also note that the wall angle was an important factor that the forming force increases with increasing wall angle. Duflou et al. (Duflou, Szekers, & Vanherck, 2005) used a Kistler 9265B six component table mount dynamometer to measure forces generated during forming. Experiments were conducted to learn the effect of step size, tool diameter, and wall angle on the forming force. It was observed that the force values increased gradually while the depth increased. After a fair amount of depth was reached, the force values were seen to be constant. The authors further divided the forces obtained into two broad regions. One was the peak force which was identified to be the highest force generated during the process. The second region, which had a constant value came after the peak force, was identified as the settled force. Doflou and Tunckol (Duflou & Tunckol, 2006) conducted experiments to study the effect of the boundary and part geometry on the forming force. It was reported that boundary condition did play a part initially in the forces generated during forming. After a sufficient depth was traversed, the steady-state forces were the same for the two experiments. To investigate the influence of the part geometry, two pyramids were formed. One had an initial wall angle of 30 degree followed by a wall angle of 60 degrees, and the other had a wall angle of 60 degrees. The other dimensions were kept the same. It was seen that the settled force was similar in both cases, and this steady-state forces were seen to be the same irrespective of the part geometry. Petek et al. (Petek, Kuzman, & Kopac, 2009) performed experiments to obtain the effect of the wall angle, tool rotation, step size, tool diameter and lubrication on the forces. They concluded that the presence of lubricant leads to a better part surface quality but it does not influence the magnitude of the forces. Filice et al. (Filice, Ambrogio, & Micari, 2006) conducted a wide variety of experiments and noted that the force patterns do not depend on the history of forming. If for instance the wall angle was increased during the process, then the instantaneously the fore would increase, but after a few passes, the force would get back to the original value.

Modeling incremental forming processes and predicting the forming forces can greatly benefit product and process design (Cui, Xia, Ren, Kiridena, & Gao). Duflou et al. (Duflou, Tunckol, & Aerens, 2007) developed a multi-linear regression model to predict the force required to form parts having complex shapes with varying wall angles. The development of the empirical model involved extensive experiments. The predicted force values had a lot of deviation when the results were extrapolated from the parameters outside of the experimented range. Aerens et al. (Aerens, Eyckens, Van Bael, & Duflou, 2010) presented a new approach for the forming forces based on results derived from experiments and finite element analysis. The aim was to establish equations which could be used to calculate forces for different materials. Combining the relations obtained from numerical simulation and regression equations from experiment, a new set of equation were developed for force prediction. Bouffioux et al. (Bouffioux, et al., 2008) performed line tests to verify the accuracy of tool force prediction from finite element analysis. Brick elements which had three layers along the thickness and shell element were used. It was found that shell elements predicted the same force with much less computation time when compared to brick elements. He et al (He, et al., 2005) performed simulation of forming a cone using two finite element codes, Lagamine and Abaqus. It was found that the force values predicted by Lagamine were over 30% higher than that was predicted by Abaqus. The same simulation was also conducted with implicit and explicit approaches. They found that the latter approach reduced the computation time by a factor of four. Using the explicit code, however, could reduce the prediction accuracy. Henrard et al. (Henrard, et al., 2005) modeled cone forming using three layers of 8-node brick elements in Lagamine. The part had a maximum diameter of 180 mm and a depth of 40 mm. With only one-quarter of the cone modeled, it was noted that simulation of each pass took around 15 to 20 hours using an 8 CPU MIPS R12000 400 MHz computer. It was also suggested that a fine mesh and a complete model of the cone was necessary to obtain accurate force predictions. He et al. (He, et al., 2005) also simulated the forming of a cone using three layers of brick elements with 2640 elements in each layer. The forces obtained from simulation were compared to the experimental results. It was seen that the calculated forces overestimated the measured forces by about 30%. The large error was thought to be due to the isotropic yield criterion used in the analysis where in reality the material exhibits anisotropy. Another possible cause for the discrepancy was attributed to the assumed coefficient of friction between the tool and the sheet metal.

Analytical models were also developed to calculate forming forces. Iseki (Iseki, 2001) presented a force model which could predict the radial and axial forces. The model was a simplified plane strain membrane model based on the assumption that the sheet metal in contact with the tool was stretched uniformly. The model predictions, however, were not compared to any experimental measurements. Pohlak et al. (Pohlak, Majak, & Kuttner, 2007) refined Iseki's model to include the effect of plastic anisotropy. The model however could not predict the peak forces at the corners when forming a pyramid. For both the models developed by Iseki and Pohlak, it is necessary to approximate the width of the elongated strip after deformation to calculate the forces.

From the review of the previous literature, it is found that the existing modeling and force prediction methods are either inaccurate or too time consuming. In the present work, single point incremental forming experiments are conducted to measure the forming forces, as presented in Section 2. Based on the observation of the force patterns, an efficient force prediction strategy is proposed in Section 3. In Section 4, the proposed method is validated with a truncated pyramid and cone shape and is further demonstrated in forming parts having different geometries. Conclusions of the present work are then presented in Section 5.

2 Experimental

In this section, the experimental setup for single point incremental forming process is first described. The force measurement data under various forming conditions are presented. The observations of the forming force data form the basis of the force prediction strategy.

2.1 Experimental Setup

In the present work, the single point incremental forming experiments were conducted on a CNC milling machine. As shown in Figure 2, the system consisted of a forming tool, a fixture, and a dynamometer mounted on the slide table of a Bridgeport CNC. Two pin-like tools having radii of 6.35 mm and 9.525 mm were designed and manufactured such that the effect of tool geometry on the forming forces can be studied. The tools were made of 41L40 steel and the tool tips were polished to reduce friction and produce good surface finish of the parts. The fixture was designed and fabricated to secure workpieces with the dimension of 125 mm × 125 mm and forming depth of 25 mm.

The dynamometer used in the experiments was a MC 818 series dynamometer from Advanced Mechanical Technology Inc. (AMTI). It has four channels to measure the forces in the x, y, and z directions and also the moment about the x axis. The dynamometer produces analog signals whose magnitude is directly proportional to the force. An MCA amplifier with the voltage gain of 4000 was used with the AMTI dynamometer. A National Instrument USB-6009 converter was used to convert the amplified analog signals coming out from the amplifier into digital signals which were then captured by the data acquisition software (LabVIEW Signal Express LE). For data acquisition, the sampling rate used for the experiments was set at 5 Hz. Digital data were exported to an Excel spreadsheet file for data analysis and creating plots.

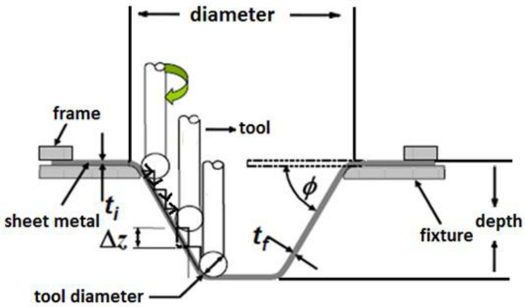
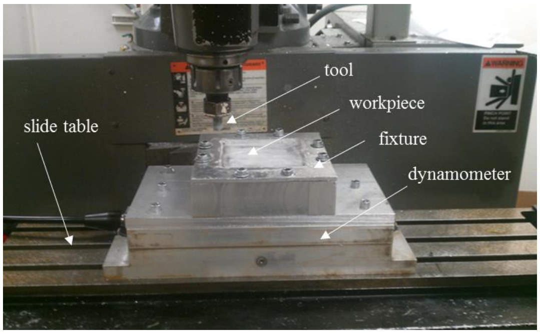


Figure 1 Single point incremental forming (Ham & Jeswiet, 2006)



2. Experimental setup

Experiments were conducted to measure the forces generated during forming. In the initial trial experiments, aluminum alloy 5052 sheets with the dimension of 125 mm × 125 mm × 0.8 mm (thickness) were used. The tool radius was 6.35 mm. Before running the experiments, an even coating of Vaseline was applied onto the sheet metal surface to reduce friction. The part geometry was a pyramid having a wall angle of 45 degrees formed with a step size of 1.27 mm. The pyramid shape was to have a depth of 25 mm. The experiments, as shown in Figure 3, were repeated multiple times to evaluate the repeatability. As shown in Figure 4, the three trials generated almost identical forming forces (only the forces in the z direction are shown). This indicates that the process condition was well-controlled, and the dynamometer and data acquisition system were producing repeatable and reliable results.

The forming force in Figure 4 provides rich information. It can be observed that the forming force gradually increases as the number of passes increases. After about 10 passes, at the depth of 12.7 mm, the "steady-state" forces were reached. It was also observed that the time required to complete a pass was gradually shorten, as the perimeter of the square decreases while the depth increases. Nevertheless, the force pattern and the peak forces repeated until the full depth was reached.

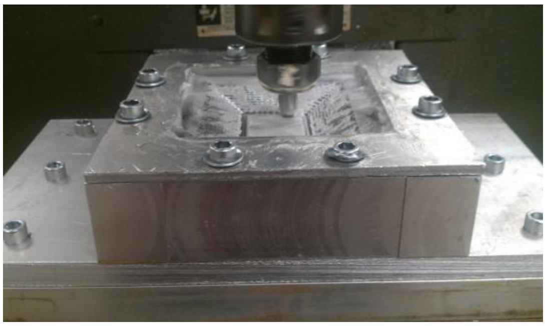


Figure 3 Forming of a pyramid

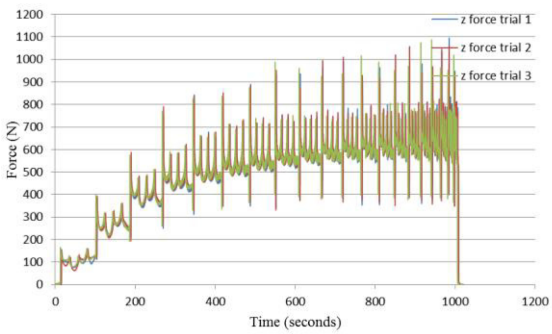


Figure 4 Forming force in the z direction (pyramid)

2.2 Experimental Results

Forces for forming a pyramid

Experiments were conducted to measure the forces generated during forming of a pyramid. Except the step size of 0.635 mm, the workpiece material (0.8 mm, Al 5052), the tool (6.35 mm radius), and the forming conditions (45 degree wall angle) were the same as those used in the trial runs described above.

The steady state forming forces are of particular interest, and the details of the force pattern for two passes are shown in Figure 5. First, it was clear that the forces were fairly constant during most of the deforming process. It was seen that while the force in the x direction was about 220 N, the force in the y direction was about 70 N. As the tool made a 90 degree turn, the forces in the x and y directions switched as expected. As the tool turned the corners, the dynamometer also detected small peak forces. Also shown in Figure 5, the steady-state force in the z direction was also constant but much larger, at about 670 N, compared to the forces in the x and y directions. The forming force in the z direction was independent of the direction (on the x-y plane) in which the tool was moving. There were three small peaks corresponding to the three 90-degree turns in one pass. The large peak force corresponded to the downward motion of the tool at the beginning of the new pass.

The vector sum of the forces in the three orthogonal directions for a pass is shown in Figure 6. The force marked 1, about 1000 N, was the force when the tool reached a corner and made a step down to start a new pass. The forces marked 2, about 850 N, were the forces measured when the tool was at the other three corners of the pyramid. With no step down, these forces were lower than force 1. The force marked 3 (700 N) was the constant deformation force measured while the tool was moving and forming the sides of the pyramid. Force 4, about 570 N, was the force measured at the end of the pass. This force was small because the workpiece was already deformed at the start of the pass. At this location, the tool was still in contact with the workpiece (resulted in the measured force) due to the springback of the sheet metal.

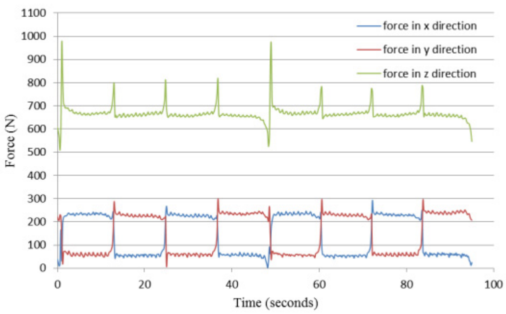


Figure 5 Steady-state forming forces of a pyramid

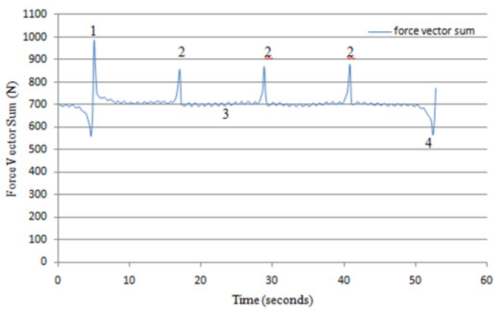


Figure 6 Vector sum of the steady-state forming forces for a pyramid

Forces for forming a cone

The forces developed in the three orthogonal directions during incremental forming of a cone having a wall angle of 45 degree were measured. The same workpiece material (0.8 mm thickness, Al 5052) and forming tool (6.35 mm radius) as those in the pyramid experiments were used. The step size was 1.27 mm for each pass. Figure 7 shows the forces measured in the x, y, and z directions. It was observed that the forming forces gradually increases as the number of passes increases. The steady-state force pattern was reached after about 8 passes. The forces in the x and y directions exhibit a phase shift, and the amplitude of both was a constant at about 300 N. In the z direction, it can be seen that for each pass, there was only one peak force, at about 1000 N, as there was no corners in the tool path. The peak force was caused by the downward motion of the tool at the beginning of each pass. Similar to forming the pyramid, there was a steady-state force at about 700N and a load drop, to about 400 N, at the end of the pass.

The vector sum of the forces in the three orthogonal directions for a pass is shown in Figure 8. The force marked 1, about 1100 N, was the force when the tool made a step down to start a new pass. The force marked 2 (800 N) was the constant deformation force measured while the tool was moving to form a circle. Force 3, about 450 N, was the force measured at the end of the pass. This force was small because the material at that location was already deformed but springback caused the metal to move up to contact with the tool.

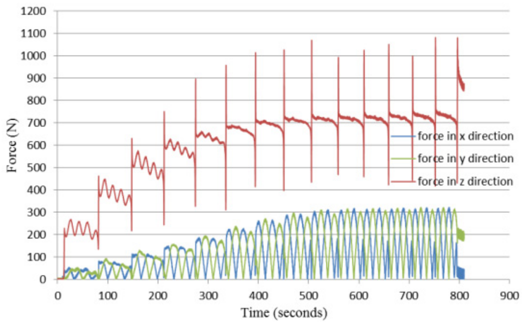


Figure 7 Forces for forming a cone

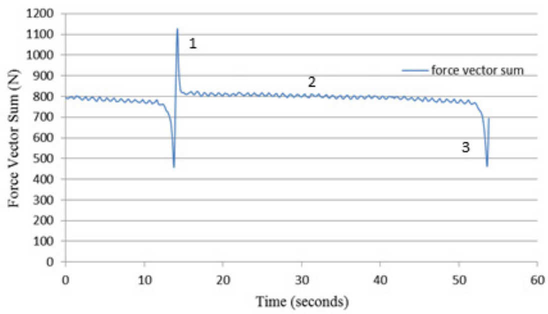


Figure 8 Vector sum of the steady-state forming forces for a cone

Comparing the forces for forming a pyramid and a cone

It is interesting to observe that the steady-state force patterns in Figures 6 and 8 were very similar. Upon close examination, it was found that other than the tool path, which controlled the part geometry, the only difference between the two experiments was the step size. Additional experiments were conducted to compare the steady-state force patterns for forming a pyramid and a cone at the same conditions: same material (0.8 mm, Al5052), same tool (6.35 mm tool radius), same wall angle (45 degrees) and same step size. Figures 9 and 10 show the vector sum of x, y, and z forces for step sizes of 0.635 mm and 1.27 mm, respectively. It can be observed that there were peaks and valleys indicating various “events” took place during the processes. There were also constant forming forces throughout most of the processes. While the peak forces are path dependent, it is clear that the constant forming force was independent of the part geometry (i.e. pyramid vs. cone). To develop an effective force prediction strategy, the experimental force measurement was further investigated based on the above observation.

3 Strategy for Force Prediction

As reported in the literature, the forces in incremental forming are affected by the workpiece material thickness and properties, tool radius, wall angle, and step size. Considering the measured forces shown in Figure 7, the critical forces of interest are those with a “steady-state” force pattern after about 8 passes. The incremental sheet forming is a displacement control process. In the early passes, the prescribed tool positions/tool paths generate large deflection in sheet surface without creating significant plastic deformation. As such, the forces in the earlier passes are all lower than the steady-state force. At this stage, the part stiffness is not fully developed and the force is not a critical concern. After a certain number of passes, the geometric stiffness of the part is fully established. At this time, the measured force pattern is *stabilized* as shown in Figures 9 and 10. The constant force is the continuous deformation force (about 700 N in Figure 9 and about 800 N in Figure 10) regardless the shape of the part. The peak forces are related to specific part geometry and process condition such as turning a corner or stepping down. Workpiece material necking or fracture often take place at these instances.

Since it is of primary interest to predict the steady-state force pattern from a semi-finished part with a fully developed geometric stiffness, creating a near finished part geometry as the starting point of numerical simulation is proposed. For example, to form a truncated cone with a depth of 20.0 mm using a step size of 1.0 mm, a truncated cone with a depth of 16.0 mm would be created. Numerical simulation of four passes, using the step size of 1.0 mm, could be conducted to achieve the 20.0 mm required depth. By allowing the forming condition to settle in the first one or two passes, the forces obtained at the depth of 18.0 mm or 19.0 mm would be considered as the predicted forces. Using such a strategy, the initial passes in the actual deformation process are skipped in the simulation to reduce computational time, and it is expected that the forming forces can be predicted with a sufficient accuracy.

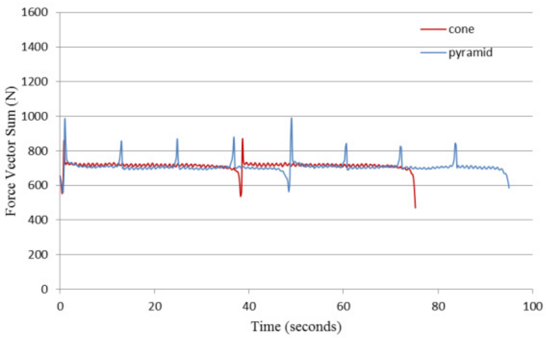


Figure 9 Steady-state forming force for step size of 0.635 mm

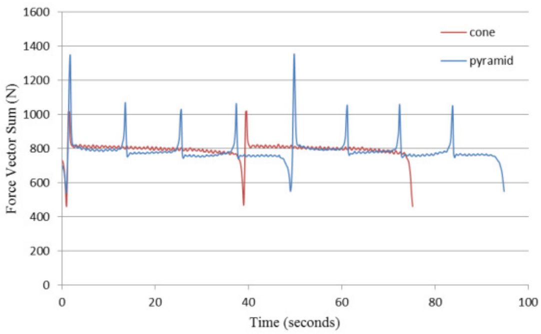


Figure 10 Steady-state forming force for step size of 1.27 mm

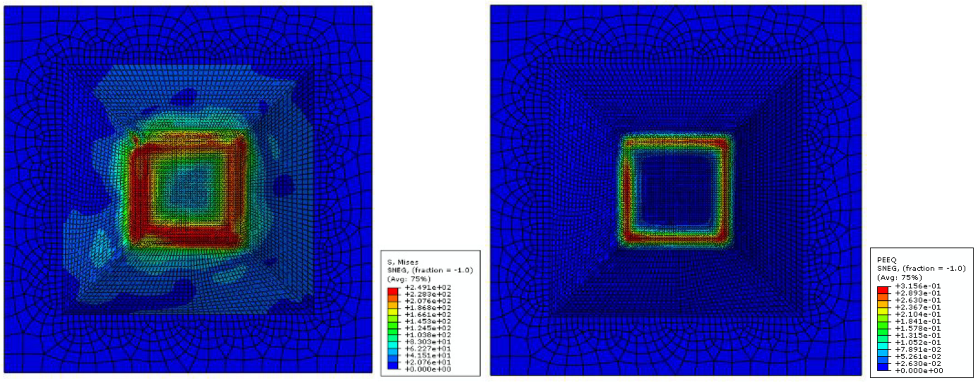
4 Numerical Simulation Force Prediction Results

4.1 Finite element simulation

In the present work, ABAQUS standard was used to simulate the deformation process and predict forming forces. Since the sheet metal thickness is small when compared to its length and width, continuum shell element S4R was used. There are five integration points along the thickness of the sheet and the default integration method was selected. A mesh density study was conducted with the equivalent plastic strain (PEEQ) of different mesh densities were evaluated in the convergency study. For the pyramid and cone with a preset depth, 6505 and 9348 elements were used respectively. The tensile test data for aluminum 5052 and measured thickness of 0.815 mm were assigned to the sheet metal. The material is assumed isotropic. The blank size is that of the experiment (125 mm × 125 mm). The forming tool was modeled as an analytical rigid body having a hemispherical end. In the rigid body, a node was chosen as a reference node and the force values were obtained at this node during the simulation.

An Encastre boundary condition was assigned to the outer region of the sheet metal part to simulate the clamping effect from the fixture. Surface to surface contact was used to describe the interaction between the tool and the sheet. The sheet surface was assigned as the slave surface and the surface of the tool was the master surface. The slave surface was defined to be the surface which can move but cannot penetrate the master surface. From testing, the friction coefficient of 0.1 was used in the simulation. The friction value was formulated using the penalty method and an isotropic directionality was assumed.

An example of a formed part with stress and plastic strain contours is shown in Figure 11. A 6.35 mm radius forming tool and a step size of 1.27 mm were used to form a pyramid with 30 degrees wall angle. It was seen that the maximum stresses occurred at the points where the tool made contact with the sheet metal. The plastic strain plot shows that the deformation was localized and was maximum at the locations where the tool moved over the sheet metal.



(a) (b)

Figure 11 Stress (a) and plastic strain (b) plots from the pyramid forming simulation

4.2 Prediction of forming forces

The problems of long computational time and large memory in simulating incremental forming were tackled by carrying out the simulation from a preset depth. The forces from simulation are compared to the forces from experimental measurement. All forces plotted in this section are the vector sum of the force components in the x, y, and z directions.

Figure 12 shows the steady-state forces for forming a pyramid having a wall angle of 30 degrees. The tool radius was 6.35 mm, and the step size is 1.27 mm. The first peak was the force experienced at the corner when the tool made a step down to start a new pass. The other three peaks were the forces when the tool made a 90 degree turn at corners. The forces between peaks were the constant forming forces when tool was moving along the sides of the pyramid between the corners. It as seen that the error between the simulation and measurement for the first peak was just 0.2%. On computing the average of the constant forming forces, it was 640 N for the experiment and 633 N for the simulation, with the error at 1.8%. The average error of the other three peak forces was seen to be 11.5%. The comparatively large error was further investigated. Upon examining the force components in x, y, and z directions, it was found that at the corners, the x and y forces in the simulation was larger than those in the experiment. This could be due to the difference between the actual process and the simulation. The tool had a rotation speed at 60 rpm during experiment, while no rotation was prescribed in the simulation. This could have changed the contact and friction conditions at the corners where there is a larger contact area between the tool and workpiece.

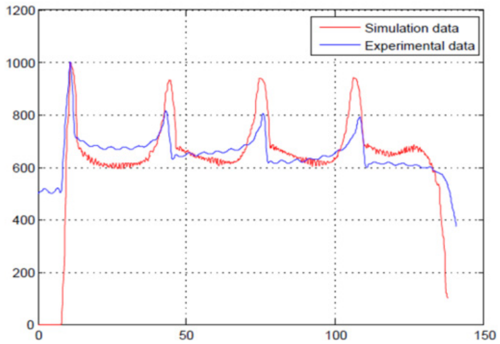


Figure 12 Force comparison between simulation and experiment, tool radius of 6.35 mm

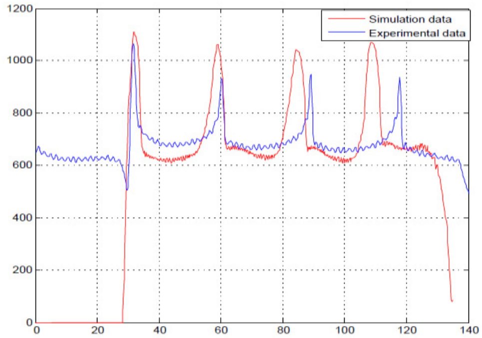


Figure 13 Force comparison between simulation and experiment, tool radius of 9.53 mm

The same study was conducted for forming the same pyramid with a tool radius of 9.53 mm. As shown in Figure 13, the first peak was observed to have an error of 5% while the constant forming forces between corners have an error of 1.3%. Again, the average error observed at the three corners was larger than the others at 13.2%. It can be observed that the peaks in the simulation lag behind those in the experiment. This is because the traveling speed of the forming tool is faster in simulation than in experiment. It took a shorter time to complete the forming process in the simulation.

It is worth noting that the maximum force occurred during the incremental forming process is at the beginning of a new pass. This force is critical and can be used to design the machine against failure. The proposed force prediction strategy accurately predicted this maximum force. Furthermore, previous model/method offered by Henrard (Henrard, et al., 2005) took 300 hours to complete the simulation with 30% error. While the FEA code and computer hardware were different from earlier work, the present simulation was completed in 9 hours and resulted in much smaller errors.

To further demonstrate the proposed strategy, a four lobed part were designed and experiments were conducted to form the part as shown in Figure 14. The tool radius was 6.35 mm, and the step size was 1.27 mm. The experiments were performed using a spiral tool path with a continuous downward path. As shown in Figure 15, the forming force gradually increased with the depth. The measured forces circled in the plot were used to compare to the simulation prediction of forming a pyramid. In Figure 16, the first peak in the simulation was due to the initial tool step-down that did not occur in the experiment. It can be observed that the constant forming force was accurately predicted with an error of only about 6% at the same forming condition regardless the shape of the parts.

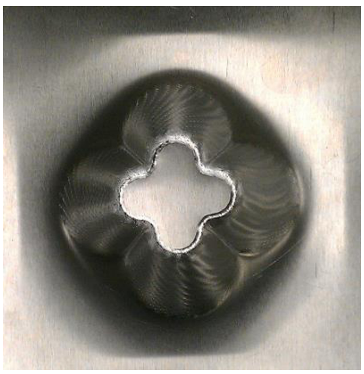


Figure 14 A four lobed part manufactured form incremental forming

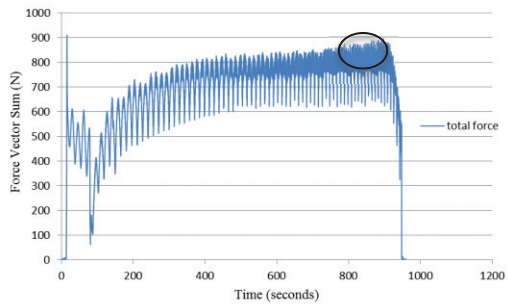


Figure 15 Force measurement for the four lobed part

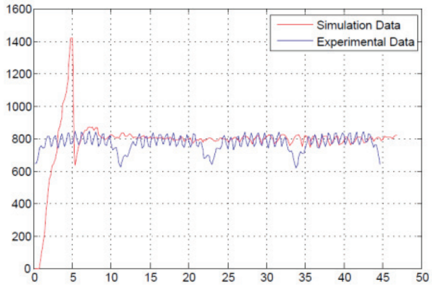


Figure 16 Force comparison between simulation of a pyramid and experiment of the four lobed part

5 Conclusions

This paper presents an efficient strategy to model single point incremental sheet forming and predict the forming forces. The conclusions of the present work can be summarized as follows:

- From the experiments, it was found that the vector sum of the forces for a pyramid and a cone was the same for a given set of input conditions. This indicates that incremental sheet forming is a localized deformation process. The deformation force is independent of the tool path.
- Based on the observation of the force measurement, it was found that the forces gradually increase with the depth. The critical steady-state force pattern appears after the stiffness of the part is fully established.
- A numerical modeling strategy was proposed to efficiently predict the forming force. The method involves the use of a near-finished part as the starting point of the simulation.
- Through forming of a truncated pyramid, it was demonstrated that the proposed strategy can accurately predict the peak force with significantly reduced simulation time.
- The proposed strategy was further tested for a new (four lobed) part formed by a spiral tool path. It was observed that the constant forming force can be accurately and efficiently predicted regardless the part shapes.

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