Simulation of Dynamic Effects in Progressive Die Operation and Control

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Abstract. The demand from the automotive industry for increasingly complex sheet metal components and higher throughput in progressive die operations has led to the increased integration of sensors and control-systems in the sheet metal forming process. However, current control-systems used in sheet metal forming are often limited to measuring the state of the tooling during the forming process, neglecting the dynamic effects of the strip during its transfer between tooling operations. Developing a control strategy that accounts for the strip dynamics requires knowledge of how various process parameters influence the strip behaviour during both the transfer and forming stages. FE element models can accurately model the behaviour of sheet metal, but by themselves cannot identify a robust control strategy. Machine learning can solve this issue by constructing a probabilistic representation for the data generated from FE simulations to be used to identify a control strategy for sheet metal forming. The goal of this work is to conduct a parametric study on a progressive die FE model and evaluate the influence of various input parameters. The data collected from this FEM study will be used to construct a neural network model that will inform a control strategy for a progressive die.

1. Introduction

Progressive sheet metal forming has achieved mass adoption in the automotive and electronics industries because of its ability to repeatability produce high precision components in large volumes at high speeds and low cost. While the sheet metal forming industry has seen large advances in the ability to form complex geometries with the assistance of finite element (FE) modelling, increases in production efficiencies are still largely dependent on the tool maker’s experience and ability to develop robust tooling designs and strip layouts. Polyblank et al. [1] conducted a thorough review of the use of control systems in sheet metal forming. They noted that in most cases, sheet metal forming operations rely on a closed-loop control to prescribe tooling motion but are limited to measuring the state of the tooling and do not directly account for final part quality. More recent developments in progressive sheet metal forming have seen the integration of sensors to measure and control the state of the product during operation. Fischer et al. [2][3] developed a control system to compensate for scattering material properties and process influences for a deep drawing operation. A closed-loop control system was implemented, using an optical measurement system to measure edge draw-in and the blank holder force as a means to adapt the process. Material properties were measured using eddy current sensors and fed
into the closed-loop control. Similarly, Endelt et al. [4] developed a feedback system to control material flow in a deep drawing process by measuring flange draw-in and adjusting the blank holder force. These and similar approaches focus on controlling the forming state which improves the stability of the forming process and can reduce the number of failed parts [5]. However, with scrap material accounting for about 44% of the total sheet metal used in passenger vehicles alone, the ability to increase cost efficiencies while retaining process stability is largely reliant on the ability of the toolmaker to develop a robust tool design and efficient strip layout [6].

The design and selection of the stretch web connectors for the strip layout are of paramount importance to the stability of the progressive die process [7]. Tool designers must select a stretch web geometry that allows for enough compliance for the component material to flow into the die cavity, but enough stiffness to prevent or limit dynamic effects during the progression of the strip. Furthermore, the design of the strip layout and stretch web selection is highly focused on material utilization to reduce component costs. Therefore, a toolmaker may utilize fewer stretch webs and thus less material at the expense of tooling that runs at a lower stroke rate due to increased strip dynamics (e.g. excessive oscillation during strip motion). A solution to allow for better material utilization in stretch web geometry while still mitigating unwanted dynamics would be the introduction of improved control strategies to progress the strip through the tooling. Currently, tool designers have limited control over the motion of the strip in a progressive die. The strip lifters are passively controlled by pre-loaded springs and the feeding rate is controlled by the stroke rate set by operator. By introducing active control in the lifters and actively adjusting the feed rate, the dynamic effects of the strip could potentially be reduced, allowing for strip layouts with better material utilization, and, ultimately a more cost effective process.

This paper presents a FE model of a progressive die, which is used to simulate the dynamic response of different strip layouts at various stroke rates. The results of this model demonstrate the opportunity for introducing new methods for controlling the strip dynamics and the importance of the strip layout in ensuring a stable and robust sheet metal forming process. Furthermore, the data generated from this FE model will be used as the basis for constructing a neural network model that will inform a control strategy to actively control the feeding and lifting of the strip during progression.

2. Model
The progressive die operation was simulated using the LS-DYNA explicit dynamic solver R9.3 MPP with 20 cores. Two strip configurations were simulated at three different stroke rates for a total of six models. ‘I’ stretch webs were used in both strip configurations with either one or two carriers, illustrating two different scenarios of material utilization. The models were simulated at 60, 120, and, 180 strokes per minute (SPM) for a total of 5 strokes. The strip was modelled as a 1 mm thick sheet of A5182. A simple von Mises plasticity model with a yield strength of 121.4 MPa and isotropic strain hardening was adopted. The stress-strain curve for the strip material can be seen in Figure 1. The component being formed is a simple square-shaped cup with a depth of 6 mm, punch profile and plan view radii of 1.4 and 3.8 mm, respectively, and die entry radius of 2 mm. The geometry and meshing of the blank and formed part can be seen in Figure 2, while Figure 3 shows the entire strip and tooling that was modelled.

![Figure 1: Stress-strain curve for 1 mm thick A5182](image-url)
One of the biggest challenges with constructing a FE model of a progressive die is the simulation run-time. To ensure reasonable fidelity during the forming operation, smaller elements are required for the sheet metal blanks, especially around die radius features. Furthermore, a large number of elements are required for the strip to span the length of the tooling. Therefore, without any mesh optimization, a progressive die FE model would tend to have a strip with a large number of small elements, requiring a large run-time. This issue is further exacerbated by the need to run the model for multiple strokes to evaluate the start-up transients of the system as it attempts to reach a steady-state operation. Therefore, to allow for a reasonable run-time of the progressive die model with different configurations, several steps were taken to reduce the run-time, as outlined in the following.

2.1. Model Simplifications

To reduce the size of the model while still focusing on the dynamic effects, the tooling-part interaction was limited to just the forming and cropping stage in the model. Cropping of the final part was also considered, but simply entailed removal of the parts at the bottom dead center position of the press stroke in what would normally comprise the cropping station. Furthermore, the number of elements on the strip was significantly reduced by using a pre-blanked strip and omitting the blanking stage. Finally, to reduce the number of elements along the strip-carrier, pilot holes were not included. It was assumed that the strip-carrier experiences limited lateral motion or bending and therefore the mesh along the strip-carrier is a single element in width. Locating pins were not directly modelled. Instead, a prescribed motion was applied to the outer nodes on the carrier where the pins would typically restrict motion. This boundary condition only restricts lateral motion toward the inside of the tooling during the forming process and is not applied during the strip progression. The last simplification made to the model was the use of rigid body switching. The assumption was made that the strip blank behaves similar to a rigid body with minimal deflection, particularly after being formed. Therefore, the blanks were modelled as rigid bodies prior to entering the forming stage, were switched to deformable elements during forming and then subsequently switched back to rigid bodies. The use of rigid body switching drastically reduced the run time since the number of deformable elements in the model at any given point was substantially reduced [8].

![Figure 2: Mesh and dimensions for both strip configurations and a formed part](image-url)
2.2. Component Set-up
The mesh for both the tooling and the strip used quadrilateral shell elements. Fully integrated shell elements (type 16) with 7 through-thickness integration points were used for the strip to avoid hour-glassing along the stretch web [9]. Rigid shell elements were used for the tooling and a penalty-based contact algorithm was employed for each contact interface. To reduce computational time, mass-scaling was enabled for the blank being formed during the forming stage of the press stroke, such that it only influenced the blank after it was clamped by the binder. All other elements, including the as-formed cups were not mass-scaled. Frequency independent damping was implemented using 0.75% of critical damping over the range of 5-1500 Hz to act over the first five natural frequencies and to act in accordance with the recommended settings [9]. The model was initialized with several pre-formed blanks (four in total) to reduce start-up transients in the predictions.

2.3. Tooling Motion and Strip Feeding
To model the progressive die, the motion of five components needed to be defined: the punch, strip lifters, binder, locating pins and the feeder, following the motion shown in Figure 4. The tooling punch follows a prescribed sinusoidal motion with a travelling distance of 22 mm. The binder is attached via a spring to an isolated node with a prescribed motion identical to the punch. Thus, the binder follows the punch motion until it contacts the strip against the die, at which point the spring compresses. The spring is pre-loaded to apply 2.5 N/mm of binder pressure to the strip upon contact. The lifters rest on springs that were preloaded to support 1.5 times the weight of the strip. Once the binder contacts the strip, the lifters compress until the strip contacts the die surface, which subsequently causes the binder spring to compress. The strip feeder is modelled using a prescribed motion that is applied to nodes falling inside a bounding box corresponding to where the feeder acts on the strip (Figure 3). A section of the strip initially begins within the feeder box and has all motion restricted until it is fed into the tooling. The feeder prescribes the strip motion using a velocity curve, which progresses the strip 60 mm to the next tooling operation. While the tooling motion follows a smooth sinusoidal motion associated with a mechanical press, the strip feeder is more abrupt and akin to an impulse.
3. Results and Discussion

Two methods were used to predict the effects of varying the stroke rate for the two different strip configurations. First, the dynamic response is evaluated by measuring the rigid body motion of several blanks as they progress through the tooling. The second method examines the predicted placement accuracy of successive blanks on the forming die. Direct assessment of the predicted dynamic response serves to illustrate how the feeder and lifter speed impact the strip stability, while errors in the blank placement accuracy manifest in the predicted forming behavior.

3.1. Dynamic Response

To evaluate the dynamic response of the strip for each case, the rigid body rotations and Z-displacement for “Part 5” were plotted in Figure 5. Referring to Figure 3, “Part 4” corresponds to the blank initially positioned on the forming die. The plotted data is the rigid body motion of the blank. During the forming process, the blank is reverted to a deformable body and therefore there is no measured rigid body motion, resulting in a brief flat section in the Z-axis plots during the first stroke.

Figure 5 illustrates the trends in the dynamic response for each strip configuration. All of the parts display an oscillatory displacement response about the Z-axis press stroke/lifter motion (when not engaged in the tooling), which increases with stroke rate. The press stroke also excites an oscillatory rotation about the X-axis, particularly for the single-carrier configuration, which is unsupported on one side of the blank/formed part.

Significant oscillations are excited by the strip feeder (X-axis motion), as observed in the Z-axis rotations. Even larger perturbations are seen in the Y-axis rotation, also caused by the feeder’s rapid transfer of the strip between tooling operations. Furthermore, once the blank has been formed, the center of mass is out-of-plane with respect to the stretch web and carrier, which contributes further to the large rotations about the stretch web axis (Y-axis). The feeder also contributes to the Z-rotation since the blank in the single-carrier configuration has an unsupported side. On the other hand, the lifters are the primary contributor to the rotation about the X-axis and the displacement along the Z-axis.

As stroke rate increases, the rotational response for the single-carrier shows a “stair-case” response indicating that the inertial loads result in permanent deformation of the stretch web, as illustrated in Figure 5. This effect is particularly noticeable for the X-rotation. In fact, a stretch web in the single-carrier configuration operating at 180 SPM experienced a large permanent set, such that the formed part collided with the tooling causing the entire strip to be pulled of the lifters.

Figure 4: Tooling displacement and velocity for a single stroke

![Tooling Motion for a Single Press Stroke](image-url)
Figure 5: Rigid Body Motion for varying strokes rates. On the left are the two-carrier configuration plots and on the right are the one-carrier configurations. The right plots are only scaled to include the 120 SPM results since there are large oscillations in the 180 SPM predictions.

3.2. Blank Placement

Figure 6 illustrates how improper placement of blanks results in part quality issues. To further evaluate how the forming operation is influenced by dynamic effects for the two strip configurations, the placement of five successive blanks in the forming die were predicted for each strip configuration. The placement error of each blank is calculated as the difference in position and orientation between the center of the blank and the center of the die once the binder has clamped the blank. Since the blank is clamped by the binder, the blank placement is assessed in terms of the X- and Y-positional accuracy and the Z-axis rotation relative to the die.
Figure 6: Formed Cups for both strip configurations at different strokes rates. At all stroke rates, the two-carrier configuration formed proper cups. The one-carrier configuration showed slight geometry errors at 60 SPM and significant errors at 180 SPM.

The results for the positional error are consistent with the dynamic response for each strip configuration as seen in Figure 7. The placement for the two-carrier configurations has less variance than the placement of the single-carrier configurations since the strip experiences less oscillation. The two-carrier strips are restricted from rotation about the Z-axis and were consistently well oriented with regard to the rotational orientation. The ‘X’ placement for the two-carrier configuration has effectively no variance. However, since there are no locating pins to position the strip carrier in the X-Y plane, the strip position shifts slightly in the X-direction before the binder clamps the strip.

As seen in Figure 7, the single carrier strip configuration experiences significantly larger positional error than the two-carrier configuration, as well as larger variance in the blank placement, which increases with the stroke rate. Referring to Figure 6, the error in the rotational placement of the single carrier configuration is likely large enough to begin exhibiting part quality issues in the final product at speeds as low as 60 SPM. At 180 SPM, the parts being formed has little resemblance to the desired final product and a collision causes the strip carrier to fall off the lifters.

3.3. Discussion

The results from the models show that there exists opportunity to improve how a sheet metal strip is fed through a progressive die. On-going work is required to validate the accuracy of the model in terms of the predicted dynamic response and forming behaviour. Future work will focus on actively changing the inputs to the feeder and lifters to mitigate unwanted dynamics to allow for greater stability in the system. By varying the active inputs to the feeder and lifter and measuring the dynamic response and forming behaviour of the blank, a neural network can be constructed to identify robust operating conditions for a given strip configuration.
4. Conclusion

The single carrier strip exhibits larger positional error due to larger dynamic response, while the two-carrier configuration allows for a faster process speed. By introducing improved control strategies to actively adjust the feeding rate and lifter response to mitigate excessive dynamic effects, strip layouts with better material utilization could potentially be run at higher stroke rates, allowing for a more cost-efficient process while retaining process stability.

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