Wrinkling failure mechanics in metal spinning

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Abstract

Wrinkling failure mechanics of conventional metal spinning is investigated by means of finite element (FE) simulation. The results of FE simulation are validated by comparing the modelled roller force with that measured during a spinning experiment. From FE simulation, large residual stresses in the form of bending moments are found to be present in the flange, induced by the roller contact. It is found that wrinkling failure begins when a plastic hinge is formed between the roller and the edge of the blank. These bending moments cause the wrinkled state of the flange to be energetically favourable, which is seen as a reduction in the magnitude of these moments and the elastic strain energy of the FE model at the point of wrinkling.

1. Introduction

Wrinkling is one of three material processing failures commonly observed in the sheet metal spinning [1, 2]. Before FE analysis was first used to simulate the metal spinning process the stress state in the forming region was accepted to be as shown in Fig. 1 [2]. Contrary to this several FE models have found that in the roller contact area the blank is subject to local bending. The side of metal blank contacting the roller is in compression whilst the other side is in tension. Sebastani et al. [3], Wang and Long [4] noted that only a small portion of the unsupported flange is under compressive tangential stresses. Sebastani et al. [3] noted a toothed stress pattern appears in the flange, however this could not be shown as a pre-state to wrinkling failure, this was also the conclusion of Wang and Long.

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Sebastani et al. [3] and Wang et al. [4] commented that wrinkling occurs if the area of high compressive tangential stress in the flange does not “recover” to a tensile tangential stress when the roller contact moves away. Music and Allwood [5] however identified two separate modes of wrinkling failure: the first, similar to the one identified above and the second happens later in the process and is more similar to wrinkling in deep drawing.

It is generally accepted that wrinkling in the flange is a sheet buckling phenomenon. Senior [6] identified that the energy method is a possible method for predicting the sheet buckling failure, whereby a defected shape is assumed and the potential energy relating to this deflection is evaluated. The critical condition is given when the total energy to restore equilibrium is equal to that of the forces which produced the deflection. This is the method used by Senior [6] to develop the instability theory for deep drawing and was later adapted by Kobayashi [7] for metal spinning. However this method may not be accurate due to Senior [6] neglecting the radial stress in the blank and the static condition imposed by use of the energy method. Further investigation is needed to develop a better understanding of wrinkling failure mechanics in metal spinning.

An investigation into wrinkling failure mechanics of metal spinning by means of FE simulation is presented in this paper. The results of FE simulation are validated by comparing the modelled roller force time history with that measured during a spinning experiment. From FE simulation results, large residual stresses in the form of bending moments are found to be present in the flange, induced by the roller contact. It is found that wrinkling failure begins when a plastic hinge is formed between the roller and the edge of the blank. These bending moments cause the wrinkled state of the flange to be energetically favourable. This is seen as a reduction in the magnitude of these moments and the elastic strain energy of the model at the point of wrinkling.

![Diagram](image)

Fig. 1. Theoretical stress distributions of forming region during spinning.

### 2. Development of finite element models

The metal spinning process contains non-linearity in the contact boundary conditions, the plastic flow of the work piece and the large deformation of geometry. Instabilities such as wrinkling failure can also cause convergence problems if dynamic implicit solution methods are used. By contrast the small time steps and linear approximation used by explicit formulations can cope well with non-linearity because displacements are calculated without reference to the end time state. The commercial software ABAQUS Explicit is used in this study. Based on authors’ previous work using both FE simulation and experimental testing [8-10], it is observed that the roller feed per pass, feed rate, thickness and material properties of the blank are important factors affecting wrinkling. The spinning process set up used in the FE simulation is shown in Fig. 2. The back plate and roller are modelled as analytical rigid bodies leaving the blank as the only deformable body in the simulation. The central portion of the blank, where it is clamped against the back plate, is neglected in order to improve the computational efficiency. The material properties of mild steel and spinning process parameters are given in Table 1.

### 3. Validation of FE model using experimentally measured roller force

The FE model developed is validated by comparing the simulated roller forces with that measured in an experimental testing [9, 10]. In the experimental testing spinning roller forces in three orthogonal directions, radial,
axial and tangential, are obtained using a Kistler piezoelectric force transducer. Fig. 3 shows the comparison of the axial roller force time history during the first roller path between the FE model and experiment. As shown in Fig. 3 the FE results are in good agreement with the experimental results with an error of only 11.3% for the maximum force. For this reason the simulation is thought to perform accurately.

Fig. 2. Spinning process simulation set up.

Fig. 3. Roller force comparison between FE simulation and experiment.

4. Results and discussion

4.1. Global stress distribution

The maximum in-plane principal stresses of the top and bottom surface of the blank are shown in Fig. 4. Zone A includes an area of high stress due to the blank being bent over the mandrel, resulting tensile stress on the top surface and compressive stress on the bottom surface. The tool contact is in a region (B) of high compressive stress on the top and tensile stress on the bottom and is responsible for the spiral pattern of stress visible in region C. The spiral region appears not only to be under equivalent compression state as previously thought [3] but also subject to bending stresses (D) with the top surface subject to high tangential tension and the lower surface in tangential compression. This is a consequence of the shape that the blank is being formed into. The top and bottom surfaces are originally equal but end with one surface compressed to become the inner surface of the spun part and the other stretched to form the outer surface.

Another region of bending exists as indicated by region E on Fig. 4. This region is bending in resistance to the

<table>
<thead>
<tr>
<th>Table 1. Material properties and process parameters.</th>
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<td>Feed per pass</td>
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<td>Feed rate</td>
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<tr>
<td>Blank thickness</td>
</tr>
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<td>Young’s modulus</td>
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<td>Yield stress</td>
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<td>Strain hardening exponent</td>
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deformation of the roller, however it is bending upwards. This can be visualised if the entire blank is thought to be to some extent pivoting around its contact with the mandrel at point A. Examination of the von Mises stress results for the bottom surface indicates that this area is yielding. This presents another mechanism for circumferential cracking as this area of the blank is under bending stresses which regularly reverse as the blank rotates.

4.2. Stress distribution during the development of wrinkling

The development of the tangential stresses on the top and bottom surfaces during the first roller pass, shown in Fig. 5, is examined by looking at lines of elements around the circumference in plane with the contact of the roller. At the start of the first pass, the tangential stress distribution is characterised by high bending stresses in the plane of the roller contact and low stresses in the rest of the circumferential ring (Fig. 5a). In addition to this the top surface away from the plane of roller movement is generally in tension while the bottom surface is in compression, this is consistent with the flange being bent inwards. All of the stresses present are below the yield stress of 250 MPa. The stress in plane with the roller ($\theta = 0^\circ$) also drops significantly as the direction of travel of the roller changes from into the blank at the start of the pass, to heading more towards the edge of the blank at the end of the pass (Fig. 5b). The moments at either side of the roller contact, resisting its motion, increase as the roller nears the edge of the blank as less support can be provided from stiffer parts of the blank nearer the clamped portion.
To examine the stress state of the blank throughout the process of wrinkling, results from three consecutive time frames have been compared. These frames correspond to a moment just before (a), during (b) and just after (c) the appearance of the first wrinkles. The stress distributions in Fig. 6a relating to the moment just before wrinkling indicate that the bending stresses in the blank away from the contact have grown such that large compressive and tensile stresses could be observed on either side of the blank. The compressive stress away from the roller contact has also risen to around 100 MPa, when comparing with the stresses during the first pass. In the area affected by the roller contact the characteristic wide resisting moments can be seen again with low tangential stresses in the plane of roller motion.

Fig. 6b showing the moment of wrinkling must be thought of as a snapshot of a now highly dynamic process. Examination of the displacement plots reveals this time frame relates to the roller passing over what is to become the bottom of a wrinkle. In this situation the plane of roller movement is flanked by residual moments which act to
force the section of the blank in plane with the roller downwards. These are relieved by the yielding of the blank in plane with the roller in the form of a plastic hinge. The radial bending stresses caused by flange leaning are also relieved. This deformation results in less stress in the blank and therefore less elastic strain, this makes the act of wrinkling energetically favorable. This is confirmed by the effect of wrinkling on the strain energy of the model which is shown in Fig. 7.

In the final frame of stress distributions, shown in Fig. 6c, relates to the moment that the top of a wrinkle is passing under the roller, this produces a very different stress pattern to the previous time frame in Fig. 6b. Here the supporting moments are very large, this could be due to similar effects as dynamic impact or the feed rate being artificially increased due to the presence of a wrinkle. It can also be seen that the stresses away from the contact are generally lower than the previous time frames due to the formation of wrinkling, shown in Fig. 6c. In addition to providing insight into the mechanisms of failure and its causes, this analysis has provided a definite point at which the blank can be said to have wrinkled. The point at which the strain energy indicates that wrinkling is occurring should be used as the time of material failure of wrinkling.

![Fig. 7. Elastic strain energy of the 3 time frames examined as indicated by dashed lines.](image)

### 5. Conclusions

The stress pattern at the edge of the blank during conventional spinning is found to be caused by residual stresses in the form of moments in the flange. These moments cause the wrinkled state of the flange to be energetically favorable. This is seen as a reduction in the magnitude of these moments and the elastic strain energy of the model at the point of wrinkling. The plastic hinge has been observed and is thought to be the mechanism by which the shape of the blank is allowed to change into a wrinkled form.

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### References


