1. INTRODUCTION

In sheet metal forming numerical simulations it is important not only to create but also to maintain appropriate meshes as for large deformations the computational mesh will eventually become severely distorted and a global remeshing might be necessary. Moreover, the accurate modelling of complex shapes requires the use of meshes comprising a large number of finite elements. In this context, the use of discretisation errors estimation in connection with adaptive mesh refinement plays an essential role Selman et al. [1997], Bonet [1994].

Another type of distortion that is often observed in sheet metals during stamping and other forming operations is surface distortion in the form of localised wrinkles. In fact, wrinkling is becoming one of the most troublesome modes of failure in sheet forming mainly because of the trend towards thinner, high-strength sheet metals.

The methods used in the past to predict wrinkling failures in sheet metals have been mostly empirical and have, unfortunately, proved to be inadequate for predicting observed trends. A more recent approach for the analysis of local wrinkling has been presented by Hutchinson and Neale [1985] and consists of formulating the problem within the context of plastic bifurcation theory for thin shell elements.

In a numerical simulation, wrinkles can be detected by a visual inspection of the deformed mesh. This implies that the computational grid is fine enough to allow a proper capture of the wrinkles. However, to keep the computational cost low (acceptable), it is desirable to proceed with a selective refinement based on wrinkling indicators.

In this work, the analysis of Hutchinson and Neale [1985] and its extension by Neale [1989] to account for more general constitutive models is used. Under a number of assumptions, limitations and simplifications a simple wrinkling criterion is obtained and used to locally define a wrinkling risk factor or simply a wrinkling indicator, which, in turn, is used in a subsequent adaptive mesh refinement process.

Hutchinson analysis is, unfortunately, limited to regions of the sheet that are free of any contact. When contact is taken into account the problem is further complicated. Moreover, given that numerical simulations of complex sheet metal forming involve large scale models, it is obvious that global wrinkling indicators should not be used because of their high computational cost. Consequently, a local indicator based on the change of curvatures under compressive stresses has been designed.

The general and comprehensive algorithm for mesh adaption in metal forming processes comprises

ABSTRACT: Discretisation errors indicator, contact free wrinkling and wrinkling with contact indicators are, in a challenging task, brought together and used in a comprehensive approach to wrinkling prediction analysis in thin sheet metal forming processes.

Keywords: Error Estimation, Wrinkling Prediction, Adaptive Mesh Refinement
the following steps:

1. Generate an initial grid to represent the computational domain and to allow an adequate initial solution
2. Advance the solution for a number of steps
3. Use the discretisation errors indicator and wrinkling indicator to determine whether mesh refinement is necessary. If yes, compute a new mesh distribution and continue - otherwise go to step 2
4. Proceed with the mesh refinement and obtain the field values of the solution on the new grid by direct interpolation from the previous grid
5. If the desired load interval has elapsed stop - otherwise go to step 2

2. DISCRETISATION ERRORS ESTIMATION

The error estimation presented by Bonet [1994] is used in this work. It is entirely geometrical and is based on the accuracy with which the finite element mesh can describe the continuous exact shape. In addition to Bonet’s geometric error estimation, a thickness error which measures the jump between the finite element solution and a solution obtained by some recovery technique to substitute for the exact solution, is also taken into account, as the thickness distribution is of primary importance in sheet metal forming, and plays a major role in wrinkling prediction analysis.

3. CONTACT FREE WRINKLING

The basic theory of plastic buckling and relevant relations for the Donnell-Mushtari-Vlasov (DMV) shallow shell theory have been developed by Hutchinson [1974]. The application of this theory to sheet wrinkling was first carried out by Hutchinson and Neale [1985] and is used in the present work.

It should be stressed that a number of assumptions, limitations and simplifications are embedded in Hutchinson analysis. In this approach we consider a sheet element, which, in the current stage of forming, has attained a doubly curved state with principal radii of curvature and thickness all assumed to be constant over the local regions being examined for susceptibility to wrinkling. It is also assumed that the stress distribution prior to wrinkling to be a uniform membrane state over these regions.

Although the analysis can account for any stress state, it is for simplicity, assumed that the principal axes of this uniform membrane stress state coincide with the principal axes of curvature. Simplifications arise from the fact that the anticipated short-wavelength modes are shallow and that they can be analysed using Donnell-Mushtari-Vlasov (DMV) shallow shell theory. Finally, the investigation is limited to regions of the sheet which are free of any contact.

To determine the critical stress state for buckling that is needed in the definition of the wrinkling indicator, Hutchinson [1974] bifurcation functional is used.

For the pre-wrinkling geometry and stress state considered here, wrinkling will in most cases be aligned with one of the principal curvatures (stress) directions. Using the wrinkling critical stress value, a wrinkling risk factor or simply a wrinkling indicator Selman et al. [2000] (perpendicular to the 1-direction, for instance) is defined as:

$$ f_\sigma = \frac{\sigma_1}{\sigma_1^\text{cr}} $$  

Therefore a wrinkling risk exists whenever $f_\sigma$ is larger than 1. This factor is used to select candidate elements for subsequent mesh refinement. The new mesh size is obtained as:

$$ L' = L/f_\sigma $$  

where $L$ is the old mesh size.

4. WRINKLING WITH CONTACT

As already stated above, Hutchinson analysis is limited to contact free wrinkling. Therefore, in the contact zones a different approach has to be used. More precisely, we looked at the change of curvatures (during a single deep drawing step) under compressive stresses. By doing so, all changes in curvatures that are not due to compressive stresses,
such as those caused for example by the geometry of the tool and the die, are filtered out. These, however, will be taken into account by the (geometric) error estimation indicator, if and when necessary.

To measure the curvature change under compressive stresses in the $i^{th}$-principal direction Selman et al. [2002], the following expression is used

$$e_i^w = \frac{1}{A} \int \left| \frac{R_i' - R_i^{\text{end}}}{R_i' R_i^{\text{end}}} \right| dA \quad i = 1, 2$$

(3)

with $i$ representing the principal curvature (stress) direction and $R_i'$, $R_i^{\text{end}}$ the radii of curvatures in the $i$-direction at the beginning and at the end of a given deep drawing step, respectively.

Noting $e^w$ the maximum of $e_i^w$ over the principal curvatures directions, that is

$$e^w = \max(e_i^w) \quad i = 1, 2$$

(4)

and using the average value of $e^w$ over all rotating elements ($e^{\text{avr}}$), a wrinkling indicator is defined as

$$f_e = \frac{e^w}{e^{\text{avr}}}$$

(5)

All elements with a wrinkling indicator larger than 1 are selected for refinement and are assigned a new mesh size as

$$L^w = L / f_e$$

(6)

To avoid excessive refinement, a check against a user specified minimum size is to be operated before the refinement actually takes place.

The present indicator can be viewed as a generalisation of the discretisation errors indicator in which a (relative) change, e.g. in the thickness or geometry, is measured between the finite element solution and a higher order solution obtained by some solution recovery technique. The change in the solution for the wrinkling indicator being between the solution (curvatures) at the beginning and the end of a given deep drawing step, considering only elements under compressive stresses.

5. NUMERICAL EXAMPLES

The performance of the wrinkling prediction procedure with adaptive mesh refinement described in this work is here demonstrated.

A hemispherical product is considered for wrinkling prediction analysis. The punch has a radius of 146.5mm and the die shoulder a radius of 30mm. The initial sheet thickness is 1mm and the product depth 100mm. Hollomon’s hardening law is used with the following set of parameters : $K = 542$, $n = 0.228$ and $r = 2.2$. A deep drawing step size of 1mm has been chosen and DST finite elements exclusively used.

5.1 Hemispherical product using the error estimator and the Hutchinson approach based wrinkling indicator

In this numerical simulation a high blank holder force is used to avoid wrinkling under the blank holder as Hutchinson approach handles contact free wrinkling only.

The simulation is started with a relatively coarse mesh comprising 2050 elements and ended with an adapted mesh of 5400 elements as shown in Figure 1.

Figure 1. Final mesh – Contact free wrinkling

The first refinement that takes place at step 30 is due to the thickness variation at the bottom of the product, the geometric error estimation in the region of the die shoulder and the wrinkling indicator that senses a potential for wrinkling in the wall of the product and, mostly in anticipation, refines the mesh.

In step 66, due to the mounting pressure under the blank holder in the die shoulder zone and because of
the near flatness of the sheet the risk factor goes beyond one and consequently the refinement is intensified.

In the final step, this effect is increased which brings the final mesh to 5400 finite elements.

5.2 Hemispherical product using the error estimator and the geometric wrinkling indicator

The initial mesh, again, comprises 2050 elements. The first refinement at step 32 is, as for the previous example, due to the geometric error estimation (around the die radius), to the geometric wrinkling indicator (in the flange) and to the thickness variation (at the bottom of the product). In step 64, the refinement is intensified around these regions.

It is noted that the drawing behaviour so far and consequently the mesh refinement is similar to the previous case whereby a high blank holder force is used.

In the final mesh comprising 8150 elements and shown in Figure 2, as expected, the refinement covers the whole area under the blank holder to properly describe the new buckles developing in that region of the sheet.

However, it is also found that this has to be linked with an error estimation routine to properly approximate the curvatures and the thickness as these play a major role in the wrinkling process.

Hutchinson approach based wrinkling indicator that handles contact free wrinkling has been complemented with a new wrinkling indicator based on local curvature changes.

A fundamental difference between these two wrinkling indicators is that Hutchinson approach based wrinkling indicator, mostly acts in anticipation. Given a set of parameters such as the local curvature, the thickness and stress distribution at a given deep drawing step, the indicator has the ability to sense potential for wrinkling and refine the computational mesh. Subsequently, wrinkling may or may not take place. If it does, then the finite element mesh would be rich enough to properly describe the wrinkling phenomena. Conversely, if it doesn’t then a de-refinement option can be considered.

On the other hand, the geometric wrinkling indicator comes into action only when a change in curvature under compressive stresses is taking place. However, this is not much of a drawback, as this indicator is able to spot wrinkling at an early stage due to its high sensitivity to any change in the curvatures.

As a benchmark, the hemispherical product has been considered with a high and a low blank holder force to distinguish between contact free wall wrinkling and wrinkling with contact that takes place in the flange.

6. CONCLUSIONS

It has been demonstrated that the use of adaptive mesh refinement in wrinkling prediction analysis is a necessary approach for reducing the computational cost and better describing the wrinkling phenomena.

Figure 2. Final mesh - Wrinkling with contact.

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8. REFERENCES

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