Buckling mode shapes in incremental forming of sheet metal

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Abstract

A common technology for manufacturing of large-scale vessel-ends is incremental forming. The first step in forming process is based on buckling phenomena. The buckling mode shapes of circular plate influence wrinkling and surface quality of final product. Increased number of wrinkles in the first forming step lengthens the manufacturing process and increases the number of forming steps needed. To obtain the desired buckling mode shape, an analysis was performed by varying tool parameters. The analysis resulted in defined relationship between tool parameters and buckling mode shapes, and guidelines for the tool design in terms of minimum wrinkling.

Keywords: *Incremental Forming, Buckling Mode Shapes, Sheet Metal, Wrinkling, Tool Design*

1. Introduction

When incremental forming is used to manufacture large products, such as spherical tank ends, wrinkling phenomena has significant influence onto quality of final products.

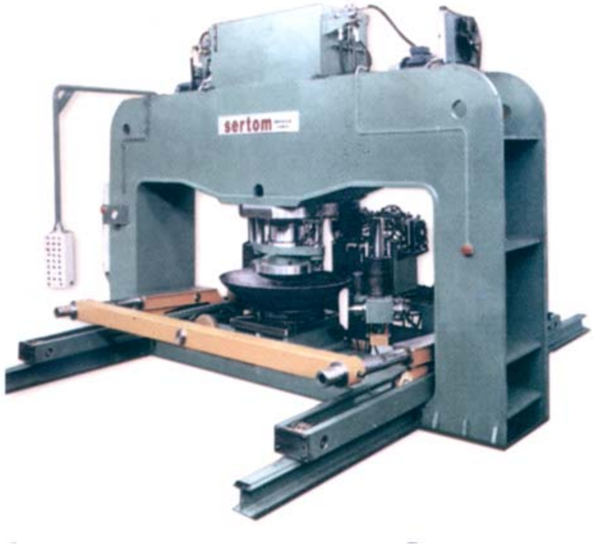

Fig. 1. Incremental forming press P2MF 200x4 - Sertom.

The tool diameter is 2 to 5 times smaller than the forming part diameter, the edge of forming part is free, and the thickness of sheet metal is small. All these facts are prerequisites for occurrence of wrinkling. Fig. 1 shows the machine for incremental forming of spherical tank ends, up to 4 meters in diameter.

A number of researches were performed recently in order to minimise errors in incremental sheet metal forming. Mackerle presented exhaustive bibliography in [1] about application of Finite element method in sheet metal forming simulation. The bibliography deals with material properties (texture, anisotropy, and formability), springback, fracture mechanics and calculation strategies, as well as with specific forming processes: bending, extrusion, deep drawing, pressing, hydroforming etc.

Ambrogio et al. in [2] focused on material formability in incremental forming and, in particular, on the evaluation and compensation of elastic springback.

Wang and Cao in [3] performed numerical analysis of wrinkling using modified energy approach, and investigated sensitivity of various input parameters and integration methods of finite element model onto buckling prediction. They analysed wrinkling phenomena by comparing critical stress and real compressive stress calculated with finite elements method. Their research showed that critical buckling stress of curved sheet metal depends on:

- local curvature radius,
- material properties,
- sheet metal thickness,
- dimensions and
- load.

According to their research, the tool velocity has no influence on wrinkling.

Similar procedure was presented by Wang, Cao and Li in [4], applied on bending of thin walled product edges. They concluded that wrinkling reduces when the length of bent edge is increased, and that thickness has no influence onto number of wrinkles, but increased thickness leads to increase in critical length of bent edge.

Kim and Yang in [5] investigated buckling phenomena in deep drawing process using energy principle. They introduced "buckling factor" which is used to predict shape and location of wrinkles in sheet metal. Fig. 2 illustrates wrinkling in deep drawing process.

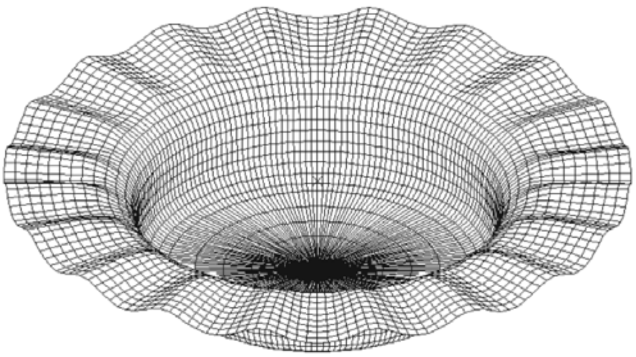

Fig. 2. Wrinkling in sheet metal deep drawing [5]

Matsubara in [6] analysed numerically controlled (NC) machine tool for forming flat metal sheets into covex shapes. Mao et al. in [7] investigated forming instability flaws in incremental forming. Kleiner et al. in [8] analysed buckling as a cause of wrinkling in sheet metal spinning. Cao et al. in [9] explained fundamentals of different buckling phenomena through a stress-based wrinkling predictor.

2. Circular Plates Wrinkling

Wrinkling occurs in areas which are not in contact with tool [3]. The only contact occurs between the plate and the edge of concave tool, and between plate and upper, convex tool. The contact surface is relatively small.

The following analysis assumes that tangential stresses before buckling are neglectable and plate thickness is uniform.

Timoshenko's energy method with various combinations of boundary conditions was used in analysis of thin plates elastic buckling. The shape of deformed plate is presumed and critical buckling criterion can be obtained when internal energy of buckled plate ΔU equals the work performed by planar membrane forces ΔT. If internal energy for every possible deformation is larger than the work performed by membrane forces, the plate is in stable equilibrium. Stability criterion is:

The process usually starts with presumed function which describes plate deformation double sine function, with shape depending on plate shape (circular, rectangular, elliptical,...). For circular plate, the function can be:

$$w = w_0 \sin\left(m\theta\right) \sin\left(\frac{n\pi(r - r_a)}{(r_r - r_a)}\right), \qquad (1)$$

$$m, n = 1, 2, 3, \ldots$$

Where: w_0 is amplitude of wrinkles, m is number of wrinkles per perimeter, n is number of wrinkles in radial direction, r_a is lower tool radius, r_r is outer diameter of the plate.

The following boundary conditions apply:

$$w = 0, \quad r = r_a \qquad (2)$$

$$\frac{d^2 w}{dr^2} + \nu \frac{1}{r}\frac{dw}{dr} = 0, \quad r = r_a \qquad (3)$$

Equations describing ΔT and ΔU are very complex in this case, and it is not feasible to calculate them. Usually numerical methods are used to solve this problem. Analytical calculations, as the one presented in [4], can show what influences critical buckling stress. That fact can be used for further analysis of wrinkling in incremental forming process.

3. Numerical Analysis

Fig. 3. shows the simplified model used for FEM analysis. The plate support is circle with radius *r*, and the force *F* acts downwards on the surface with radius *f*. The plate's outer radius is *R* and the thickness is *d*.

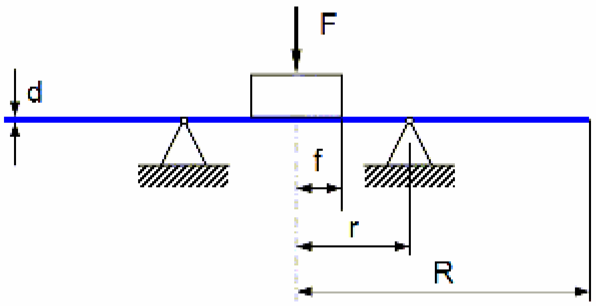

Fig. 3. Simplified model used for FEM analysis

The analysis is performed by calculating critical buckling force for a range of parameters: thickness, outer plate radius and support radius.

a) b) c)

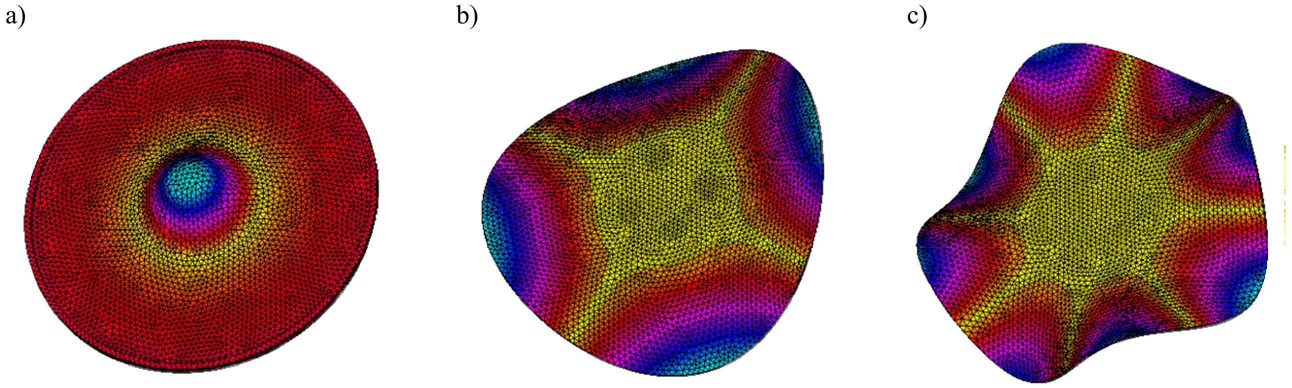

Fig. 4. Buckling mode shapes: (a - without transversal waves, b - with 4 waves, c - with 8 waves).

The results are sorted out according to the number of wrinkles (waves), in order to predict the most affordable set of parameters: it is the case when there are only one circular wave and no transversal waves.

Fig. 4. shows three typical cases of buckling. Since numerical analysis results are sorted by buckling force intensity, it is important to determine the shape to be able to relate the number of waves with quality of final product.

This major assumption of this research is that the first, elastic buckling plays key role in further quality of product manufactured by means of incremental forming. The lower the number of wrinkles in the first forming operation, the less incremental operations is required to obtain the final shape.

3.1 Plate Thickness

The first parameter examined is the plate thickness. It was varied between 3,0 and 7,0 mm. The FEM analysis results are shown in Fig. 5.

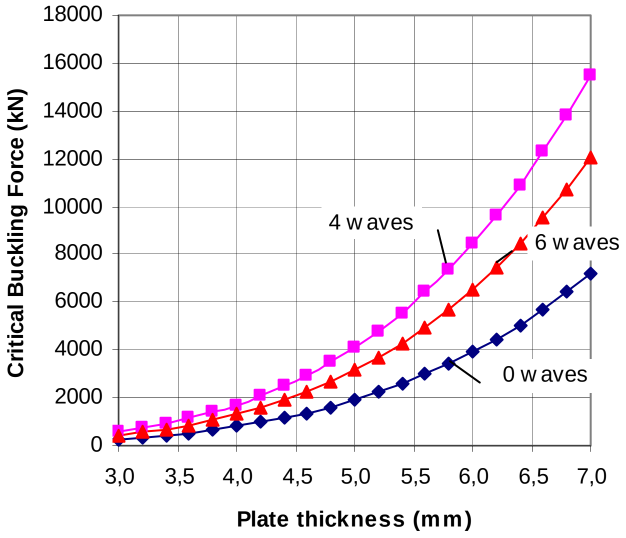

Fig. 5. Critical buckling force for different plate thickness

Increased thickness refers to larger force needed for buckling to occur. The Fig. 5 shows that mode shape without transversal waves is obtained when the force is lower. Therefore, the lower the force, the better quality of spherical shape.

3.2 Outer Radius

Another parameter varied was the outer radius of the circular plate being pressed. The analysis was performed for radii between 796 and 986 mm. As research in [4] showed, it was expected to obtain better results (less wrinkles) with larger outer radius.

As opposed to these results, there was practically no change in critical buckling force for different values of outer radius. For all values of outer radius, the results were almost the same. The only change was between values for different number of waves; the lower the force, the fewer waves in buckled plate.

Fig. 6. shows the relation between outer radius and critical buckling force for different wave number.

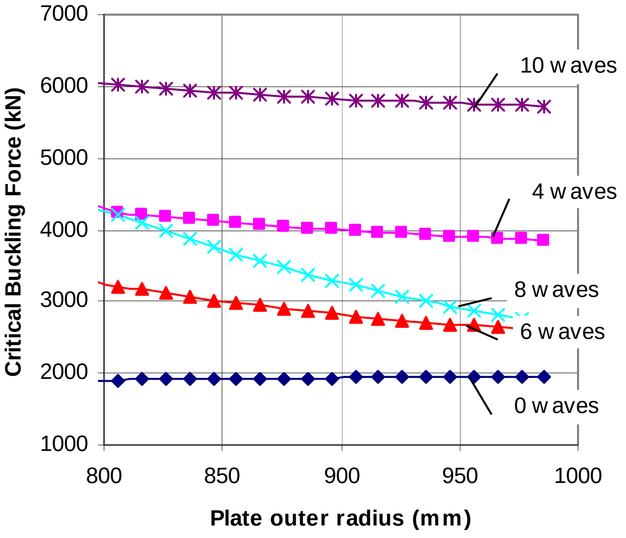

Fig. 6. Critical buckling force for different outer radius

3.3 Tool Radius

The final parameter examined was the lower tool radius (the radius of circular support). The calculation was performed for lower tools with radius between 210 and 390 mm. The results are shown in Fig. 7.

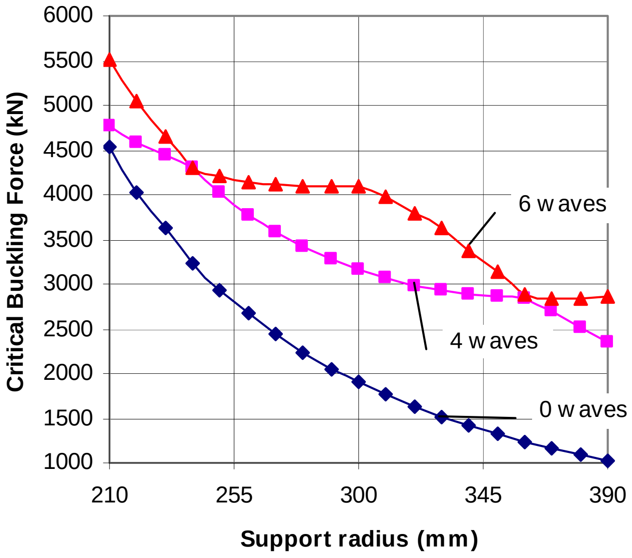

Fig. 7. Critical buckling force for different support radius

4. Experimental Measurements

In order to confirm the analysis results, the influence of parameters was tested by varying the press force and measuring geometry of buckled plate. The measurement results confirmed FEM analysis results; the lower the press force, the less wrinkles occur after first forming operation.

Fig. 9. shows measurement results projected on cylindrical surface. The figure represents the case that corresponds to buckling mode shape with 4 wrinkles. The x-axis is given in degrees, and the y-axis represents the measured amplitude for different measurement radii (0, 185, 555 and 930 mm).

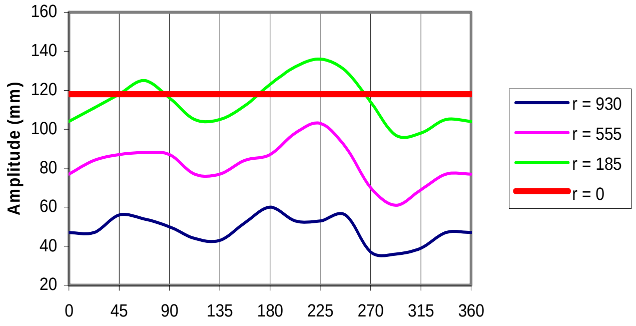

Fig.9. Example of buckling mode shape with 4 wrinkles

5. Conclusions

According to analysis performed, the following conclusions can be drawn:

- It is desirable to have lower press force for the first forming operation, since it will produce the buckling mode shape without wrinkles.
- The plate thickness has significant influence onto wrinkling; thicker plate will have less wrinkles.
- The outer radius of the starting plate can be kept at its minimum, since it has no influence on number of wrinkles.
- The lower tool radius should be as large as possible. If radius of lower tool is too small, it is harder to control press force in order to obtain less wrinkles.

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