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Using Buckling Analysis to Predict Wrinkling in Incremental Sheet Metal Forming

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The idea of using buckling analysis to predict wrinkling of sheet metal products manufactured by incremental forming is presented in this paper. We start from assumption that buckling analysis can be used to obtain geometry of product after first forming operation. That shape and critical buckling force are calculated using finite element method in elastic domain. The analysis was performed for various values of tool diameter. Results were tested through measurement of product geometry after first forming operation. The analysis showed that upper tool diameter can be reduced without change in product quality expressed through number of wrinkles.

Keywords: sheet metal forming, incremental forming, buckling, finite element methods

0 INTRODUCTION

Incremental sheet metal forming is usually being used in small-scale products manufacturing. These products are always manufactured with clamped edges and normally do not have geometrical imperfections related to wrinkling (Fig. 1).

On the contrary, when incremental forming is used to manufacture large products, such as spherical tank ends, wrinkling phenomena has significant influence onto quality of final products. 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 plate is small. All these facts contribute to wrinkling occurrence. Figure 2 shows the machine for incremental forming of spherical tank ends up to 4 meters in diameter and sketch of 3 forming steps. The press uses two-part tool; upper tool is convex, and lower tool is concave, both having the same diameter. Step 3 in Figure 2 is repeated many times in order to incrementally obtain the desired form.

A number of researches were performed recently in order to minimize errors in incremental sheet metal forming. Mackerle [1] gave an exhaustive bibliography 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,

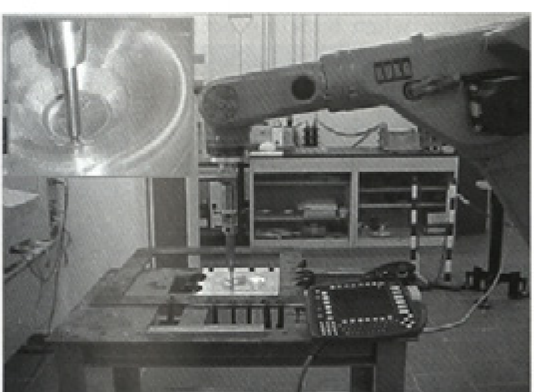

Fig.1. *Incremental forming of small-scale products*

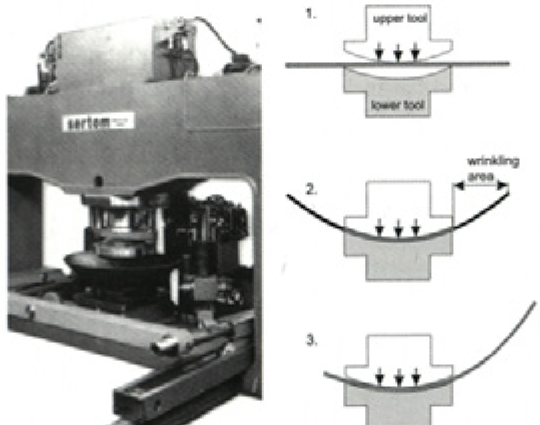

Fig.2. *Incremental forming press P2MF 200x4 – Sertom, Milan, Italy*

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extrusion, deep drawing, pressing, hydroforming etc.

Cao and Boyce [2] used forming limit diagrams as a criterion for disproportional tool load regimes. Their research showed that clamping force can be used to influence and to control wrinkling.

Wang and Cao [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. Their model was based on assumption that stress distribution in sheet metal is uniform. By defining appropriate boundary conditions, critical buckling stresses can be determined in sense of material properties, Poisson's ratio, sheet metal thickness and other geometry parameters. Wrinkling phenomena was than analysed by comparing thus obtained critical stress and real compressive stress calculated with finite element 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 [4], applied on bending of thin walled product edges. They offered an interesting conclusion that wrinkling is reduced when the length of bent edge is increased. That conclusion could be used to make an assumption: increasing starting sheet diameter could reduce wrinkling of spherical tank ends. They also investigated the influence of thickness and concluded that thickness has no influence onto number of wrinkles, but increased thickness leads to increase in critical length of bent edge.

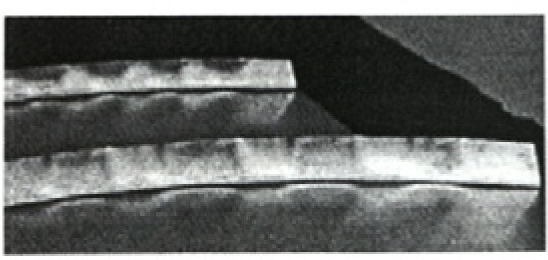

Fig.3. *Wrinkling of bent edges of thin walled products [4]*

Pohlak et al. [5] observed this process in rapid prototyping. They performed numerical calculation in order to optimize manufacturing process.

Lee et al. [6] analysed the differences between static implicit and dynamic explicit integration method in time to compare numerical results in simulation of cold forming manufacturing process. They divided defects which occur in cold sheet metal forming into three categories: wrinkling, tearing (during deformation phase) and elastic springback (after tool removal).

Schafer and Schraft [7] compared various methods of flexible sheet metal forming with incremental deformation process. Their research was more focused on behaviour of manipulator robot rather than of the material itself. They proposed rapid tool movement, such that the tool acts onto sheet metal with strokes.

Ambrogio et al. [8] focused on material formability in incremental deformation process, particularly on estimation and compensation of elastic springback. They used integrated numerical/ experimental procedure to limit geometry deviations.

Kim and Yang [9] 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. Figure 4 illustrates wrinkling in deep drawing process.

Similar approach was used in this research. Buckling mode shapes were analysed in order to obtain tool parameters for incremental forming process resulting with minimum dimensional deviations of spherical tank end. The first forming operation, when buckling occurs, was analysed using finite element method.

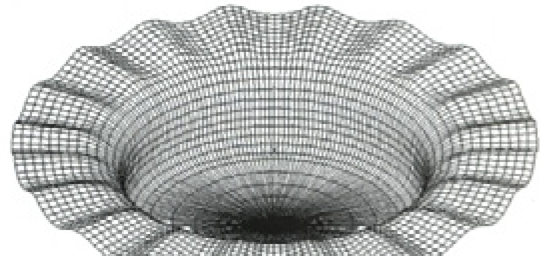

Fig.4. *Wrinkling in sheet metal deep drawing [9]*

1 THEORETICAL BACKGROUND

Wrinkling occurs in areas which are not in contact with tool [3]. In incremental forming of spherical tank-ends, the only two contacts occur between the plate and the edge of lower concave tool, and between the plate and upper convex tool.

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

Well known 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 equals the work performed by plane membrane forces. If internal energy for every possible deformation is larger than the work performed by membrane forces, the plate is in stable equilibrium.

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

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

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

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:

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

Fig.5. *Incremental forming of spherical tank end*

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

Equations describing internal energy and work are very complex in this case and it is common to use numerical methods to solve this problem. Analytical calculations, as the one presented in [4], can show what influences critical buckling stress and wrinkling in incremental forming process. Proposed double-sine function, when visualised, corresponds to mode shapes obtained by experimental and numerical results presented here. Nevertheless, this function can be used only to confirm the assumption that buckling mode shapes play significant role in wrinkling occurrence during incremental forming.

2 EXPERIMENTAL SET-UP

The geometry of incrementally formed spherical tank (Fig. 5) was measured after first forming operation, in order to determine the buckling mode shape. Fig. 6 shows the layout of measurement points. Some parameters were varied to determine their influence onto buckling mode shape.

The measurement results are shown in Table 1. The number of lateral waves refers to modal diameters, while number of radial waves refers to modal circles. The press (Fig. 2) has only indication of pressure in hydraulic cylinder, which corresponds to press force. For deeper analysis, this pressure should be calculated or measured by means of force transducers.

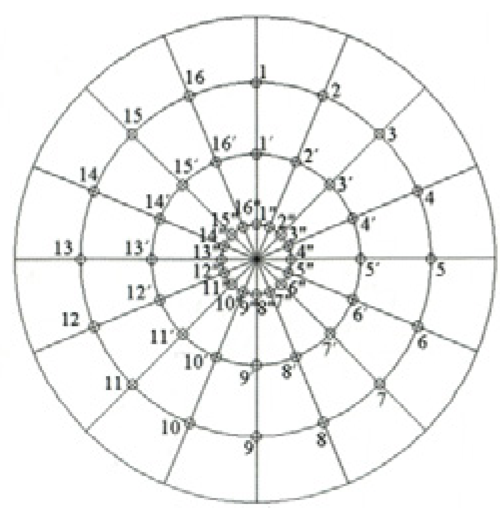

Fig.6. *Measurement points scheme*

Table 1. *Geometry measurement results*

	Pressure [MPa]	Lower tool radius [mm]	Upper tool curvature radius [mm]	Maximum amplitude [mm]	Number of lateral waves	Number of radial waves
a	10	350	700	163	4	0
b	10	350	650	156	6	2
c	10	350	250	136	6	0
d	13	350	250	185	4	0

Table 2. *Material chemical composition*

C	Mn	Si	P	S	Al	Cu	Cr	Ni	Mo	Ti	V	Nb	N
0.17	1.26	0.014	0.015	0.006	0.043	0.03	0.02	0.01	0.002	0.015	0.001	0.039	0.005

The desired buckling mode shape is the one with 0 lateral waves and 1 radial wave. Such a shape can be obtained by changing tool radii or pressure. Finite element analysis was then performed in order to obtain the combination of tool radius and press force which would lead to ideal buckling mode shape after first forming operation.

3 BUCKLING ANALYSIS

The tool radii, as the most controllable parameters, were varied in order to estimate their influence onto buckling and wrinkling. The simplified model shown in Figure 7 was used. The plate support is circle with radius r (free rotations, fixed translations), the force F acts downwards on the surface with radius f. The plate's outer radius is R and the thickness is d.

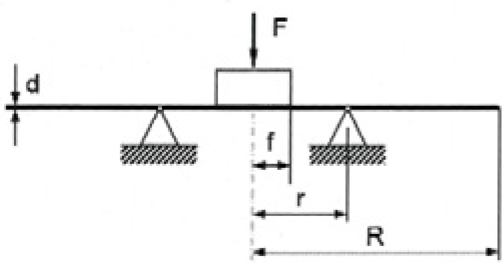

Fig.7. *Simplified model used for numerical analysis*

Material used is steel St 52-3 (S355J2G3) with chemical composition given in Table 2. The software used for analysis was UGS I-deas v.11. To relate the tool radius with wrinkling, it was important to sort the results according to buckling mode shapes.

The following values were used:

R = 1250 mm d = 12 mm
f = 50 to 250 mm r = 200 to 600 mm
F = 1000 kN

3.1 The influence of upper tool radius

The linear buckling analysis was performed for set of upper tool radii. Figure 8 shows analysis results for lower tool radius r=300 mm and variable upper tool radius f, sorted according to number of waves.

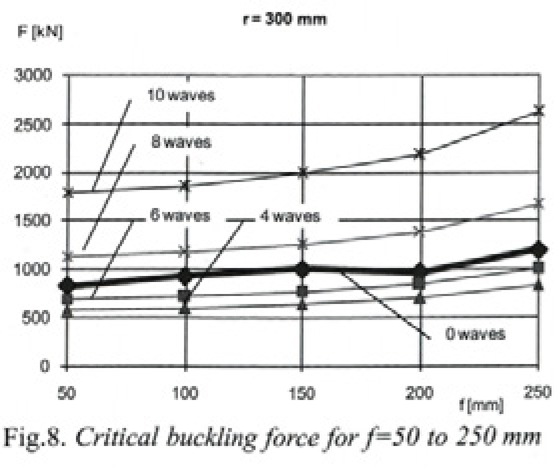

Fig.8. *Critical buckling force for f=50 to 250 mm*

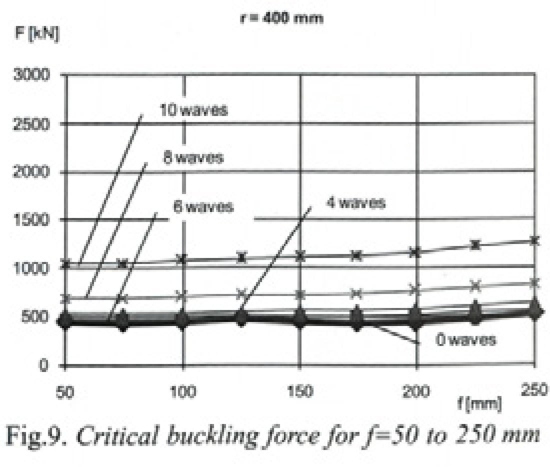

Fig.9. *Critical buckling force for f=50 to 250 mm*

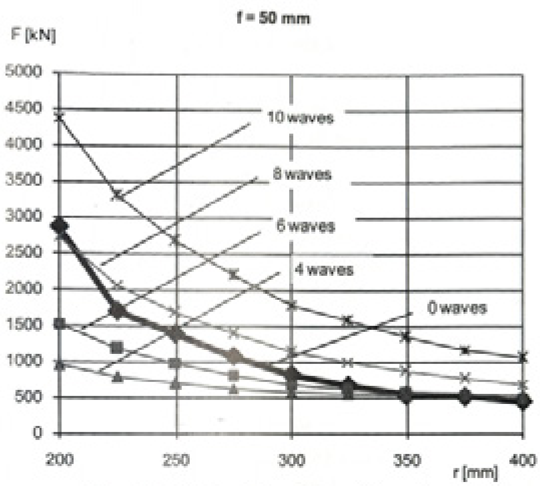

Fig.10. *Critical buckling force for f =200 to 400 mm*

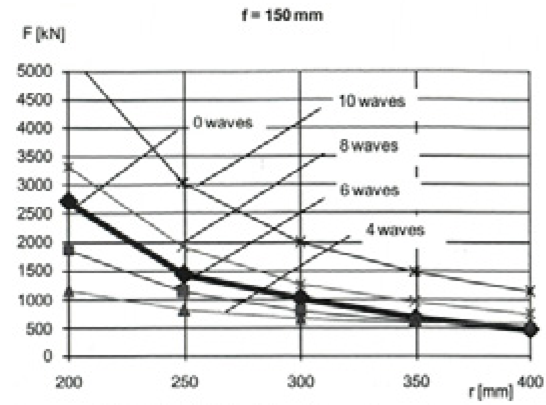

Fig.11. *Critical buckling force for f =200 to 400 mm*

It is evident from Figure 8 that number of wrinkles does not change significantly with change in upper tool radius *f*.

The analysis performed with lower tool radius *r*=400 mm and variable upper tool radius *f* showed even smaller influence of upper tool radius *f* onto critical buckling force (Fig. 9).

3.2 The Influence of Lower Tool Radius

Another analysis was then performed, varying the lower tool radius *r* values, keeping upper tool radius *f*=50 mm constant. Figure10 shows that increase in lower tool radius reduces critical buckling force.

Since results presented in Figure 10 showed increased influence of lower tool radius, similar analysis was performed with larger upper tool radius and variable lower tool radius. Figure 11 shows analysis results for upper tool radius *f*=150 mm.

3.3 Buckling Mode Shapes

The mode shapes which were used to sort the FEM analysis results are shown in Figure 12. The number of waves can be controlled with press force; the critical buckling force determines the buckling mode shape.

It is desirable to control manufacturing parameters in such a way that buckling mode shape shown in Figure 13 occurs. The analysis performed here showed that tool radius and press force can be used to change the mode shape, but it is rather hard to obtain desired shape, because different mode shapes have overlapping curves.

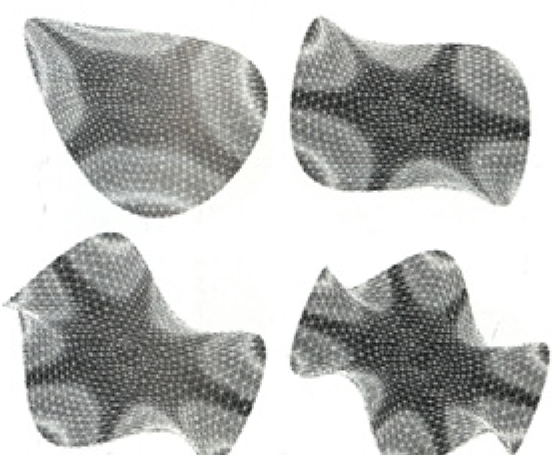

Fig.12. *Mode shapes with 4, 6, 8 and 10 waves*

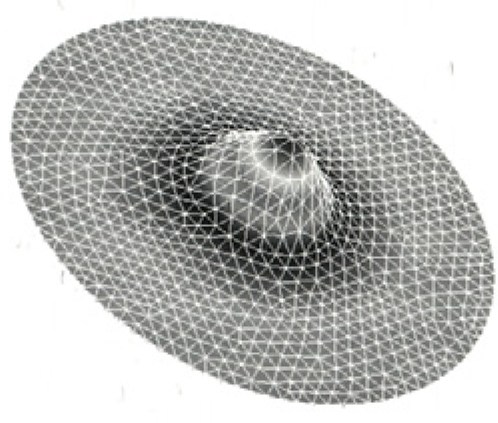

Fig.13. *Buckling mode shapes without waves*

Finite element method uses solution of eigenvalue problem to calculate both buckling and vibration mode shapes. In mathematical terms, every solver algorithm gives results sorted by size. It is important to visualise all numerical results, to be able to determine number of waves (wrinkles) from FEM results. For example, FEM solver gives 10 mode shapes accompanied with 10 critical force values, and visualisation must follow to determine the number of waves for each critical force value.

3.4 Experimental Results

To check the validity of numerical results, the geometry of incrementally formed spherical tank was measured after first forming operation. As numerical results led to conclusion that upper tool radius has low influence onto number of wrinkles, the measurements were performed for three different curvature radii of upper tool, between 250 and 700 mm. As Figure 14 shows, the larger curvature radius, the larger contact surface between upper tool and the sheet metal being formed.

According to results presented in Table 1, significant decrease in upper tool radius led to neglectable change in number of waves (wrinkles), as opposed to press force, which has strong influence onto buckling mode shape, in terms of both number of waves and buckling amplitude.

Therefore, both FEM and experimental analysis showed that upper tool radius has neglectable influence onto buckling mode shapes and number of wrinkles after first forming operation.

Figure 15 shows mode shapes modelled according to measurement results. The captions a, b, c, d correspond to mode shapes presented in Table 1.

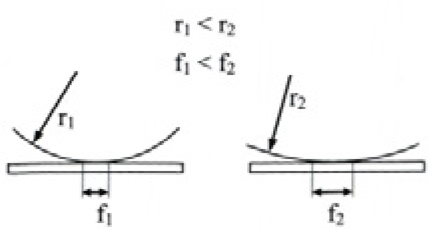

Fig.14. *Relation between curvature radius and contact surface*

4 CONCLUSIONS

Linear elastic finite element analysis was used in this research in order to obtain buckling mode shapes for various radii of upper and lower tool. The analysis showed that number of wrinkles, which corresponds to number of waves in buckling mode shape, cannot be easily controlled by means of tool radius. The curve corresponding to zero-wave mode shape (the shape without wrinkles) propagates over entire domain and intersects other curves, as shown in Figures 8 to 11.

However, the upper tool radius is proven to have less influence onto critical buckling force and number of waves. That means the upper tool could be kept smaller, thus reducing the tool costs, keeping product quality the same.

It is hard to control process parameters to provide conditions when desirable mode shape occurs. The press force should be controllable if one wants to influence the buckling mode shape.

It is shown that conclusion given in [4] is not applicable in cases with free, unclamped edges.

Thin sheets wrinkle more easily and due to large lateral deformation. In contrary, thick plates wrinkle when deformation is limited; buckling occurs when major stress is compressive. In this manufacturing process upper surface is compressed and it buckles in a predictable mode shape. The higher mode shapes calculated by FEM correspond to wrinkles measured experimentally.

The major lack of this research is inability to control press force precisely, which is limitation introduced by press design. Further experiments should be performed on press with controllable force.

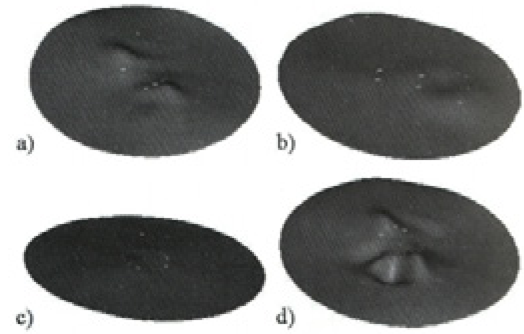

Fig.15. *Measured buckling mode shapes*

5 REFERENCES

[1] Mackerle, J. Finite element analyses and simulations of sheet metal forming processes. *Engineering Computations*, Vol. 21 (2004) No. 8, p. 891-940.

[2] Cao, J., Boyce, M.C. A Predictive Tool for Delaying Wrinkling and Tearing Failures in Sheet Metal Forming. *Transactions of the ASME*, Vol. 119 (1997), p. 354-365.

[3] Wang, X., Cao, J. On the prediction of side-wall wrinkling in sheet metal forming processes. *International Journal of Mechanical Sciences*, 42 (2000), p. 2369-2394.

[4] Wang, X., Cao, J., Li, M. Wrinkling analysis in shrink flanging. *Transactions of the ASME*, Vol. 123 (2001), p. 426-432.

[5] Pohlak, M., Küttner, R., Majak, J. Modelling and optimal design of sheet metal RP&M processes. *Rapid Prototyping Journal*, 11/5 (2005), p. 304-311.

[6] Lee, S.W., Yoon, J.W., Yang, D.Y. Comparative investigation into the dynamic explicit and the static implicit method for springback of sheet metal stamping. *Engineering Computations*, Vol. 16 (1999), No. 3, p. 347-373.

[7] Schafer, T., Schraft, R.D. Incremental sheet metal forming by industrial robots, *Rapid Prototyping Journal*, 11/5 (2005), p. 278-286.

[8] Ambrogio, G., Costantino, I., De Napoli, L., Filice, L., Fratini, L., Muzzupappa, M. Influence of some relevant process parameters on the dimensional accuracy in incremental forming: a numerical and experimental investigation. *Journal of Materials Processing Technology*, 153-154 (2004), p. 501-507.

[9] Kim, J.B., Yang, D.Y. Prediction of wrinkling initiation in sheet metal forming processes. *Engineering Computations*, Vol. 20 (2003), No. 1, p. 6-39.