Simulation of Effects of Material Deformation on Thickness Variation in Conventional Spinning

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Summary

This paper reports the development of Finite Element simulations of a conventional metal spinning process. Using Finite Element dynamic explicit formulations, the simulation of the forming of a cylindrical spun part by the single pass of a roller was conducted, with the intention to understand the effect of the material deformation on variations in wall thickness of the spun part. The simulation provides predictions of distributions of radial, tangential and thickness strains induced in the workpiece during spinning. The results show that unbalanced and non-uniformly distributed radial and tangential strains have a determinant effect on thickness variations of the formed part in metal spinning processes.

1. Introduction

The process of metal spinning has drawn increased attention in recent years owning to its advantages of flexibility and near net shape in production, no need for specifically designed dies and tools, therefore ensuring reduced time and cost to market for customized products [1,2]. Despite the conceptual simplicity of the metal spinning process, determining the spinning process parameters and controlling the product quality remain challenging tasks. Each part spun requires a unique combination of process parameters to be correctly determined to achieve the required geometrical shape and dimensional accuracy and to prevent various forms of material failure during spinning. These process parameters, such as the roller feed rate, spindle speed, the shape of roller path as well as spinning ratio must be co-ordinately determined. For different products, the material type, initial sheet thickness and geometrical configuration may be varied. Thus it is desirable for the process parameters to be swiftly determined to allow effective process development of new spun products. In the present industrial practice, the trial and error approach is still commonly used and it inevitably results in significant variations and discrepancies in product quality and geometrical dimensions. The whole procedure of the process development and validation is also costly and time consuming.

Research efforts have been made to investigate and understand the material deformation mechanism and its effects on the variation of wall thickness of the formed part during spinning. Using experimental techniques, Kang et al [3] investigated the effects of three different types of roller paths on the deviation of wall thickness of conical and spherical shaped parts by shear spinning. They concluded that the deformation mode of the spinning of plates was mainly shear spinning and the wall thickness in the deformed area correlated well with the sine law. It has been observed that the deformation in the first pass had a decisive effect on the wall thickness distribution of the spun product. Quigley and Monaghan [4] analysed radial and hoop strain distributions in shear spinning and conventional spinning of a spherical part using both multi-pass and single-pass operations. Based on experimental measurements and theoretical strain calculations, the results showed that the radial strain was significantly larger than the hoop strain. The differences between the measured and predicted hoop strains implied that there was a certain degree of shear forming in the first roller pass of conventional spinning. Based on a simplified 2D model using Finite Element method, J.H. Liu et al [5] modelled distributions of radial, hoop and thickness stresses and strains of a conventional draw-spinning in the first pass of the process. Three types of roller paths, straight line, involute and quadratic curves were used and variations of stress and strain distributions under these roller paths were observed. The results showed that stresses and strains obtained under the involute path were small and evenly distributed in comparison with those of the other two roller paths. Based on experimental investigations, Xia et al [6] studied one-path deep drawing spinning of cups. Forming conditions considered in their research included the material property, the feed rate of the roller, nominal deep drawing ratio, and relative clearance between the roller and mandrel, which were found to be important parameters affecting the spinning force, nominal thickness strain and material formability.

This paper reports the development of Finite Element simulations of a conventional metal spinning process. Using Finite Element dynamic explicit formulations, the simulation of the forming of a cylindrical spun part by the single pass of a roller was conducted, with the intention to understand the effect of the material deformation on variations in wall thickness of the spun part. The simulation provides predictions of distributions of radial, tangential and thickness strains induced in the workpiece during spinning. The results show that unbalanced and non-uniformly distributed radial and tangential strains have a determinant effect on thickness variations of the formed part in metal spinning processes.

2. Finite Element simulation of metal spinning

2.1. Deformation of material during metal spinning

The conventional metal spinning involves localised bending of a sheet metal blank through a series of sweeping strokes to produce a desired shape with a reduction in diameter of the blank over the whole length or in defined areas without the change of the original blank thickness. The incremental passes of the forming tool induce compressive tangential (hoop) stresses in the flange region. Shown in Fig. 1 [7], as the roller moves towards the edge of the blank, radial tensile stresses are generated, which produce a flow of material in the direction along the mandrel causing thinning. However this is compensated for by the thickening effect of the tangential compressive stresses. As the roller traverses in the reverse direction, towards the centre of rotation, a build up of material occurs in front of the roller. The resulting radial and tangential compressive stresses generate a displacement of material towards the mandrel [7]. Distributions of radial and tangential stresses have a determinant effect on the thickness of spun part, one of the important dimensions to control the quality of the forming part in metal spinning.

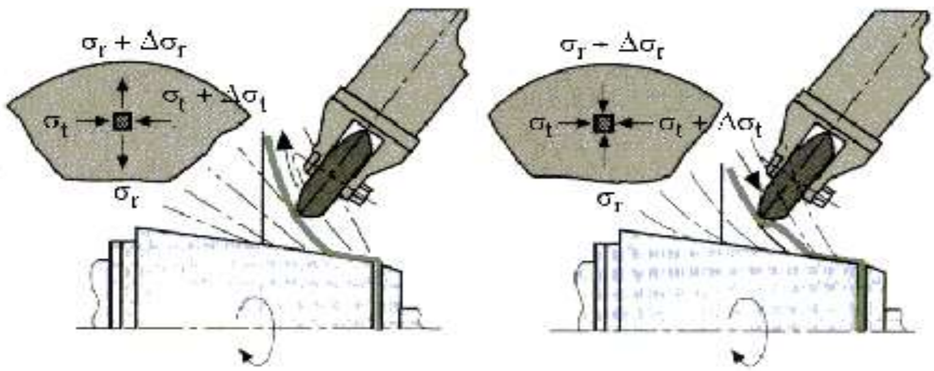

Fig. 1: *Radial and tangential stresses during conventional spinning [7]*

2.2 Explicit dynamic Finite Element method

Deformation analysis and modelling of a metal spinning process involves three types of non-linearity: material non-linearity, boundary non-linearity and geometric non-linearity. The material non-linearity is attributed to the material elastic-plastic behaviour and the effects of strain-rate and temperature dependences. Boundary non-linearity is intrinsic to metal spinning because of the complex and changing contacts and interactions between many independent bodies. When the workpiece deforms incrementally over the mandrel under the load applied by the roller, it leads to discontinuous effects resulting from the changing contact conditions and frictional forces. Geometric non-linearity is present in spinning because of the magnitude of the displacements resulting from the plastic deformation and possible post buckling of the spun metal, which affects the response of the structure. In addition, representative metal spinning geometries generally require three-dimensional modelling of very large models and consequently a long computing time. Because the simulation size is large and the nonlinearity dominates in metal spinning modelling, the explicit dynamics Finite Element (FE) approach is more feasible and less expensive computationally than the implicit quasi-static approach, commonly used in some metal forming process simulations.

The commercial software ABAQUS is used in this research to modelling metal spinning processes. ABAQUS/Explicit uses a central difference method to integrate the equations of motion explicitly through time, using the kinematic conditions at one increment to calculate the kinematic conditions at the next increment [8]. At the beginning of the time increment (t), the nodal accelerations, $\ddot{u}$, are calculated based on dynamic equilibrium as given in Equation (1)

$$\ddot{u}\big|_{(t)} = (M)^{-1}(P - I)\big|_{(t)} \tag{1}$$

where **M** is the nodal mass matrix, **P** is the vector of the external applied forces, and **I** is the vector of internal element forces. The acceleration of any node is determined completely by its mass and the net force acting on it without the need to solve simultaneous equations, making the nodal calculations very inexpensive. Knowing the accelerations, the velocities and displacements are advanced "explicitly" through each time increment Δt, as shown in Equations (2) and (3) [8]:

$$\dot{u}\big|_{(t+\Delta t/2)} = \dot{u}\big|_{(t-\Delta t/2)} + \frac{(\Delta t\big|_{(t+\Delta t)} + \Delta t\big|_{(\Delta t)})}{2}\ddot{u}\big|_{(t)} \tag{2}$$

$$u\big|_{(t+\Delta t)} = u\big|_{(t)} + \Delta t\big|_{(t+\Delta t)}\dot{u}\big|_{(t+\Delta t/2)} \tag{3}$$

For the method to produce accurate results, the time increments, Δt, must be quite small so that the accelerations are nearly constant during an increment. Since the time increments must be small, analyses typically require many thousands of increments. In order to simulate metal spinning processes effectively, "load rate scaling" and "mass scaling" may be used to speed up the simulations. The load rate scaling artificially reduces the time period required by the spinning process, or equivalently, increases the linear velocity of the roller in proportion to the increase of the rotational velocity of the mandrel to keep the feed ratio unchanged. However, this may cause two possible errors. If the rotational velocity of the mandrel is increased too much, the inertia forces may become too large and will change the predicted response. The other error is resulted from the material behaviour, for example, if the material is strain-rate dependent. The mass scaling technique artificially increases the material density to speed up the time of simulation but allow the treatment of strain-rate dependent material and other behaviours. Similar to load rate scaling, mass scaling factor must not be set too large to allow the inertia forces to dominate and, thus, to significantly change the solution.

3. Finite Element model and definitions

In FE simulation, an aluminium sheet blank of an original diameter of 192 mm with thickness of 3 mm is spun into a cylindrical part with an internal nominal diameter of 118 mm by the conventional spinning process using a single roller pass. The geometries and dimensions of the mandrel, clamping holder and roller are taken from the published papers by C.H. Liu [9] and Xia et al [6]. A three-dimensional FE analysis model containing the workpiece and the tools is developed as shown in Fig. 2.

The workpiece is modelled using 3D 8-node hexahedral elements, the number of elements is 3590 and the number of nodes is 7372. The mandrel, holder and roller are modelled using analytical rigid bodies. The principal advantage of representing these parts as rigid bodies instead of deformable bodies is the computational efficiency. Coulomb friction is assumed between the workpiece and the mandrel, holder, and roller, with frictional coefficients of 0.2, 0.5 and 0.05, respectively. The isotropic strain hardening of flow stress of pure aluminium (A1100-O) is defined as $\sigma_Y = 148.8\varepsilon^{0.233}$. Isotropic elasticity is assumed, with Young's modulus of 70 GPa, Poisson's ratio of 0.3 and mass density of 2700 kg/m^3. No rate dependence or temperature dependence of flow stresses is taken into account in the simulation. The process parameters used in the simulation are the same as given in the papers by C.H. Liu [9] and Xia et al [6], with the rotational velocity of mandrel, holder and workpiece of 200 rpm and the roller feed rate of 1 mm/rev.

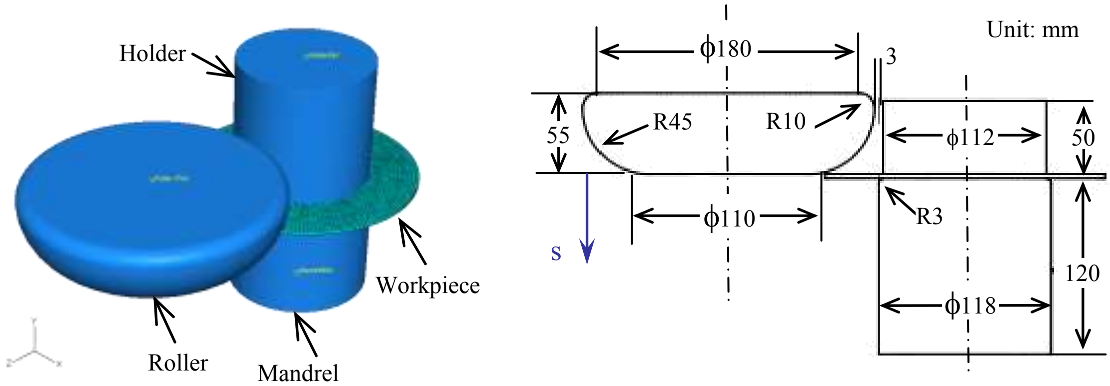

Fig.2 *Finite Element model of a single-pass conventional spinning*

4. Results and discussions

The simulations were performed using an Intel® Xeon™ computer of CPU 2.80GHz. The load rate scaling technique was employed to speed up the simulation time; kinetic and internal energies of the workpiece were checked to ensure the control of effects of the inertia forces caused by the scaling.

Fig. 3 shows the material deformation of the workpiece at various displacements of the roller. At the initial stage, the workpiece undergoes the plastic deformation due to bending, as shown at the roller displacement of 17.4 mm. The deformation progresses to a combination of a global triaxial and a localised deformation as the roller continues forming the material over the mandrel. The global deformation causes severe material deformations over the edge of the mandrel due to drawing, for example, as can be seen at the displacement of 58 mm. The compressive localised deformation occurs directly under the roller, which is most visible as shown at the displacement of 58 mm. Some of the localised deformation recovers after the roller moves away to its next contact area. As the roller approaches its end of the displacement, the workpiece deforms further over the mandrel and takes the shape of the mandrel. For the material between the holder and the mandrel, it undergoes a simple compression.

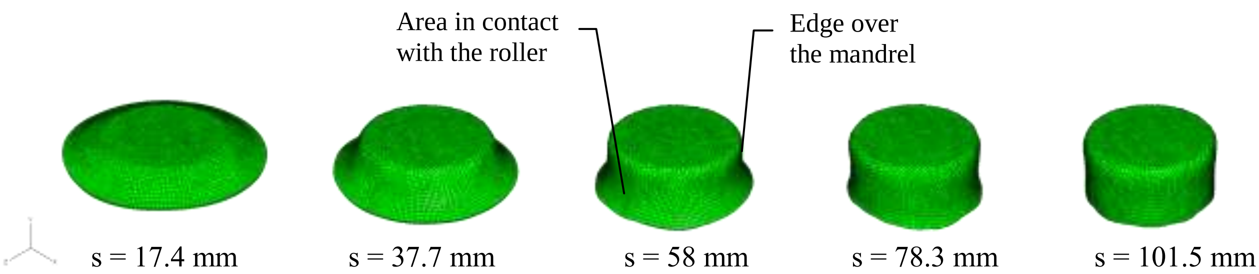

Fig. 3 *Material deformation during spinning*

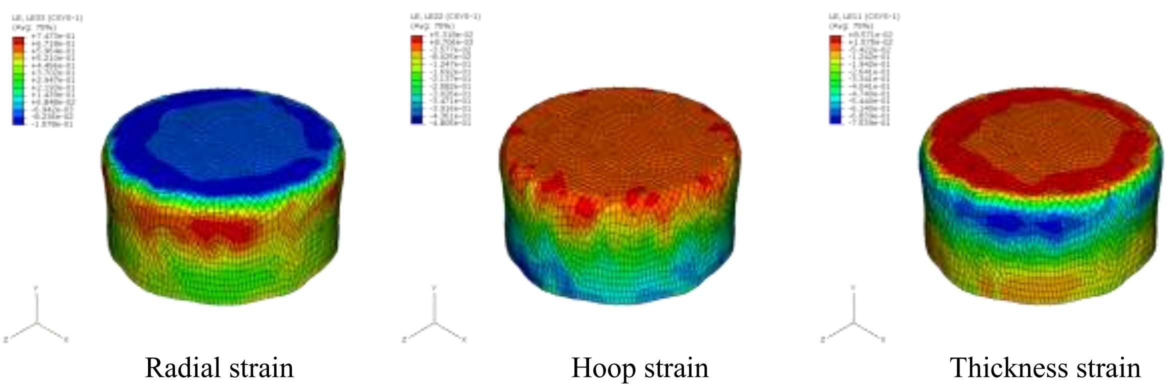

Fig. 4 *Distributions of radial, hoop and thickness strains*

Distributions of radial, tangential (hoop) and thickness strains of the fully deformed workpiece are shown in Fig. 4. There are considerable tensile radial strains developed in areas close to where the workpiece rounds the mandrel edge. The magnitude of the tensile radial strain gradually reduces towards the opening of the cup. In contrast, compressive hoop strains are experienced by the workpiece and highest strains can be seen at the cup opening and lowest strains are around the edge over the mandrel and at the bottom of the cup. From the distribution of thickness strains, it shows that negative thickness strains present throughout the spun region of the cup with highest thickness strains located close to the edge over the mandrel. The magnitude of the tensile radial strain is visibly greater than that of the compressive hoop strain. It is clear that radial, hoop and thickness strains are all non-uniform distributed along the circumferential direction and the depth of the cup. The distributions of radial and hoop strains have a decisive effect on variations of the thickness strain.

Fig. 5 shows the distribution of thickness strains and changes of wall thickness in a section through fully deformed workpiece. Axial sections of the formed cup readily show a variation in wall thickness of the spun part. Fig. 6 details variations of radial, hoop and thickness strains of a cross section along the depth of the fully deformed cup. The positive radial strain reaches the maximum at the location close to the edge of the mandrel then reduces gradually in the middle region of the cup, and slightly rises again at the cup opening. On the other hand, the negative hoop strain gradually increases its magnitude with the increase of the cup depth, and reaches the maximum at the cup opening. It is evident that the magnitude of the radial strain is greater than that of the hoop strain. Due to the difference of these two strains resulted from the roller passing, it causes the thinning of the spun part throughout its depth, particularly around the edge of the mandrel, termed as necking, as evident in Figs. 5 and 6. The spun part also exhibits the irregular/ragged edge at the cup opening, as shown in Fig.5, due to the unbalanced and non-uniformly distributed radial and hoop strains.

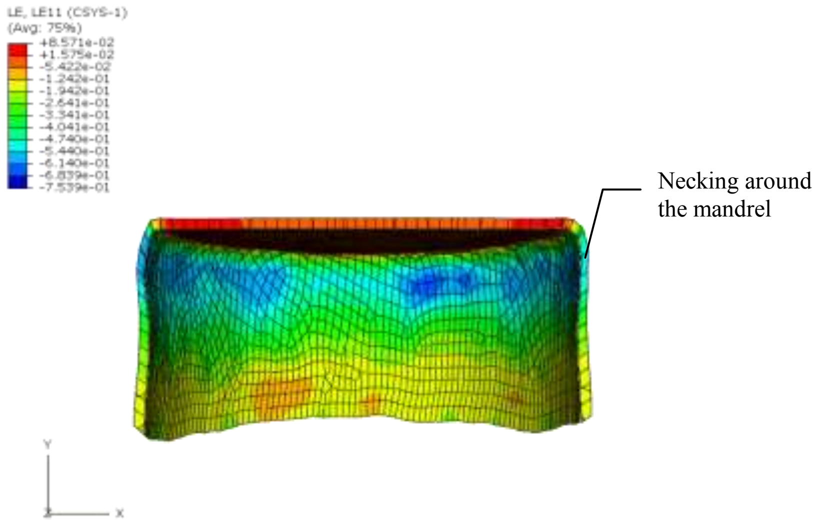

Fig. 5 *Thickness strain distribution of a cross section*

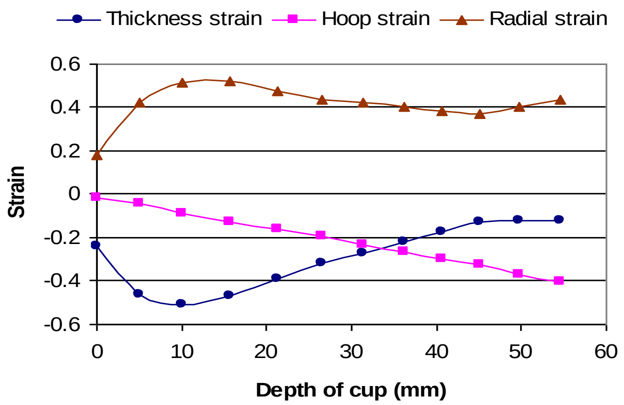

Fig. 6 *Variations of strains of a cross section along the depth of cup*

The above changes and distributions in wall thickness of the formed cup obtained by the simulation agree well with experimental results suggested by Xia et al [6] and Hagan & Jeswiet [1]. It confirms that this single pass process is not solely a conventional spinning process, as has been suggested by Quigley & Monaghan [4] and C.H. Liu [9], but to some extent shear spinning occurs resulted in the thinning of the workpiece. The above results agree with the assertion made by Wong, Dean & Lin [2] that a single pass process cannot be exclusively regarded as a conventional spinning process.

5. Conclusions

From simulation results presented above, the following conclusions can be drawn:

- Significant tensile radial strains are presented in areas close to where the workpiece rounds the mandrel edge. The magnitude of the tensile radial strain is visibly greater than that of the compressive hoop strain. The non-uniformly distributed radial and hoop strains have a decisive effect on the variation of the thickness strain.
- There is a considerable variation in wall thickness of the spun part. Due to the unbalanced tensile radial strain and compressive hoop strain induced in the workpiece, it causes the thinning of the spun part throughout its depth, particularly in areas around the edge of the mandrel. The spun part also exhibits the irregular/ragged edge at the cup opening.
- Results obtained show a general agreement with the published experimental work by Xia et al [6]. It confirms that the single pass process is not solely a conventional spinning process but to some extent shear spinning occurs resulting in the non-uniformly thinning of the workpiece.

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