FINITE ELEMENT ANALYSIS OF ORBITAL FORMING USED IN SPINDLE/INNER RING ASSEMBLY

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Summary

In this study, 3D FEM simulation technique for optimizing parameters in orbital forming of spindle and inner ring assembly was investigated by a) measuring the computation time and b) comparing the results of simulations with experiments. Commercial FEA software DEFORM^{TM} 3D v4.0 that has an efficient numerical algorithm for simulating incremental forming processes was used for the simulations and the amount of savings in computation time was shown. Thanks to a new development in DEFORM 3D, the computation time required for simulating the incremental orbital forming process has been dramatically reduced. The predicted tab geometry of the spindle and maximum forming load by FEM simulation were compared with experimental measurements. For the particular example, the effect of axial feed rate and tool axis angle on the assembly was investigated to generate design guidelines. This study showed that 3D FEM is a reasonably reliable tool to optimize the orbital forming process used for the spindle and inner ring assembly.

Keywords: orbital forming, FEM, incremental forming

1 Introduction

Using 2D FEM simulation technique, it is now possible to design and optimize many forming processes. The application of 3D FE simulation started in the mid 1990s and gained rapid acceptance. However, in spite of improvement in computing speed, the time and cost associated with 3D FEM simulation is still quite large. Further reduction in computation time is still important to make 3D FEM simulation practical, efficient, and robust for industrial applications. Application of 3D FEM to an incremental forming process like an orbital forming, where a huge amount of computation time is necessary, is still limited. In orbital forming, **Figure 1**, the rotating tool, tilted at 3 to 6 degrees with respect to the axis of the lower die, moves axially to form the part. Unlike conventional compression forming where the process is completed in a single pass, orbital forming requires progressive forming actions (several tool revolutions with axial feeding) and typically takes 1.5 to 3 seconds to complete. Orbital forming offers great flexibility and can be used to form a wide range of materials and geometries [1,2], and has the following advantages:

- Internal stresses generated in assembled components are greatly reduced due to low axial load.
- Smooth surface finish is obtained and the possibility of crack formation is reduced.

- Axial load required for forming is reduced (up to 80%), As a result, press size, floor space and costs are greatly reduced.
- Due to lower forming forces, tool life is increased (Tooling costs are greatly reduced).
- Orbital forming is usually much quieter than other cold forming operations.

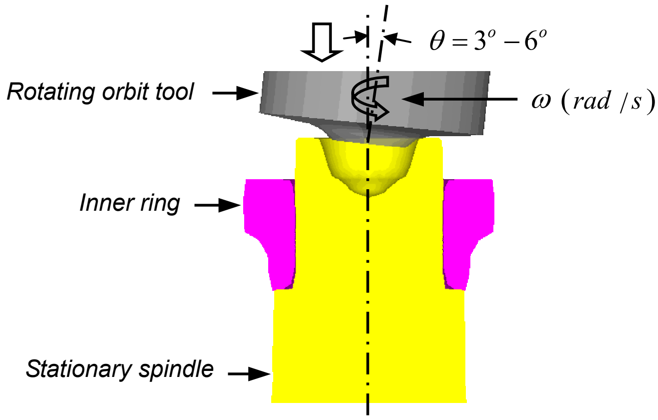


Figure 1: *Principle of orbital forming of wheel spindle bearing assembly.*

In orbital forging the force is applied only on a small segment of the workpiece. Therefore, friction is reduced substantially and the metal can flow much easier in radial direction. The metal flow and tool stresses are mainly affected by:

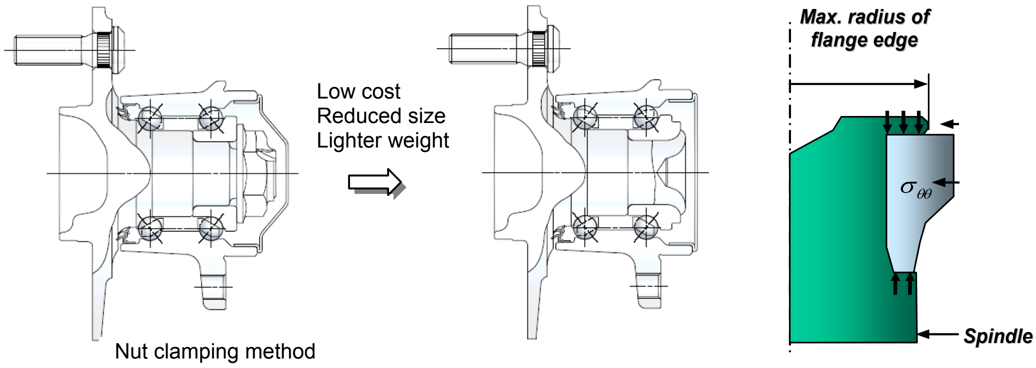
- Axial feed speed (axial movement of the tool)
- Spindle RPM (rotational speed of the tool or the workpiece)
- Tool axis angle
- Lubrication

Earlier studies showed that the forming force and the radius of deformed part increase with increasing axial feed [3,4]. Furthermore, the axial force decreases and the formed part radius increases with increasing tool axis angle. In this study, the 3D FEM process simulation technique was applied to the design of orbital forming process, used in automotive spindle and inner ring assembly operation. The effect of process parameters including feed rate and tool axis angle were investigated in order to generate design guidelines for a robust assembly process operation.

2 Finite element analysis of spindle/inner ring assembly

2.1 Introduction to spindle/inner ring assembly operation

Due to advantages over the conventional nut clamping assembly process, orbital forming is now widely used by bearing manufacturers such as NSK, Delphi, and Timken. As shown in **Figure 2(a)**, the wheel bearings manufactured by orbital forming process require fewer components and are therefore less costly, lighter in weight and smaller in size. Moreover, bearings used for driven wheels require no preload control in assembly, making them easier to mount on axles.



(a) (b)

(a) Comparison of bearing assembly by conventional method and swaging or orbital forming [5]
(b) Clamping force and residual stress in the spindle/bearing assembly

***Figure 2**: Spindle/bearing assembly.*

The quality of spindle/inner ring assembly can be controlled by estimating the holding force and internal residual stresses created during the assembly operation. Magnitude of the holding force is determined by the formed tab (deformed flange) geometry. Thus, the size of the flange holding the assembly of the spindle and the inner ring should be controlled in order to vary the holding force, **Figure 2(b)**.

2.2 Finite element modeling

The FE model of spindle was generated with 9875 nodes and 43231 tetrahedral elements, **Figure 3(a)**. The spindle is assumed to be rigid plastic object and flow stress of $\bar{\sigma} = 780\bar{\varepsilon}^{0.138}\,(MPa)$ was used. The tool and the inner ring were rigid objects and shear friction factor of m_f=0.15 was used, assuming lubricated condition. The time step size was determined as 0.0025 (sec/step) based on tool movement, represented by feed rate; axial feed per revolution. Constant feed rate of 0.39 mm/rev was assumed in the simulation. This time step size provides 48 incremental steps per one revolution of the rotating tool and 500 simulation steps were assigned to complete the process.

2.3 Simulation results

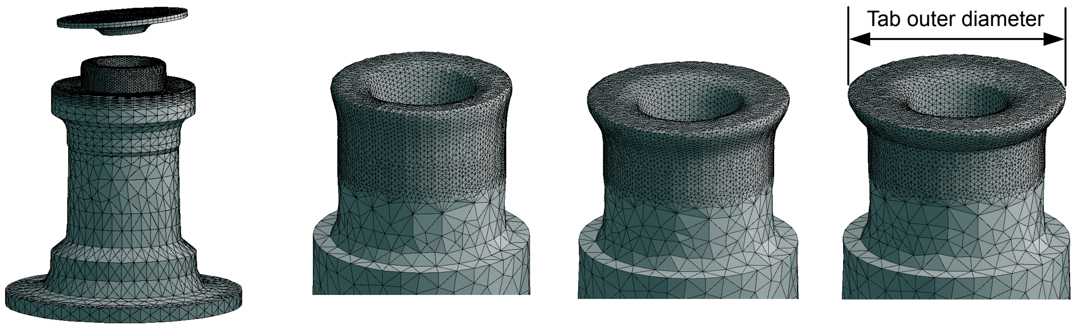
In some metal forming processes such as drawing, extrusion, rolling, bending, and orbital forming, localized plastic deformation is often observed while majority of the workpiece undergoes rigid body motion. To take advantage this unique behavior, an innovative approach called Rigid Super Element (RSE) is developed in DEFORM™ 3D v4.0 [6]. Using this method, the equations associated with the nodes in the non-deforming zone are now reduced to six representing the rigid body motion. These equations are coupled and solved simultaneously with the equations in the deforming zones. Therefore, the number of equations and solution time can be reduced significantly. In **Table 1**, the results of two simulations are summarized. When the simulation was made using Rigid Super Element in DEFORM™ 3D v4.0, 8 hrs. 30 min. was required to complete the assembly process. However, when this new method was inactivated, the CPU time was dramatically increased up to 98 hrs. Thus, around 91%

saving of computation time was achieved with the improved version of the software.

Table 1: *Comparison of two simulation results (Machine: HP J6000 w/2GB Memory).*

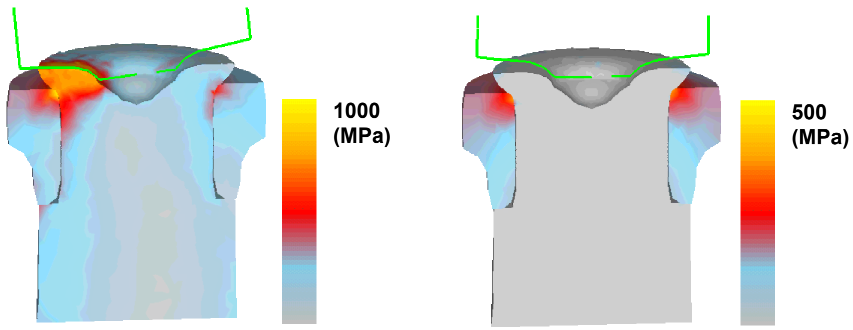
	Activating new algorithm	Using the old algorithm
Overall CPU time	8 hrs. 12 min.	100 hrs.
CPU Time / Iteration	0.5~1.0 sec.	30~40 sec.

In **Figure 3(b), (c), and (d)**, the predicted deformation at different punch strokes near the tab of the spindle are shown. The predicted outer tab diameter is defined in **Figure 3(d)**. When the simulation results were compared with the experimental measurements, about 1% overestimation in the tab outer diameter and about 15% overestimation in forming force were observed. In **Figure 4(a)**, the predicted effective stress distribution is shown. The inner ring was under tensile stress and the maximum 500 MPa was predicted at the top inner side of the inner ring below the spindle tab as shown in **Figure 4(b)**.



(a) 3D FE model (b) 40% punch stroke (c) 80% punch stroke (d) 100% punch stroke

Figure 3: *FE model and predicted metal flow of spindle at intermediate stages.*



(a) Effective stress (b) Hoop stress

Figure 4: *Predicted stress distribution by FEM.*

3. Effect of process parameters in an example assembly

3D FEM has been used to examine the influence of a) the axial feed rate and b) tool axis angle on the orbital forming of an example assembly. The model geometry was obtained from the spindle/inner ring assembly, shown at the NSK's company brochure [5]. The example spindle was modeled as plastic and meshed with about 40000 tetrahedral elements. The inner ring was modeled as rigid and switched as elastic during the last rotation to predict the elastic stress distribution. The simulation was conducted until the tab height of 3 mm was reached using a tool speed of 500 rpm. Figure 5 gives the profiles of various axial feed rates used in the simulations. Tool axis angle used was 4^{o}.

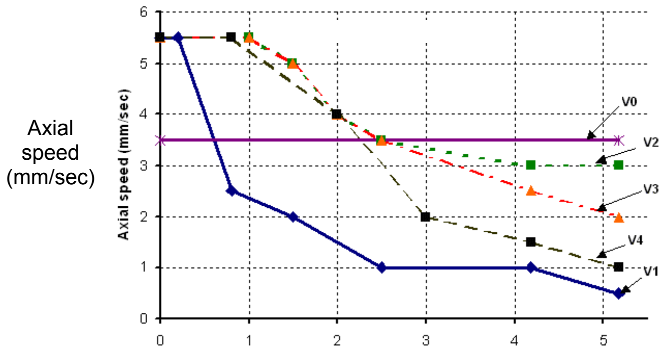


Figure 5: *Various axial feed rates used in the simulation.*

The feed rates V_0, V_2, V_3 and V_4 formed the tab as desired. However, with the axial feed rate V_1, undesirable inward metal flow was observed. This may be because of very low axial feed rate towards the end, **Figure 6**. As the feed rate decreases the axial forming force drops, **Figure 7**. Lower forming forces are desired as they lead to lower residual stresses in the inner ring and better assembly quality. **Table 2** gives the predicted hoop stresses in the inner ring and its deflection for various feed rates.

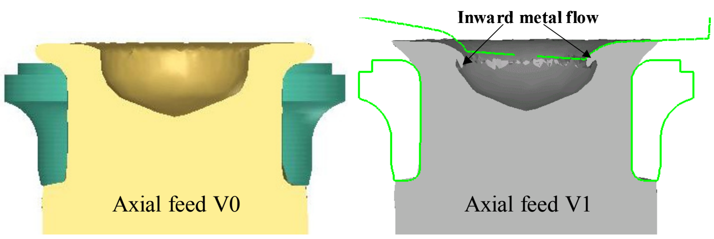


Figure 6: *Deformation pattern for axial feeds V_0 and V_1.*

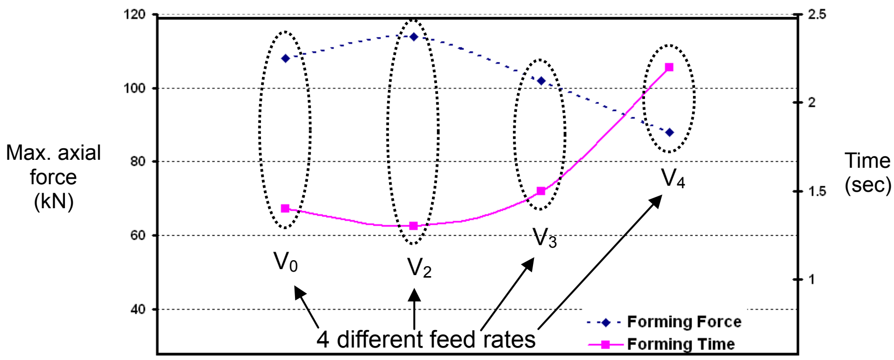


Figure 7: *Maximum forming force and forming time variation with feed rates.*

The inclination of tool (tool axis angle) affects the metal flow and the quality of the assembly. In order to investigate this, two different angles, 4 and 6 degrees were selected. With the increase in the tool axis angle, the forming force and thus the stresses in the inner ring decrease as shown in **Table 3**.

Table 2: *Estimated hoop stresses and inner ring deflections for different feed rates.*

	Axial feed V_3	Axial feed V_4	% Difference
Max. hoop stress in inner ring at the end of forming operation (MPa)	310	200	35
Max. hoop stress in inner ring after unloading (MPa)	290	190	33
Max. inner ring deflection (mm)	0.005	0.003	40

Table 3: *Comparison of hoop stresses in the inner ring for different tool axis angles.*

	Max. hoop stresses (MPa)			
Conditions	Axial feed V_3		Axial feed V_4	
	End of forming	After unloading	End of forming	After unloading
Tool axis angle - 4^o	310	290	200	190
Tool axis angle - 6^o	216	200	110	100
% Difference	30	29	29	29

4. Summary and conclusions

In this study, FEM simulations of orbital forming for assembly of wheel spindle bearing were conducted using DEFORM^{TM} 3D v4.0. It is concluded that the CPU time required for simulating the orbital forming process has been significantly reduced, by 91%, thanks to the newly developed Rigid Super Element (RSE). The effect of process parameters including the axial feed rate and tool axis angle on the orbital forming process was investigated successfully by conducting 3D FEM simulations. With the increase in feed rate, the forming force increases. Lower feed rates are preferred to have a uniform metal flow and lower forming force. However, there is a lower limit to this value, below which it is difficult to form the part. In this particular example, the lower limit was 1 mm/sec at 500 RPM. With the increase in tool axis angle, forming force and thereby stresses and inner ring expansion can be further reduced. This general trend can be applied to other orbital forming assembly processes. This study illustrated that the use of 3D FEM in simulating and optimizing the orbital forming seems to be a reasonably reliable tool for process and tool design in this process.

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