Simulation Analysis of Spinning Forming of D6AC Ultrahigh-Strength Low-Alloy Steel

Cheng-Shun Chen, Jen-Hsin Ou, Huei-Guo Hu

***Abstract*—** Spinning forming is a continuous and complex deformation process. In this paper, a finite element numerical simulation software, ANSYS/LS-DYNA is used to analyze the spinning forming of D6AC ultrahigh-strength low-alloy steel, and the distribution rules of spinning force, forming stress and strain under different wall thickness in a single pass of forward flow forming. Preliminary results indicate that the spinning force will be greater in accord with the increase of reduction rate and the reduction rate can be up to 70%, which can provide an important reference for spinning process.

***Keywords*—**Spinning, Finite Element Method, D6AC, Ultrahigh-strength Low-alloy

I. Preface

SPINNING is a plastic forming process that a blank is fixed on the rotation mandrel, and then rollers put pressure on the blank, making the material flow to the way where the resistance is smaller. Usually, some metals, including steel, aluminum or copper are suitable for spinning process to produce high strength, hollow and symmetric products. With its excellent processing properties, such as good quality, chip-less machining, shorter processing, easy preparing, high material utilization, and elastic production process, the spinning can be used for big, thin, and long tube manufacturing. Recently, it is also applied on light and precise manufacturing, and is widely suitable for auto, aerospace, and military industries.

There are three methodologies for spinning research: theoretical analysis (upper bound; lower bound; and slip line field methods), numerical analysis (finite elements method, FEM analysis), and experiment. In the earlier time, it was impossible for theoretical analysis and experiment methods to take complex deformation into considerations, especially for the residual strain analysis. Later, with simplified forming process, the stress and power consuming could be gotten, but there were no sufficient principles to explain that phenomenon. Recently, with the development of computer, numerical analysis and simulation for spinning by finite element elements method is a practicable method.

Some factors can affect spinning result, including material properties, spindle speed, angle of roller, roller's feed, and reduction rate. The material plastic properties and heating treatment characteristics will directly affect the surface quality of work piece. Usually, the plasticity and toughness can be improved by choosing high ductility materials with multiple anneal heating treatment process. The processing parameters vary from the different manufacturing conditions, and they must be properly regulated to prevent from cracking. Tsai[1] used Taguchi quality planning method to analyze the influence between spinning parameters and work piece qualities, and to find the optimal parameters. It can also be used to save the cost and time for modeling, and to get the variation of reliability for different deformation rates during spinning process, which can be the basis for spinning parameters adjustment and risk assessments.

When spinning, rollers put pressure on blank. The material failures resulting from stress and strain can be discussed from dynamics. Quigley [2] analyzed the relationship of stress and strain for different spinning types, and proposed the restrain conditions of spinning. By experiment and calculating stress and strain, he introduced the variations of stress and strain after spinning for contour forming, shear forming, single-pass forming, and multi-pass forming.。

Cheng [3] discussed the distribution of stress and strain during spinning, and analyzed the affection between various parameters and spinning. It shows that for the thick blank with large reduction rate, when processing single-pass forming, there will have a better quality if a resistance force should be applied on the free end of blank, and a greater feeding is adopted.

Hun et al. [4] analyzed the distributions of stress and strain for different thinness of tube spinning by 3-D finial elements analysis. It shows that when the reduction rate increases, so does the spinning pressure, and at the time when rollers contact with blank, there will be the maximum ring stress in the piling part of material. The Circumferential and axial stress are far greater than the radial stress, so they are the primary factories that will make the material failure during spinning process.

Mohebbi [5] discussed the processing of local plastic deformation, and studied the residual strain of spinning process by experiment and numerical analysis. The results show that there is a great amount of shear strain existing on the axial and radial cross section. It will deeply affect the blank. The inverse strain will also be significant during deformation processing, but there is no significant effect for finial result. Besides, piling effect will increase residue strain on the surface of blank. It will increase not only shear strain

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on the surface of blank, but also the equivalent elastic strain.

The metal spinning is a process that consists of complex 3D elastic deformation. It is also a process with great scale of strain and deformation, and with physical non-linear or geometry non-linear. The boundary conditions are complex and non-linear. In the past, the try-and-error experiment method was used to do rollers design and process planning, but it is time tedious and raise the cost. By using finial elements analysis to analysis great scale elastic deformation, the metal flowing during spinning and the stress and strain distribution of material can be easily observed. It can also show that the effects on deformation for various parameters can be gotten from proper simulation and analysis, and so the process planning can be improved and the cost can be reduced.

An ANSYS/LS-DYNA Explicit Method will be used in this paper. It can effectively overcome the limit of Implicit Method, and is generally used to solve some problems, such as dynamics, contact, material failure and non-linear static state. A single forward flow formation process for D6AC thin tube will be studied. The material flow and effect of stress and strain distribution will be also analyzed by 3D finial elements numerical simulation.

II. Basic Theories

A. Flow Forming Diagram

There are three types of forming, including bending forming, shear forming, and flow forming. The flow forming, also called as tube forming, can be classified as forward flow forming and backward flow forming, shown as Fig1.

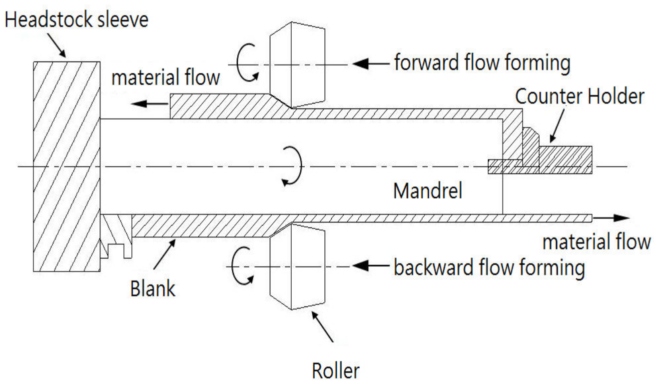


Fig 1 Flow Forming Diagram

The flow forming is a process that the blank is fixed on the mandrel, and rotates with the mandrel by friction force. When rollers move axially, the blank is extruded to flow and makes a plastic deformation. The volume of the blank keeps the same during the forming process. After forming, the thinness of blank is reduced, and the length becomes longer along with the axial direction. The reduction rate can be expressed as equation (1).

$$\varepsilon_t = \frac{(S_0 - S_1)}{S_0} \times 100\% \qquad (1)$$

Where ε_t is reduction rate, S_0 is the thinness of blank before spinning, S_1 is the thinness of blank after spinning。

The length of work piece after spinning can be calculated form equation (2).

$$L_1 = L_0 \frac{S_0(d_i + S_0)}{S_1(d_i + S_1)} \qquad (2)$$

Where L_1 the length after spinning, L_0 the length of work piece before spinning, d_i the inner diameter of tube. There are two types of spinning. When mandrel moves along with the flowing of blank, it’s called forward spinning, otherwise, the backward spinning. Usually, forward spinning is suitable for high precise shell tube, such as launcher, hydraulic cylinder, and pressure container. The backward spinning is suitable for manufacturing larger diameter tube, especially for the low ductility materials that can’t sustain extension stress during processing, such as wielding and casting tube. The forward spinning is more practicable than backward spinning especially when the material flow is longer than the length of mandrel because there will be no any support on the material, resulting in bell-shape-deformation [6].

B. Finite Element Theory: Non-linear Finite Element Analysis

When solving non-linear problems, the Newton-Raphson method is usually practicable. It is a method that gets the roots of non-linear equations by approaching. Fig2 shows the relation between force (F) and displacement (u) in a structure. The function F(u) is a non-linear equation. When solving the displacement u at force F_{app}, the roots can be found by solving the equation F(u)=F_{app}. The Newton approaching method is used. Take P0 as the start point. When doing the first iteration, make a tangent line(the slop is KT , or tangent stiffness) to contact with vertical line at point P1. Repeat the same processes for 4 times (K=4), and find the point P4. The displacement will be u(4), and the stress F(u(4)). If it satisfies with convergent rule as equation (3), the analysis is converged.

$$\left| F_{app} - F(u^{(k)}) \right| \le \delta \qquad (3)$$

Where, δ is convergence (tolerance) , $u^{(4)}$ the approximate root of F(u)=F_{app} , or the displacement corresponding to force F_{app}. .However, for finite elements analysis problem, it is more important to solve the roots for a set of non-linear equations $[K_T]\{\Delta u\} = \{\Delta F\}$, rather than a single equation $F(u)=F_{app}$. The method is as figure 2.

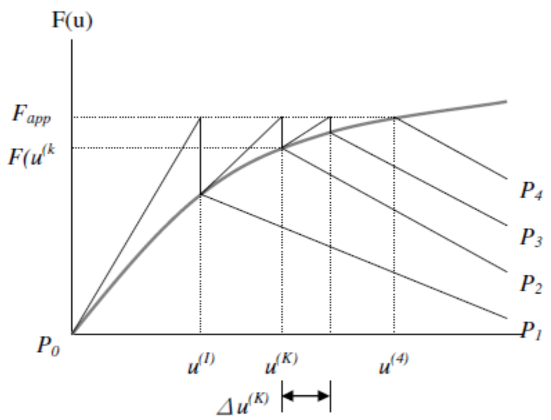


Fig 2 Newton-Raphson method [7]

C. *Explicit Method*

The " explicit" means that at the end of a particular period of time, only displacement, velocity, and acceleration of present time are concerned, or, the time present is only related to the time just before [8]. There are neither rigid matrixes involved nor solving equations required because the calculation is simplified. According to the basic principle of finite elements method for plastic dynamic analysis, the velocity and acceleration can be defined as matrixes of displacement, making the finite differential format being the explicit equations. Let *t be* the time, the explicit dynamic finite element equation can be expressed as equation (4).

$$[M]\ddot{u}+[C]\dot{u}+[K]u=F(t) \tag{4}$$

Where, $[M]$ the mass matrix , $[C]$the damping matrix, $[K]$ the rigidness matrix, $F(t)$ the loading , $\ddot{u}$ the acceleration , $\dot{u}$ the velocity , u the displacement.

The explicit method is also called as" central difference method" . It is a method that takes the displacement during a short time as a linear relationship, shown as Fig 3. The velocity and acceleration can be expressed as the relationship of displacement.

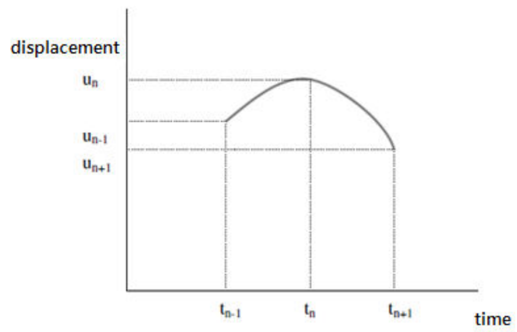


Fig3. Explicit method [8]

By using central difference method, the velocity and acceleration can be expressed as equations (5) and (6).

$$\dot{u}_n=\frac{1}{2\Delta t}(u_{n+1}-u_{n-1}) \tag{5}$$

$$\ddot{u}_n=\frac{1}{\Delta t^2}(u_{n+1}-2u_n+u_{n-1}) \tag{6}$$

Take (5)and (6)into (4) , there is equation (7)。

$$F_n=\frac{[M]}{\Delta t^2}(u_{n+1}-2u_n+u_{n+1}) + \frac{[C]}{2\Delta t}(u_{n+1}-u_{n-1})+[K]u_n \tag{7}$$

After calculating, there is equation (8)

$$\left(\frac{1}{\Delta t^2}[M]+\frac{1}{2\Delta t}[C]\right)u_{n+1}= F_n-\left([K]-\frac{2}{\Delta t}[M]\right)u_n-\left(\frac{1}{\Delta t^2}[M]-\frac{1}{2\Delta t}[C]\right)u_{n-1} \tag{8}$$

During mental forming process, it is a complex static issue of non-continuous and non-linear. In this study, finite elements analysis software called ANSYS/LS-DYNA, which is based on explicit method, will be used to simulate the process.

III. Finite Element Simulation and Analysis

The ANSYS/LS-DYNA will be used to analysis material flow, stress, and strain distribution after plastic deformation by single forward spinning at different reduction rates, shown as Fig 4.

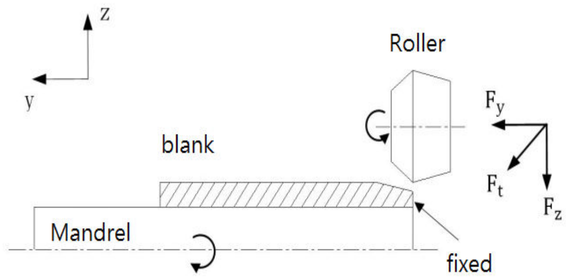


Fig 4 Simulation diagram

A. *Modeling*

The initial model is shown as Fig 5, and the parameters of blanks and rollers are shown as Table 1.

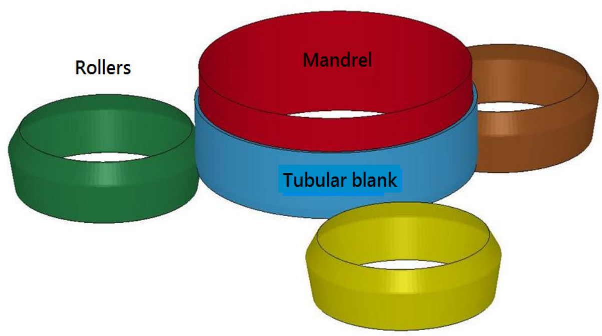


Fig 5 Finite element model

Table 1 Spinning Process Simulation Parameters

Blank			
Inner diameter(mm)	Outer diameter (mm)	Length(mm)	Thickness(mm)
208	214	100	6
Roller			
Outer diameter (mm)	Leading angle	Smoothing angle	Radius(mm)
148.5	30°	10°	4
Spinning parameters			
Spindle speed (rpm)	60		
feeding(mm/rev)	0.7		
Reduction rate (%)	50	60	70

The three rollers distribute along a circle at the angle of 120°. The bigger the leading angle, the higher the bulge will be, leading an unstable material flowing. If the angle is too small, the contact surface between blank and rollers increases, raising the spinning pressure. Normally, the angle is about 20°~30°, and the leading angle of steels is about 30°. The smoothing angle relates to the smoothness of product.

B. Material Properties and Types of Element

D6AC(45CrNiMoV) is a kind of Ultrahigh-Strength low-alloy Steel developed by Ladish. It is made by Air Melting and vacuum arc re-melting, and has excellent material quality because of its purified effect. Its tensile stress at room temperature is 1800~2000MPa. It is widely used in military and aviation industry because of its properties, including high stress, light weight, strong toughness, and good heat treatment effect. Its chemical composition is shown as Table 2.

Table 2 Chemical composition of D6AC (Wt%)

chemial composition	C	Mn	P	S	Si	Cr	Ni	Mo	V	Fe
ASM6431 D6AC	0.42~0.48	0.6~0.9	<0.01	<0.01	0.15~0.3	0.9~1.2	0.4~0.7	0.9~1.1	0.05~0.1	balance

D6AC is a high stress and toughness alloy, and has different mechanical properties after being heat treatment, such as quenching, tempering, and stress relief. The mechanical properties in this study are shown as Table 3 [9].

Table 3 Mechanical properties of D6AC

Density	7780(kg/m^3)
Elastic modulus	218 (GPa)
Yield strength	980 (MPa)
Ultimate strength	1220.1 (MPa)
Poisson's ratio	0.32

When doing spinning simulation analysis [10], ANSYS/LS-DYNA takes the elements as SOLID 164 solid unit for each blank. As shown in Fig 6, it is a hexahedral dynamic 3-D unit with 8 nodes. Each node has 9 freedom degrees, and each represent the displacement, velocity, and acceleration in X、Y、Z axis.

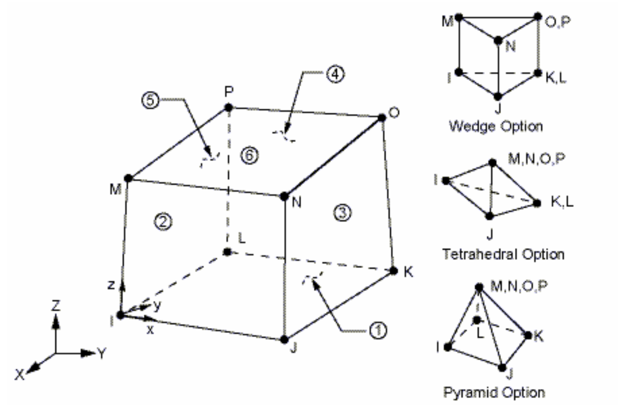


Fig. 6 SOLID 164 element model

Both rollers and mandrel doesn't deform during spinning process. They are seemed as rigid when doing simulating. The material properties are shown in Tab4. It takes SHELL 163 shell unit, as shown in Fig 7, to save the calculation time. There are 4 nodes for each shell unit, and each node has 12 freedom degrees, representing the displacement, velocity, acceleration , and rotation angle in X、Y、Z axis.

Table 4 Mechanical Properties of Rigid Material

Density	7850(kg/m^3)
Elastic modulus	210 (GPa)
Poisson's ratio	0.3

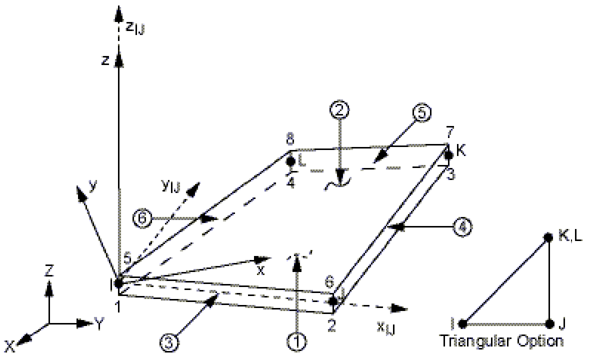


Fig. 7 SHELL 163 element model

C. Mesh Planning

Spinning is a great scale plastic deformation process. Too many meshes will result in longer simulation time. Too little meshes will lead to less precise and cause mesh distortion. To prevent simulation calculation failure or decreasing accuracy, it is very important to take a suitable planning. For the rollers, the sectioned mapping meshes are used to make sure the entire element is even. The thickness of material is divided to five layers to ensure the simulation accuracy. For the part without being processed, the bigger meshes are used. The rollers and mandrels can be set as rigid, so the mesh will be wider. The total meshes are about 2800, and the mesh model is shown as Fig 8.

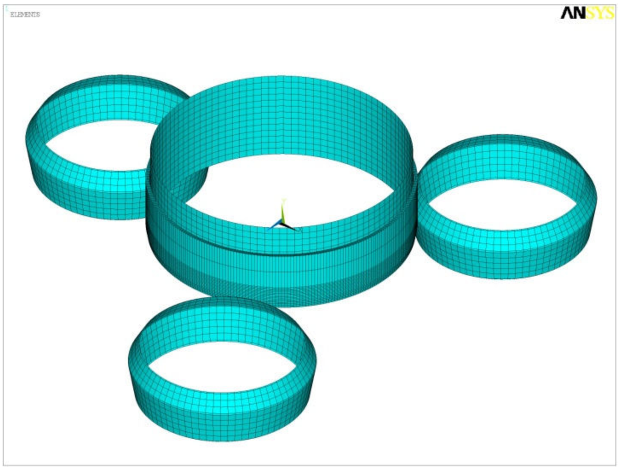


Fig. 8 Mesh Planning Model

D. Boundary Condition Setting-Define Fraction Contraction

During spinning process, the mandrel rotates and drives blank rotate because of fraction force. The rollers press blank and make it flow with deforming. There are lubrication and heat cooling treatments for the contact surfaces between blank, mandrel, and rollers, so the heat effect creating from plastic deformation and fraction can be neglected. The spinning contact is a complex process. The contact surfaces between blank, mandrel, and rollers are simplified as surface to surface-forming (FSTS). For the ideal condition, there is no slipping between blank and mandrel, so the fraction force can be seemed as constant. Set the fraction index between blank and mandrel is 0.1, and that of material and rollers is 0.01.

E. Loading and Initial Conditions

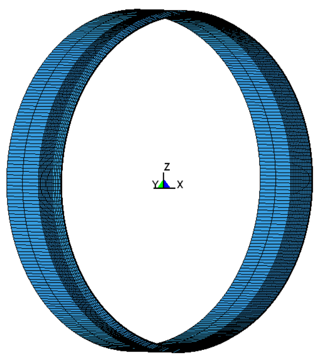
The mandrel has freedom degree of angular velocity in axial rotation. There is no restricted freedom degree for blank. The rollers have freedom degree of axial constant rotation angular velocity, as well as freedom degree of axial constant velocity. The rollers axial rotation speed can be expressed as equation (9).

$$r_1\omega_1 = r_2\omega_2 \tag{9}$$

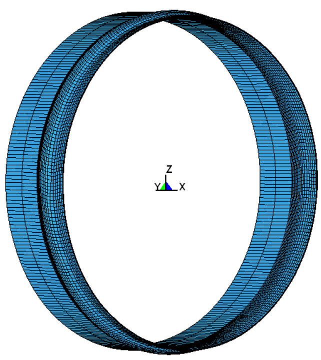
Where r_1 is the radius of mandrel, r_2 the radium of rollers , ω_1 the rotational speed of mandrel , and ω_2 the rotational speed of rollers. The mass proportional factor is set as 100 , and the simulation time lasts 10 second. The rotation speed of rollers is 219.91 rad (35.02 revolution) , the axial displacement 4.5mm , and feed rate 0.7 mm/rev.

IV. Result Discussion

By using ANSYS/LS-DYNA, the simulation processes of single forward spinning for each contraction rate can be observed, and the distribution of stress, strain and spinning pressure during forming revealed from lspreposted. Fig 9 shows the forming of blank after spinning.



(a) before forming



(b) after forming

Fig 9 results of spinning forming simulation

A. Spinning Pressure Analysis

The pressure which rollers put on blank is called spinning pressure, and it is mainly related with the plastic flow pressure and the contact area of rollers with blank. The spinning pressure of three rollers is put evenly on the blank. As shown in Fig 10, the higher the reduction rate, the bigger the spinning pressure becomes. The spinning pressure will be gradually increasing in all directions during spinning process. However, it will not increase without limitation, and will be even when the spinning pressure gets to its maximum. The main factors relating to blank deformation are axial (z-axis) spinning pressure and circumferential (x-axis) spinning pressure. However, overpressure will lead in blank fracture as Fig 11.

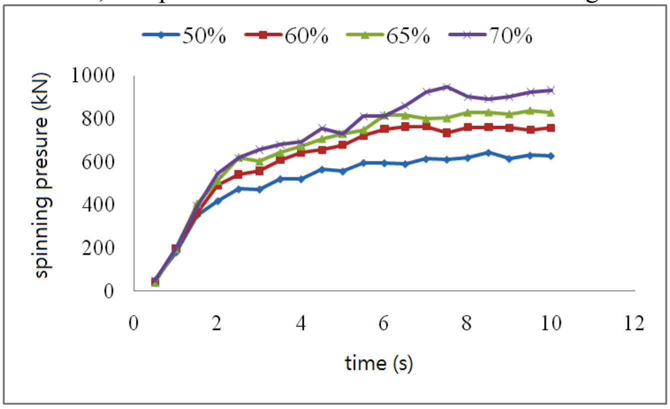


Fig 10 The Relationship Curves for Different Reduction Rate and Spinning Pressure

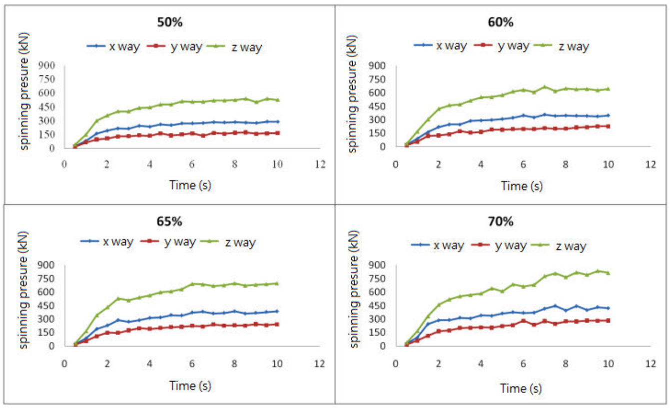
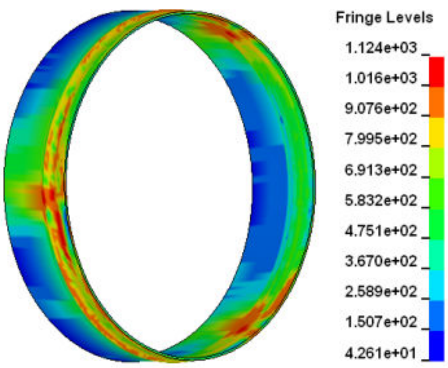


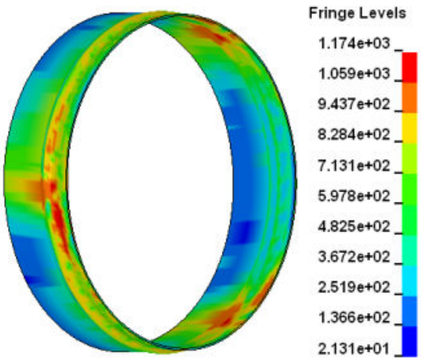
Fig. 11 Spinning Pressures in Each Ways for Different Reduction Rate Materials

B. *Stress Analysis*

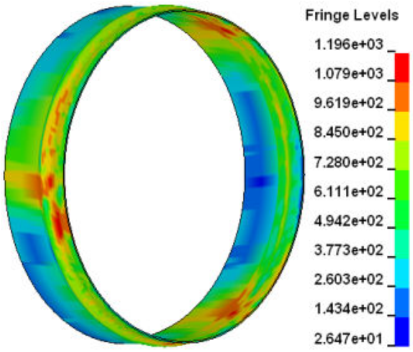
By using ANSYS/LS-DYNA finial elements analysis, the equivalent stress distribution for different reduction rate on the blank can be solved. The variation between equitant stress and reduction rate can be expressed as Fig 12.



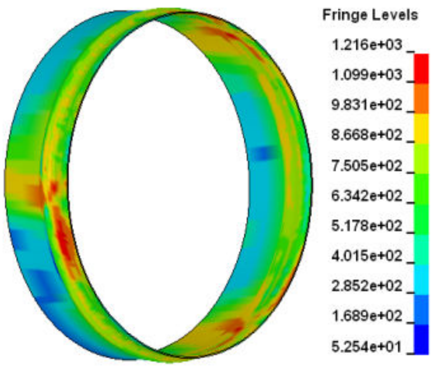
(a) Reduction rate 50%



(b) Reduction rate 60%



(c) Reduction rate 65%



(d) Reduction rate 70%

Fig. 12 The Equivalent Stress Diagrams for Each Reduction Rate Materials

During forward spinning process, the material will be elongate in axial way. For those parts before contacting, the radial deformation is elongate, and the axial is contracted. The material piles up when processing, as shown in Fig 13.

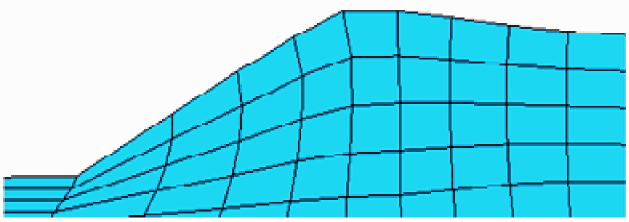


Fig. 13 Piling Up

The yield stress of D6AC is about 980MPa, and the ultimate stress is about 1220MPa, as shown in Fig 14. The reduction rate increases as the equivalent stress raises, and then the material becomes permanent plastic deformation when it is over yield stress. When the reduction rate is over 65%, the equivalent stress is gradually approaching its ultimate stress, resulting in material cracking. The stress distribution for different reduction rates are shown as Fig 15. It shows that the blank is under stressed condition in axial, radial and tangle ways.

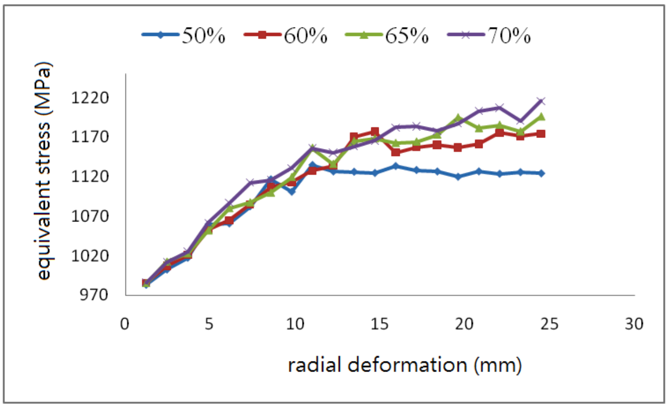


Fig.14 The Relationship Curves for Equivalent Stress and Contraction Rate

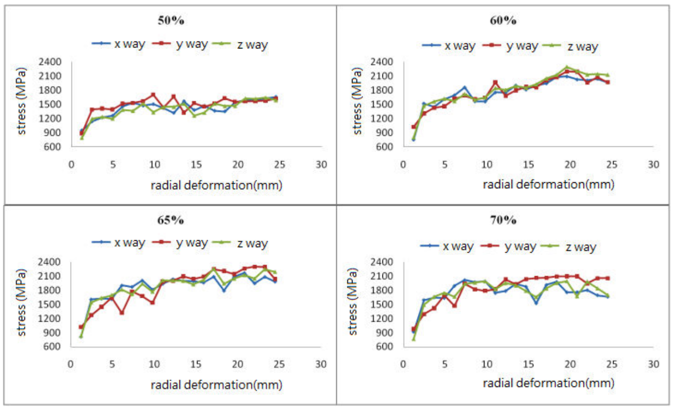
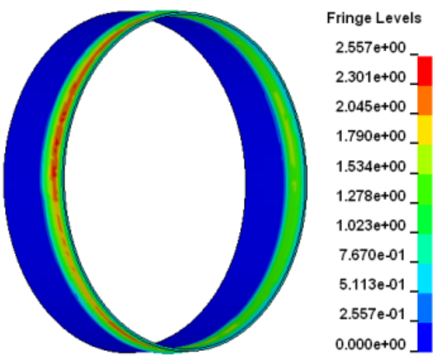


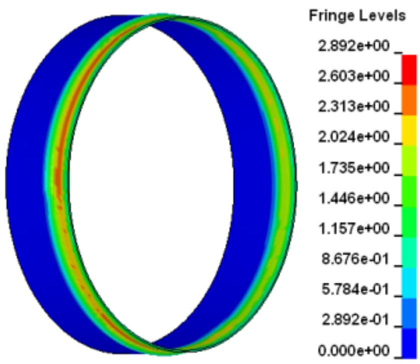
Fig. 15 Curves for Contraction Rate in Each Way Stress

C. *Strain Analysis*

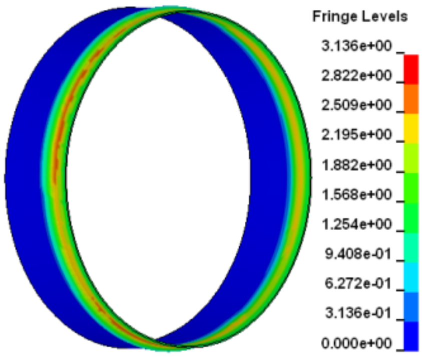
The change between equivalent strain and reduction rate is shown as Fig 16.



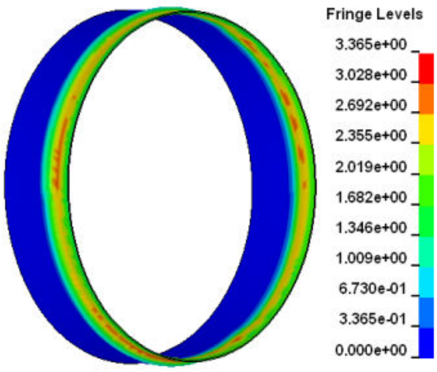
(a) Reduction rate 50%



(b) Reduction rate 60%



(c) Reduction rate 65%



(d) Reduction rate 70%

Fig. 16 The Maximum Equivalent Strain Diagrams for Each Reduction Rate Materials

The plastic deformation for material is related with equivalent strain. The equivalent strain will increase as the rollers move axially, as shown in Fig 17. For the part before rollers contacting, the material is in axial compressive strain, and after the contracted area, it is in extension strain. When the extension strain is bigger than the compressive strain, the blank will be elongate, as shown in Fig 18.

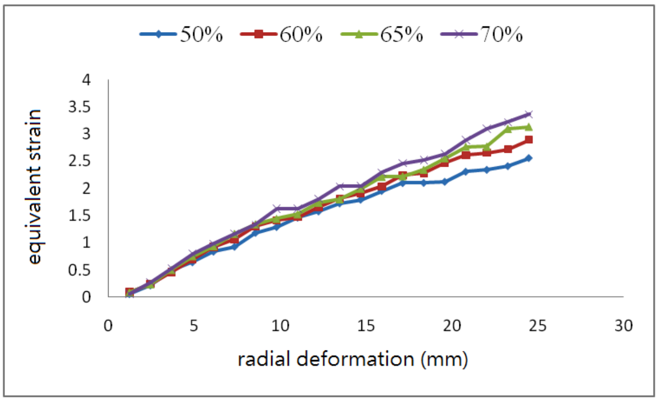


Fig. 17 The Relationship Curves for Equivalent Strain and Contraction Rate

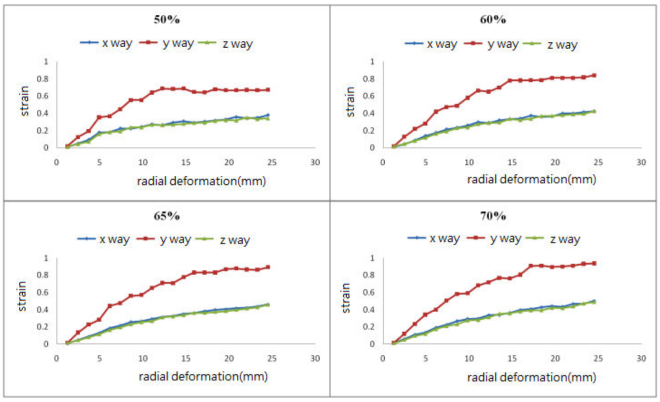


Fig. 18 Curves for Contraction Rate in Each Way Strain

V. Conclusion

Large In this study, the single forward spinning process is analyzed and simulated by 3-D plastic finial elements analysis method. There are two conclusions.

1. According to the mechanical properties of alloy D6AC, the simulation shows that the reduction rate for ingle forward spinning process can be up to 70%.
2. The spinning pressure in all ways will rise as the reduction rate increases. It will not go up to the infinite, instead, it will get even as the spinning pressure reaches its maximum value. The axial and circumferential spinning pressures are two factors for blank deformation.

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