

# A Practical Approach to Analysis of Hydro-Mechanical Deep Drawing of Superalloy Sheet Metals Using Finite Element Method

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Received: 4 September 2011, Revised: 19 April 2012, Accepted: 25 July 2012

**Abstract:** Hydro-mechanical deep drawing (HDD) is one of the most convenient processes in which a sheet metal is drawn against a counter pressure rather than a rigid die in conventional stampings. This process has been increasingly used to produce aerospace and automotive components. More recently, aerospace industry is demanding new materials with capability to produce high strength to weight ratio products. Moreover on hydro-mechanical deep drawing investigations, numerical considerations are used in order to design the process parameters to produce a cost-effective with high quality components. While, this process has not been investigated for superalloy cups. Nickel-based superalloy sheet metals are more prominent in aviation and spaceflight industries. In this paper, numerical simulation of hydro-mechanical deep drawing for Haynes230 nickel based superalloy has been investigated. Moreover, the pressure paths which yield rupture and wrinkling have been realized. Furthermore, differences between applying uniform and gradual pressure into the pressure chamber have been detected to nominate a pressure path for successfully producing a superalloy cup made by HDD. Subsequent to that, chamber pressure against punch travel curves was depicted. For this investigation, 3-D finite element method was employed and the results obtained from numerical simulation were validated using experimental data already available in the literature.

**Keywords:** Hydro-Mechanical Deep Drawing; Haynes230; Pressure Path; Wrinkle

**Reference:** Janbakhsh, M., Riahi, R., and Djavanroodi, F., "A Practical Approach to Analysis of Hydro-Mechanical Deep Drawing of Superalloy Sheet Metals Using Finite Element Method", Int J of Advanced Design and Manufacturing Technology, Vol. 6/No. 1, 2013, pp. 1-7.

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## 1 INTRODUCTION

More recently, Sheet hydroforming (SHF) has gained increasingly interest to produce light-weight components made by various materials. With respect to other manufacturing processes, SHF has the potential to form materials with different formability due to flexibility characteristics.

The hydro-mechanical deep drawing (HDD) as a combination of conventional deep drawing with sheet hydroforming, has been widely used in the forming of complex-shaped sheet materials [1-4]. In the sheet metal forming field, this process has been known as an advanced, novel and practical manufacturing process in automotive, aerospace, aviation and electrical industries [5]. In HDD, hydraulic pressure rather than a rigid female die, forms the sheet against the contour of the punch. Due to the counter pressure, it is assumed that no bending force is required to bend the sheet material around the rounded draw ring (Fig. 1).

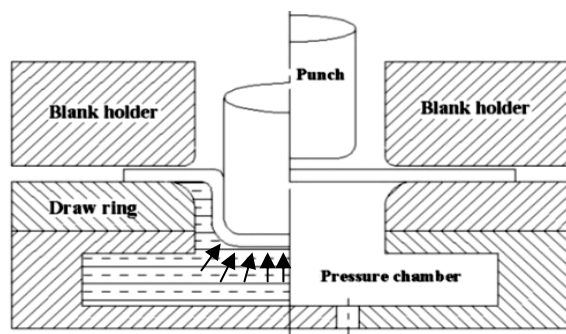


Fig. 1 Illustration of hydro-mechanical deep drawing

The HDD process has many variations in workshop operations, such as hydrostatic deep drawing, hydrodynamic deep drawing and radial pressure deep drawing. Some process parameters can affect the success of the process such as chamber pressure, blank holder force, tool profile radii, punch speed, friction between blank and tool components and the pre-bulge pressure. Recently, some sheet materials such as aluminum, copper, magnesium, steel, titanium and superalloys have been studied being formed through HDD process [6].

Although the study of superalloy forming has been carried out experimentally, there is no approach in the literature dealing with numerical simulation of superalloy cups made by HDD. Hence, it is viable to analyze this process with finite element method [7]-[11]. As a result, many principal phenomenal aspects of this process such as wrinkling, rupture, thinning and even earing can be predicted. Consequently, there is no need to conduct costly experimental iterations.

## 2 OBJECTIVE OF THIS STUDY

The main objective of this study is to establish a framework in order to analyze the hydro-mechanical deep drawing process for superalloy sheet metals by using finite element method.

The detailed objectives are:

- (1) Obtain a pressure path to successfully produce a cylindrical superalloy cup made by HDD in different drawing ratios.
- (2) Study the effect of pre-bulge pressure on the quality of product.
- (3) Differentiation between applying uniform/constant and gradual chamber pressure in order to reach success in finite element simulation process.

## 3 THEORETICAL APPROACH

### 3.1. Blank holder force

Blank holder force plays a significant role in the success or failure of the process. Low blank holder force may result in appearance of wrinkling in flange area for the product, where with high blank holder force, premature rupture is likely to occur. Blank holder pressure,  $p_n$ , which is a normal pressure between blank and blank holder and between blank and draw ring, should be set properly to avoid wrinkling in the area between blank holder and draw ring. For axi-symmetric components it can be written as follows [12]:

$$p_n = 0.002 \dots 0.0025 \left[ (\beta_0 - 1)^3 + 0.5 \frac{d}{100t} \right] \sigma_{uts} \quad (1)$$

Where  $\beta_0$  is drawing ratio,  $D_{punch}$  is the punch diameter,  $t_0$  is the initial sheet thickness, and  $\sigma_{uts}$  is the ultimate tensile strength. For non axi-symmetric components, it is essential to control material flow by adjusting blank holder force properly and/or by using draw beads [12].

$$F_{BH} \geq p_n \cdot \frac{\pi}{4} (D_0^2 - d^2) \quad (2)$$

In Eq. (2),  $F_{BH}$  is the blank holder force and  $D_0$  is the initial sheet diameter.

### 3.2. Determination of chamber pressure curve

A chamber pressure curve includes three different factors. These factors are initial pressure, pressure path and final pressure reached at the end of the process. Exploiting the characteristics of the pressure curve, a rather simplified method based on FEM can be utilized

instead of the upper bound technique. Since the punch penetration volume during the forming is also monotonically increasing, similar to the pressure curve, the pressure path has been assumed to be proportional to the punch penetration volume [13].

### 3.3. Initial pressure

In early steps of hydro-mechanical deep drawing, shearing deformation mode occurs in area between the draw ring and punch as punch penetrates into the pressure pot. Afterwards, drawing, stretching, bending or mixed deformation occurs. If initial chamber pressure is low, the blank tends to lift up from draw ring surface as punch penetrates. Therefore, initial pressure should be enough to avoid the blank lift up. Eq. (3) expresses punch force which yields blank shearing and Eq. (4) is blank holder force due to hydraulic pressure applied on flange region.

$$F_{punch} = \pi dt \frac{\sigma_y}{\sqrt{3}} \quad (3)$$

$$F_{flange} = \frac{\pi}{4} (D^2 - d^2) \cdot p_{req} \quad (4)$$

Where  $\sigma_y$  is the yield strength of the sheet material; while blank holder force is lower than the punch force, blank tends to lift up from the draw ring surface. Therefore, in order to avoid this phenomenon, blank holder force due to fluid pressure should be higher than the punch force for stabilization in start up of the process. So that, the initial pressure which prevents the blank from wrinkling can be expressed as [13]:

$$p_{req} = \frac{4dt \sigma_y}{\sqrt{3}(D^2 - d^2)} \quad (5)$$

Once the wrinkling occurs, it will always be increased and also will intensify which never diminishes due to peripheral compressive stresses. Therefore, this drawback should be avoided from early steps of forming process. Since the required initial pressure to avoid wrinkling determined in Eq. (5) does not ponder forming specifications, e.g., folding, the initial pressure has then been modified as [13]:

$$P_{initial} = \beta \cdot p_{req} > \beta \frac{4dt \sigma_y}{\sqrt{3}(D^2 - d^2)} \quad (6)$$

Where  $\beta$  is the correction factor to compensate the forming difficulties due to shape of cross-sections  $\beta \geq 1$ ; circular sections:  $1 \leq \beta \leq 2$ ; polygonal sections:  $2 \leq \beta \leq 3$ ; sharp-radius of curvature:  $4 \leq \beta \leq 5$  [13].

## 4 MATERIAL CHARACTERIZATION

In this paper, Haynes230 superalloy sheet is numerically investigated for producing circular cups made by hydro-mechanical deep drawing. Haynes230 alloy is a nickel-chromium-tungsten-molybdenum alloy with combination of high temperature strength, resistance to oxidizing environments up to 2100° F (1149° C), premier resistance to nitriding environment, and long-term thermal stability. This alloy has good ductility and may be readily formed by most conventional and advanced forming methods. To form this alloy, more powerful tools are required due to its higher strength in comparison with regular steels. Moreover, heavy-duty lubricants are used during cold forming. The chemical compositions and mechanical properties in room temperature for this alloy are shown in Table 1 and Table 2, respectively.

**Table 1** Chemical ingredients of Haynes230 alloy

Element	Percentage, %
Aluminum	0.2 - 0.5
Boron	0.015 max
Carbon	0.05 - 0.15
Chromium	20 - 24
Cobalt	5 max
Iron	3 max
Lanthanum	0.005 - 0.05
Manganese	0.3 - 1
Molybdenum	1 - 3
Nickel	Balance
Phosphorus	0.03 max
Silicon	0.25 - 0.75
Sulphur	0.015 max
Tungsten	13 - 15

**Table 2** Mechanical properties of Haynes230 alloy

Properties	Value
Yield stress, $\sigma_{0.2}$ (MPa)	390
Ultimate tensile strength, $\sigma_{uts}$ (MPa)	860
Elongation at break, $\delta$ (%)	47.7
Young's modulus, E (GPa)	211
Density, $\rho$ (Kg/m <sup>3</sup> )	8900

## 5 FINITE ELEMENT APPROACH

Forming characterizations rely heavily on the experience of the process design engineer. Iterative trial-and-error development cycles are time-consuming and costly. In this study, ABAQUS/Explicit commercial code as an effective simulation tool, is used to reduce time and costs associated with physical

trial-and-error method in order to produce a cylindrical superalloy cup made by HDD.

In the above mentioned commercial code, the explicit time integrations are deployed to solve nonlinear dynamic processes. As such, the hydroforming process itself is static, thus, an effective quasi-static solution provided the time period of the event and the loading rates are chosen properly [14].

### 5.1. Geometrical, Tribological, and boundary condition specifications of the model

The model consists of a punch, a blank holder, a draw ring and a blank. All dimensions are shown in Table 3. The blank holder, the draw ring and the punch are considered as analytical rigid parts. Coulomb friction equation was used to model the frictional conditions between the blank and the tools. In order to model the applied hydraulic pressure, a uniform pressure distribution was used to apply the fluid pressure which is created in the pressure chamber. To introduce and analyze how the pressure is applied (uniform or gradual), amplitude tool was implemented in this software. The finite element model created in the software is illustrated in Fig. 2.

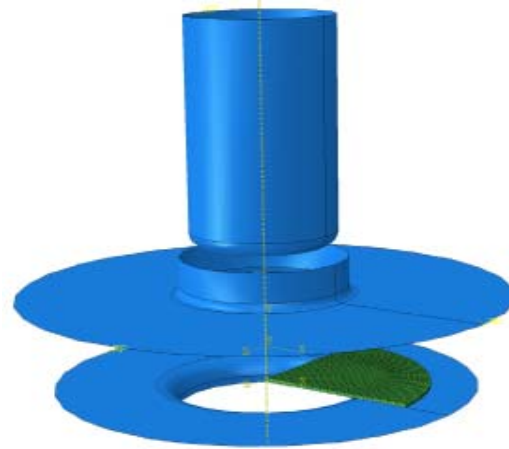
**Table 3** Process parameters used in simulation

Process parameter	Value
Blank diameter (mm)	80
Punch diameter (mm)	33
Punch profile diameter (mm)	8
Diameter of die opening (mm)	36
Die profile radius (mm)	8
Sheet thickness (mm)	1
Punch speed (mm/s)	5
Punch travel (mm)	40
Drawing ratio	2.45

For modeling the contacts between surfaces, two distinctive tangential behaviors were introduced. Between blank and punch:  $\mu=0.15$ ; between blank and blank holder and between blank and draw ring:  $\mu=0.05$ . The punch is moved vertically to form the cup with a total stroke of 35mm. In this simulation, the fixed gap method was used between blank and blank holder. Consequently, the reference point which was introduced to blank holder was fully constraint.

Furthermore, the rubber diaphragm was not modeled; instead, a uniform hydraulic pressure was applied directly to the blank. Due to symmetry of the circular components, only a quarter-symmetry of the blank was modeled. Symmetry boundary conditions were specified on proper edges of the blank. Total process time was 7 seconds and due to long duration of analysis time, the mass scaling was used. Different pre-bulge

pressures were studied for different drawing ratios. Furthermore, in order to define the optimum pressure path, several counter pressures against punch stroke curves were prescribed for the simulation.

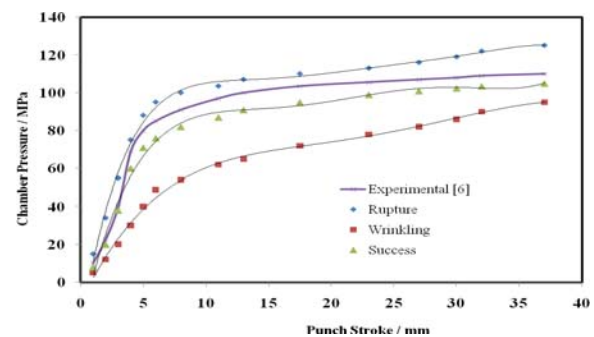


**Fig. 2** Finite element model created in ABAQUS

## 6 RESULTS AND DISCUSSION

### 6.1. Validation of numerical approach

Different pressure paths were studied in order to avoid wrinkling, tearing and also earring. As discussed in section 4, the haynes230 alloy has high strength with good formability characteristics. Consequently, high pressure is required to form this alloy into desired shape. In hydro-mechanical deep drawing of GH3044 superalloy which has been studied in the literature, the maximum chamber pressure reached 100MPa [6]. In order to validate the numerical simulation carried out in this paper, the pressure path yielding a complete deep drawn cup for drawing ratio  $\beta_0=2.45$  has been compared with the experimental data in the literature. Fig. 3 shows a good agreement between numerical and experimental approaches.



**Fig. 3** Chamber pressure curve against punch stroke without considering pre-bulge pressure

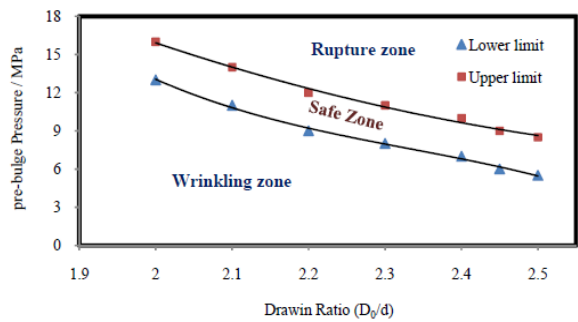


Fig. 4 Optimum pre-bulge pressure for various drawing ratios

Note: Although in the literature [6] the pressure path has been applied without considering pre-bulge pressure, Fig. 6 illustrates upper and lower limits which yield a successful HDD cup considering pre-bulge pressure.

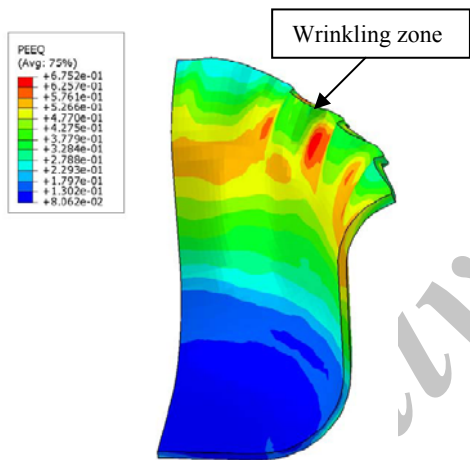


Fig. 5a a: FE model when wrinkling occurs due to insufficient pre-bulge pressure

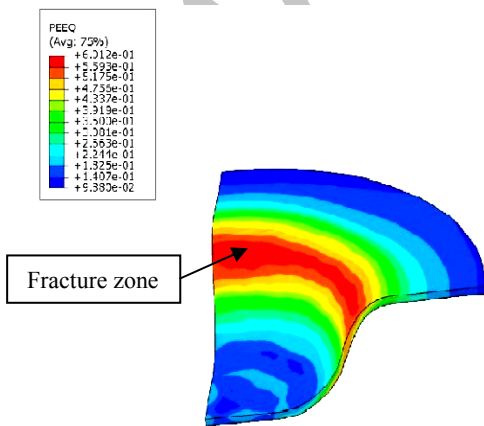


Fig. 5b b: FE model when premature rupture occurs due to high pre-bulge pressure

As shown, according to Eq. (6) the initial chamber pressure could be in different ranges for different drawing ratios to successfully produce a superalloy cup where this can be proven by FE simulation. Pressures lower than the initial required chamber pressure could result in wrinkling and pressures above this may result in premature rupture. Fig. 5 illustrates the FE models when wrinkling and premature rupture occurs due to insufficient and high pre-bulge pressure respectively.

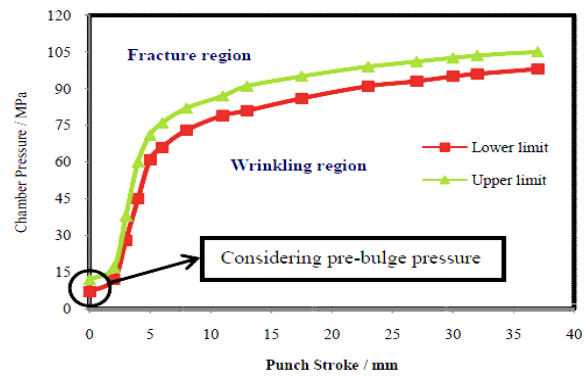


Fig. 6 Upper and lower limits for pressure path considering pre-bulge pressure for drawing ratio 2.45

### 6.2. Uniform and gradual pressurization

Following investigation of differences between applying uniform/constant pressure and gradual pressurization for a complete process, various pressure paths were introduced in numerical simulation. As it can be seen in Fig. 7, due to high pre-bulge pressure, high constant pressure could result in necking in punch radius and finally yields rupture in sheet material. Low constant pressures may perform wrinkling in flange area. In this paper, with respect to constant pressure path, gradual pressurization paths associated with fixed gap considered between blank holder and draw ring were examined to achieve an optimum pressure path.

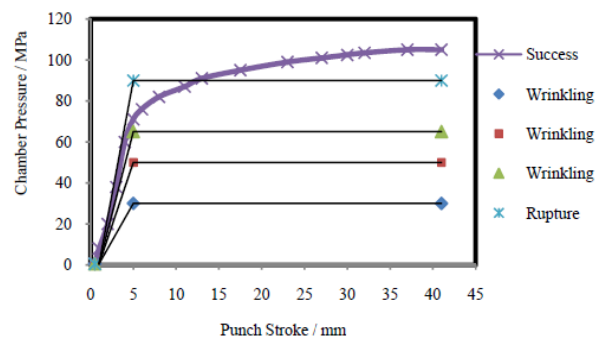
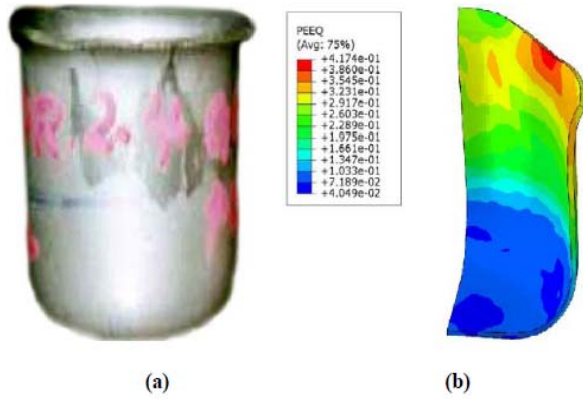


Fig. 7 Differentiation between applying uniform and gradual chamber pressure

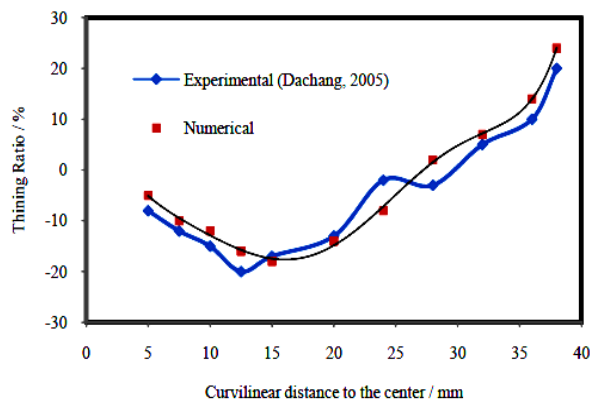
Figure 8 shows a good correlation between finite element model and a manufactured superalloy cup made by hydro-mechanical deep drawing.



**Fig. 8** Illustration of good correlation between a: experimental approach [6] and b: FE analysis

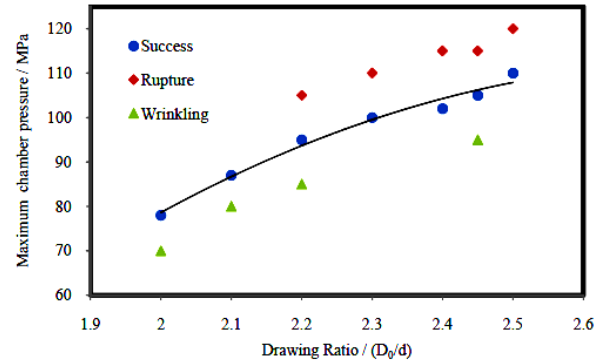
It has been proven that for superalloys, unlike aluminum and copper, successful drawing could not be realized without the seal. Due to the seal, the chamber pressure reaches certain value first and then because of overflow, the chamber pressure drops [6]. The pressure in the pressure pot should reach a suitable level in order to make sufficient friction between the blank and the punch.

The thinning ratio versus the curvilinear distance to the cup center is also illustrated in Fig. 9. Similar to conventional deep drawing processes, for having a complete deep drawn cup, the maximum value of thinning should not pass beyond 20% [6].



**Fig. 9** Distribution of thickness thinning ratio

Figure 10 displays maximum chamber pressure needed to successfully produce a hydro-mechanical deep drawn cup for different drawing ratios.



**Fig. 10** Maximum chamber pressure distribution

Generally, the maximum chamber pressure increases with increase in drawing ratio. Although chamber pressure should be high enough to make the blank free from contact with the die profile, fracture may occur in die profile region in the blank when chamber pressure reaches a high value. To successfully produce a superalloy cup with different drawing ratios made by HDD, a working line for maximum chamber pressure is depicted in Fig. 10.

## 6 CONCLUSION

In this study, it was numerically illustrated that for producing a desired circular cup from Ni-based superalloy made through hydro-mechanical deep drawing, high chamber pressure is required in comparison with that needed for such as mild steel. Different pressure paths were implemented to the process to form a cup into proper shape. Consequently, for drawing ratio  $\beta_0=2.45$  a pressure path was obtained which was in a good agreement with the experimental data available in the literature.

Moreover, it was discerned that high pre-bulge pressure will lead the process to rupture in early stages of forming process and low pre-bulge pressure will yield wrinkling in flange area of the cup. Furthermore, the effect of applying constant pressure during the process time and gradual pressurization on finished product were investigated.

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