Construction of aluminum alloy constitutive model based on BP neural network and the study of non-isothermal hydroforming

Xiao Jing Liu · Xue Feng Ma · Chao Li · Jin Qin · Peng Chen

Received: 22 April 2021 / Accepted: 22 March 2022 / Published online: 10 May 2022
© The Author(s), under exclusive licence to Springer-Verlag London Ltd., part of Springer Nature 2022

Abstract
With the continuous development of high-end technology in aerospace and automotive, the materials used are lightweight and strong to meet the needs of high performance, high precision, and lightweight of parts; however, they are too difficult to deform, which means that it is difficult to obtain high-quality and high-precision parts. In order to improve the forming quality and precision of parts, taking Aluminum Alloy 6061-T6l cylindrical cup with spherical bottom as the research object, the non-isothermal hydroforming process is studied by combining numerical simulation with experiment. The key of numerical simulation technology lies in the accuracy of simulation, which depends on the establishment of a suitable rheological stress relationship. For this reason, a constitutive model that can truly reflect the thermoforming characteristics of Aluminum Alloy 6061-T6l materials is established through a uniaxial tensile test and BP neural network. Applying the constitutive model to the study of numerical simulation of non-isothermal hydroforming, the cylindrical cup with spherical bottom with high quality is obtained through the optimization of non-isothermal process parameters. After experimental verification, the results of numerical simulation are highly compatible with the actual forming results of parts, and have high reliability.

Keywords Constitutive model · BP neural network · Non-isothermal hydroforming · Numerical simulation

1 Introduction
With the continuous development of high-end technology in aerospace and automotive, the shape of various automotive components has become more complex, and some parts have been unable to achieve forming performance under normal stamping. At present, because of low density and higher strength, aluminum alloy materials have gradually become the focus of research in aerospace and automotive [1, 2]. However, due to plasticity restrictions, some parts, with complex surfaces or small fillets, are difficult to form precisely under complex stress states, and often have problems such as rupture and wrinkle.

In order to improve the forming performance of parts, domestic and foreign scholars have developed some new forming processes; one of them is the hydrodynamic deep drawing. It is that using the liquid chamber instead of the die, the blank is firmly attached to the punch during the deep drawing process until it is formed under the pressure of cavity. With the further development of this process, a large number of forming methods have been derived, such as applying independent radial hydraulic pressure, using double-layered blank, and utilizing a combined floating and static die cavity (HDDC), effectively improving the forming limit, precision, and forming quality of parts [3–5]. Another method is the thermoforming process of aluminum alloy; the production of many parts has been applied to the automotive industry [6–8]. The combination of thermoforming and hydrodynamic deep drawing has the advantages of these two advanced manufacturing techniques; it can improve the performance of the material and has an excellent forming effect on the precision of complex parts [9, 10].

Due to the different combination of elements, the properties of aluminum alloy materials of different alloying elements are also different. Compared to other aluminum alloys, the six-series aluminum alloy materials are
stronger, more wear-resistant, more corrosion-resistant, and most importantly, those materials are better formed and meet the lightweight production requirement. Meanwhile the Aluminum Alloy 6061-T6l (AA6061-T6l) is widely used in various industrial structures because it has good plasticity and corrosion resistance, but does not have stress corrosion cracking tendency. In this paper, AA6061-T6l material is selected, its constitutive model is established, the forming law is analyzed by numerical simulation, and the optimal forming parameters are selected for experimental verification. A constitutive model is established through uniaxial tensile test and BP neural network, which can reflect the temperature deformation characteristics of AA6061-T6l. This model is applied to numerical simulation. The forming numerical simulation of the cylindrical cup with spherical bottom is carried out in parallel between the hydroforming deep drawing and the non-isothermal hydroforming. Using the cavity pressure as the variable, the optimal cavity pressure curve is obtained by analyzing the wall thickness distribution of the forming part under different cavity pressures. Then on this basis, explore the optimal temperature loading by controlling the non-isotherms between the punch and the blank. This study will provide guidance for the machining of such kind of parts.

A thermal tensile test is carried out using the MTS universal electronic testing machine (as shown in Fig. 1).

The experiment selected AA6061-T6l blank with thickness of 2 mm, and the chemical composition of the blank is shown in Table 1, where wt is the mass fraction. According to the requirements of ISO 204:1997, the scale of tensile specimen is shown in Fig. 2 and the specimen is shown in Fig. 3.

In order to build a more accurate constitutive model, it is necessary to obtain as much experimental data as possible that can reflect the characteristics of the material. The test was conducted at three strain rates of $10^{-1}$, $10^{-2}$, and $10^{-3}$, and each strain rate is tested 6 times at different temperatures. In order to ensure the reliability of the test results, three tests were carried out on the test pieces at the same temperature and at the same tensile rate, and the median value was determined to be valid. In order to ensure the uniform temperature in the furnace of the MTS universal electronic testing machine, the furnace temperature is heated to the desired temperature for drawing, and the temperature is expected to be maintained for 1 h; then the furnace is opened and the sample is held, and then the temperature of the furnace is raised to the target temperature insulation for 5 min to begin the tensile test [11].

The results of the tensile of AA6061-T6l with a strain rate of 0.1 s$^{-1}$ at different temperatures are shown in Fig. 4; from top to bottom, it is 25 °C, 50 °C, 100 °C, 150 °C, 200 °C, and 250 °C.

In order to solve the construction equation, the experimental data of stress–strain obtained from the thermal uniaxial tensile test need to be converted to the true stress–strain curve, as follows [12]:

| Element | Si  | Mg | Fe  | Cu  | Mn  | Cr  | Zn  | Ti  | Al  |
|---------|-----|----|-----|-----|-----|-----|-----|-----|-----|
| Content (wt%) | 0.6 | 1.0 | 0.7 | 0.28 | 0.15 | 0.20 | 0.25 | 0.15 | Margin |

![Fig. 1 MTS universal electronic testing machine](image1)

![Fig. 2 Scale of tensile specimen](image2)
The engineering stress $\sigma_n$ is converted as

$$\sigma_n = \frac{F}{S_0}$$  \hspace{1cm} (1)

where $F$ is the load applied to the specimen and $S_0$ is the initial area of the specimen.

The engineering strain $\varepsilon_n$ is converted as

$$\varepsilon_n = \frac{\Delta l}{l_0}$$  \hspace{1cm} (2)

where $\Delta l$ is the distance between the gauge length and $l_0$ is the amount of elongation between the gauge length.

The interval between the gauge length is extended from $l$ to $l + \Delta l$ during specimen drawing; the amount of change is $dl$, so the amount of strain change is converted as

$$d\varepsilon = \frac{dl}{l}$$  \hspace{1cm} (3)

Solve $\varepsilon$, and it is determined as follow:

$$\varepsilon = \int \frac{dl}{l} = \ln l - \ln l_0 = \ln \frac{l}{l_0}$$  \hspace{1cm} (4)

Available in association with formula 2, $\varepsilon$ can be determined as follow:

$$\varepsilon = \ln(1 + \varepsilon_n)$$  \hspace{1cm} (5)

Because of the principle of constant volume,

$$Al = A_0l_0$$  \hspace{1cm} (6)

Linked-up, the stress $\sigma$ is shown as follow:

$$\sigma = \sigma_n(1 + \varepsilon_n)$$  \hspace{1cm} (7)

The original stress–strain data is converted using formula 7, which obtained by the universal electronic testing machine, and the true stress–strain curve at different strain rates is shown in Fig. 5.

As can be seen from the stress–strain curve at same strain rates but different temperatures, elastic deformation is the primary at the beginning of stretching, and the rate of strain changes with stress is about the same. When plastic deformation is the main, with the increase of temperature, the yield strength decreases, and the tensile strength decreases.

As can be seen from the stress strain curve at same temperatures but different strain rates, in the elastic deformation-oriented, the smaller the strain rate, the smaller the elastic limit. And enter to plastic deformation-based, the smaller the strain rate, the more moderate the rate of stress increase, the smaller the tensile strength.

The following conclusions can therefore be drawn from Fig. 5; the AA6061-T6 has poor plasticity and lower limit strain value at room temperature. When the temperature reaches 150 °C, the plasticity change is not obvious; the limit strain value is increased by 17% relative to room temperature, but at this time the intensity begins to decrease. When the temperature reached 250 °C, the plasticity increased significantly, and the limit strain value was increased by 50% compared to room temperature. When the temperature is 200 to 250 °C, the softening of AA6061-T6l flow is obvious [13, 14], and the plasticity is strong in this temperature range. At same temperature, with the increase of strain rate, the tensile strength becomes larger, but elongation rate decreased because strain hardening becomes faster, and with the higher of temperature, the impact of the strain rate becomes greater.
Build neural network model

Artificial neural networks (ANN) is a large class of parallel processes that mimic the brains of animals [15]; it can learn from experimental data, find the law between these data, and then fit the data. The essence of ANN is to identify and predict data by nonlinear equations. After inputting in the input layer, the initial data begins to flow through the neural network. Data inputted by multiple neurons enters the hidden layer for multiple iterations and is output at the output layer. Usually using three hidden layers can solve any complex problem. The increase of hidden layer will improve the computational accuracy of neural networks, but the operation speed is slower because the neural network is too complex. Today, because it has a strong nonlinear fit capability and is easy for computers to implement, the back propagation (BP) is the most common ANN model when dealing with material structure problems in engineering, whose training process consists of several iterative processes, each of them in turn contains back propagation. In this paper, BP neural network [16] is used; its structure is shown in Fig. 6.

BP neural networks can be implemented by a variety of programming languages, such as MATLAB, C++, and Python. The Python language is simpler than MATLAB, and has a complete documentation, which can greatly reducing the learning threshold for engineering students. And the Python language runs faster than the C language. Therefore, this paper uses Python language to build the neural network model.

3.1 Data normalization

A large amount of experimental data is obtained from the uniaxial tensile test; the floating range of the data is relatively large. Thus the data need to be normalized and organized into a certain area to facilitate the calculation. In this paper, the max–min standardization is used for normalization; the way to normalize class $a$ is shown as follows:

![Figure 5: The true stress–strain curve at different strain rates](image)

![Figure 6: The structure of back propagation neural network](image)
\[ Y = 0.1 + 0.8 \times \frac{ax - \text{mina}}{\text{maxa} - \text{mina}} \]  \tag{8}

where \( Y \) is the normalized data, \( \text{mina} \) is the minimum value in class \( a \), and \( \text{maxa} \) is the maximum value. The temperature and stress of uniaxial tensile test are normalized by using this method.

The strain rate changes greatly, using this normalization method results in a large difference between the data, which would affect accuracy. In order to improve accuracy, the method shown in formula 9 is used.

\[ \dot{\varepsilon} = \frac{(3 + \lg \dot{\varepsilon} - 0.95(3 + \lg \dot{\varepsilon}_{\text{min}}))}{1.05(3 + \lg \dot{\varepsilon}_{\text{max}}) - 0.95(3 + \lg \dot{\varepsilon}_{\text{min}})} \]  \tag{9}

### 3.2 The selection of parameter

This article selects the structure of the single hidden layer. The number of neuron nodes in the hidden layer is usually determined by empirical formulas. As shown in formula 10,

\[ \delta = \sqrt{m + n + a} \]  \tag{10}

where \( \delta \) is the neuron node, \( m \) is the input node, \( n \) is the output node, \( a \) is the adjustment parameter, and \( a \in [1 \sim 10] \).

This paper explores the constitutive relation in the warm state of AA6061-T66; the main factors are temperature \( T \), strain \( \varepsilon \), strain rate \( \dot{\varepsilon} \), and stress \( \sigma \). The temperature \( T \), the strain \( \varepsilon \), and the strain rate \( \dot{\varepsilon} \) are used as inputs, and the stress \( \sigma \) is output. Therefore, \( m = 4 \), \( n = 1 \), \( a = 4 \), and the number of hidden nodes \( \sigma = 6 \).

A total of 342 data sets were participating, with 85 percent training data and 15 percent test data. After the simulation run, the target accuracy is set to \( 1 \times 10^{-3} \), the learning rate to \( 1 \times 10^{-3} \), and the maximum times of learning is 1100.

### 3.3 Determination of the transfer function and the processing of the results

The transfer function uses the Sigmoid function, whose function definition is shown as follows:

\[ f(x) = \frac{1}{1 + e^{-x}} \]  \tag{11}

The input form is

\[ \text{net} = x_1\omega_1 + x_2\omega_2 + x_3\omega_3 + \cdots + x_n\omega_n \]  \tag{12}

The Sigmoid function output is

\[ y = f(\text{net}) = \frac{1}{1 + e^{-\text{net}}} \]  \tag{13}

The conductor output of the Sigmoid function is

\[ f'(\text{net}) = \frac{1}{(1 + e^{-\text{net}})^2} \left[ y(y - 1) \right] \]  \tag{14}

The S-type function and derivative curve are shown in Fig. 7.

As can be known from Fig. 7, its derivative is positive at net \( \in (−5,0) \) and the value is getting larger. This shows that the value of \( f(x) \) is getting larger and the growth rate too. But its derivative is positive at net \( \in (0,5) \); the value is getting smaller. Explain that the value of \( f(x) \) is getting larger but the growth rate is slowing. In order to facilitate the neural network training in this paper, the net should be controlled within the fast convergence interval.

In order to facilitate the neural network’s processing of data, the input data is normalized; it is necessary to reverse the stress \( \sigma \) processing of the output \[17\]. The reverse processing formula is shown as follows,

\[ \sigma = \sigma_{\text{min}} + 1.25(\sigma_n - 0.1)(\sigma_{\text{max}} - \sigma_{\text{min}}) \]  \tag{15}

where \( \sigma \) is the predicted true stress value, \( \sigma_{\text{max}} \) is the maximum value in the stress test sample, and \( \sigma_{\text{min}} \) is the minimum value in the stress test sample. \( \sigma_n \) is the stress value after normalization. The correlation curve between the neural network prediction value and the true value is shown in Fig. 8, where the fitting coefficient \( R \) is 0.9991, which means the fit is good.
3.4 Comparison of forecast results

The true stress–strain curve from the uniaxial tensile test is compared with the stress strain predicted by the BP neural network model at different strain rates and temperatures; the results are shown in Figs. 9, 11, and 12.

As can be known from Figs. 9, 10, and 11 above, the data predicted by the BP neural network are very highly fitted with the true stress–strain data, and the stress–strain curve between different temperatures at the same strain rate is more and more fitted as the temperature increases. It can be seen that the BP neural network has a good effect in the prediction of the AA6061-T6l constitutive equation, and the constitutive model can be applied in the numerical simulation to provide data that approximates the properties of the true material.
The study of numerical simulation

4.1 The size of part and blank

In this paper, the AA6061-T6l blank is used as the research object to analyze cylindrical cup with spherical bottom under non-isothermal hydroforming. The mechanical property of AA6061-T6l is shown in Table 2, and the CAD model of cylindrical cup with spherical bottom is shown in Fig. 12.

The blank size is estimated by the BES blanking project of DYNAFORM software. It is concluded that the blank size is 128 mm in diameter. A 3D model of the mold is built in Creo software, and the detailed tool size is shown in Table 3. The models of mold and blank are imported into Abaqus to create a numerical simulation model of the cylindrical cup with spherical bottom, as shown in Fig. 13. The analysis process is selected: display-temperature-power-displacement; the total duration of the analysis process is set to 0.5 s, where in the first 0.1 s is the pre-bulging duration, the stamping stroke is 64 mm, and the stamping speed is 10 mm/s.

4.1.1 Effect of cavity pressure curve on forming

Pre-bulging refers that the blank reverse-expanded under the pressure of the cavity before the punch down, which can improve the depth limit and reduce the break tendency of the blank, which due to excessive thinning during the deepening process. In order to determine the optimal pre-bulging pressure, according to the summary of the relevant paper, the pre-bulging time is set to 0.1 s, and six different pre-expansion pressures are numerically simulated by ABAQUS software, namely, 6 MPa, 8 MPa, 10 MPa, 12 MPa, 14 MPa, and 16 MPa; the results of which are shown in Fig. 14.

Table 2 Mechanical properties of Aluminum Alloy 6061-T6

| Yield strength $\sigma_s$ (MPa) | Tensile strength $\sigma_b$ (MPa) | Elastic modulus (GPa) | Poisson’s ratio | Elongation (%) |
|--------------------------------|---------------------------------|----------------------|----------------|----------------|
| 276                            | 310                             | 68.9                 | 0.33           | 12             |

Fig. 11 The stress–strain comparison curve at strain rate $\varepsilon=0.001$

Fig. 12 CAD model of cylindrical cup with spherical bottom

![Fig. 11](image.png)

![Fig. 12](image.png)

![Fig. 13](image.png)

![Fig. 14](image.png)

![Fig. 15](image.png)
As the pre-bulging pressure increases, the blue area has a downward diffusion trend, where the same color represents a small thickness difference. When the pre-bulging pressure reaches 14 MPa, the blue area covers the entire ball bottom area and part of the straight wall area, and the minimum wall thickness reaches a maximum, 0.8539, at which point the thinning rate has been reduced to 14.61%, achieving a good forming effect. However, the minimum wall thickness decreased when the pre-bulging pressure is raised to 16 MPa; it is too large that the blank thinning seriously. On basis of all above, when the pre-bulging pressure is 14 MPa, the cylindrical cup with spherical bottom is best formed.

With the end of pre-bulging, the punch down, driving the blank began to enter the cavity, the pressure of the cavity make the blank close to the punch. In order to determine the optimal cavity pressure curve, on the basis of pre-bulging pressure, a total of 9 cavity pressure combinations, 5 MPa, 10 MPa, 15 MPa, 20 MPa, 25 MPa, 30 MPa, 35 MPa, 40 MPa, and 45 MPa, were simulated. The numerical simulation cavity pressure curve was shown in Fig. 15. The wall thickness distribution map after the simulation is shown in Fig. 16.

As shown in Fig. 16, when the cavity pressure increases from 5 to 45 MPa, the thinnest part gradually diffuses from the top to the part where the spherical bottom is combined with the straight wall area, peaking at 35 MPa. As the pressure continues to increase, the minimum thickness of the blank gradually decreases. When the cavity pressure is increased to 45 MPa, the minimum wall thickness has been reduced to 0.734, at which point the maximum thinning rate is greater than 25%, proving that the top is nearly cracked at this time, and the part is not qualified. When the cavity pressure is less than 14 MPa, with the downstream of the punch, it is less than the pressure of the pre-bulging; it is not possible to reduce the friction between the blank and the die, and the flow of the blank in the flange area can be regarded as equivalent to the effect of normal rigid mold deep. Therefore, it will lead to excessive thinning of the part where spherical bottom is combined with the straight wall area. When the cavity pressure reaches 15 to 35 MPa, the friction between the die and the blank is gradually reduced with the lubrication phenomenon of the fluid in the cavity, the flow of the blank is enhanced in the flange area, and the wall thickness of the top area of the spherical shape is

Fig. 13  CAE model of cylindrical cup with spherical bottom

Fig. 14  The wall thickness distribution diagram of the pre-bulging pressure

(a)=6MPa  (b)=8MPa  (c)=10MPa

(d)=12MPa  (e)=14MPa  (g)=16MPa
evenly distributed. When the cavity pressure is 35 MPa, the wall thickness of blue area reaches the maximum, and the minimum wall thickness of the spherical bottom is 0.8759 parts, the overall wall thickness distribution is more uniform, and the forming effect is better. However, with the further increase of cavity pressure, when it is 45 MPa, the slow flow of the blank causes it to accumulate too much in the flange area, and the top area of the spherical bottom is thinned seriously, resulting in cracking. The minimum wall thickness is distributed with the cavity pressure as shown in Fig. 17. On basis of all above, when the pressure is 35 MPa, the cylindrical cup with spherical bottom is best formed.

4.2 The effect of non-isothermal on forming

The numerical simulation of non-isothermal hydroforming needs to build the non-isothermal environment. This paper is simulated in the Abaqus software, applying a separate temperature to the punch, and another separate temperature to the die, blank, and blank holder, and to achieve the non-isotherms by controlling the difference between the two temperatures.

4.2.1 The scheme of non-isothermal simulation

When the AA6061-T6l cylindrical cup with spherical bottom part is non-isothermal hydroforming, it is very important to

Fig. 15 Loading path of the cavity pressure

Fig. 16 Wall thickness distribution map after simulated forming

(a)=5MPa  (b)=10MPa  (c)=15MPa

(d)=20MPa  (e)=25MPa  (f)=30MPa

(g)=35MPa  (h)=40MPa  (i)=45MPa
control the temperature of each area of the blank. In order to facilitate the experimental operation, this paper simulates the application of non-isotherms to punch and die. The temperature of the die is used below to refer to the temperature of the die, blank, and blank holder. According to a paper [18], the molding properties of 5000 and 6000 series alloys can be greatly improved in the range from 100 to 250 °C, and high temperatures can significantly increase the depth of the part. In order to construct non-isothermal conditions, the initial temperature of the blank is defined at 25 °C (room temperature), and the punch temperatures are selected to be 25 °C, 50 °C, 100 °C, and 150 °C; corresponding to the die temperature are 150 °C, 200 °C, and 250 °C, respectively, for the non-isothermal hydroforming numerical simulation; the simulation scheme is shown in Table 4.

4.2.2 The effect of non-isothermal hydroforming of on equivalent plastic strain

The plastic changes caused by the temperature increase during the forming of the blank are evaluated by Plastic Equivalent Strain (PEEQ). The PEEQ is the index of accumulative plastic strain in the deep drawing of the blank. And the PEEQ distribution map derived from the numerical simulation of non-isothermal hydroforming is shown in Fig. 18.

Combinations 1 to 12 in Fig. 18 correspond to the non-isothermal simulation scheme in Table 4; at the beginning of the deep drawing process, the deformation of the flange region is mainly elastic deformation, and the part contacts with the punch begins to plastic deformation, and as the punch continues to deform to the full forming stage, the deformation is mainly plastic deformation. It can be seen from the numerical distribution of medium-effect plastic strain in the figure that the plastic strain is greatest in the flange area. The blank is compressed and deformed from the flange into the die, so the plastic strain in the flange area is greatest. The minimum plastic strain occurs at the bottom of the ball, when the punch comes into contact with the blank, the area where the punch comes into contact with the blank is thinned and the plastic strain is small.

The plastic equivalent strain is in transition at the area that the straight wall area in contact with the bottom of the ball, and the equivalent plastic strain value is more balanced. The punch has the same temperature in same column in Fig. 18, and the die has the same temperature in the same row. Equivalent plastic strain increases as the temperature of the die increases in order in each column, and the trend occurs in each row that first increase and then decrease, with the maximum equivalent plastic strain appearing in 50 °C of punch in each row. The maximum point of equivalent plastic strain value appears in combination 6, its value is 8.466, and the minimum value of equivalent plastic strain is small. The conclusion of the uniaxial tensile test is verified, and the softening effect of AA6061-T6l is best when the temperature of die is 50 °C and the plasticity reaches the maximum in the combination.

4.2.3 The effect of non-isothermal hydroforming on thickness distribution

This section evaluates the effect of temperature changes on part thickness during the non-isothermal hydroforming by the thickness distribution of the cylindrical cup with spherical bottom. According to the simulation scheme shown in Table 5, there are 12 combinations of non-isotherms. In the ABAQUS software, the numerical simulation of non-isothermal hydroforming is carried out, and the thickness distribution of the cylindrical cup with spherical bottom base is shown in Fig. 19.
Fig. 18 Equivalent plastic strain distribution map
Table 5  The maximum, minimum, and difference of the wall thickness

| Combination | Maximum (mm) | Minimum (mm) | Difference (mm) |
|------------|--------------|--------------|-----------------|
| 1          | 1.511        | 0.8796       | 0.6314          |
| 2          | 1.456        | 0.8539       | 0.6021          |
| 3          | 1.506        | 0.8629       | 0.6431          |
| 4          | 1.460        | 0.8233       | 0.6367          |
| 5          | 1.476        | 0.8675       | 0.6085          |
| 6          | 1.461        | 0.8612       | 0.5998          |
| 7          | 1.461        | 0.8588       | 0.6022          |
| 8          | 1.476        | 0.8675       | 0.6085          |
| 9          | 1.506        | 0.8629       | 0.6448          |
| 10         | 1.511        | 0.8776       | 0.6034          |
| 11         | 1.454        | 0.7766       | 0.6774          |
| 12         | 1.470        | 0.7640       | 0.706           |

As shown in Fig. 19, the punch has the same temperature in each column, and the die, blank, and blank holder have the same temperature in each row. The areas with the greatest thinning rate are mainly concentrated in the bottom and the transition area of the bottom to the straight wall, and thickening appears at the flange and the transition area that the flange to the straight wall. Due to the flange area can be removed later, the thickening value of the transition area from the straight wall to the flange is used as the thickening analysis. The maximum, minimum, and difference of the wall thickness are shown in Table 5.

The data in Table 5 have been shown as follows: when the punch temperature is 25 °C (combinations 1, 5, and 9 in Table 4), the minimum thickness of the blank decreases gradually as the die temperature increases. This is because the blank has a higher temperature relative to the punch; the temperature difference is large between blank and punch. During contact, the temperature drops too fast, resulting in the “shock chilling” effect, similar to quenching in heat-treating. Due to extreme cooling the pull strength increases but the plasticity decreases, the area of punch fillet is thinned excessively, and the difference between thinning rate is larger and the molding effect is poor. Although a lower temperature of punch is required for the thinning rate of the part, it is not appropriate to use a low temperature of punch for the uniformity of the wall thickness distribution.

The data in Table 5 show that the wall thickness difference of the blank is large when the temperature of punch is greater than or equal to 100 °C (3, 4, 7, 8, 11, and 12 of Table 5), which proves that the blank uniformity is poor. This is because the temperature difference is too small between the punch and the blank, which causes the blank to cool down slowly; the increase rate of plasticity is much higher than the rate of decrease in tensile strength. In particular, the difference is maximum in wall thickness distribution when the punch is greater than 100 °C, such as combinations 11 and 12; the maximum wall thickness is 1.454 in combination 11, and 1.470 in combination 12. The value is not very large in terms of the maximum wall thickness alone; this is because the blank temperature is 200 °C and 250 °C at the beginning of drawing, and AA6061-T6l blank began to appear softening behavior at 200 °C. Blank fluidity increased but the maximum thickness of the flange area becomes smaller. The minimum thicknesses of combinations 11 and 12 are 0.7766 and 0.7640, respectively. As can be seen from the combination 16, the minimum wall thickness is distributed at the transition area from the bottom to the straight wall area; this area is excessively thinned due to a significant decrease in tensile strength, and the minimum wall thickness value is 0.7640 in the combination 12, which has reached the edge of rupture. Therefore, in order to improve the part quality, the temperature difference should be smaller between the punch and the blank, and the punch temperature must not be greater than 100 °C.

In the wall thickness distribution map of the punch temperature from 25 to 100 °C, it is found that the minimum wall thickness increases and then decreases; when the punch temperature is 50 °C, the wall thickness difference is minimal, so the optimal temperature of the punch is 50 °C. Observe the die temperature change, when the punch temperature is 50 °C (combinations 2, 6, and 10 in Table 5). The wall thickness difference is larger in combination 2; this is mainly because the blank temperature is low, and the plasticity has not been significantly improved. Therefore, there is not much difference between this temperature combination and the environment that the non-isothermal is not applied. The maximum thickness is 1.461 in the combination 6, at which point the blank has reached 200 °C, and the softening behavior has begun to appear of AA6061-T6l blank, as can be seen from the wall thickness distribution map of Fig. 19; the difference is minimal when the minimum wall thickness value is 0.8612. In combination 10, the rate of blank plasticity increase and tensile strength decrease do not match, resulting in uneven wall thickness distribution and large difference.

In this section, the numerical simulation forming effect of non-isothermal hydroforming is analyzed from the maximum wall thickness value, minimum wall thickness value, and wall thickness difference. The analysis leads to the following conclusions: the temperature difference between die and punch should be as large as possible, in this way, the plasticity of the blank to be reduced and the tensile strength to be enhanced, this is because of the heat exchange generated by the contact between blank and punch. However, the punch temperature cannot be too low, the optimal temperature is 50 °C, and the temperature of the blank cannot be selected too high; when the temperature is greater than 250 °C, the rate of tensile strength decreases far beyond the
Fig. 19 Wall thickness distribution map
increase rate of plasticity, and the transition area is exces-
svously thinned or even cracked between the part ball bot-
tom and straight wall. Therefore the optimal temperature of 
blank, blank holder, and die is 200 °C.

5 Experimental verification

The blank material is Aluminum Alloy 6061-T6 rolled blank, 
the thickness is 1 mm, and the blank radius is 128 mm. Place 
a plastic film between the blank and the die to protect the 
surface of the die.

In the experimental verification based on the best process 
parameters obtained by the simulation, the pre-bulging pres-
sure is 14 MPa, the cavity pressure is 35 MPa, the gap of 
blank and blank holder is selected at 1.1 mm, the speed of 
deep drawing is 10 mm/s, and the depth is 64 mm. Accord-
ing to the above-mentioned numerical simulation scheme of 
non-isothermal hydroforming, the punch temperatures are 
25 °C (room temperature), 50 °C, 100 °C, and 150 °C, and 
the temperature of the die and the blank holder are 25 °C 
(room temperature), 150 °C, 200 °C, and 250 °C, respec-
tively. During the test, thermocouples were placed in the 
straight area of the punch, at the bottom fillet, at the bottom 
corner, and at the fillet of the die, respectively, to measure 
the temperature change. Grease the die and blank holder 
to facilitate the flow of the blank. Set the initial conditions 
and carry out the experiments of ordinary hydrodynamic 
deep drawing and the non-isothermal hydroforming. The 
hydraulic equipment is shown in Fig. 20, and the working 
parameters of it are shown in Table 6.

The experimentally obtained parts are shown in Fig. 21, 
where Fig. 21a is the ordinary hydrodynamic deep drawing 
and Fig. 21b is the non-isothermal hydroforming; using the 
MT500 ultrasonic thickness gauge shown in Fig. 22, the wall 
thickness value is measured from bottom to top along test 
point shown in Fig. 21. Each part is measured 70 times and 
the measurement data is fitted in the origin software. The 
figed wall thickness distribution is shown in Fig. 23.

The wall thickness distribution is shown in Fig. 23, 
with the same process parameters but different tempera-
ture conditions, room temperature, and non-isotherms. 
From Fig. 21a, it can be seen that the blank appeared 
wrinkles in the flange area, because of the low plastic-
ity at room temperature, the accumulation caused by the 
difficulty of the flow of blank. In Fig. 21b, the plasticity 
of the blank material is improved at non-isotherms, so 
there is no wrinkle in the flange area. By measuring the 
thickness of the test point, the wall thickness distribution 
obtained after fitting is shown in Fig. 23. It can be found 
from the figure that blank thickness uniformity is better 
under the non-isothermal hydroforming; the difference is 
small between the maximum and minimum values of the 
wall thickness, but the difference is larger at room tem-
perature. The resulting part wall thickness is evenly dis-
tributed, and the experimental data are basically consistent 
with the simulation data, and the distribution of wall thick-
ness obtained by the experiment is more consistent with 
the wall thickness law obtained by numerical simulation 
that the minimum value of wall thickness appears in the 
bottom area and the wall thickness is relatively flat in the 
transition area between the bottom and the straight wall.

Table 6 Working parameters of hydraulic equipment

| Project                        | Parameter          | Unit |
|--------------------------------|--------------------|------|
| Nominal force                  | 2000               | kN   |
| Ejection force                 | 250                | kN   |
| Stock of knock-out cylinder    | 200                | mm   |
| Stock of slide                 | 710                | mm   |
| Maximum operating pressure of cavity | 1120     | MPa  |
| Maximum distance between slider and counter-top | 1120 | mm |
| No-load speed                  | 100                | mm/s |
| Maximum opening height of the blank holder slider | 1300 | mm |
| Worktable size                 | 1000×940           | mm   |
| Backing velocity               | 60                 | mm/s |
6 Conclusion

In this paper, AA6061-T6 cylindrical cup with spherical bottom is as the research object, the temperature forming performance of AA6061-T6 is studied by uniaxial tensile test, and the thermoforming constitutive model is constructed based on BP artificial neural network. This model is used to simulate the process of the non-isothermal hydroforming in the ABAQUS software to arrive at the optimal combination of parameters. The conclusions obtained are as follows:

1. Comparing the BP neural network model prediction with the true stress–strain curve from the data converted from the uniaxial tensile test, the fit is $R = 0.9991$ between the data predicted by the neural network and the true stress–strain data, and the accuracy reaches the required 0.001. At the same strain rate, the fit is getting higher and higher as the temperature increases. It can be seen that the BP neural network has a good effect in the prediction of the AA6061-T6 structure equation, and the model can be applied to the numerical simulation to provide data that is closer to the properties of the real material.

2. With the downstream of the punch, due to the low cavity pressure, it is not possible to reduce friction through overflow, which can lead to excessive thinning of the straight wall area near the flange. With the further increase of cavity pressure, the slow flow of blank causes it to accumulate too much in the flange area; the top area of the spherical shape is thinned seriously, resulting in cracking. The part is better formed when the pressure of the chamber is 35 MPa.

3. The blank temperature is lower at the bottom of the punch, the material strength is higher, and the temperature at the corner of the die is high, and the softening effect is obvious but the intensity is low of the flowing blank. The optimal difference temperature is set to 50 °C for the punch, and 200 °C for the die, blank holder, and blank, at which point the equivalent plastic strain and thickness are evenly distributed.

4. Using the data of the best cavity pressure curve and optimal temperature combination, the results show that the wall thickness distribution of the experimental part is more consistent with the wall thickness law of numerical simulation, the non-isothermal hydroforming improves the plasticity of the blank, and the wall thickness distribution of the experimental part is more uniform.
Author contribution Xue Feng Ma: conceptualization, methodology, writing — original draft preparation, experimental scheme design. Xiao Jing Liu: writing — reviewing and editing. Li Chao: experiment. Jin Qin: verification, validation. Peng Chen: supervision.

Funding This paper was financially supported by Harbin Academic Leader Fund (2017RAXXJ008) and National Natural Science Foundation of China (51975167).

Availability of data and materials The data obtained in the framework of this study are available to the journal upon request.

Declarations

Ethics approval Not applicable.

Consent to participate Not applicable.

Consent for publication Not applicable.

Competing interests The authors declare no competing interests.

References

1. Li H, Yan Z, Cao L (2018) Bake hardening behavior and precipitation kinetic of a novel Al-Mg-Si-Cu aluminum alloy for lightweight automotive body. Mater Sci Eng 728:88–94. https://doi.org/10.1016/j.msea.2018.05.014

2. Tiszai M, Czinege I (2018) Comparative study of the application of steels and aluminium in lightweight production of automotive parts. Int J Lightweight Mater 1(4):229–238. https://doi.org/10.1016/j.ijlmm.2018.09.001

3. Khosrojerdi E, Bakshi-Jooyhari M, Gorji A et al (2017) Experimental and numerical analysis of hydrodynamic deep drawing assisted by radial pressure at elevated temperatures. Int J Adv Manuf Technol 88(1–4):1–11. https://doi.org/10.1007/s00170-016-8753-7

4. Jalil A, Gollo MH, Sheikhi MM, SeyediKashi SH (2016) Hydrodynamic deep drawing of double layered conical cups. Trans Nonferrous Met Soc 26(1):237–247. https://doi.org/10.1016/S1003-6326(16)64109-2

5. Wang H, Shen X (2021) A novel hydrodynamic deep drawing utilizing a combined floating and static die cavity. Int J Adv Manuf Technol. https://doi.org/10.1007/s00170-021-10927-5

6. Bolt PJ, Lamboo NAPM, Rozier PJCM (2001) Feasibility of warm drawing of aluminum products. J Mater Proc Technol 115(1):118–121. https://doi.org/10.1016/S0924-0136(01)00743-9

7. Haiyoung LV, Dongqiang S (2020) Application of lightweight materials and forming technology in automobile body. Modern Manuf Technol Equip 05:92–96. https://doi.org/10.16107/j.cmte.2020.0464

8. Phao G, Jieshi C, Lei Y (2019) Research on warm forming for AA5182 aluminum alloy used in automobile. Forging &Stamping Technology 44(05):136–141. https://doi.org/10.13330/j.issn.1000-3940.2019.05.024

9. Xiao Jing Liu, Hong Ying Cao, Chao Li, Jin Qin, Ji Cheng Gao (2020) Construction of 6061-T6 aluminum alloy constitutive model based on hot bulging test and study on the non-isothermal hydroforming process. Int J Adv Manuf Technol 109:1625–1641. https://doi.org/10.1007/s00170-020-05776-y

10. Liu XJ, Gao JC, Li C, Ding HF (2020) Investigation on precision warm hydroforming with independent circumferential pressure of high-performance aluminum alloy parts with special-shaped bottom. Int J Adv Manuf Technol 109:201–213. https://doi.org/10.1007/s00170-020-05618-x

11. Toros S, Qzturk F, Kacar I (2008) Review of warm forming of aluminum–magnesium alloys. J Mater Process Technol 207(1–3):1–12. https://doi.org/10.1016/j.jmatprot.2008.03.057

12. Jiang Yun Peng, Yue Zhi Feng, Han Xiao Ping (2003) Determination of the materials stress and strain relationship from the tensile smooth and notched bars. J Mech Strength 02:151–153+158. https://doi.org/10.16579/j.issn.1001.9669.2003.02.009

13. Koç M, Mahabunphachai S, Bilir E (2011) Forming characteristics of austenitic stainless steel sheet alloys under warm hydrodynamic conditions. Int J Adv Manuf Technol 56:97–113. https://doi.org/10.1007/s00170-011-1369-x

14. Gerrit Kurz (2016) Heated hydro-mechanical deep drawing of magnesium sheet metal. Essen Readings in Magnesium Technol 389–393. https://doi.org/10.1007/978-3-642-48099-2_62

15. Sun-Chong Wang (2003) Artificial neural network. Interdisciplinary computing in java programming 743:81–100. https://doi.org/10.1007/978-1-4615-0377-4_5

16. Rumelhart DE, Hinton GE, Williams RJ (1986) Learning representations by back-propagating errors. Nature 323:533–536. https://doi.org/10.1038/32353a0

17. Sheng HM, Huan T (2016) High temperature flow stress behavior of B10 copper alloy and BP neural network constitutive model. China Metal forming Equip Manuf Technol 51(06):112–115. https://doi.org/10.16316/j.issn.1672-0121.2016.06.028

18. Bolt PJ, Lamboo NAPM, Rozier PJCM (2001) Feasibility of warm drawing of aluminum products. J Mater Process Technol 115(1):118–121. https://doi.org/10.1016/S0924-0136(01)00743-9

Publisher’s Note Springer Nature remains neutral with regard to jurisdictional claims in published maps and institutional affiliations.

This article is completed under my independent research, and without the phenomenon that quotes largely or plagiarizes other articles and so on. Therefore, I will be corresponding responsible for the thing.