Investigation of deformation in stretch forming based on distributed displacement loading

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Abstract. Stretch forming based on distributed displacement loading is a new stretch forming process, in which distributed displacements are applied at a series of discrete points, therefore, the deformation in different positions of sheet metal can be individually controlled. To investigate the deformation of sheet metal in stretch forming, the rational loading trajectory is designed, and it is determined by the respective length of longitudinal cross-section curve. The numerical simulation results show that, the loading trajectory is valid to form three-dimensional surface parts, and the relatively small shape errors between the simulated results and target results make it possible to form qualified parts. Meanwhile, the longitudinal strains are uniformly distributed along the longitudinal material lines, and longitudinal strains increase evenly with the process of stretch forming. Finally, experimental tests proved the effectiveness and feasibility of the stretch forming based on distributed displacement loading.

1. Introduction
Stretch forming, as a vital process for manufacturing three-dimensional surface parts, has been widely applied in diverse industries, especially to the external bodies of aircraft, automobile and high-speed train [1]. Conventional stretch forming requires rigid gripping jaws, obtaining equal displacement at the end of sheet metal clamped by rigid clamps [2]. Since sheet metal in conventional stretch forming can’t deform automatically with the die surface in the transverse direction (perpendicular to the tensile direction), forming defects such as crack, wrinkle and severely local deformation may customarily occur in large-curvature surface parts.

Multi-point stretch forming introduces the idea of discretization, and adopts flexibly discrete die and clamps, which can form three-dimensional surface parts of diverse shapes [3-6]. Multi-point stretch forming is controlled by using force loading on the discrete clamps, including horizontal force, vertical force and tilting force, so curved surface parts with large curvatures are susceptible to springback after unloading tensile force, which could lead to larger shape errors compared with acquired ideal forming result.

The stretch forming based on distributed displacement loading (SF-DDL), which is a new forming method for three-dimensional surface parts, applies different displacements loading on a series of discrete points on the two ends of sheet metal, and each individual material fibre is locally prescribed to deform along a respective deformation path [7]. The reasonable loading trajectory is the key to forming qualified curved surface parts, and the sheet metal can deform automatically with the die surface in the transverse and longitudinal directions, which can achieves to manufacture qualified large-curvature surface parts by deformation as small as possible [8].
2. Principle of stretch forming and design of loading trajectory

In the forming process, the corresponding displacements are applied at the reference points of the discrete clamps so that the sheet metal can be stretched and wrapped around the die surface. Each loading unit moves along a combined horizontal and vertical path, furthermore, it rotates a certain angle in order to maintain tangent relation between the die surface and the sheet metal.

![Figure 1. Diagram of SF-DL: (a) diagram of die (b) sheet metal in forming.](image)

It is assumed that the strains on the longitudinal material lines are uniformly distributed along the longitudinal direction (the tensile direction), and longitudinal strains satisfy

\[ \varepsilon_{ij}(t) = \xi(t) \varepsilon_{ij} \]

where \( \varepsilon_{ij} \) is the final strain of longitudinal liber at the ith loading point, \( \varepsilon_{ij}(t) \) is the longitudinal strain at time \( t \), and \( \xi(t) \) is the function of the loading time.

At time \( t = t_i \), the length of longitudinal fibre of the deformed sheet metal can be calculated by

\[ l(t_i) = \int_0^l e^{\xi(t_i)\varepsilon_{ij}} dx = l_0[1 + \xi(t_i)\varepsilon_{ij}] \]

(1)

The loading trajectory of the ith loading point can be described by the displacement of the ith clamp \( \Delta x_{ij} \) in \( x \) direction and \( \Delta y_{ij} \) in \( y \) direction, as shown in figure 1. Then, the displacements of the ith loading point at time \( t = t_i \) should be

\[
\begin{align*}
\Delta x_{ij} &= [l_0[1 + \xi(t_i)\varepsilon_{ij}] - \int_0^\theta R(\theta)d\theta] \cos \theta_i + R_0(\theta) \sin \theta_i - l_0 \\
\Delta y_{ij} &= R_0(\theta) \cos \theta_i - [l_0[1 + \xi(t_i)\varepsilon_{ij}] - \int_0^\theta R(\theta)d\theta] \sin \theta_i - R_0(\theta)
\end{align*}
\]

(2)

Where \( l_0 \) is the initial length of sheet metal, \( R_0(\theta) \) is the curvature radius of longitudinal section curve of the die surface, and \( \theta_i \) is the normal angle of the ith loading point at time \( t = t_i \).

3. Numerical simulations of stretch forming based on distributed displacement loading

3.1 deformation of sheet metal under the different loading trajectories

Numerical simulations of SF-DL are performed under ABAQUS/Explicit environment, and 1/4 finite element model (as shown in figure 2a) is applied to forming three-dimensional surface parts on the basis of the symmetrical relation of the formed parts. The aluminum alloy of 2024-O is used, and the relevant mechanical properties are the following: the density \( \rho = 2.78 g/cm^3 \), the Young modulus \( E = 40.6 GPa \), the yield stress \( \sigma_y = 77.5 MPa \) and the Poisson’s ratio \( \nu = 0.33 \).

![Figure 2. Diagram of numerical simulation: (a) a quarter FE model (b) loading curve](image)

The spherical parts of R400 as target radius are simulated in SF-DL, and the dimension of the
initial blank is 400mm × 300mm with the thickness 1mm. The elongation of sheet metal at ith loading point is determined by equation (1), and $\xi(t)$ respectively adopts $\xi(t) = t^{1/2}$, $\xi(t) = t$, $\xi(t) = t^2$, (as shown in figure 2b) at different times, so three different loading trajectories are obtained. In the three trajectories, the elongation of longitudinal fibre is different at diverse loading steps, and the displacement can be respectively acquired by equation (2). The longitudinal strain distributions of three trajectories are shown in figure 3, and it can be observed that, longitudinal strains are more uniform at the effective forming area when adopt $\xi(t) = t$. So it is possible that the deformation of the sheet metal is more stable when the elongation is uniformly increased.

3.2 Longitudinal strain distributions and the shape error

The spherical and saddle parts of $R500$ as target radius are simulated in SF-DDL, and the elongation of sheet metal increase evenly in the forming process. The longitudinal strain distributions on spherical parts and saddle parts are shown in figure 4a and 4b respectively, and formed parts embrace high quality without defects such as crack and wrinkle, which can demonstrate that the loading trajectory of distributed displacement loading is valid to form three-dimensional surface parts.

Then, extract strains of cross section of formed parts at different steps, as shown in figure 4c and 4d, in which the longitudinal strains basically reveal horizontal lines at different times. It indicates that the longitudinal strain distributions are relatively uniform along longitudinal direction, and longitudinal strains increase evenly with the stretch forming process, which verify the assumption that the strains on the longitudinal material line are uniformly distributed and satisfy $e_{ij} = \xi(t)e_{ij}$ as mentioned above.

To verify the validity of the loading trajectory, the three-dimensional point-cloud data of simulated parts are compared with the target parts, then, shape error distributions of the spherical parts and

![Figure 3. Longitudinal strain distributions of different trajectories: (a) $\xi(t) = t^{1/2}$ (b) $\xi(t) = t$ (c) $\xi(t) = t^2$.](image)

![Figure 4. Longitudinal strain distributions: (a) spherical part (b) saddle part (c) strains of spherical part at different times (d) strains of saddle part at different times.](image)
saddle parts are obtained, as shown in figure 5. The shape error distributions of spherical part are mainly in 0.5mm to -0.5mm, which is quite small and is allowed in mechanical manufacturing. While shape error distributions of saddle part change from 0.79mm to -0.79mm, which are larger slightly than the ones of spherical part, maybe, the saddle part surface is under the deformation in both positive and negative directions simultaneously. In brief, the relatively small shape errors make it possible to form qualified parts in accordance with the trajectory of distributed displacement loading.

![Figure 5. Shape error distributions: (a) spherical part (b) saddle part.](image)

4. Numerical simulation results and experimental validation

In SF-DDL process of spherical part, the sheet metal is susceptible to no contact with the surface of die on the edge. However, in order to manufacture three-dimensional surface parts of high quality, the effective forming area of the sheet metal should be full contact with the die surface. In numerical simulation, the dimension of the initial blank is 1000mm × 800mm with the thickness 1mm, and the target radius of spherical part is 1500mm.

![Figure 6. Numerical simulation results: (a) deformation process (b) shape error](image)

Numerical simulation results of spherical part are shown in figure 6, it can be seen that the effective forming area can full contact with the surface of die. Extracting the cross-section line in different locations, shape errors between the simulated part and the target part are shown in figure 6b. And it can be observed that shape errors are minimum in the middle area and change from 0.10mm to 0.15mm, however, shape errors are greater on the edge region and fluctuate in the range of 0.33mm to 0.47mm, which have illustrated that the shape error is extremely small and ideal shape of the curve surface part can be obtained in SF-DDL. By fitting the curvature radii of extracting contours, the radii of the curves 1, 2 and 3 (as shown in table 1) are respectively 1532mm, 1514mm and 1483mm, which are closed to the target radius ($R = 1500mm$).

![Table 1. Curvature radius of spherical part in different positions](image)

| Location | 1       | 2       | 3       |
|----------|---------|---------|---------|
| Radius(mm)| 1532    | 1514    | 1483    |

To verify the feasibility of the loading trajectory and the accuracy of the numerical simulation, the experiments of stretch forming spherical parts have been carried out on a home-made apparatus, and the experimental spherical part is obtained, as shown in figure 7. In experiment, the aluminum 2024-O material is put into use, and the target radius of the spherical part is 1500mm.
Different displacements are applied at a series of discrete points on the two ends of sheet metal, and the deformation of sheet metal can be individually controlled at the discrete points. By the loading method, we have been realized stretch forming based on distributed displacement loading. It can be observed that the spherical part is with good surface quality and without any defects such as crack and wrinkles. The experiment results demonstrate that the qualified three-dimensional surface parts can be acquired and used in engineering manufacture.

5. Conclusions
To study the deformation in SF-DDL, the optimal loading trajectory was designed, meanwhile, loading trajectory validation and longitudinal strains variation were investigated, and some experiments were carried out to verify the results of numerical simulation. Finally, the following conclusions can be acquired:

1) The loading trajectory is determined by the length of longitudinal cross-section curves in different clamps. And the numerical simulations of spherical parts and saddle parts demonstrate that the loading trajectory is valid to form three-dimensional surface parts.

2) The strains on the longitudinal material lines are uniformly distributed along the longitudinal direction, and longitudinal strains increase evenly with the process of stretch forming, which can prove that it is reasonable to adopt the mode of distributed displacement loading to forming three-dimensional surface parts.

3) In experiment, the effective forming area of the sheet metal can be full contact with the surface of die and obtain high-precision curved surface parts. And the experimental results show that the feasibility of the loading trajectory and the accuracy of the numerical simulation.

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