NUMERICAL AND EXPERIMENTAL STUDY ON MANUFACTURE OF A NOVEL HIGH-CAPACITY ENGINE OIL PAN SUBJECTED TO HYDRO-MECHANICAL DEEP DRAWING

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Abstract. The oil pan is equipped at the bottom of engine crankcase of the automobile to prevent impurity and collect the lubrication oil from the surfaces of the engine which is helpful for heat dissipation and oxidation prevention. The present study aims at manufacturing a novel high-capacity engine oil pan, which is considered as a complex shaped component with features of thin wall, large size and asymmetric deep cavity through both numerical and experimental methods. The result indicated that it is difficult to form the current part through the common deep drawing process. Accordingly, the hydro-mechanical deep drawing technology was conducted, which consisted of two steps, previous local drawing and the final integral deep drawing with hydraulic pressure. The finite element analysis (FEA) was carried out to investigate the influence of initial blank dimension and the key process parameters such as loading path, draw-bead force and fillet radius on the formability of the sheet blank. Compared with the common deep drawing, the limit drawing ratio by hydro-mechanical deep drawing can be increased from 2.34 to 2.77, while the reduction in blank wall thickness can be controlled in the range of 28%. The formability is greatly improved without any defects such as crack and wrinkle by means of parameters optimisation. The results gained from simulation keep a reasonable agreement with that obtained from experiment trials.

1. Introduction
The engine oil pan is classified to flat bottom and uneven bottom with different cavities depth according to the appearance shape. The conventional forming methods often are sheet stamping and common deep drawing [1,2]. However, it is easy to cause cracks because of a large amount of deformation if the sheet is only formed by a single step. For the oil pan with two steps, it is necessary to have multiple procedures to form the component for the reason of two different cavities depth and local deformation difference. Even the intermediate heat treatment is needed to improve material formability of latter forming process. Furthermore, a large amount of spring back will lead to a significant reduction in the dimensional accuracy of parts. At the same time, the depth of the cavity is increased in order to increase the storage capacity of the oil pan and further improve the battery life and maintenance cycle. Therefore, the conventional forming process cannot meet the development of the novel high-capacity oil pan, which
provides demand on the design and development of new forming process \([3,4]\). The development of hydro-mechanical deep drawing (HMDD) process can be traced back to 1890s as a special hydroforming process. The process principle is that certain liquid is filled in the drawing die, and the liquid can produce corresponding reverse pressure that makes the blank close to the surface of punch (usually it is called the effect of pre-bulging) when the punch moves downwards. The HMDD can reduce the sheet defects, improve the production efficiency and component precision compared to the conventional process. It combines the advantages of conventional deep drawing and hydroforming, and the limit draw ratio can reach to 2.8 \([5-7]\). So the advanced process is very suitable for forming the blank with the obvious asymmetric deep cavity, which is good for increasing the volume and losing weight. Schultz has mentioned that the fuel efficiency can be increased by 6–8% if the weight can be decreased by about 10% \([8]\).

The paper mainly focuses on the process of HMDD to make the oil pan of the asymmetric deep cavity for the final hydroforming process. The finite element analysis (FEA) was carried out to investigate the influence of the key process parameters such as loading path, draw-bead force and fillet radius on the formability of the sheet blank.

2. The characteristics and process scheme of the part

2.1. The part of novel high-capacity engine oil pan

As is illustrated in figure 1, it is the novel high-capacity engine oil pan part used for the certain heavy truck. The initial wall thickness of blank is 2mm and the adopted material is the AISI 304\([9]\). The volume of the novel oil pan can be enhanced 30 litres by employing this kind of complex structure, which improves the cruising endurance from 20000 km to 100000 km and increases the maintenance cycle greatly.

![Figure 1.](image)

2.2. The design of process scheme

As depicted in figure 1, the depth difference of light and the deep cavity is more than 220mm. The calculated drawing ratio of the oil pan is 2.77 according to the drawing ratio concept of box type part. But the limit drawing ratio for AISI 304 is only 2.34 with the method of literature, which is confirmed difficult to manufacture by common deep drawing even with middle annealing \([10]\).

The HMDD process includes previous local drawing and the final integral deep drawing, the process scheme is shown in figure 2. Firstly, the deep cavity is deformed with the help of hydraulic pressure. The punch moves downwards with constant velocity until the displacement reached 200mm. Afterwards, the final integral cavity is manufactured. The deep drawing die moves downwards with 208mm under the assist of the kinetic mechanism while the punch is stationary. Subsequently, the punch continues to feed down after the hydraulic pressure is generated which activate the function of pre-bulging. So the shell component is formed successfully by the continuous HMDD process.

![Figure 2.](image)
2.3. The finite element models and parameters

2.3.1 Specifications of finite element models
The initial shape and dimensions of blank are calculated by using the Blank size estimate (BSE) module of Dynaform5.9 that the shape of the initial blank is just like a “shoe” which is very beneficial to form the asymmetric depths of the cavity. It helps the blank material flow smoothly to the cavity considering variant quantity demand of material in the light and deep cavity and the length and width of the initial blank is 1618mm and 1026mm, respectively. The initial blank is discrete into 53927 elements of 2mm thickness quadrilateral shell. The Belytschko-Tsay shell element is employed because of the high computational efficiency. The calculated time of a quadrilateral Belytschko-Tay element is only 9μs that saves 30~50% calculation time than miscellaneous elements.

2.3.2 Material and process characterizations
The mechanical properties of AISI 304 and the process parameters which used in FEM are summarised in table 1 and 2 respectively.

Table 1. The mechanical properties of AISI 304 material

| Parameters                        | Values       |
|-----------------------------------|--------------|
| Yield strength                    | 239 MPa      |
| Young’s modulus                   | 207000 MPa   |
| Density                           | 7.83×10^2 kg/mm³ |
| Poisson’s ratio                   | 0.28         |
| Strain hardening exponent n       | 0.23         |

Table 2. The main process parameters of HMDD

| Parameters                                | Values       |
|------------------------------------------|--------------|
| The gap between punch and drawing die/ mm | 2.5          |
| Drawing die fillet radius/ mm            | 20, 50       |
| Punch velocity/ mm/s                     | 20           |
| Binder force of first and second stage / MPa | 1, 2         |
| Chamber pressure/ MPa                   | 1, 2, 3, 4 and variant |
| Draw-bead restraining force/ N           | 1063         |
| Friction coefficient of deep drawing punch/die | 0.125/0.05  |

3. Comparative study of different processes based on FEA
The finite element analysis can be used in the process of HMDD. The procedure of process development can be shortened and the experimental cost will be reduced by using FEA to predict the influence of each parameter on forming and optimise the original process parameters. The one-step and two-step common deep drawing process are attempted to manufacture the component.

3.1. The common two-step deep drawing process
The crack defects occur at the junctions of deep cavity bottom and drawing straight wall when employing the common one-step deep drawing. So the two-step of conventional deep drawing is designed and employed based on the defects of the previous process. Namely, the first step is used to form the deep cavity and the second step is applied to the shallow cavity forming to avoid the “contest with material” effect. But the comprehensive cracks also happen at the intersection of deep cavity bottom and drawing straight wall during the first drawing step. As illustrated in figure 3, the blank material located at the fillet of drawing die endures poor lubrication condition on account of the absence of hydraulic pressure that contributes to the large friction in the die fillet area. Hence, the blank material is difficult to flow into the die cavity. It is the initial deformation and the subsequent transformation that finally incurred the crack defects in the area near to the bottom.
3.2. HMDD process

As previously mentioned, the sheet blank is deformed by two successive stages of forming processes with hydraulic pressure in the drawing die. As depicted in figure 4, the HMDD process can successfully form the complex component without wrinkles and cracks.

4. The optimisation of HMDD process parameters

4.1. The influence of draw-bead on formability

It is necessary to apply the blank holder on the mold and the provision of corresponding draw-bead is critical to form the parts with complex characteristics of asymmetric depths of cavity [1].

Firstly, the draw-bead force is set relatively large during the first and second stage which is reflected as figure 5. For the first stage, the fraction of draw-bead is 50 and 30 % respectively in the area of straight edges and fillet corners. The setting takes into full consideration on the discrepancy of material flow at straight and curved edges.

As shown in figure 6(a), the FLD results reveal the whole circumferential cracks happen at the junction of the bottom and straight walls and the largest thinning ratio exceeds 45 % from figure 6(b). The simulation results demonstrate that the relative large setting of the draw-bead force dramatically increases the difficulty of material flow to the deep cavity, which leads to the crack defects near the bottom.
Secondly, the draw-bead force is set relatively small during the first and second stage deep drawing according to section 4.1. For the first stage, the fraction of draw-bead is 15 and 10 % respectively in the area of straight edges and fillet corners. And for the final integral deep drawing stage, the fraction of draw-bead is 15 and 12.5 % respectively in the area of straight edges and fillet corners.

As is shown in the graph 7(a), (b), the defects are the apparent wrinkles that appear at the fillet corners of straight walls when the draw-bead force is set relatively small. The reason is that the constraint force for the sheet blank is relatively small in the area of straight wall edges which contribute to the inhomogeneous material flow compare to the area of fillet corners. The sheet materials in the straight edges flow more quickly than that in the corners. So the redundant materials in the corners will accumulate gradually to form the severe wrinkles (usually is called dead wrinkles) that cannot be eliminated by subsequent hydroforming, on the contrary, will seriously influence the later process.

According to the previous simulation results, the draw-bead force is optimised and the reasonable value is obtained. The specific draw-bead forces setting are shown in figure 8. On the basis of default restraining force value 1063 N, the fraction of draw-bead force is set to 30 and 10 % respectively in the area of straight edges and the rounded corners during the first stage. And the fractions are 25 and 12.5 % respectively in the second stage and even reach to 35 and 50 % in the area of the straight edge near to symmetry axis. The setting method of draw-bead force is similar to B.Endelt [11], for which the variable blank holder system is designed by setting different modules to achieve variant draw-bead force in different positions. The subsequent FEM will adopt the proper setting of draw-bead force.

4.2. The influence of loading path on formability
The loading path is significant to the process, which stands for the loading curve of hydraulic pressure. For the first stage, the constant hydraulic pressure may be the good choice for the almost square box deep drawing. So the constant pressure is set as 1,2,3,4 MPa, respectively to investigate the influence on the formability of the “shoes” shape blank. The simulation results illustrate that the different values of pressure even don’t have an obvious influence on the forming of the blank, so the 1MPa is selected
stems from the economy consideration. However, for the second stage, the situation is totally different on account of the asymmetric depth of the cavity. The loading paths are set as figure 9 include constant and variant hydraulic pressure loading. For loading path of 8, 9, 10, the hydraulic pressure is corresponding high before the inclined shallow segment of punch fully contact with the blank (time is 1.46 s), which promotes the wrinkles in the fillet corner of drawing die, as shown in the figure 10(a), 10(b). So the pressure should not exceed 1MPa before the punch makes fully contact with the blank. The loading path 4(pressure is constant 1MPa) is an ideal option of the hydraulic pressure for its simple form compared to loading paths 1, 2, 3, 5, 6, 7, which are relative complex. The deep drawing result under loading path 4 is reflected in figure 10(c).

![Figure 9. The loading path of 2nd stage](image)

![Figure 10. The forming under different loading paths](image)

4.3. The influence of fillet radius on the wall thickness reduction

To investigate the influence of fillet radius on the process, the fillet radius is employed as 20mm under the premise that does not change other mould and process parameters. As shown in figure 11(a), the serious wrinkles indeed 3 to 5 folds happen in the area of bottom corners and the severe cracks form at the edge of the straight wall when the deep drawing depth reach to 192mm. As depicted in figure 11(b), varying degrees of thickening happen in the four entrance corners and the most serious thickening has reached to 31%. In the same time, the thickness reduction is about 22 % in the area of bottom fillet and ranges from 24 to 30% at junctions of straight walls. In conclusion, the material is hard to flow into the cavity because the small fillet radius that decreases the lubrication area and weaken the function of hydraulic pressure. And the fillet radius 50mm is selected as the reasonable parameter for the entire simulation and experiment by means of FEM and relative optimisation.

![Figure 11. The influence of die fillet radius on the formability of blank](image)

4.4. Wall thickness distribution of the component

The simulation of HMDD is conducted based on the proper parameters such as draw-bead force distribution, loading path, fillet radius of drawing die. The wall thickness is treated as the output information which located at the symmetry plane. It is divided into 9 subareas including straight and fillet segment along the outline of oil pan component. According to the figure 12, the distribution of wall thickness is inhomogeneous and the difference of thickness is apparent. The wall thicknesses have the trend of decreasing firstly and then increasing along the length of the component in the areas of I and IX [12]. And the minimum of the wall thickness always happens at the middle area of the straight wall because it remains obvious tensile stress state and the material near to the bottom is strengthen
which prevents the occurrence of fracture, but the material strength of the middle area is relatively weak which deserves to thin or even crack. The maximum of wall thickness reduction reaches to 21.58 % in area I and equals to 7.63 % in the region IX. Moreover, the wall thickness decreases sharply from area V to VI and becomes the least of the whole symmetrical section in the middle of the fillet with the value of 21.84 %. This is attributed to the relatively long blank on the side of shallow cavity which causes greater friction and makes the material be difficult to flow to the deep cavity.

![Figure 12. The simulation results](image)

4.5. Experimental results
As shown in figure 12(a) and 13(a), the simulation results give good agreements with the verification experiment from the point of geometric dimension view. Using the same test method with section 4.4, the wall thickness results are revealed in figure 13(b). For the most of the test points, the wall thickness of the actual part is less than the simulated one especially for the area of deep cavity near to the bottom, which indicates the thinning is more obvious for the actual parts. The minimal wall thickness of actual component is only 1.53 located at the middle position of the straight wall I, which indicates that the thinning ratio has reached to 23.5%. The simulation results agree with the consequence of experiments with the maximum relative error value is -4.88 %. That means the simulation of the deep drawing process can reflect the trend of the wall thickness of the actual process and provide theoretical guidance for the actual forming.

![Figure 13. The experimental results](image)

5. Conclusion
It was confirmed that the process of HMDD was feasible and suitable to manufacture the novel oil pan part with the support of FEM and related verification experiment. The two stages of the HMDD process are employed in considering the specific characteristics of the deep and shallow cavities, which can form the component with a total drawing ratio of 2.77 exceeds the material limit drawing ratio 2.34. The variant distribution of draw-bead forces can sufficiently solve the defects of wrinkles and fracture. For the first stage, the reasonable fractions of restraining force are 30 and 10 % with the straight and fillet...
corner edges, respectively. And proper fractions are 25, 50 and 12.5% in the area of long straight, short straight and fillet corner edges, respectively.

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