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Process window diagram of conical cups in hydrodynamic deep drawing assisted by radial pressure

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Abstract: Major defects in forming of conical cups are wrinkles and rupture. Hydrodynamic deep drawing assisted by radial pressure (HDDRP) is a sheet hydroforming process for production of shell cups in one step. In this work, process window diagrams (PWDs) for Al1050-O, pure copper and DIN 1623 St14 steel are obtained for HDDRP process. The PWD is determined to provide a quick assessment of part producibility for sheet hydroforming process. Finite element method is used for this purpose considering the process parameters including pressure path, and the blank material and its thickness. Numerical results are validated by experiments. It is shown that the sheets with less initial thickness and higher strength show better formability and uniformity of thickness distribution on final product. The results demonstrate that the obtained PWD can predict appropriate forming area and probability of rupture or wrinkling occurrence under different pressure loading paths.

Key words: conical cups; hydrodynamic deep drawing; finite element simulation; process window diagram

1 Introduction

Hydrodynamic deep drawing (HDD) is a sheet hydroforming process which is a combination of conventional deep drawing and hydroforming, comprising the advantages of both technologies. HDD is known by different titles such as hydraulic counter pressure deep drawing, fluid former, aquadraw and hydromech [1]. HDD is categorized as a flexible forming process, and has a wide range of applications in different industries due to its capability of forming complex parabolic and conical shapes with high limiting drawing ratio (LDR) in a single step. In HDD process, a shaped punch forces the blank into the liquid-filled die cavity, so that the liquid is pressurized and forms the blank around the punch [2,3]. The created frictional force between the blank and the punch allows to apply higher pressures, thus stress concentration is reduced on the blank at the punch tip area and the formability will be improved. On the other hand, the exerted pressure provides a bed for the free portion of the blank between the punch and the die shoulder, pushing the blank upward to create the tensile circumferential stresses that assist in preventing from wrinkles. In this flexible process, the same die can be used in forming of various geometries using different punches.

Hydrodynamic deep drawing assisted by radial pressure (HDDRP) is a special application of HDD, in which the pressurized forming liquid is applied also to the outer edge of the blank at flange area to improve the material flow during the forming process [4]. There is no sealing in the flange area in HDDRP and the gap between the die and blank-holder is slightly bigger than the blank thickness. When the punch moves down and the liquid is pressurized, the sheet is drawn into the die cavity while stuck to the punch surface and the blank-holder. At this time, the pressurized liquid can flow into the gap between the blank-holder and the die. This gap causes a uniform radial pressure around the sheet edge in the flange area assisting in more efficient flow of material into the die cavity [5]. HDDRP has a lot of advantages compared with conventional deep drawing such as higher drawing ratio and dimensional accuracy, uniform thickness distribution, better surface quality and more complex products. The radial pressure can be created around the blank with a little modification in the HDD die set. Figure 1 shows a schematic of this process.

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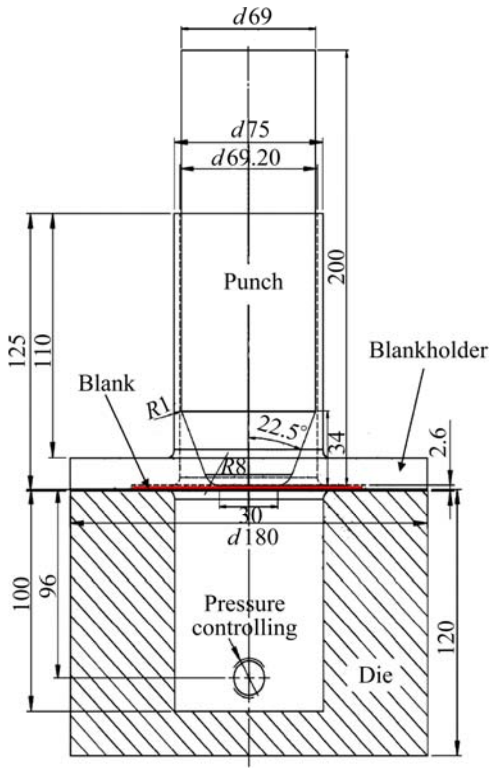

Fig. 1 Die set of HDDRP process used in this research (unit: mm)

During the last decade, a few researches have been conducted in forming of conical parts by hydroforming techniques. KAWKA et al [6] investigated the simulation of wrinkling in deep drawing of conical cups. Finite element results showed that the type and number of meshes are very effective on final results even for minor changes. THIRUVARUDCHELVAN and TAN [7] proposed a new method for forming of conical cups in conventional deep drawing by an annular urethane pad. In this method, the urethane pad prevents the direct contact of punch tip to the blank, and delays the rupture especially at early stages of the process. LANG et al [8] studied the effect of calibration stage on forming of conical cups in sheet hydroforming process. The results demonstrated that the calibration method can prevent the fracture and remove the wrinkles. GORJI et al [9] investigated hydrodynamic deep drawing for conical–cylindrical cups numerically and experimentally. They considered different pressure paths and studied the effect of those paths on thickness distribution and drawing ratio of the products.

Several studies were devoted to designing the process window diagrams (PWD) for different materials in various forming processes. CHU and XU [10] proposed a theoretical PWD for hydroforming of aluminum extrusion tubes. PWD was designed based on the internal pressure versus axial compressive force to predict buckling, wrinkling and bursting. OH et al [11] used ductile fracture criterion to predict forming limit diagrams in hydro-mechanical deep drawing of steel sheets. VOLLERTSEN and HU [12] investigated the effect of punch velocity on PWD in micro deep drawing. It was concluded that the allowable upper limit of the blank-holder pressure increases with increasing the punch velocity. GAO et al [13] designed PWDs of tube-compression by viscous pressure forming considering the tube-compression length and tube-blank diameter. PWDs showed that the safe zone and the wrinkles elimination area decrease with increasing the tube-compression length, while the safe zone decreases and the wrinkles elimination area increases with increasing the tube-blank diameter.

In this work, HDDRP process is studied for three types of materials using finite element method considering forming pressure path, initial thickness and material of the blank. The process window diagrams (PWD) for forming of conical parts are determined. The PWD is determined to provide a quick assessment of part producibility for sheet hydroforming process. No PWDs were reported for HDDRP yet. The proposed PWD can predict the proper forming area and occurrence of wrinkles and rupture. It is also possible to approximate the maximum thinning percentage in different forming zones. In order to determine the PWDs, three types of materials including pure copper, Al1050-O and DIN 1623 St14 steel (mentioned as St14 hereafter) with different thicknesses (between 0.5 and 2.5 mm with 0.25 mm interval) were evaluated. Different pressure paths were applied for each specimen in finite element simulations to determine the desirable and undesirable forming areas. Numerical model and PWDs are validated by experiments based on the thickness distribution of final parts. Experimental tests were performed with different pressure paths determined from the PWD to achieve sound parts, wrinkles and failures at different thicknesses.

2 Experimental

Three different materials St14, Al1050-O and pure cupper (99.9%) sheets with different thicknesses are used in HDDRP process to produce conical parts in a single step. Table 1 shows the mechanical properties of these materials obtained from universal tensile tests along three directions: parallel (0°), diagonal (45°), and perpendicular (90°) to the rolling direction of the initial sheet.

Dimensions of the workpiece used in this research are shown in Fig. 2. A 200 kN universal testing machine was used in the experiments. Figure 3 shows the experimental setup. A typical pressure loading path used

Table 1 Materials' properties

Parameter	Al1050-O	Pure copper	St14
Yielding stress, σ_y/MPa	32	123	162
Poisson ratio	0.33	0.32	0.3
Elastic modulus/GPa	70	117	210
Strain hardening exponent, n	0.25	0.44	0.34
Hardening coefficient, k/MPa	140	530.98	668.3
Anisotropy coefficient, r_0	1.39	1	1.87
Anisotropy coefficient, r_{45}	1.24	1	1.65
Anisotropy coefficient, r_{90}	1.46	1	2.14

during the forming process is illustrated in Fig. 4. Only the trend is shown in this figure and the real values are given in final PWDs. A pre-bulging pressure was applied on the sheet to increase the sheet/punch contact and improve the formability. The maximum pressure ($p_{\max}$) was adjusted manually by a pressure relief valve. This pressure is one of the most effective parameters in formability of conical parts in HDDRP process.

3 Finite element simulations

Commercial finite element software ABAQUS 6.12 was used for numerical analysis. Material behavior was assumed to be anisotropic for St14 and Al1050-O and isotropic for pure copper. Plastic stress ratios were used to incorporate anisotropic coefficients in process simulation [14]. The values shown in Table 2 are calculated by Eqs. (1) to (4).

$$R_{11}=1 \tag{1}$$

$$R_{22}=\sqrt{\frac{R_{90}(R_0+1)}{R_0+R_{90}}} \tag{2}$$

$$R_{33}=\sqrt{\frac{R_{90}(R_0+1)}{R_0+R_{90}}} \tag{3}$$

$$R_{12}=\sqrt{\frac{3R_{90}(R_0+1)}{(2R_{45}+1)(R_0+R_{90})}} \tag{4}$$

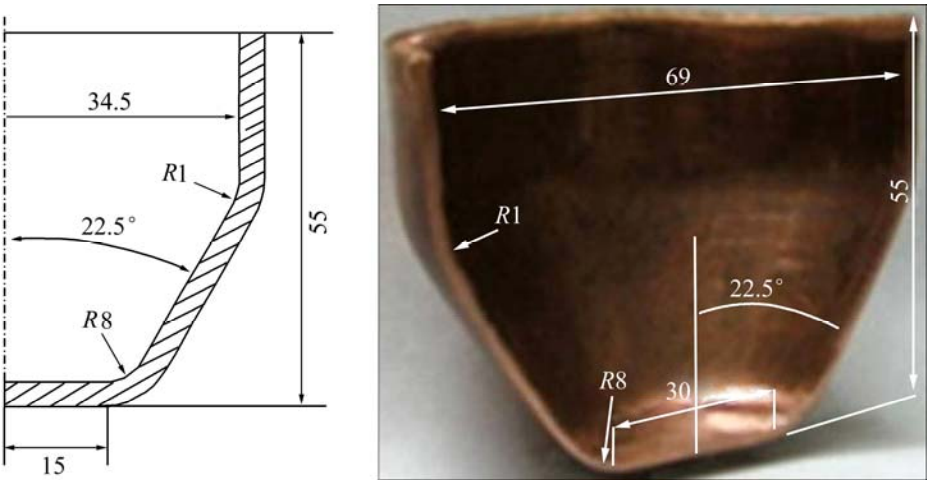

Fig. 2 Part geometry of workpiece (Unit: mm)

Fig. 3 Experimental setup of HDDRP

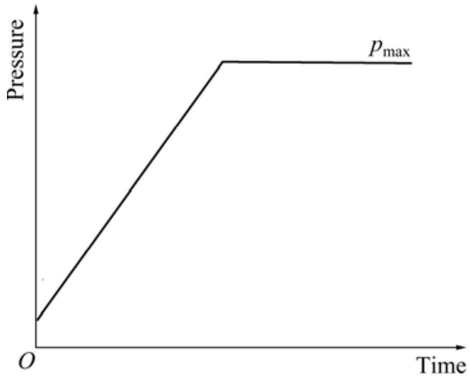

Fig. 4 Typical pressure loading path used in experiments

Table 2 Plastic stress ratios of studied materials

Material	R_{33}	R_{22}	R_{12}
St14	1.0227	1.2376	0.9311
Al1050	1.0148	1.1053	0.9045

The blank was meshed as a 3D deformable axisymmetric mesh with C3D8R 8-node elements. Element size was determined by sensitivity analysis, 4 elements at thickness direction and 78 elements along the length. The die was modeled as a 3D discrete rigid body with a 4-node element R3D4. The die and the blank-holder were fully constrained while the punch could move with a constant velocity along *Z*-axis. The gap between the die and the blank was obtained based on the initial sheet thickness. The actual punch velocity was 0.2 m/min but the multiplication factor of 100 was used in the simulation in order to reduce the calculation time [5]. Only a quarter of geometry was modeled due to axisymmetric geometry. Surface-to-surface contact type was used to model the contact between the parts. Contact friction was modeled using the Coulomb friction model. Friction coefficient of 0.14 was used at blank/punch interface, and 0.04 between the blank and other surfaces [15]. Failure criterion was determined as 30% thinning which is proved to be an acceptable estimation [16−18]. Figure 5 indicates the FE model for HDDRP process.

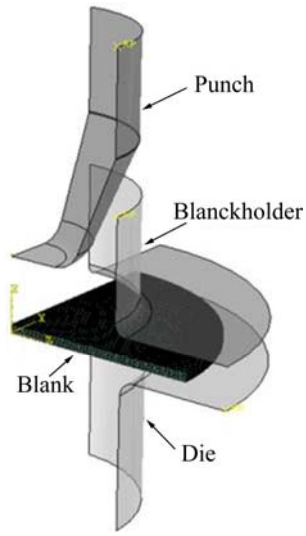

Fig. 5 Finite element model for HDDRP process

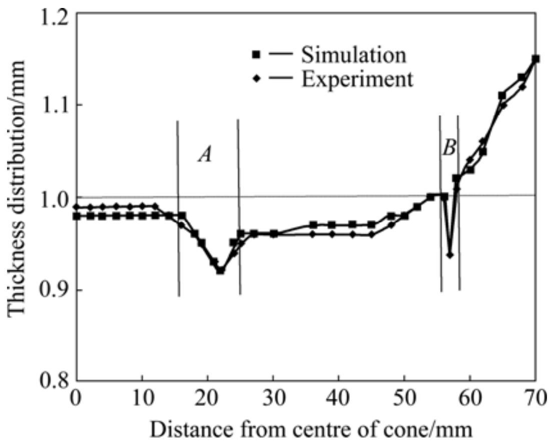

Fig. 6 Thickness distribution of St14 specimen with initial thickness of 1 mm under maximum pressure of 20 MPa

4 Results and discussion

Experiments were performed to validate the finite element results. Figure 6 compares the thickness distribution of one steel sample with initial thickness of 1 mm obtained from experiments and simulations. Thickness of the specimen was measured using a micrometer with 2 mm intervals between each measure point. It is seen that there is a good agreement between the results. Maximum difference is about 1%, showing the reliability of the finite element model. Different frictional conditions and material's anisotropic properties could be the reasons of slight difference between the experimental and numerical results. Two critical areas related to the punch tip radius (Area *A*) and transition area of conical to cylindrical section (Area *B*) are specified in Fig. 6. The critical forming area can be transpired at one of these areas, *A* or *B* based on the maximum forming pressure. But as Area *A* suffers more from thinning, the probability of fracture at this zone is higher.

Pressure loading path has an important role in formability and thickness distribution of final parts. Loading paths with different maximum pressures were investigated based on the typical path shown in Fig. 4. Loading path is considered as a main parameter for prediction of PWDs by finite element analysis of conical parts. The pressure range to form a sound part or probability of defects occurrence alters according to the initial thickness. Therefore, the blank thickness is an effective parameter in determination of PWD in this research.

Figure 7 represents the PWDs in forming of conical parts with assistance of HDDRP process for pure copper, St14 and Al1050-O based on different pressure paths and initial sheet thicknesses. Appropriate and non-appropriate forming areas are determined in these PWDs. Safe zone, in which a sound part is formed, displays the proper range of maximum pressure versus sheet thickness. This zone is divided into three areas: desired forming (Area I), forming with increasing pressure (Area II) and forming with decreasing pressure (Area III).

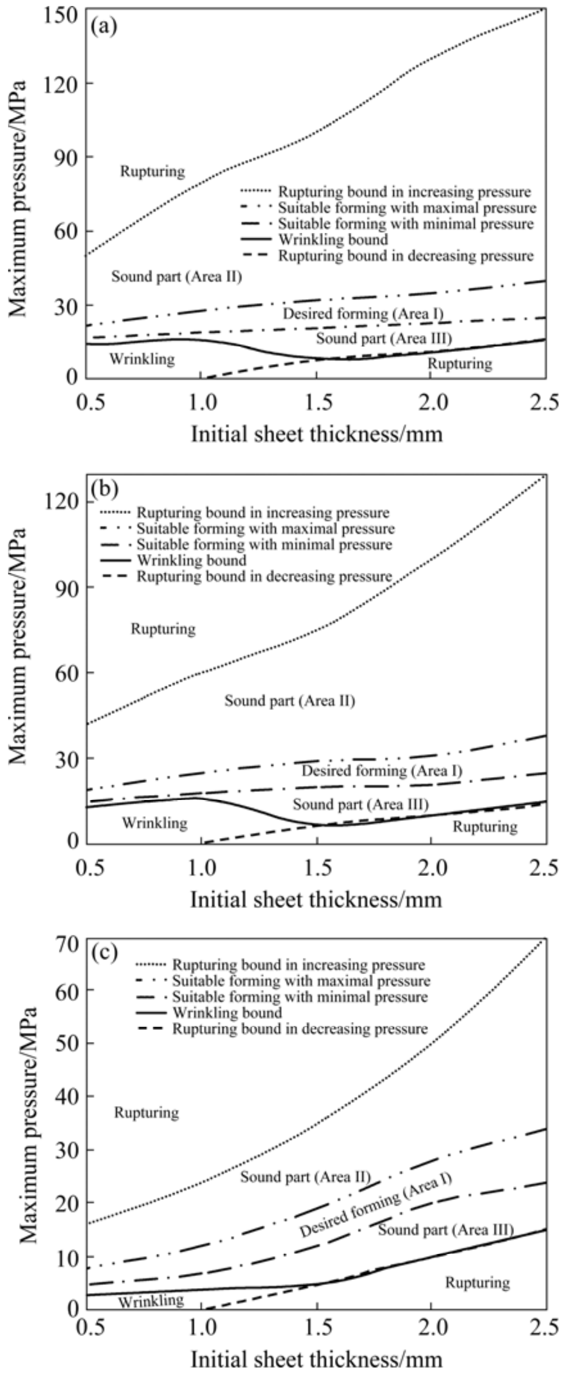

Fig. 7 Process window diagrams for conical parts: (a) St14; (b) Pure copper; (c) Al1050

Production of a part with uniform thickness distribution and minimum thinning percentage in critical areas is defined as a desired forming. Forming area with increasing pressure stands in the upper section of the desired forming bound. With increasing the maximum pressure at this region, thinning percentage at critical areas increases, but does not exceed the failure criterion (30% thinning). It finally approaches to the rupture border. Forming area with decreasing pressure settles in the lower section of desired forming bound. Thinning in Area III increases similar to Area II with decreasing the maximum pressure, but there is probability of occurrence of wrinkling or rupture dependent on the initial sheet thickness. With more pressure reduction from Area III, three conditions exist: 1) for initial sheet thickness of 1.5 to 2.5 mm, rupture happens, 2) for initial sheet thickness less than 1 mm, wrinkling happens, and 3) for initial sheet thickness of 1 to 1.5 mm, first wrinkling and then rupture occurs. Wrinkling happens when the required force is not enough to push the blank completely against the punch. Regarding the obtained PWD, with decrease of initial sheet thickness from 2.5 mm to 0.5 mm, the maximum pressure for sound part reduces up to 74% for steel, 79% for aluminum, and 75% for pure copper. Also, pressure range of desired forming is decreased for all mentioned materials between 20% and 70% with decrease of blank thickness 2.5 mm. It is shown that safe zone becomes 20% to 70% smaller with reduction of initial blank thickness, while the probability of wrinkling increases.

Pressures of 16 to 50 MPa for steel, 16 to 42 MPa for copper and 15 to 16 MPa for aluminum in the safe zone from their related PWD resulted in non-defective products. With comparison of these results for steel, copper and aluminum sheets, it is concluded that the material with higher strength has a wider safe zone. It can be seen that the total trend of pressure vs thickness curves defining different forming regions is similar for different materials.

Sound parts of pure copper and St14 produced under 25 MPa and Al1050 produced under 24 MPa are shown in Fig. 8. The initial thickness of all blanks was 2.5 mm. Quite acceptable shape conformity exists between the experimental products and numerical results.

Defective parts in rupture area are shown in Fig. 9. As is seen, the maximum pressures of 4, 5 and 6 MPa, respectively for a 2 mm-thick St14, pure copper and Al1050 cause fracture at tip radius (Area *A*). So, as previously discussed, it is concluded that the occurrence of rupture at Area *A* is more probable than that at Area *B*.

Wrinkling defect in experimental parts is compared with FE predicted results for specimens with 1 mm in

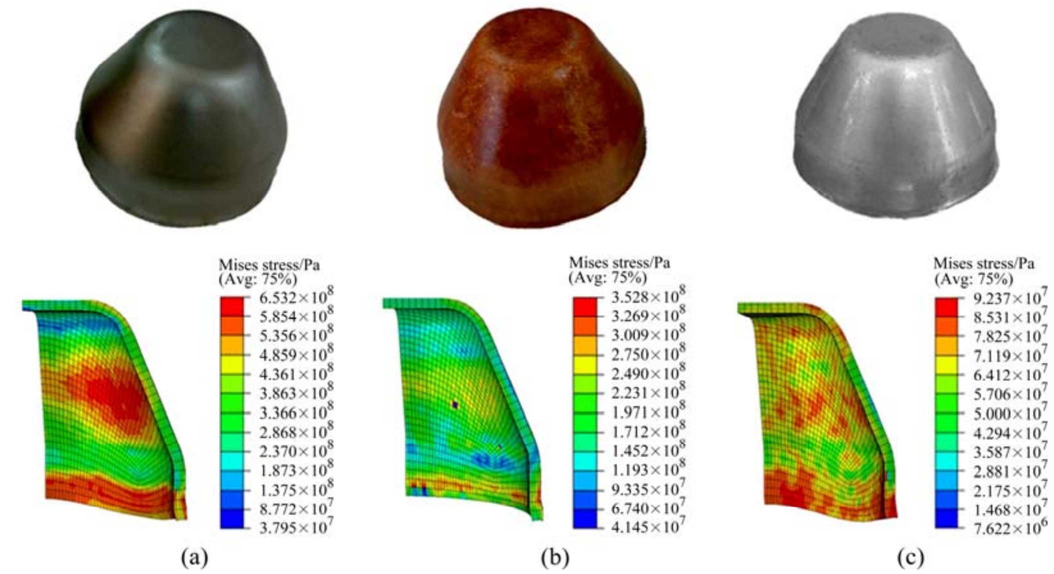

Fig. 8 Sound parts with thickness of 2.5 mm using suitable pressure paths: (a) St14 with 25 MPa; (b) Pure copper with 25 MPa; (c) Al1050 with 24 MPa

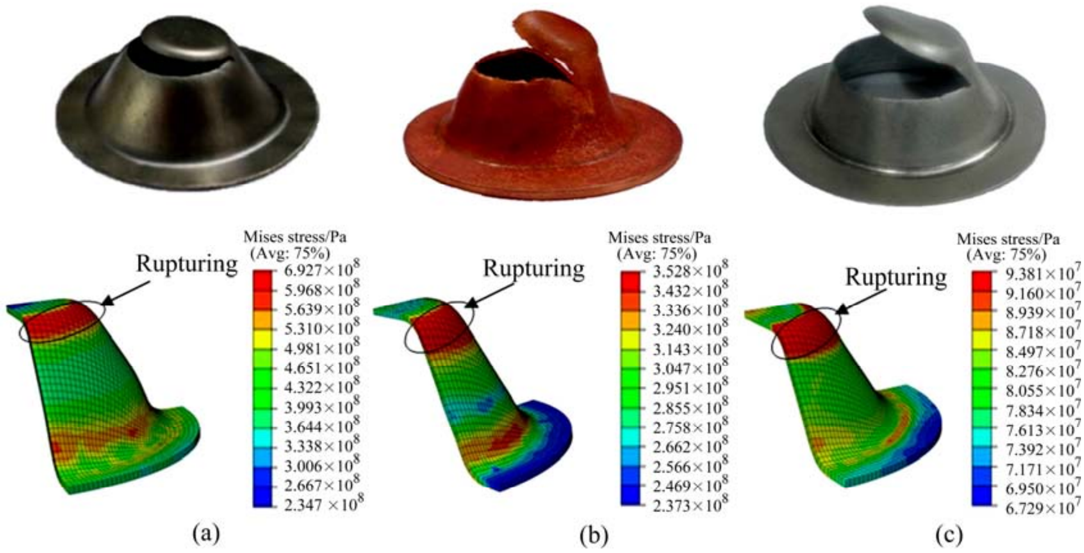

Fig. 9 Parts with rupture in thickness of 2 mm: (a) St14 with maximum pressure of 4 MPa; (b) Pure copper with maximum pressure of 5 MPa; (c) Al1050 with maximum pressure of 6 MPa

thickness in Fig. 10. The predicted number of wrinkles in FE simulations is less than that in experiments. It may be raised from higher punch velocity in finite element method compared with the real one. Wrinkles in finite element models of Fig. 10 have been explicated by insufficient connection between the formed part and the punch. Pressure paths of maximum 6, 5 and 4 MPa were applied to illustrating wrinkling in 1 mm-thick steel, copper and aluminum parts, respectively.

Figure 11 shows the thinning percentage of formed parts under suitable pressure path for different blank thicknesses according to the determined PWDs for pure copper, St14 and Al1050. It can be observed that with the increase of blank thickness, the thinning percentage increases from 8% to 12% for St14, 9% to 16.4% for pure copper and 10% to 18.8% for Al1050. Therefore, lower blank thickness results in more uniform thickness distribution, and hence better formability for conical parts in HDDRP process. The reason is emanated from reduction of the maximum pressure required for desired forming of thinner blanks, and subsequently less circumferential stresses during the forming process. With regard to Fig. 11, steel parts encounter less thinning than other two materials. Thus, the highest uniformity of thickness distribution and the best formability happen in St14 with thickness of 0.5 mm.

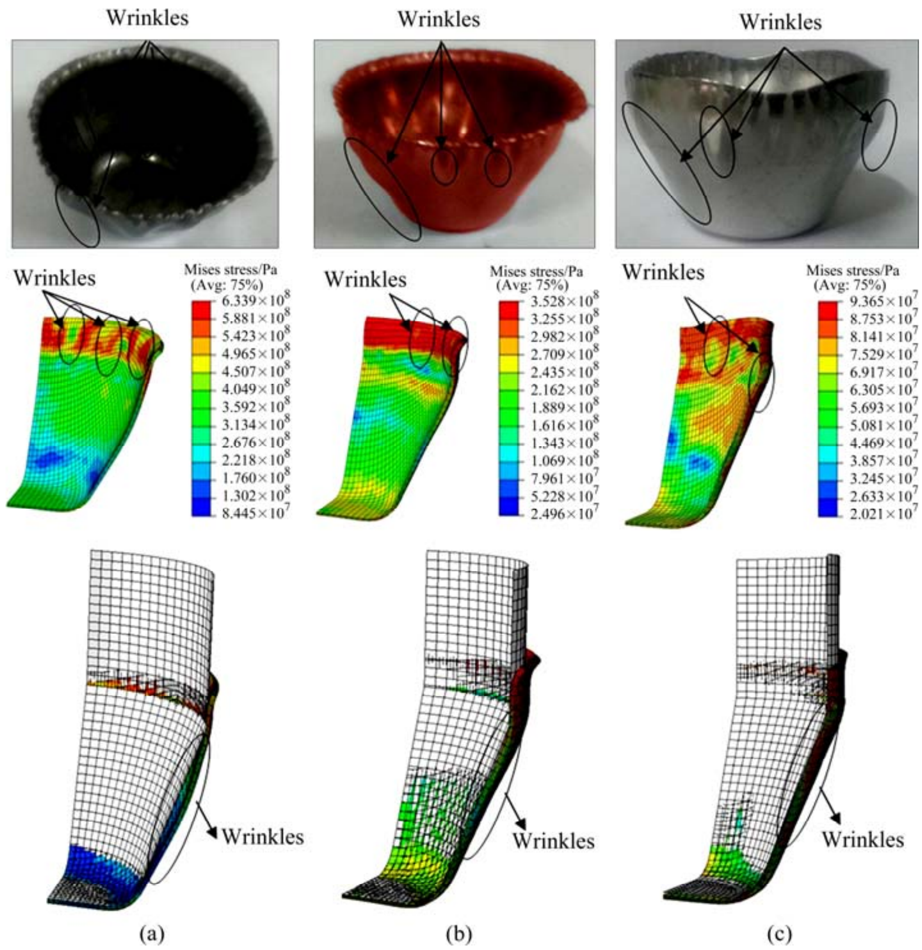

Fig. 10 Parts with wrinkles in thickness of 1 mm: (a) St14 with maximum pressure of 6 MPa; (b) Pure copper with maximum pressure of 5 MPa; (c) Al1050 with maximum pressure of 2 MPa

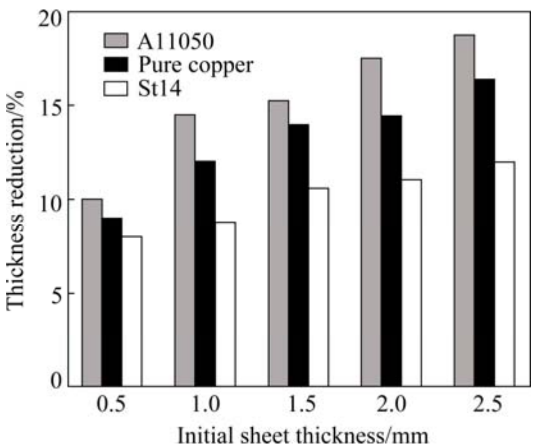

Fig. 11 Thickness reduction in critical area *A* obtained by suitable pressure path

5 Conclusions

1) Process window diagrams (PWDs) for production of conical parts using HDDRP process are developed for Al1050-O, pure copper and DIN 1623 St14 steel. Three forming zones including safe, wrinkling and rupture zones are determined based on maximum pressure and blank thickness.

2) Safe zone is divided into three areas: desired forming, forming with increasing pressure and forming with decreasing pressure. Ideal part with the best thickness distribution and minimal thinning is produced in Area I. Above Area II rupture occurs and below Area III rupture or wrinkling happens based on the initial sheet thickness.

3) Thinner sheet leads to a smaller safe zone and higher probability of wrinkling and rupture. However, the sheet with less initial thickness and more strength shows better formability and uniformity of thickness distribution on final product. The presented PWDs are a reliable design tool for determination of process parameters in industrial manufacturing of cups made of mentioned materials using HDDRP.

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径向压力辅助充液拉深锥形杯的工艺窗口图

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摘　要：起皱和破裂是锥形杯成形过程中的主要缺陷。径向压力辅助充液拉深是一步成形筒形件的板材液压成形技术。获得了径向压力辅助充液拉深 Al1050-O、纯铜和 DIN1623 St14 钢板的工艺窗口图。该工艺窗口图可快速评估板材液压成形零件的可制造性。采用有限元方法对径向压力辅助充液拉深进行模拟，并研究压力路径和原始材料及其厚度的影响。通过实验对模拟结果进行验证。结果表明：对于初始厚度较薄和强度较高的板材，其成形性更好，最终产品的的厚度分布也更均匀。所得工艺窗口图可以预测在不同加载路径下合适的加工区间以及破裂或起皱的可能性。

关键词：锥形杯；充液拉深；有限元模拟；工艺窗口图

(Edited by Yun-bin HE)