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Die design for deep drawing with high-pressured water jet utilizing computer fluid dynamics based on Reynolds' equation

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ABSTRACT

This paper proposes a new die design for deep drawing with high-pressured water jet. The authors had previously proposed a deep drawing method with high-pressured water jet. The water jet enables deep drawing without oil or other chemical lubricants, which might require some additional processes for lubricant removal and become a nuisance in the environment. One of the problems in the method using a prototype die with 8 nozzles in the hoop direction had been that the pump pressure had to be boosted significantly high for successful deep drawing, leading to scars on the surface of the deep drawn product. In the present paper, two new concepts of design were introduced with the help of computational fluid dynamics (CFD) for water film considering the blank deformation obtained by the finite element method (FEM). The first concept is that the number of nozzles should be increased from 8 to 16, and that the position of the added 8 nozzles should be positioned on the flange part of the die as a result of the CFD. The second concept is to shallowly engrave a looped ditch linking the nozzles. The CFD showed that while the die without the looped ditch generated an area of reduced pressure between the nozzles, the ditch-engraved die maintained the pressure, resulting in satisfactorily strong uplift force on the blank even at relatively low pump pressure. A series of experiments also verified the numerical results, and proved the excellence of the ditch-engraved die.

1. Introduction

Lubricants have been practically used in metal forming. The main purpose of using lubricants is to reduce friction. Reducing friction has an effect on improving forming limit, decreasing forming force, preventing burn on and galling, prolonging the life of the die, and improving surface quality. Various types of lubricants are used depending on the purposes and conditions of metal working. Metal soap is used with the combination of zinc phosphate coating in the case of rather severe cold forming such as forging or wire drawing (Kuboki, 2012). Forming oil or oleaginous solution are more common and general lubricants for cold metal forming such as rolling and spinning (Yamamoto et al., 2001).

Deep drawing is also a forming process for which forming oil is used. Suitable lubrication could improve the drawing ratio and prevent surface damage. However, oleaginous or chemical lubricants might generally require some additional processes for lubricant removal and become a nuisance in the environment. There are some way to form a metal without lubricants. Coating a thin layer to the die (Klocke et al., 2006) or pre-coated sheet metal (Kim et al., 2002) is one of them. Also ceramic die which has high tribological properties successfully deformed a metal in dry condition (Kataoka et al., 2004). But the problem is that forming limit is low and coating is expensive in general. Water-soluble lubricants could be some solutions (Gariety et al., 2007).

Hydromechanical deep drawing (HDD) is used for enhancement of the surface integrity and forming limits, or for suppression of material and die costs (Nakagawa et al., 1997). Numerical analyses using the Finite Element Method have been tried to clarify the effect of process parameters on the shape and defect of aluminum and mild steel blank for HDD (Zhang et al., 2000). Complex analysis conditions such as boundary condition for HDD was discussed in detail (Lang et al., 2004). However, the size of the equipment is large and complex because of the huge clamping force, the supplying system of pressure media and the media sealing devices. In addition, cycle time is long which causes problems in productivity.

Water itself could be the ultimate solution if it could be supplied by relatively concise devices. Therefore, the authors had proposed

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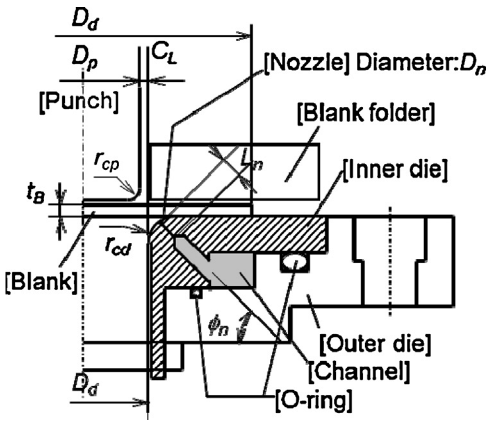

Fig. 1. Composition of experimental setup with nozzles for high pressured water jet.

a deep drawing method using high-pressured water jet (Murata and Kuboki, 2006). Although the proposed method successfully deformed a blank into a cup shape, some scars were observed on the surface of the cup because the nozzle type and its positions were determined by trial and error.

This paper proposes a new die design for deep drawing with high pressured water jet, based on the results of a new numerical approach. In the analysis, computational fluid dynamics (CFD) using Reynolds' equation was introduced for the evaluation of the thin water between the die and sheet metal. The CFD considers the blank deformation obtained by the finite element method (FEM). Firstly, the effects of a nozzle number and the elevation angle were examined by the analysis. Secondly, a new concept of a looped shallow ditch linking the nozzles was introduced and the effect was also numerically studied. Finally, a series of experiments also was conducted for the verification of the excellence of the ditch-engraved die.

2. Deep drawing with high-pressured water jet

Deep drawing with a high-pressured water jet is very unique because it has nozzles on the die shoulder as shown in Fig. 1. The basic composition is similar to the conventional deep drawing machine. The die is composed of an outer and inner die so that various types of nozzles might be attempted by replacing the inner die. The high-pressured water is supplied from the pump and flows through the nozzles and makes a water film between the die and the blank, and the water film thickness depends on the pump pressure. The detailed conditions of the equipment are shown in Table 1. Blank holding force F_b was set to 1 kN based on the authors' previous experiment.

The mechanical properties of 1100 aluminum are shown in Table 2. The properties were determined by uni-axial tensile test and were used for the finite element analysis.

Table 1
Deep drawing conditions.

Drawing conditions	Blank holding force F_b/kN	1
	Clearance C_L/mm	1.15
Punch	Diameter D_p/mm	30
	Corner radius R_{cp}/mm	5
Die	Inner diameter D_d/mm	32.3
	Corner radius R_{cd}/mm	5
Nozzle	Diameter D_n/mm	0.6
	Length L_n/mm	4
Blank	Thickness t_b/mm	1
	Diameter D_b/mm	56, 57, 58.5, 60
	Material	1100 aluminum

Table 2
Mechanical properties of 1100 aluminum.

Elastic properties	Young's modulus E/GPa				72
	Poisson's ratio ν				0.33
Plastic strain	0.0	0.02	0.04	0.06	0.08
Uni-axial stress	89	108	109	109	109

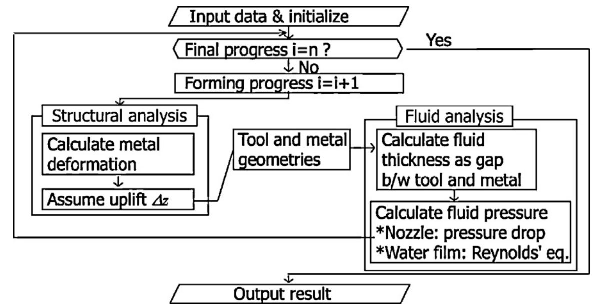

Fig. 2. Combination of numerical analysis.

3. Numerical analysis

3.1. Combination of numerical analyses

FEM was carried out to obtain the deformation of the material, which was used for the CFD based on Reynolds' equation for calculating the fluid condition between the die and material. Another theoretical examination was carried out for the evaluation of the water flow in the nozzles. The flowchart is shown in Fig. 2.

3.2. FEM model for blank deformation

Elastic-plastic analysis was carried out using the commercial code ELFEN, which was developed by Rockfield Software Limited, Swansea. An implicit scheme was used and a von Mises' yield criterion was adopted, and the normality principle was applied to the flow rule. Constraints were dealt with by the penalty function method. The analysis was carried out in axisymmetric way, and a quadrilateral element was used because of the simplicity of the material deformation. The detailed conditions of the FEM are shown in Table 3. Blank deformation in FE analysis is shown in Fig. 3.

3.3. Water flow condition inside the nozzle

Although both the nozzles and water film between the die and material could be resumed in a CFD, it might be complicated to compose the model and lead to instability in analysis. Therefore, the relationship between flow velocity and pump pressure was experimentally examined, and the result was compared with a theoretical equation. Fig. 4 shows the experimental set-up used for the evaluation of the nozzle characteristics. The water was pressured by the plunger pump being supplied to the container. A pressure gauge was attached to the container for the measurement of the water pressure inside. There are nozzles on the container top and the nozzles' diameter is 0.6 mm, which is the same as the one for the deep drawing die. The relationship between the water pressure and

Table 3
Conditions for FE analysis.

Friction coefficient	Blank holder side	0.15
μ	Die side	0.08
Mesh division	Thickness/degrees div^{-1}	0.25
	Radius/degrees div^{-1}	0.28
Analysis scheme	2D static implicit	
Element type	Quadrilateral	