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Electromagnetic pulse-assisted incremental drawing of aluminum cylindrical cup

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ABSTRACT

Based on the needs of low plasticity materials and large height diameter ratio parts forming, a new forming approach named electromagnetic pulse-assisted incremental drawing (EMPAID) has been proposed in this study. The radial magnetic force produced by circular auxiliary coils on and underneath a flange pushes sheet metal in the radial direction. The axial magnetic force generated by drawing coil in the bottom of the punch pushes the sheet metal into the die cavity. The magnetic force produced by the corner coil provides a through-thickness pressure on the sheet metal around the die corner, which prevents wrinkling. The forming process and principle of the new method are analyzed in this study. To investigate the effects of the auxiliary and corner coils, which are added to stamping tools to improve the wall-thickness distribution, the stress state, and the forming quality, two different cases are compared and analyzed in simulation and experimentally. The result indicates that the radial magnetic force generated by the auxiliary coil could reduce the radial tensile stress, which mitigates the crack of the workpiece. Using this new forming method, the limit drawing height can be increased to 2.16 times of that in the conventional drawing.

1. Introduction

Due to the poor cold formability of aluminum alloys during deep-drawing procedure, many forming methods have been explored to increase the drawing ratio. Hydro-forming is one of the most effective methods. Thiruvarudchelvan and Tan (2007) provided a technique that allowed a hydraulic pressure to apply a peripheral force on a flange and applies a counter pressure in the die cavity to provide frictional support at the cup wall. This process also provided excellent lubrication at the radius of the die. Using this forming method, a cup with a drawing ratio of 2.77 has been successfully drawn compared with an LDR of approximately 2.2 with the conventional deep drawing method. For certain thin wall parts with larger LDRs, the radial tensile stress produced by plastic deformation is sufficiently large that fractures can easily occur near the punch nose due to flange shrinkage. Thus, Nakamura and Nakagawa (1987) proposed a new forming process called counter-pressure deep drawing assisted by radial fluid pressure, in which aluminum blanks with a thickness of 0.8 mm have been drawn at a draw ratio of 3.6. However, the radial pressure acting on the periphery of the flange is provided by the chamber fluid through a bypass and is thus equal to the fluid pressure and cannot be changed independently. Yang et al. (1995) developed certain improvements to this forming process by imposing a radial pressure to the rim of the flange that was separate from the chamber pressure. Therefore, it is easy to increase the assisted radial pressure independently when operating deep drawing. As a result, the forming limit can be improved dramatically.

Psyk et al. (2011) noted that electromagnetic forming is a typical high-speed forming process that uses a pulsed magnetic field to apply Lorentz' forces to form sheet metal with high conductivity, such as aluminum alloys. Compared with conventional quasi-static processes, the forming limits of several materials can be extended due to high deformation velocities and strain rates. Seth et al. (2005) show that a high deformation velocity can significantly increase the formability of steels with low quasi-static ductility. Oliveira et al. (2005) showed that the strain to failure in low-ductility materials can markedly increase during electromagnetic forming into a selected die cavity. As reported by Golovashchenko (2007), the electromagnetic forming and quasi-static forming limit curves were created based on the experimental results. Those authors reported that no significant increase in formability for free-formed aluminum alloys; however, a significant increase was reported in the forming limits with electromagnetic forming when forming into a

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conical or V-shaped die. Imbert et al. (2005) analyzed the effect of work-piece-tool interaction on damage and found that the compressive hydrostatic stresses caused by the impact of the sheet metal and the tool can effectively mitigate damage from occurring, improving the formability of materials. Additionally, Thomas et al. (2007) electromagnetically loaded Al AA6063-T6 tubes; their experimental results showed a 2- to 3-fold increase in the forming limits with respect to the quasi-static case. Those researchers thus attributed the improved formability to the strain-rate sensitivity with possible additional influence from inertia.

Based on the above examples of the electromagnetic forming of sheet metal or tube, electromagnetic forming can markedly increase a material's formability. However, the formability in deep-drawing procedure must be improved. To extend the forming capacity of deep drawing, several approaches have been proposed to combine conventional stamping with electromagnetic forming. Vohnout (1998) successfully used the matched tool-electromagnetic (MT-EM) method to produce a door inner made of an aluminum alloy. First, the part was pre-formed to an optimum extent via conventional stamping; then, an electromagnetic force was used to reform the softened corners into their design radii. Plane strain values in excess of 25% were observed on the electromagnetically reformed panel, and the values were larger than those in conventional stamping. This experimental result shows that the incorporation of electromagnetic coils with the conventional stamping tools can improve the forming limits of sheet metal. Additional, Shang (2006), and Shang and Daehn (2011) introduced a lower-energy electromagnetic-assisted stamping method to form axisymmetric drawing parts. In this method, only appropriate small magnetic pulses are applied to the strategically chosen regions of the sheet metal to control the strain distribution, while the tool punch advances. For blanks with a diameter of 101.6 mm, the maximum cup height achieved by conventional deep-drawing was 10.4 mm; using this new forming method, the maximum cup height was dramatically increased to 34.5 mm after 27 electromagnetic pulses. However, a high blank-holding force is required to prevent wrinkling, and the material flow inward to the die cavity is also inhibited. However, Lai et al. (2015) developed a dual-coil system for deep-drawing of sheet metal with a large drawing ratio. Using this dual-coil system, the maximum forming height of AA1060-H24 cup increased from 8.44 mm to 20.28 mm. This forming method requires two sets of pulsed power systems; after one discharge, the distance between the flange and the coil 2, which is set on the periphery of the flange, increases to counter subsequent discharges. The axial force on the flange region was also strong, which would increase the frictional force between the work piece and the die, and would block the flow of the flange material inward to the die cavity.

Cowan et al. (1986) invented reconnection electromagnetic launching at Sandia National laboratories (SNLA) in 1986. The single-stage launcher consisted of two rectangular, coaxial coils that are separated by a relatively small gap. When a flat-plate projectile passes through the gap in a direction that is orthogonal to the axis of the coils, an eddy current will be induced in the projectile, and the interaction between the magnetic field generated by the coil and the eddy current will generate a forward force at the rear of the projectile, moving it forward. The experimental results show that a 500-kg projectile can be accelerated to 290 m/s using this single-stage launcher. Thus, if considered a flange made of sheet metal as the flat-plate projectile, and arranged two identical coils in the holder and the die, respectively, it should be determined whether the flange material can be accelerated into the die cavity. Based on this idea, Fang et al. (2014) proposed a new technology named electromagnetic pulse-assisted progressive deep-drawing. This method combined reconnection-electromagnetic-launching technology and the electromagnetic forming method with conventional deep-drawing. To manufacture cylindrical parts, many sets of rectangular coils have been arranged on the rim of the flange along the circumferential direction, thus the flange material, which is located under the gap between two adjacent auxiliary coils, experience no or little magnetic force. Thus, the sheet metal's deformation becomes non-uniform. For this reason, it is better to use two concentric coils as the driver coils, which can provide a radial magnetic force at the periphery of the sheet metal to help the flange material flow into the die cavity. In this study, we developed certain improvements for this forming process and added a corner coil in the blank holder above the die corner, which prevents wrinkling. This process allows cup parts with a high depth-to-diameter ratio to be manufactured. This study presents the experimental and simulation investigation to confirm the feasibility of the EMPAID process.

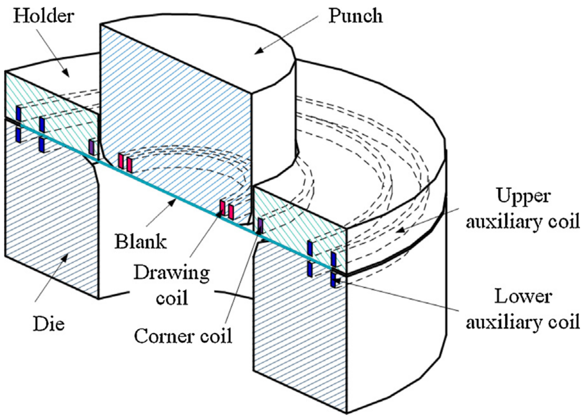

Fig. 1. Schematic diagram of the compound die used in the EMPAID process.

2. Forming principle of electromagnetic pulse-assisted incremental drawing (EMPAID)

As shown in Fig. 1, the compound die for the forming process of the EMPAID process includes three types of coils.

The first type is the drawing coil, which is embedded under the surface of the punch. It used to push the sheet metal under the punch into the die. The second type of coil is the auxiliary coil, including the upper auxiliary coil and the lower auxiliary coil, which are embedded in the blank holder and the die, respectively. Both the upper and lower auxiliary coil are concentric circular coils. The distance between the upper surface of sheet and the upper auxiliary coil should be the same as that between the lower surface of the sheet metal and the lower auxiliary coil. The role of the auxiliary coils is to push the flange portion of the sheet metal into the die.

As shown in Fig. 2, the auxiliary coils function by both applying an electric current in the same direction, producing a magnetic flux that creates transverse and radial force that are similar to those in a rubber band, as shown in Fig. 2(a) and (c). These forces push the flange part of the sheet metal flow inward to the die, as shown in Fig. 2(b). The purpose of the auxiliary coils is to overcome the friction in the flange area so that it can decreases the tensile stress in the corner and side area. This also improves the deep-drawing limit of the cylindrical part. During the forming process, in order to let the flange portion of the sheet metal can receive sufficient electromagnetic force in any position, sometimes it is necessary to set up multiple coils, as shown in Fig. 2(c) and (d). The magnitude of the magnetic force is related to the section of the coil, the number of turns of the coil, the distance between each turn, and the discharging voltage. The study of this related content is in the process; it is thus limited in this study.