Process Modeling of Piercing Micro-hole with High Pressure Water Beam

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Abstract

During the fabrication of very small or fine hole, usually referred to as micro-hole, technical difficulties often arise due to limitation on the precision capability of tooling systems including those associated with alignment. The present project attempts to develop a new process for piercing micro-hole, using high pressure water beam. In this paper, a numerical model for the micro-hole manufacturing is developed which provides helpful insight into the mechanics of the micro-hole forming process and the tooling design. The ALE (Arbitrary Lagrangian-Eulerian) method of dynamic FEM model is used to simulate water hammer and the water beam penetration into the workpiece material. An experiment for hydro-piercing process is also developed to validate the numerical model. The effects of micro-hole parameters, diameter and workpiece thickness, and water pressure on the micro-hole formation are investigated. It is found that the fracture occur near the die corner in workpiece material and that the pressure increases dramatically when the ratio of hole diameter to thickness is less than 1.

Keywords: Microhole, Hydropiercing, FEM, ALE

1. Introduction

There is an increasing demand for manufacturing micro holes. Micro holes have applications in, electronic components, pneumatic sensors and manipulators, fluidic filters, fuel injection nozzles, bio-medical filters, inkjet printer nozzles, optical apertures, high pressure orifices, micropipettes, guides for wire-bonders and spinning nozzles [Masuzawa, T. et al., 2000]. Various micromachining methods such as microdrilling and micro-EDM can produce the holes with a high degree of accuracy. However, their productivity is usually low and, this, limits applicability. Micro forming processes due to their 160% average growth in world market of electronic parts, will be of great importance, compared with the above less productive and environmentally more polluting technologies [Geiger, 2001] [Kals, 1995] [Gieger, 1996]. There have been many investigations about micro blanking and micropiercing processes, such as fine hole piercing using viscoplastic pressure medium (VM process) [Kurosaki, 1990] [Rhim, 2005] and ultra-fine piercing by fiber punch [Mori et al., 1998] [Kurimoto, 2004]. However, all these research papers mostly discuss about technological problems like tool and machine accuracy, punch material and piercing die making, and feasibility of piercing process.

Masuzawa [Masuzawa, 1990] developed a new method, called wire electro discharge grinding (WEDG), for the machining fine pin shaped tools as small as 2.5μm from tungsten carbide or any other conductive material. He also made a special CNC micropunching machine, which could also have WEDG and EDM functions. In this special micropunching system he made a

punch, which also served as an electrode tool for EDMing the die. Therefore, this system was free of an adjusting procedure and a very well aligned die set could be obtained in a very short time, typically less than one hour. In this micro punching system no blank holder was used and the die set had to be used on the CNC WEDG machine. Oh and his coworkers [Joo, 2001] developed a micro hole punching system to make 100μm diameter holes on brass sheet of 100μm thickness. In this work a downscaled conventional piercing die has been used, which consists of a ground punch, a guiding blank holder and a micro electro discharge machined die. Among the shortcomings of their method are difficult punch–die-blank holder alignment and difficulties encountered in extension of their approach to multi punch dies. A new, rather simple and economic ultra- fine piercing process using ceramic SiC fiber with a diameter of 14μm, as a punch has been proposed by Mori et al. [1998] and S. Kurimoto et al [2004, 2002]. However, it was found that tool life was too short to put this method into practical use. In this method, SiC fiber was used not only as a piercing punch but also a tool for making a die hole in perfect alignment with the punch. There was no blank holder in this die set. Sasada et al. [2003, 2004] conducted experiments and FEM analysis on small hole piercing. In their investigation, small hole piercing is defined as piercing performed using punches that have smaller diameter than the material thickness. They reported that: 1) shearing force, stripping force and pushing force are considerably affected by the friction between the punch flank and inner surface of pierced hole, 2) the use of tapered punch is effective for reducing frictional force, and 3) increasing the liner portion at the punch tip increases the shearing force.

Small hole piercing by non-traditional manufacturing processes have been carried out by researchers. Kurosaki et al. [1987, 1990] conducted the simultaneous punching on copper and high-strength carbon steel foils of 5-100 μm in thickness to fabricate holes of 50-100 μm in diameter with silicon polymer punch as a pressure medium and metal die. Takhashi et al. [1991] carried out the blanking process on amorphous alloy sheets of 25μm in thickness for large complicate-shape products of several tens of mm in diameter with rubber punch and tungesen carbide die. Watari et al. 2003] conducted punching of SUS304 sheets of 50 and 100 μm in thickness for single circular holes of 1-5 mm in diameter with urethane sheet as a pressure medium and steel die.

In this paper, a numerical model for hydro-piercing micro-hole is developed by using ALE method of dynamic FEM model to simulate the penetration of water beam into the workpiece material. An experiment for hydro-piercing process is also developed to validate the numerical model. The effects of micro-hole parameters, diameter and workpiece thickness, and water pressure on the micro-hole formation are investigated.

2. Development of the Numerical Model

High speed penetration of water beam into metallic workpiece introduces large deformations in both the water and target involving solid-fluid interaction. The solid-fluid interaction can be effectively modeled by ALE (Arbitrary Lagrangian-Eulerian) formulation. In ALE formulation, the Lagrangian domain deals with the movement/deformation of the structure part, and Eulerian domain handles the movement of fluid. Therefore, the ALE capability is used to model the solid-fluid reaction between high speed water beam and metallic workpiece in this research. All simulations are performed using the explicit non-linear FEA code LS-DYNA 970. The most significant aspects of the FEM model includes geometrical discretization, applied boundary conditions, material modeling and contact modeling and are detailed below.

2.1   Geometrical discretization

Five parts are required to model the hydro-piercing process, namely workpiece (sheet or foil), die container, piercing die, and water beam as well as void mesh. Figure 1 (a) shows the ALE model which presents the half of piercing process due to axi-symmetric nature of the process, while the Figure 1 (b) and (c) present the Lagraingian and Eulerian domains respectively. The Lagrangian domain covers die container, sheet/foil and piercing die. The void mesh and water beam define the Eulerian domain. The numerical geometry is governed by the experiment set-up where the sheet/foil thicknesses are 0.025 and 0.05 mm respectively,   diameters of water beam (also diameters of micro-hole) are 0.015, 0.025, 0.05 and 0.1 mm, and piercing die corner angle is 0.005 mm. The sheet/foil is composed of 1200 elements characterized as single-point integration solid Eulerian elements with single material and void, while the die container and piercing die are modeled using Belyschko-Tsay elements of the Lagrangian formulation [Hallquist, 1998] [LS-DYNA 970 KEYWORD USER'S MANUAL]. In the ALE formulation the material is not constrained to the original workpiece, therefore an void mesh is constrained to allow the water flowing to penetrate the sheet/foil throughout the simulation. As the void mesh initially did not contain any material, it is set as a void medium. It is necessary to model this void mesh large enough to provide ample space for any possible material flow, therefore it consists of 1300 Eulerian elements of single-point quadrature.


(a) ALE model   (b) Lagrangian Domain   (c) Eulerian Domain
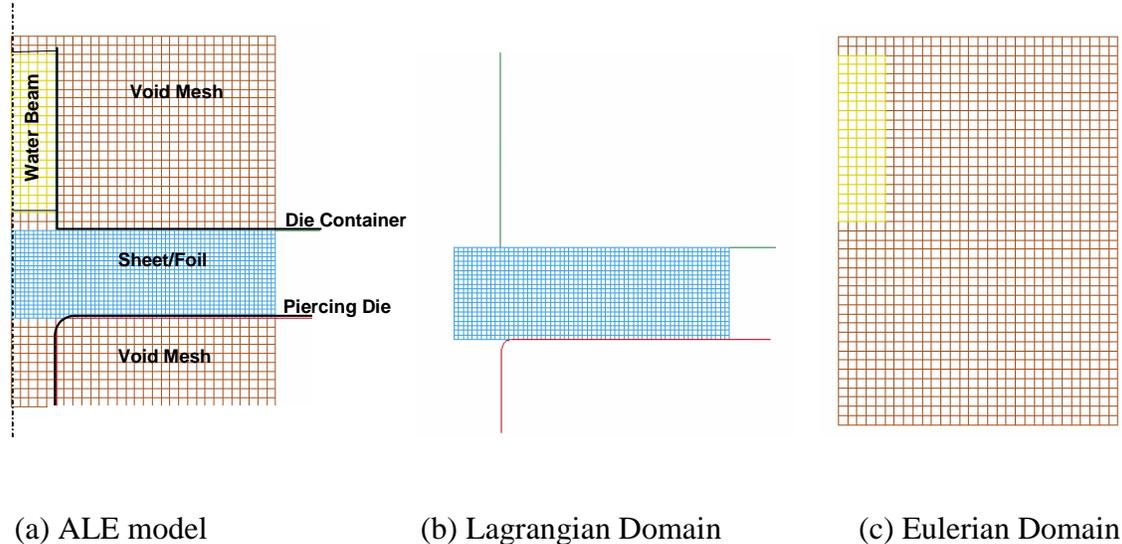
Figure 1 FEM Model for hydro-piercing

2.2 Applied boundary conditions

To properly reflect the experimental set-up, all element nodal points of the piercing die and die container are restricted from motion in all degree of freedom and the material of sheet/foil is constrained along its outside nodal points in horizontal direction. The water beam is assigned the appropriate velocity to form high speed water pressure effect. Material on nodal points of the void mesh and sheet/foil lying on the symmetric plan are constrained to move only within the symmetry plane.

2.3 Workpiece material modeling

Workpiece materials used in this research are: aluminum foil and copper foil. Material type employed in defining workpiece behavior in this ALE-FEM simulation is an elastic-plastic isotropic hardening with a bilinear stress-strain response. Material data of the aluminum is obtained from Ref. [Chen, 1995] while the copper from Ref. [MatWeb], Table 1. Figure 2 illustrates the bilinear behavior of the flow stress vs. strain for aluminum. In comparison to the power-law model the bilinear model provides excellent agreement at large strains while discrepancies are evident at true strain levels less than 0.2. Because penetration produces large strains in the target, the discrepancies at low strain levels are not expected to have an adverse effect on the solution. Hence, the bilinear model is considered acceptable Ref. [Chen, 1995].

Table 1 Material properties of workpiece

	Aluminum	Copper
Density	2.7 g/cm^3	7.93 g/ cm^3
Young's modulus	68.9 GPa	115 GPa
Poisson ratio	0.33	0.33
Hardening modulus	25.78 MPa	137.5 MPa
Yield stress	340 MPa	195 MPa
Plastic failure strain	0.8	0.8
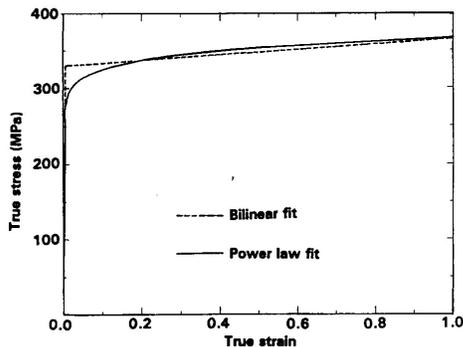
Figure 2 Flow stress of Al foil [Chen, 1995]

During the piercing process, severe distortions of elements take place in the sheet/foil along the interface of water-workpiece. Physically, these elements contain material which has been severely deformed and provide little or no resistance to further penetration. However, severe distortions in these elements can cause inversion of elements and hence numerical instability. Numerical stability can be maintained by deleting these highly distorted elements based on a selected failure criterion. If the deleted elements are indeed physically insignificant, then elimination of them from further computation should not have an adverse effect on the final result. For the present research, because the workpiece behaves as an elastic-plastic material, a failure criterion based on equivalent plastic strain (EQPS) is chosen to control element deletion. In other words, when the EQPS of an element in the workpiece attains a critical value, this element is instantly deleted from the further calculation. Based on the experimental data and computational efficiency, the critical EQPS value for all subsequent calculations is fixed at 0.8.

Since the deformation of the tool is negligible in comparison to the workpiece and the water beam, the tool was modeled as a rigid entity. Properties of the tool material used in the material model are listed in Table 2.

3. Results and Discussion

FEM simulations are carried out with two different sheet/foil thickness, namely 0.025 mm and 0.05 mm (25 µm and 50 µm), and four hole diameters, namely 0.015, 0.025, 0.05 and 0.1 mm (15, 25, 50 and 100 µm). During the simulation, the water beam is given a high initial velocity to create enough pressure to deform the sheet/foil material and penetrate into the sheet/foil material to make a hole. The simulation results are compared to the experimental data and are illustrated in the following sections.

3.1   Some observation from FEM simulation and experiment

Table 2 shows the deforming behavior and shearing process of the workpiece foil during penetration of water beam for different hole-diameters. It is seen from listed deformation pictures that that shearing occurs and the fracture of workpiece material takes place near the die corner area.

Table 1

Piercing time	FEM simulation (t = 0.025 mm)				
	D/t = 1.67	D/t = 1.0	D/t = 2.0	D/t = 4.0	D/t = 6.0
0.074 µm					
0.084 µm					
0.11 µm					
0.13 µm					
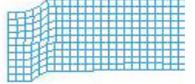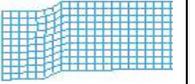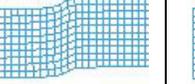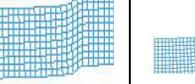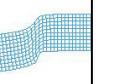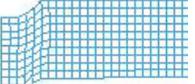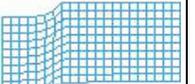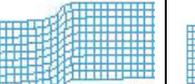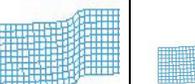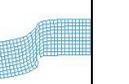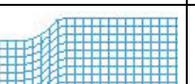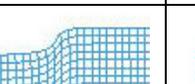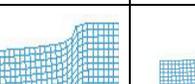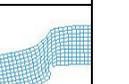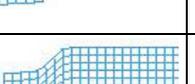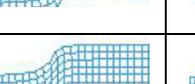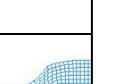
The observed deformation behavior is different from that in conventional piercing process where the shearing starts near the punch corner area and the fracture takes place inside the workpiece in the shearing zone. This is because there exist a strong hydrostatic effect (compressive stress state) on the upside of the workpiece foil which retards the shearing failure, while there exists a tensile stress state around die corner area which is favorable for the occurrence of fracture.

3.2   Piercing pressure

Figure 3 and 4 illustrate the relationship between the minimum pressure for the start of piercing (critical pressure) and the ratio of diameter to foil thickness.
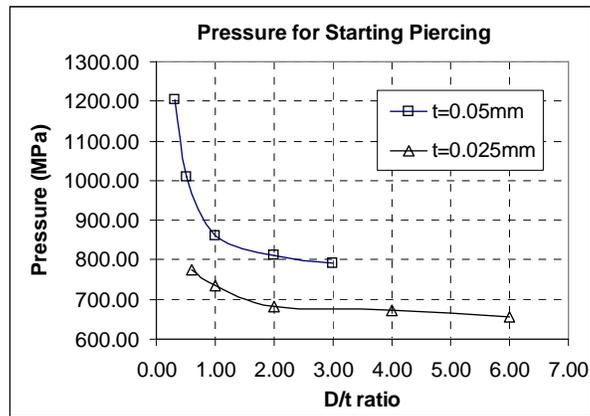
**Figure 3** Critical piercing pressure vs. D/t ratio for aluminum foil
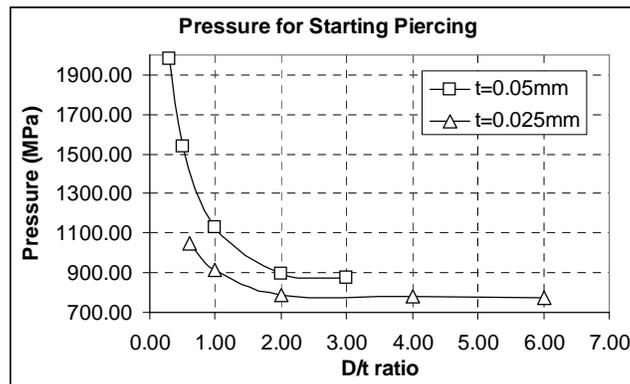
Figure 4 Critical piercing pressure vs. D/t ratio for copper foil

It is seen that with the decrease of ratio of diameter to foil thickness, the piercing pressure increases sharply. It is found that the pressure increases dramatically when the ratio of the hole diameter to thickness is less than 1. For aluminum foil, the critical pressure to start piercing a hole with diameter of 15 μm (thickness of 25 μm) is about twice that of 150 μm with the same foil thickness. In piercing copper foil, the critical pressure for 15 μm hole is about 3 times that for 150 μm hole with the same foil thickness.

4. Conclusion

In this research, the feasibility of hydropiercing microhole by high pressure water is established. A numerical model is develop for process optimization.

The process of hydro-piercing for micro-hole was analyzed by both analytical and numerical methods. The deformation and shearing process of workpiece foil during the hydro-piercing process are investigated. It is observed that the shearing and fracture occur near the die corner in workpiece material which is different from that in conventional piercing process. The working pressure obtained from the developed model can be used to design the micro-piercing/perforating die.

Acknowledgement

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