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NUMERICAL ANALYSIS OF MAGNETIC PULSE FORMING AND DEFORMATION STRUCTURE OF PURE Al AND Cu SHEETS

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ABSTRACT

Magnetic pulse forming (MPF) is one of the extreme high-speed forming processes. A metal sheet which is accelerated by electromagnetic force is collided onto a mold and fine and sharp details of the product can be obtained. The deformation mechanism of the MPFed metal cannot be understood only by the microstructure observation of the deformed metal. The deformation behavior of the metal should be investigated also by considering the local microstructure change with strain, strain rate and temperature change during deformation. Numerical analysis is an effective method to achieve this requirement. In this study, pure Al and Cu sheets were deformed by MPF. Impact velocity of the metal sheet was calculated by using ANSYS Emag-Mechanical. Based on the obtained impact velocity, the deformation behavior of the metal sheet was reproduced, and local strain, strain rate, and temperature were analyzed by using ANSYS AUTODYN. The relationship between the local microstructure change of Al and Cu sheets and the deformation parameters was examined.

KEYWORDS

Magnetic pulse forming (MPF), Numerical analysis, Microstructure change, Strain distribution, Strain rate change, Temperature distribution

INTRODUCTION

Magnetic pulse forming (MPF) is one of the high-speed forming processes using electromagnetic force. Fine and sharp details of the product can be obtained, and springback after deformation is extremely reduced in comparison to the conventional forming processes (Psyk, Risch, Kinsey, Tekkaya, & Kleiner, 2011). Figure 1 shows a schematic diagram of MPF. A metal sheet is placed over the coil in the discharge circuit. The discharge current runs through the coil, and magnetic field is produced around the coil. An eddy current is induced in the metal sheet. Interaction between magnetic field and eddy current creates electromagnetic force. The metal sheet accelerated by electromagnetic force collides onto the mold. Forming is completed in a few tens of micro-seconds. MPF is suitable for metals with a high electrical conductivity like Al and Cu. The MPFed metal may have characteristic microstructure because of high strain rate deformation.

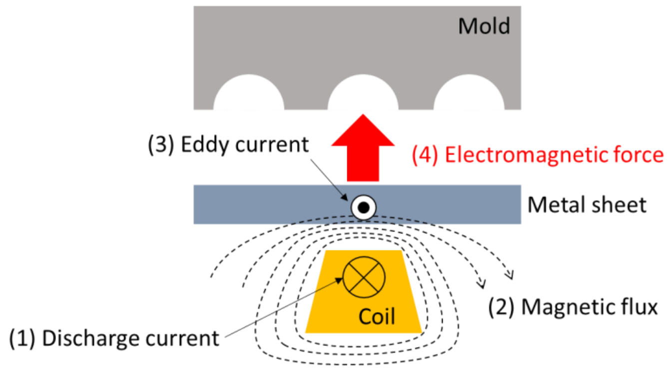

Figure 1. Schematic diagram of magnetic pulse forming method

There are several reports which examined the microstructure of MPFed metals. Liu et al. reported that the electromagnetic formed 5052 Al alloy sheet had high dislocation density (Liu, Yu, & Li, 2012). Jiang, Li, Xiong, Li, and Liu (2014) reported dislocation slip mechanism of electromagnetic bulged pure Cu based on microstructure observation. However, the deformation mechanism cannot be understood only by microstructure observation of the deformed metal. This is because the deformation behavior of MPFed metal includes the local microstructure change with strain, strain rate and temperature change during deformation. It is difficult to examine these changes only by experimental measurements. The introduction of numerical analysis is required to deal with the present subject. Some researchers employed numerical analysis to investigate MPF behavior. Cui et al. (2014) investigated bulging behavior of the MPFed metal sheet by using ANSYS Emag and ANSYS Mechanical. However there are few studies concerning local microstructure change of the metal during MPF. In this study, pure Al and Cu sheets were deformed by MPF. Impact velocity of the metal sheet was calculated by using ANSYS Emag-Mechanical. Based on the obtained impact velocity, the deformation behavior of the metal sheet was reproduced, and the local strain, strain rate, and temperature were analyzed by using ANSYS AUTODYN. The relationship between the local microstructure change of Al and Cu sheets and these parameters was examined.

EXPERIMENTAL PROCEDURE

Figure 2 shows the schematic diagram of experimental setup for MPF. The MPF was performed by using a Bmax MP 12.5/25 machine with capacitance of 40 µF. A pure Al sheet (A1050 hereafter Al, 200×70×0.8 mm) and a pure Cu Sheet (C1020 hereafter Cu, 200×70×0.75 mm) were used as the metal sheet. A steel block with a groove as shown in Figure 2 was used as the mold. The size of the groove is 500 µm in depth and 1000 µm in width and the bottom of the groove has a right angle. The metal sheet was placed over the coil and the mold was fixed above the metal sheet. The gap and overlap were defined as shown in the Figure 2 (b) and (c). The longitudinal direction of the coil, the direction in which the groove was engraved, and the directions perpendicular to them were defined as CD, GD and VD respectively. The experimental conditions are shown in Table 1. After forming, microstructure observation was conducted for the transverse cross section normal to the GD.

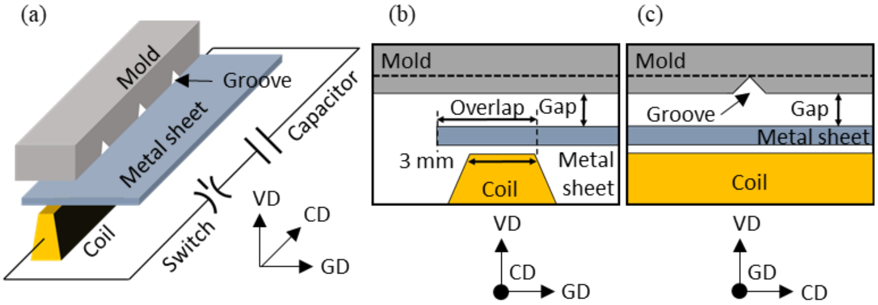

Figure 2. (a) Schematic diagram of experimental setup (b) view from CD direction (c) view from GD direction

Table 1. Experimental conditions

Metal sheet	Gap (mm)	Overlap (mm)	Charging energy (kJ)
Al	1.15	8	6
Cu	1.20	5	8

NUMERICAL ANALYSIS METHODS

Estimation of Impact Velocity

In order to analyze the electromagnetic field and deformation behavior of the metal sheet, ANSYS Emag-Mechanical was used. Figure 3 shows the model of Emag-Mechanical. This consists of the FEM circuit and FEM model. The FEM circuit consists of inductance, capacitor, resistance and coil. The FEM model consists of metal sheet, mold, coil, air and infinite boundary. A coil in the FEM circuit and the FEM model are coupled. Discharge current, magnetic flux and electromagnetic force are analyzed by using Emag. The deformation behavior of the metal sheet is analyzed by Mechanical, and the impact velocity is estimated. In the first step, the discharging current through the coil was calculated from the FEM circuit. In the second step, the magnetic flux around the coil was calculated, and the eddy current produced in the metal sheet was analyzed by Emag FEM model. The electromagnetic force was calculated from the interaction between the magnetic flux and the eddy current. In the third step, the deformation behavior of the metal sheet by electromagnetic force was reproduced by Mechanical FEM model. These steps were repeated until the metal sheet collides onto the mold, and the velocity at the moment of collision was defined as the impact velocity (V).

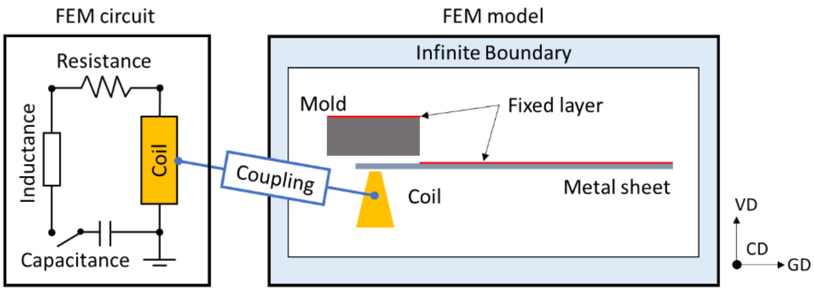

Figure 3. Model of Emag-Mechanical

Reproduction of Metal Sheet Deformation in the Groove

The deformation behavior of the metal sheet in the groove was reproduced by ANSYS AUTODYN. Smoothed particle hydrodynamics (SPH) method was used to simulate the very large deformation of metal sheet in the groove. The SPH method is a mesh-free analysis method which is superior to analyze heavy deformation. In the SPH method, particles are defined as interpolated points of physical quantities. The diameter of a particle is defined as smoothing length (h). The physical quantity of the particle is calculated in reference to neighboring particles inside a circle of radius $2h$. Figure 4 is a schematic diagram of the SPH model setup. The V obtained from Emag-Mechanical was given to the metal sheet as the initial condition. The h of the metal sheet was set to 3 µm. The h of the mold was set to 3 µm near the surface and h gradually increased moving away from the surface as shown in Figure 4. The Mie-Gruneisen EOS based on the shock Hugoniot was applied for metal sheet and mold. The Steinberg-Guinan constitutive model was applied for the metal sheet, and Johnson-Cook constitutive model was applied for the mold. Gauge points, which are used to record the time history of each particle, were arranged on metal sheet, and local strain, strain rate and temperature changes during deformation were analyzed by using SPH method.

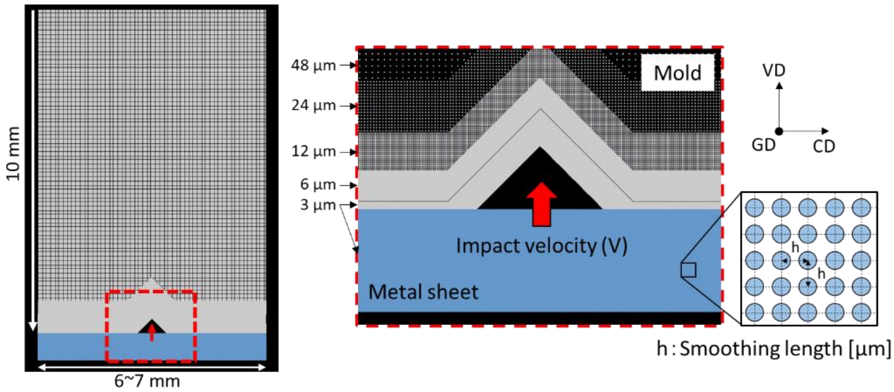

Figure 4. Schematic diagram of the SPH model setup

RESULTS AND DISCUSSION

General and Local Microstructure Change of Metal Sheet After MPF

Figure 5 shows the optical micrographs of the cross section of deformed Al and Cu. The groove was completely filled with the deformed Al and Cu. Grain morphology of Al and Cu at the slope area was different from the initial form and it was elongated along the slope of the groove as shown in the middle figures of Figure 5 (a) and (b). On the other hand, grain morphology at the center area was the same with the initial form, as shown in the right panels of Figure 5 (a) and (b).

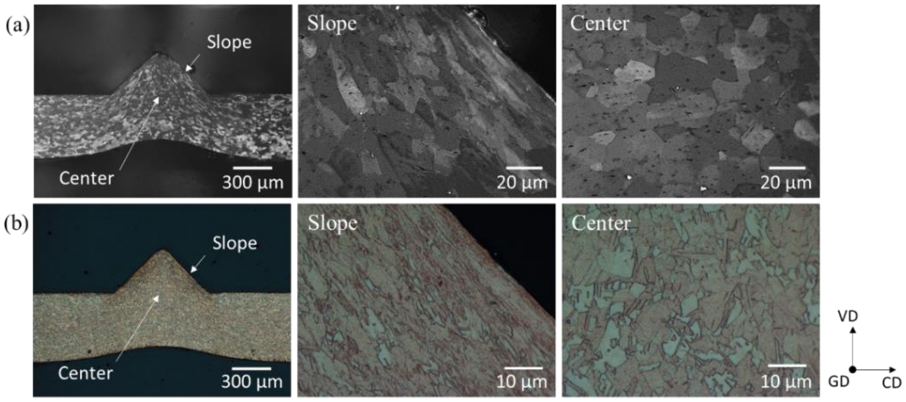

Figure 5. Optical micrographs of MPFed (a) Al and (b) Cu

Impact Velocity

Magnetic flux, electromagnetic force and deformation manner of the Al and Cu were reproduced by using Emag-Mechanical. Figure 6 shows the deformation behavior of the Al and Cu reproduced by Emag-Mechanical. The local area of the sheet located above the coil deformed radially and hit the mold. The elapsed time from the onset of discharge current introduction was 8.5 µs for Al under 6 kJ and 11 µs for Cu under 8 kJ. The location where the sheet first hit the mold surface was defined as the first impact point. The impact velocity was obtained from the analytical results of velocity profile of the first impact point. The impact velocity for Al and Cu was 305 m/s and 220 m/s, respectively.

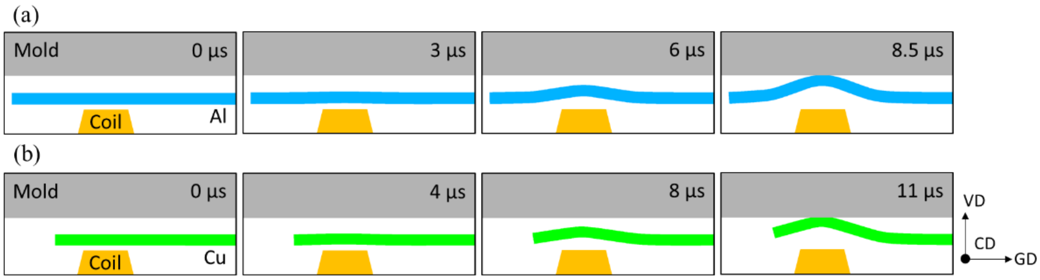

Figure 6. Deformation manner of (a) Al and (b) Cu reproduced by Emag-Mechanical

Deformation Behavior and Strain Distribution During Deformation

The deformation behavior of Al and Cu sheets in the groove were reproduced by using AUTODYN as shown in Figure 7, where, 0 µs means the time instant at which the metal sheet collided with the mold surface. The location of the metal fronts moving up along the mold surface of the groove was indicated by black arrows. The metal fronts indicated by black arrows flowed into the groove faster than the metal front of the middle area. The groove was filled with Al and Cu completely only in 0.8 and 1.7 µs, respectively. Figure 8 shows the strain distribution in each metal sheet. Extremely large strain was observed at the sheet surface deformed in shear along the slope. In contrast, strain of the center area was negligibly small. Such a strain distribution corresponded very well to the change in grain morphology, as shown in Figure 5.

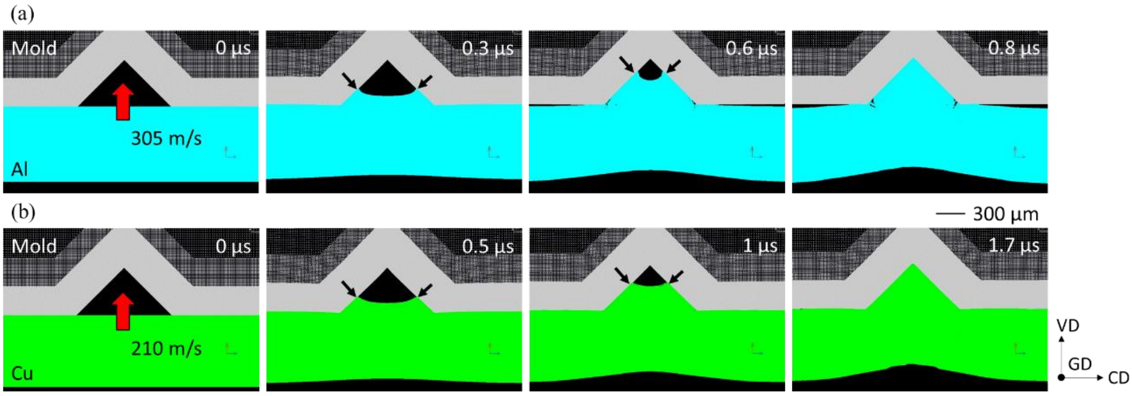

Figure 7. Deformation behavior of (a) Al and (b) Cu in the groove

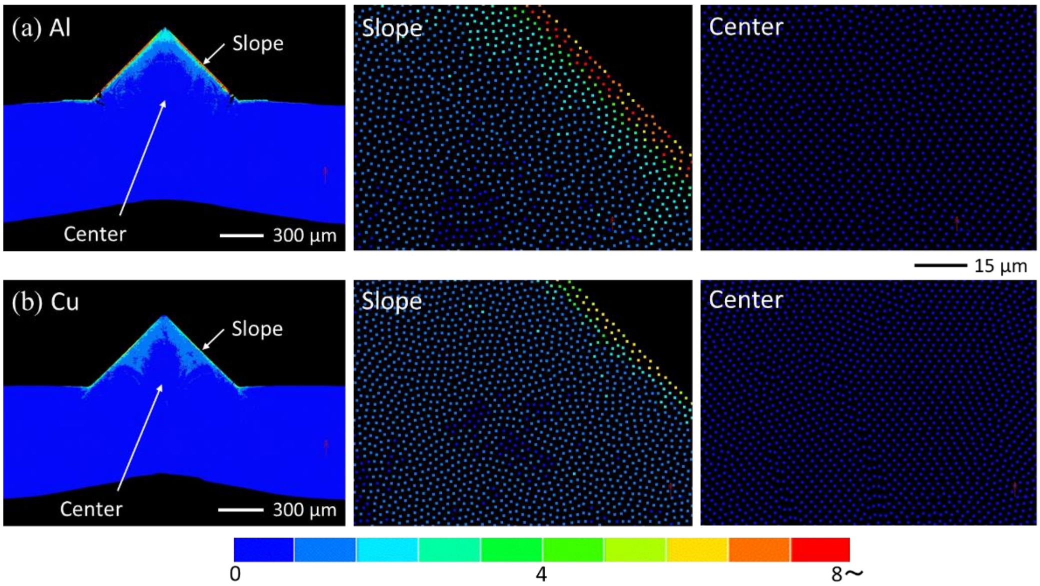

Figure 8. Strain distribution after deformation of (a) Al and (b) Cu

Local Strain Rate Change During Deformation

The strain rate change during deformation was monitored by using the travelling gauge points located in the near-surface along the slope and in the center area. The upper diagrams of Figure 9 (a) and (b) show the positions of each gauge point before and after deformation. The bottom graphs of Figure 9 (a) and (b) show the strain rate change for each area during deformation. A large strain rate exceeding 10^7 s^{-1} was observed during deformation at the point A and C. On the other hand, strain rate was very small at point B and D compared to that of point A and C.

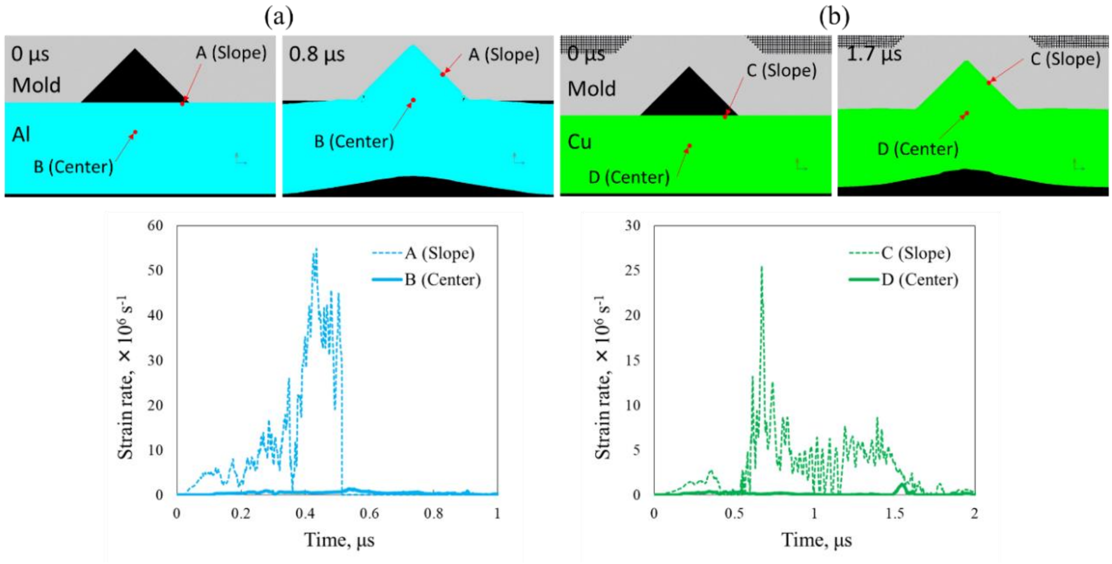

Figure 9. Location of travelling gauge points and the obtained strain rate profile during deformation (a) Al and (b) Cu

Temperature Increase by Deformation

Table 2 shows the ultimate temperature caused by the deformation at the selected points as shown in Figure 9. The ultimate temperature of point A and C was 1140 K and 1150 K, respectively. The temperature of point C in Al reached 1140 K, and exceeded the melting temperature of Al. On the other hand, the temperature increase of point B and D was very small.

Table 2. Temperature after deformation of each location

Metal sheet	Temperature of each location (K)	
	Slope	Center
Al	1140 [Point A]	330 [Point B]
Cu	1150 [Point C]	320 [Point D]

SUMMARY

To investigate the deformation behavior of MPFed metals, pure Al and Cu sheets were hit onto the mold steel with a groove at a high speed by using MPF process. Progress of metal deformation in the groove was also reproduced by using numerical analysis. The deformation of the metal sheet by electromagnetic force was reproduced by Emag-Mechanical, and its impact velocity onto the mold was obtained. Precise deformation behavior of the metal sheet in the groove was reproduced by using AUTODYN-SPH formulation. The characteristic deformation pattern of the metal sheet in the groove was revealed by the simulation. Extremely large strains were observed at the sheet surface, but strain was negligibly small at a mid-thickness area of the sheet. Strain rate change and temperature increase during deformation were also monitored by using the function of travelling gauge points. An extremely large strain rate exceeding 10^7 s^{-1} and high ultimate temperatures over 1100K were observed at the sheet surface. The local microstructure change observed in the MPFed metals showed good agreement with the simulation results.

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