Numerical Simulation and Experimental Study for Magnetic Pulse Welding Process on AA6061-T6 and Cu101 Sheet

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Abstract

Magnetic Pulse Welding (MPW) is a collision welding process, similar to Explosive/impact Welding (EXW), but it utilizes electromagnetic force as the acceleration mechanism. Therefore, the available energy is much lower than EXW and it makes the process safer and more reproducible for sheet seam welding. However, the available energy must be better focused and controlled. In the sheet seam MPW process, a flyer sheet is driven and collides with a target sheet. True metallic bonding is achieved at the mating interface if contact takes place above a critical impact velocity at an appropriate impact angle. The impact velocity and angle are determined by the primary and induced electromagnetic fields. Both of them are strongly related to the geometry of the electromagnetic actuator and the discharge characteristics. An MPW launch system that will robustly provide bonding can either be developed empirically or through simulation. Here we attempt to provide the basis for a simulation-based approach to system design. The oblique MPW impact of AA606-T61 and Cu101 were analyzed using the newly available Electromagnetism (EM) module in LS-DYNA®. This module allows performing coupled mechanical/thermal/electromagnetic simulations. The simulation can predict the impact velocities and the temperature distribution along the mating interface. The simulation results were validated with measurement by Photon Doppler Velocimetry (PDV) measurement. Additionally, the simulation results also indicated rapid thermal cycling on the mating interface.

Introduction

Magnetic Pulse Welding (MPW) uses electromagnetic force to accelerate one metal piece (flyer plate) onto another stationary metal piece (target plate). It has been reported that the velocities attained during this process range from 200 m/s to 500 m/s[1-3] and the joining completed within microsecond [4]. Because of the short impact period, the extent of heating is minimal along the joints. Therefore, comparing to the traditional fusion welding process, the main noticeable advantage is that there is no significant heat affected zones in MPW joints[5]. It is generally agreed that the joining mechanism is similar to explosive joining where the surface oxide of the mating interfaces is disrupted due to the jet action and metallurgical bonding is achieved between clean surfaces. However, MPW has not been utilized and the details of impact process and the critical impact velocity for successful welding are not clearly understood. With these limitations, the implementation of MPW has not been well-developed. The overall study in the paper involves both experimental and numerical study on impact velocity. This paper presents selective results on impact velocity on two materials, AA6061-T6 and Cu101. The

Photon Doppler Velocimetry (PDV) was used to measure the impact velocity and the Electromagnetic (EM) module in LS-DYNA® was used to simulate MPW process.

It is known that a moving surface produces Doppler shifted light and once it combines with the incident light, they produce beat frequency. The beat frequency is proportional to the velocity of the moving surface. Therefore, by measuring the beat frequency, the velocity of the free moving surface can be analyzed. Recently, Strand[6] and the co-works introduced a new method of measuring the velocity of free surfaces with exceptional temporal resolution by PDV. The system includes optic lasers and high-speed oscilloscopes as shown in Figure 1. The technique provides sub-micron displacement resolution, temporal resolution in the nanosecond range, and it is straightforward to collect at multiple locations with several channels. Maximum measurable velocity depends upon the speed of the oscilloscope and instrumentation. We modified and packaged PDV into MPW process. The built-up PDV at OSU can measure four independent velocity channels at the range from zero to about 775m/s over a period of up to 2ms. This can correspond to a displacement of about 1.5m for the maximum speed acting over 2ms duration. For MPW, the typical measured displacements are on the order of centimeters.

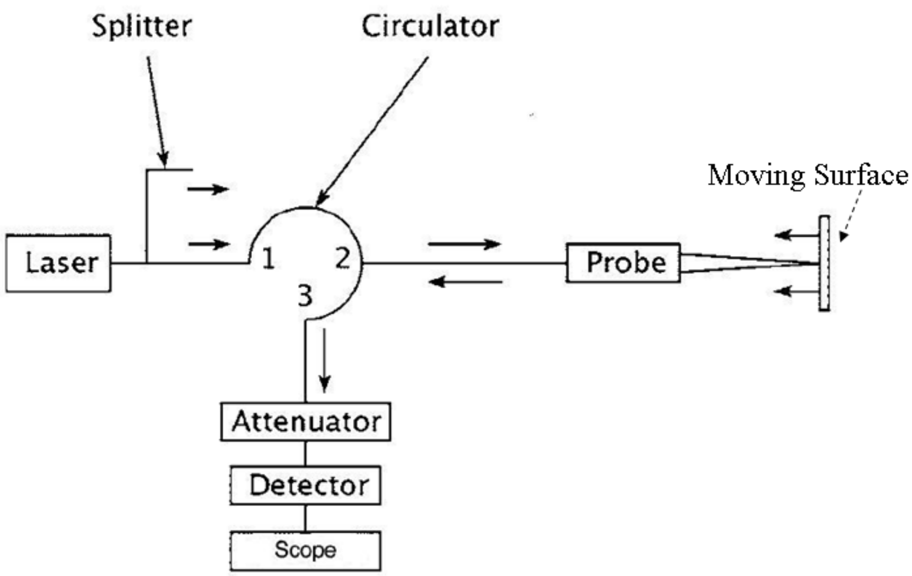

Figure 1 Schematic diagram of PDV system. The arrows indicate the direction of the incident and reflection beam.

MPW is a transient impact process which involves mechanical, thermal and electromagnetic properties. Conventional FEM based approaches could not solve the coupled mechanical, thermal and electromagnetic problem. By the EM module[7, 8] developed in LS-DYNA, the MPW process could be studied.

Materials and Pre-flanged MPW Experiment

In this paper, we studied AA6061-T6 and Cu101 for MPW, because they have high electric conductivity and good weldability. The material properties are listed in Table 1. MPW technology on these materials will promote wide potential applications in automobile, marine and aerospace industries for the fabrication of the light structure components[9-11]. It is known that the impact angle and impact velocity are the two main parameters to make a successful welding. In order to simplify the problem, this paper focuses on the velocity study and the thermal cycle for the flying surface at 45^{o} impact angle. The MPW setup is shown in Figure 2. When the actuator is discharged, the nearby bended flyer plate will accelerate and collide against the target plate. Both the flyer and the target plates have a square shape with a 152.4mm length. For the flyer plate, one edge was flanged to 45^{o} with the bended length 12.7mm. The thickness for both target and flyer plate is around 0.5mm.

Table 1 Material Property of AA6061-T6 and Cu101[12]

Properties	Actuator (Cu101)	Flyer Workpiece (AA6061-T6)	Target Workpiece (Cu101)
Electrical Conductivity ($10^{6}/\ \Omega$ mm)	0.0584795	0.0250627	0.0584795
Mass Density (g/mm^{3})	$8.94\ \ 10^{-3}$	$2.7\ \ 10^{-3}$	$8.94\ \ 10^{-3}$
Young's Modulus (GPa or$10^{9}g/mms^{2}$)	115	68.9	115
Poisson Ratio	0.31	0.33	0.31
Yield Stress (MPa or$10^{6}g/mms^{2}$)	195	276	195
Heat Capacity (J/g ^{o}C or $10^{9}mm^{2}/s^{2o}C$)	0.385	0.896	0.385
Thermal Conductivity (W/mK or $10^{6}gmm/s^{3}K$)	391	167	391
Melting Point (^{o}C)	1083	582~651.7	1083

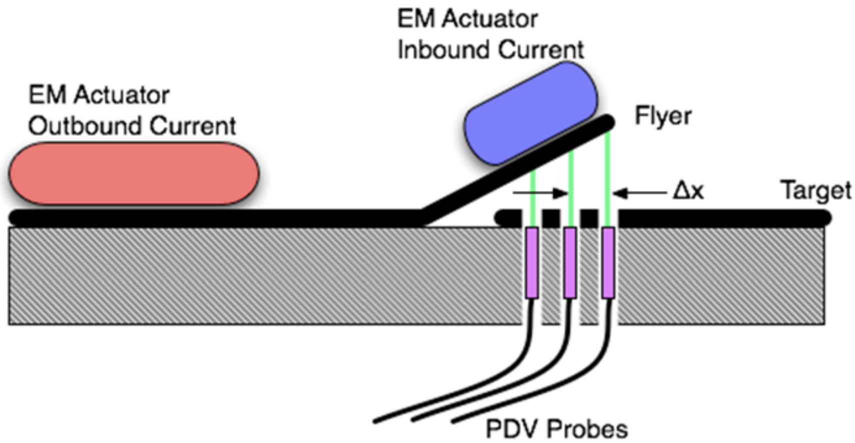

Figure 2 Sketch of the experimental setup of the pre-flanged MPW process. The pre-flanged angle for the flyer plate is around 45^o and it is near to the actuator with certain standoff distance. At this moment, only the middle probe was used to measure the impact velocity. The other two probes will be used experimentally soon.

There are several adjustable process parameters for MPW, such as the discharge energy, the standoff distance and the overlap. We fixed the setup geometry and only changed the discharge energy level at 2.4kJ, 4.8kJ and 7.2kJ for both AA6061-T6 and Cu101. The PDV probes were packaged up into the MPW system to measure the impact velocity and induced current. The spot size of the incident infra-red beam is around 3mm and the initial distance between the flyer surface and the probe is 11.5mm. The beam reflecting surface was scratched in order to obtain scattered diffraction. The collected velocity data were analyzed by a subroutine in Matlab® software.

Experiment Result and Discussion

When the actuator is charged, the primary current inside of the legs generates an Eddy current in the nearby flyer plate. We used a Rogowsky coil coupled with the oscilloscope to capture the primary current signal for both AA6061-T6 and Cu101. The results are shown in Figure 3 and 4, which indicates that the primary current is a function of time. These current versus time profiles were used as the input current for the simulations in LS-DYNA. It was noticed that the primary currents for different discharge energy have similar period but different magnitude. The higher discharge energy generated a larger magnitude for the induced current. Figure 3, 4 also indicate that the primary current for AA6061-T6 plate is similar to the primary current inside of the Cu101 plate. However, the induced current for them are quite different. It is because Cu101 has a two times larger electric conductivity than AA6061-T6 as shown in Table 1.

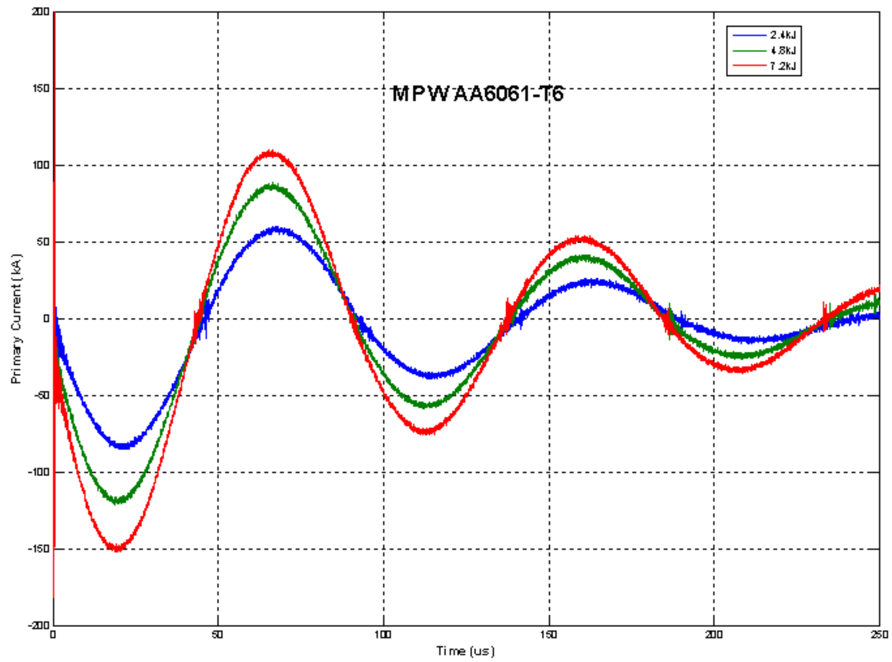

Figure 3 Induced current file for AA6061-T6 with different discharge energy.

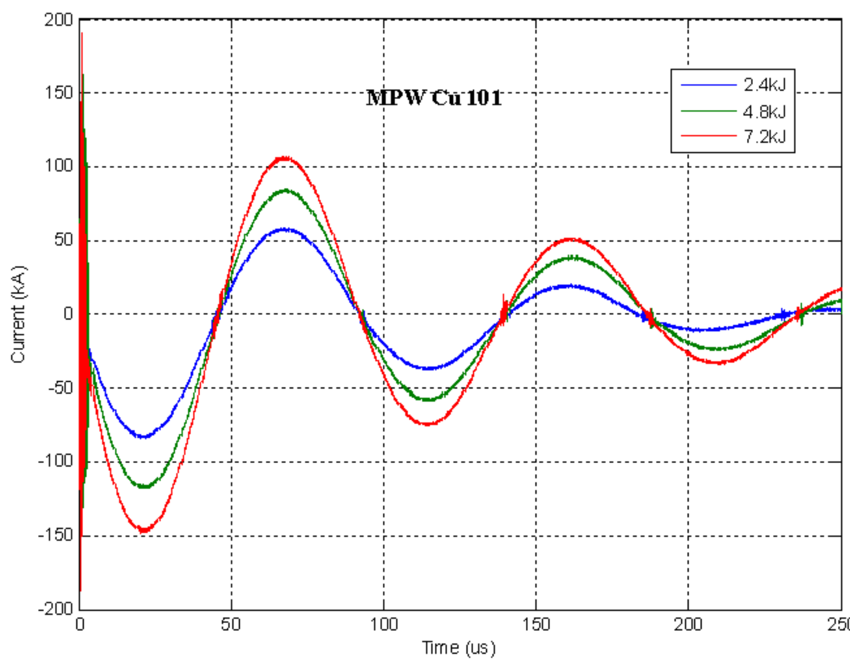

Figure 4 Induced current file for Cu101 with different discharge energy.

PDV can capture high speed process accurately. In this paper, it was also used to measure the impact velocity. The beat frequency of the incident and reflecting beam on the free moving flyer surface is proportional to the impact velocity. Taking Cu101 at 4.8kJ discharge energy for MPW as the example shown in Figure 5, a Matlab subroutine was used to analyze the beat frequency and the result indicated that the flyer plate reached a peak velocity of about 91m/s within 60μs. The impact velocities on AA6061-T6 and Cu101 surface with different energy level were collected and are shown in Figure 6. Both the AA6061-T6 and Cu101 plates have the same volume. However, the AA6061-T6 plates gave higher velocities at the same discharge energy level, because the mass density and the inertia for AA6061-T6 are smaller than Cu101. In other words, in order to make a successful welding on Cu101, it is necessary to input more discharge energy. This result is close to our previous research work on linear MPW system, which suggested that the minimal discharge energy for successful linear welding is 4.8kJ for AA6061-T6[13] and 5.6kJ for copper[14].

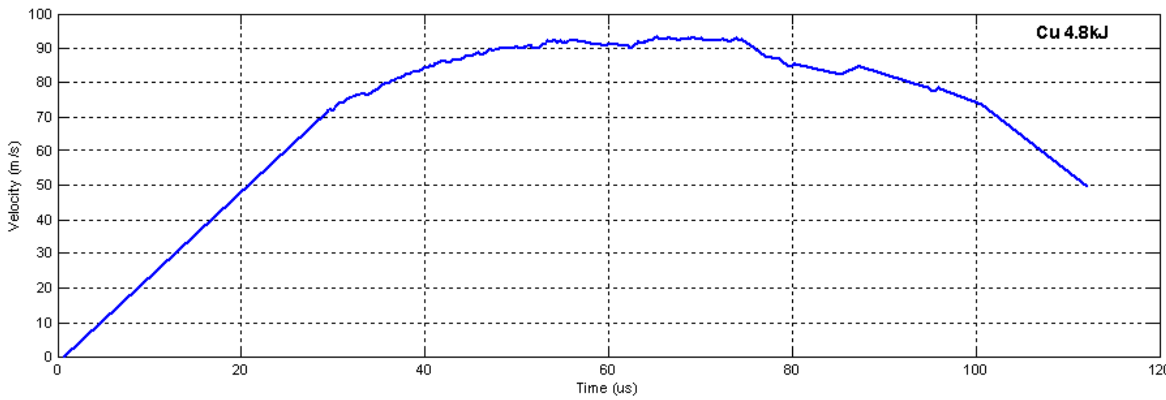

Figure 5 Impact velocity as a function of impact duration for Cu101 at 4.8kJ discharge energy.

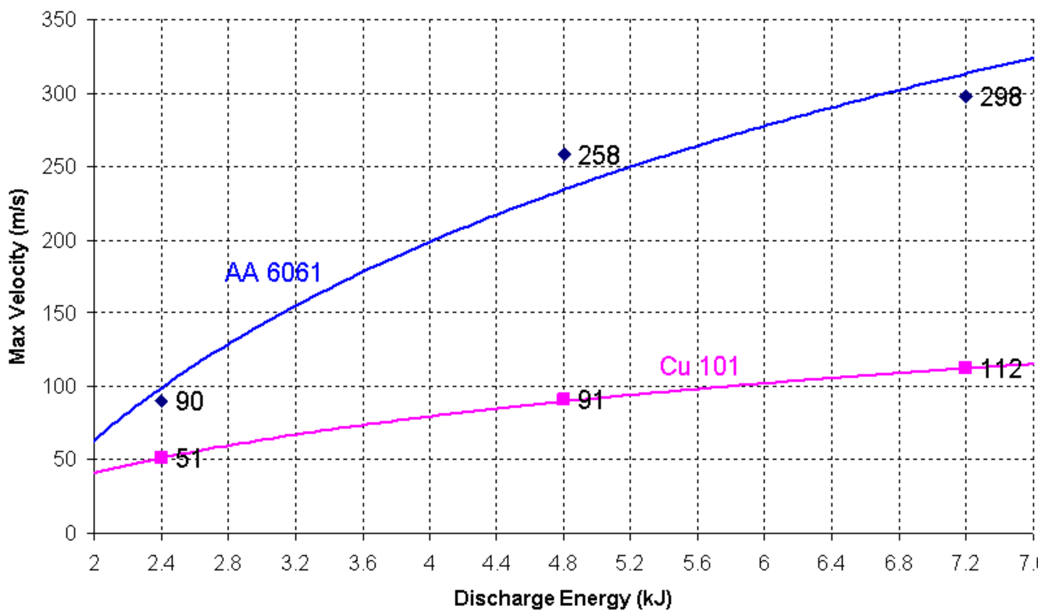

Figure 6 Comparison of the peak velocity for AA6061-T6 and Cu101. The data were collected from the same thickness plates with same pre-flanged angle.

Numerical Simulation Result and Discussion

The three dimensional simulation model in LS-DYNA was built up and shown in Figure 7. There are three parts: the actuator, flyer plate and target plate, respectively. All of the parts are meshed using solid hexahedral elements, with 4 elements through the thickness of the plate. The mesh on the actuator was refined near the chamfered leg. The model is a coupled mechanical, electromagnetic and thermal model. The entire simulation time was setup as 40μs for every process. We also introduced the current-time profile into the solid actuator, and the associated magnetic field, electric field, and current density were calculated by solving Maxwell equations. The current density was shown in Figure 8. For the solid parts, a Finite Element Method (FEM) was used and for the surrounding air a Boundary Element Method (BEM) was used. The magnetic force was added to the mechanical solver and generated the deformation on the workpiece. Therefore, the moving velocity of the flyer pieces could be studied. At the same time, the electromagnetic field also introduced some Joule heating. The temperature of the mating interface was solved by the thermal solver. In turn, the temperature study is very important for the understanding of the MPW mechanisms. The simulation results were interpreted using LS-PREPOST. Figure 9 shows the cross-section of the MPW system at different times. The flyer plate was forced against the target plate and both of them were plastically deformed. We would like to point out that the entire MPW process is completed within 100μs, but due to the elongated BEM faces on the side of the workpiece, the computation time is extremely long. Therefore, we only set the simulation time as 40μs to save time. This is the shortcoming of the simulation work and it should be improved in the near future.

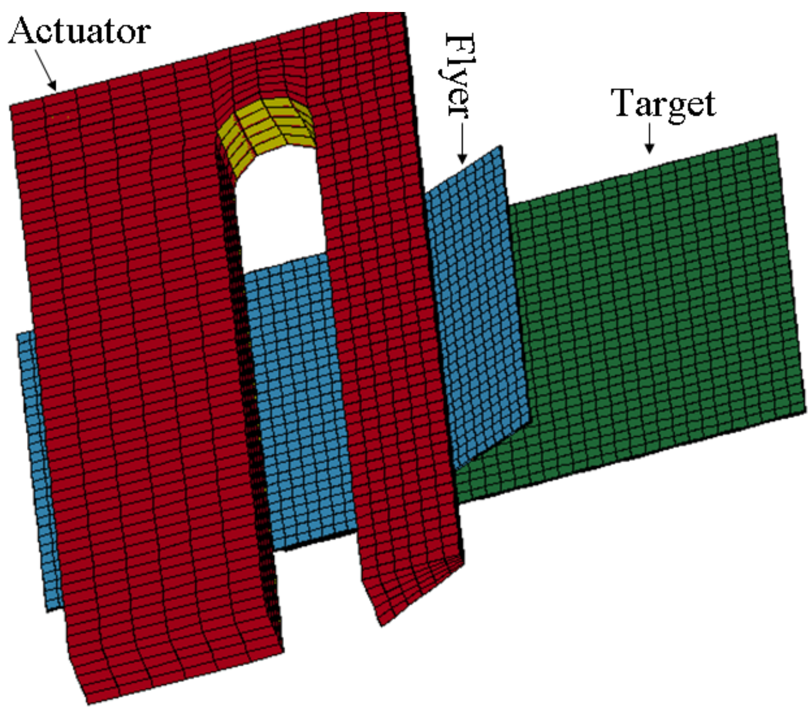

Figure 7 Meshed three-dimension model of pre-flanged MPW system in LS-DYNA. The three parts are actuator, flyer plate, and target plate.

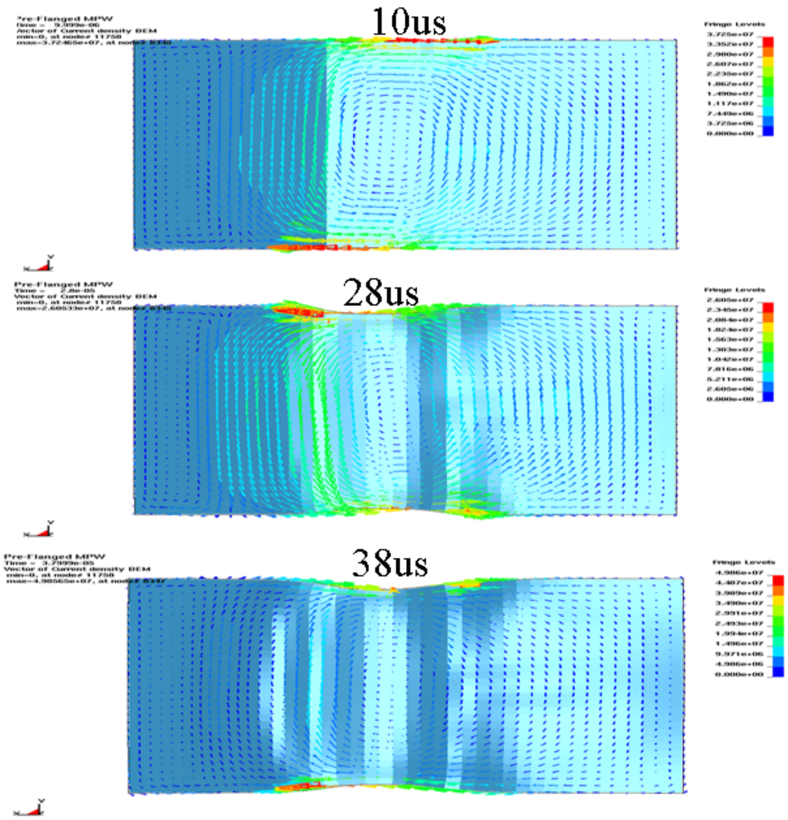

Figure 8 The current density on the flyer plate. This is the view from the bottom of the flyer plate on AA6061-T6 at 2.4kJ discharge energy.

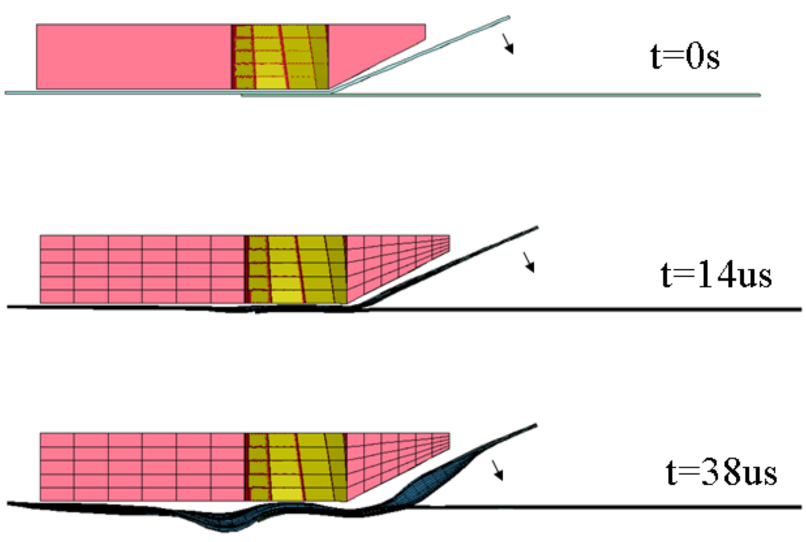

Figure 9 Selected side view of the pre-flanged MPW process at different time step. The images were taken from 'd3plot' for AA6061-T6 at 2.4kJ discharge energy. Arrow indicates the impact direction.

The calculated velocities for AA6061-T6 and Cu101 were compared with the experimental results as shown in Figure 10 and 11. Along the impact surface, three calculated nodal peak velocities were taken into consideration and the average value of these three peak velocities were compared with the experimental results. The simulation result also indicated that AA6061-T6 plates had larger velocity than Cu101 plates. The difference between the experimental and calculation velocity could come from the simulation model setup. In order to simplify the simulation, we shortened the simulation time and did not set up any constraint on the target plates. However, in the real experiment, the target plates were supported by a solid die and could not move.

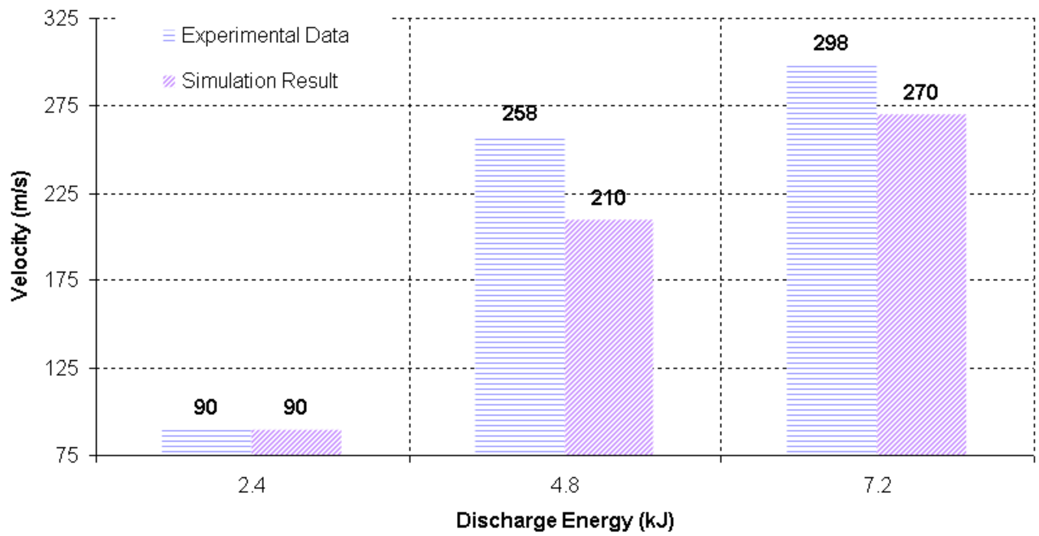

Figure 10 Comparison between the experimental and simulation velocity on AA6061-T6.

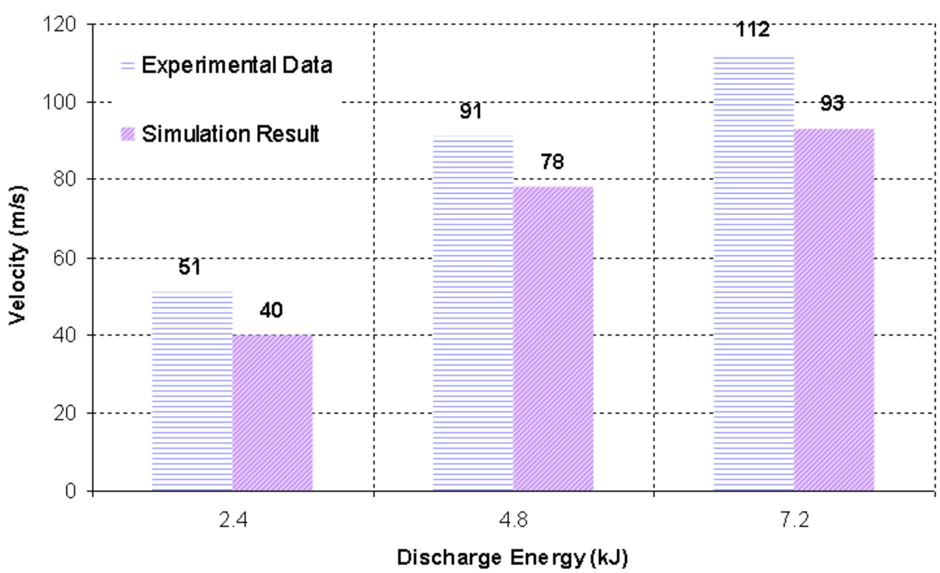

Figure 11 Comparison between the experimental and simulation velocity on Cu101.

Due to long calculation time, we did not complete the thermal calculation on all of the workpieces. Only the result for MPW on AA6061-T6 plate at 2.4kJ discharge energy was available and shown in Figure 12. The five node temperatures along the impact surface indicated that when the velocity increased, the temperature also increased but it was lower than the melting point (T_m) and close to the recrystallization point, which is around 0.5~0.6T_m. Therefore, the grain size near the impact surface could be recrystallized and refined by the fast heating and cooling cycling. This conclusion matched with the microstructure observation which was reported in our previous paper[13]. Future work will be carried out to carefully study the impact surface temperature.

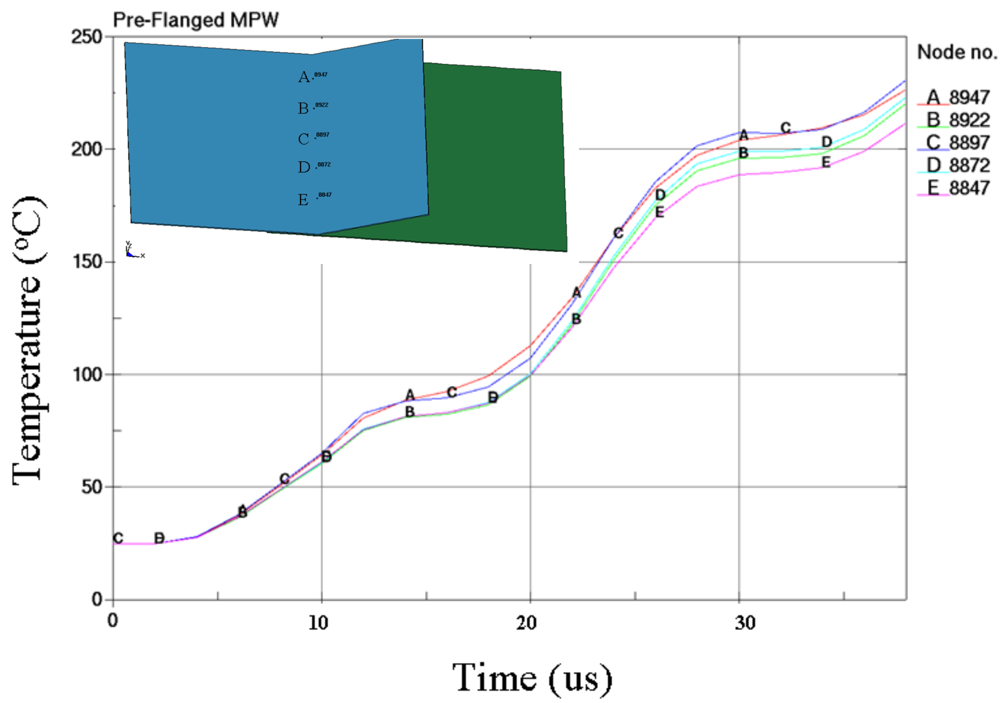

Figure 12 Temperature profile for MPW on AA6061-T6 at 2.4kJ discharge energy for five nodes.

Conclusion

The pre-flanged MPW process was studied by PDV and LS-DYNA in this paper. The measurement of the impact velocity and the simulated impact velocity were compared. It was found that the numerical simulation results were close to the experimental result and thus the built up model in LS-DYNA can be valid with certain approximations. Based on this model, the EM field, the plastic deformation and the thermal cycles are studied. Our preliminary thermal study indicated that there is no melting occurred along the welded interface.

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References

[1] El-Sobky H. Mechanics of explosive welding: Applied Science Publishers, 1983.
[2] Holtzman AH, Cowan GR. Bonding of Metals with Explosives. Welding Research Council Bulletin 1965;104.
[3] Johnson W. Impact strenth of Materials. New York: Crane,Russak & Company, Inc., 1972.
[4] Marya M, Marya S. Interfacial microstructures and temperatures in aluminium-copper electromagnetic pulse welds. Science and Technology of Welding and Joining 2004;9:541.
[5] Aizawa T, Kashani M, Okagawa K. Application of Magnetic Pulse Welding for Aluminum Alloys and SPCC Steel Sheet Joints. Welding in the World 2005;49:212.
[6] O.T.Strand. In: D.L.Paisley, D.R.Snyder, B.J.Thompson, editors. SPIE. Bellingham, WA, 2005.
[7] Pierre L'Eplattenier, Grant Cook, Cleve Ashcraft, Mike Burger, Shapiro A, Daehn G, Seth M. Introduction of an Electromagnetism Module in LS-DYNA for Coupled Mechanical-Thermal-Electromagnetic Simulations. 9th International LS-DYNA users conference, 2006.
[8] Daehn GS, Zhang Y, Golowin S, Banik K, Vivek A, Johnson JR, Taber G, Fenton GK, Henchi I, L'Eplattenier P. Coupling Experiment and Simulation in Electromagnetic Forming Using Photon Doppler Velocimetry. 3rd International Conference on High Speed Forming. Dortmund, Germany, 2008.
[9] M.Pezzutti. Weld. J. 2000;79:43.
[10] D.Winter. Auto World 1999;35:57.
[11] K.Buchholz. Automot. Eng.Int. (USA) 1998;106:41.
[12] Alcoa. http://www.matweb.com/search/DataSheet.aspx?MatID=9391&ckck=1.
[13] Zhang Y, Babu SS, Zhang P, Ed AK, Daehn G. Microstructure Characterization of Magnetic Pulse Welded AA6061-T6 by Electron Backscattered Diffraction. Science and Technology of Welding and Joining 2008;in print.
[14] Zhang Y, Zhang P, Babu SS, Daehn G. Studies of Material Behavior during Magnetic Pulse Welding. Materials Science and Technology. Detroit, MI, 2007.