Characterization of High-Speed Flyer Evolution by Multi-Probe Photon Doppler Velocimetry

T. Lee[1,*], G. Taber[1], A. Vivek[1], G. S. Daehn[1]

[1] Department of Materials Science and Engineering, The Ohio State University, U.S.A
*Corresponding author. Email: lee.7272@osu.edu

Abstract

In this paper, the shape evolution of an aluminium flyer is characterized by a 16-probe Photonic Doppler Velocimeter while being impulsed by a Vaporizing Foil Actuator. For high-speed manufacturing, understanding the shape evolution of a flyer can advance the understanding of the characteristics of the applied pressure as well as the dynamics of the material; however, shock-driven process conditions often make it difficult to perform an in-situ study due to its rapidity and high non-equilibrium nature. Characterization of flyer evolution is also essential for comprehending the mechanism of impact welding, as it can enable measuring the process parameters at the time of collision, thus allowing for the prediction of the weld interface structure. An example is provided with an Al-Mg weld interface, showing the process-microstructure relationship of an impact welding process.

Keywords

Impact Welding, Flyer Evolution, Photon Doppler Velocimetry, High Strain Rate

1 Introduction

Since its initial development (Strand et al. 2006), utilization of Photon Doppler Velocimetry (PDV) has largely enabled measuring velocities in high speed experimentation which would have been nearly impossible otherwise. Although traditionally there have been other techniques such as Velocity Interferometer System for Any Reflector (VISAR) and high-speed cameras, the number of users for PDV has grown rapidly mostly because of its easiness to use and relatively inexpensive installation.

Our group has developed PDV systems for impulse manufacturing processes and the apparatus is reported in (Johnson et al. 2008). In more recent papers, the development of the PDV systems took an essential role for understanding the process parameters of impact welding. For example, (Vivek et al. 2014) used PDV to show the impact velocities of the flyers launched at various input energies so that the resulting microstructures can be analysed in terms of the conventional weldability window. While the collision angles were controlled by the groovy target, they successfully showed the process parameter dependence on the microstructure. Along with other researchers that performed empirical and numerical studies, critical ranges of collision angles and impact velocities are suggested for each material combination for welding, thus defects such as intermetallic compounds and cracks can be mostly avoided.

Recently, we developed a multi-probe PDV system that can measure velocities at 16 individual locations simultaneously. By using multiple probes, displaying the history of the flyer evolution as well as monitoring the impact condition is possible. This information can also be used to understand the pressure distribution from the impulse method – Vaporizing Foil Actuator, Electromagnetic, Explosives, etc. Figure 1 shows how a linear array of four probes can be used to measure the collision angle as well as the impact velocity at separate locations. When the velocity information is resolved with respect to time and displacement, the collision angle at a section between two probes can be calculated based on the relative displacements at a certain time.

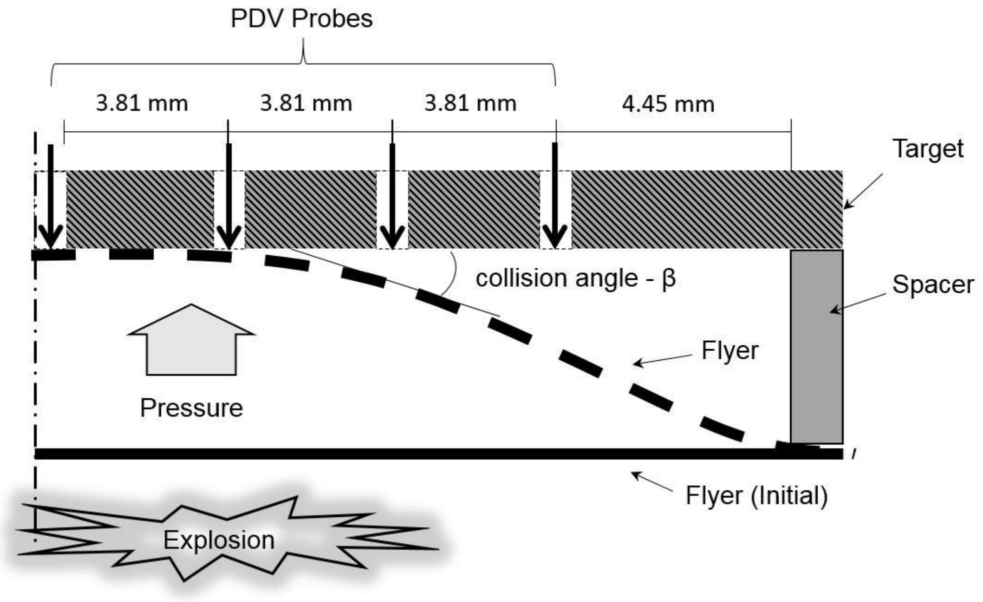

Figure 1: *A schematic showing collision angle measurement by multi-probe PDV during impact welding*

In this paper, we demonstrate a flyer evolution of an AA 1100 – O sheet launched by a Vaporizing Foil Actuator (VFA). The VFA method has shown its robustness as a versatile means of impulse manufacturing processes; the practical working principles can be found in (Vivek et al. 2015). In particular, Vaporizing Foil Actuator Welding (VFAW) can weld similar and dissimilar metals in the solid-state and generate high-strength joints. While this paper does not provide mechanical characterization of the weld created by

VFAW, the effects of the process parameters on the weld interface are discussed and demonstrated by the novel multi-probe PDV system.

2 Experimental Method

A 0.8128 mm thick AA 1100 – O sheet was used as the flyer. The flyer was prepared as a 50.8 mm X 50.8 mm coupon and laid over the active zone of VFA (Figure 2). A 0.0762 mm thick dog-bone shape aluminium VFA, which has been used for spot welding and forming processes, was used for this experiment. There were 1.6 mm spacers, with a separation distance 31.75 mm, between the flyer and target to provide a distance to accelerate. An input energy 6 kJ was used from the capacitor bank to vaporize the VFA and hence drive the flyer.

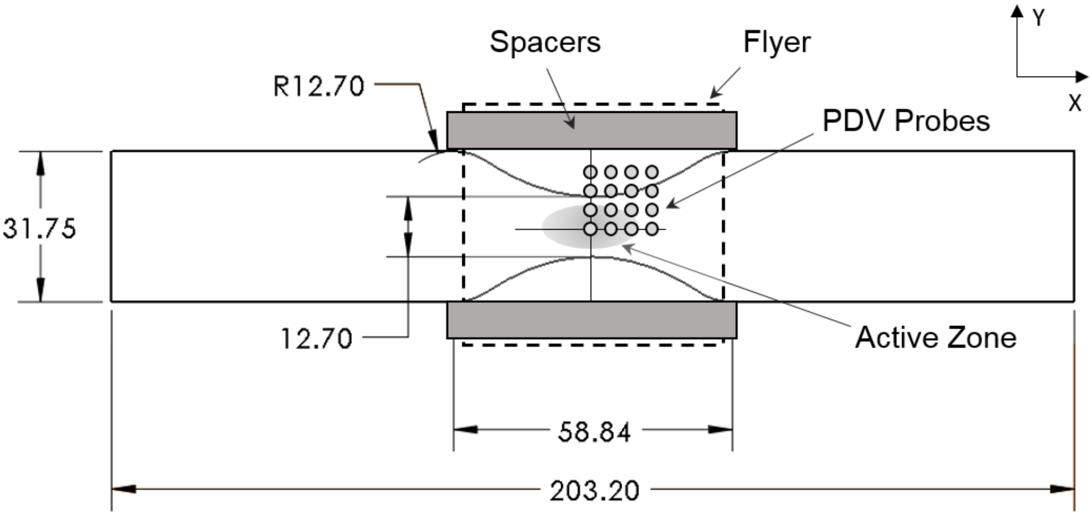

***Figure 2:** Geometry of the Vaporizing Foil Actuator (VFA) used in this study with 16 PDV probes for characterizing the flyer evolution. This figure displays the top view of the experimental setup without the target material. Dimensions are in mm.*

The newly built 16-probe PDV system is equipped with a 1-Watt laser of 1550 nm wavelength, a 2.5 GHz 4-channel oscilloscope, and 16 fibre optics with 42 mm of working distance. The optics are grouped into four acquisition channels and the signals in each channel are separated by a 30 μs time delay. For example, the probes labelled # 1, 2, 3, 4 are set to display the data in 0, 30, 60, 90 μs after the trigger. Likewise, the remaining probes (5 through 16) are grouped and separated in the same way so that the data from all 16 probes can be shown in the 4-channel oscilloscope.

In order to achieve a high spatial resolution, the 16-probe optics were set equidistant in a 4 X 4 (11.43 X 11.43 mm) matrix array such that the matrix covers a top-right quarter of the spot weld, including the centre portion of the weld. The distance between the probes was set to be 3.81 mm. A high reflective retro-tape was attached to the surface of the flyer to enhance the data intensity.

The impulse experiment was repeated with a welding experiment. Using a flyer of the same material and geometry, the flyer was welded onto a 3.175 mm thick AM60B target. The weld interface microstructure was prepared and observed by standard metallography.

3 Results and Discussion

3.1 Velocity Measurement

The Doppler-shifted frequency obtained by PDV over time is analysed with a digitizer, so the frequency can be converted into velocity. A simple conversion is done by

$$v\ (\mathrm{m/s}) = 775\ (\mathrm{nm}) \div \text{Doppler-shifted frequency (Hz)} \tag{1}$$

where v is the velocity, and 775 nm comes from one half of the wavelength of the laser incident beam – 1550 nm. The velocity can also be shown with respect to displacement of the flyer, as the displacement is found by the integration under the velocity trace over time.

Figure 3 shows the history of the velocities obtained from four probes aligned along the width of the flyer: Probe 1 is aligned over the centre of the flyer and VFA and where the flyer is driven by the highest pressure. It is also the location where the collision angle between the flyer and the target is zero. When the travelled distance is integrated, the impact velocity of Probe 1 at a 1.6 mm stand-off distance turns out to be about 770 m/s. Probes 2, 3, 4 are located at a 3.81, 7.62, 11.43 mm offset from Probe 1, respectively, and the data sets are shown in one acquisition channel with a 30 µs time delay as shown in Figure 3. Note that the peak velocity decreases further from the centre of the flyer due to the decrease in pressure as well as an increase in collision angle.

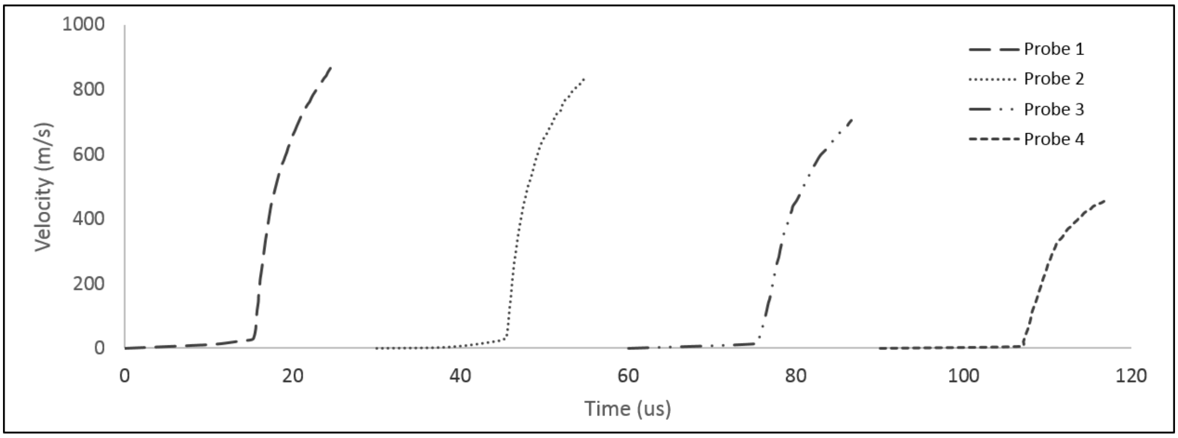

Figure 3: *History of the velocities measured by four probes aligned over a half of the width of the flyer. Probe 1, 2, 3, 4 are located at 0, 3.81, 7.62, 11.43 mm distant from the centre of the flyer, respectively. The velocity traces are separated by a 30 µs time delay.*

3.2 Flyer Shape Evolution

The evolution of the flyer shape is plotted in three-dimension using the relative displacements measured by PDV. The shape evolution of the upper-right quarter of the AA 1100 – O flyer is shown in Figure 4.

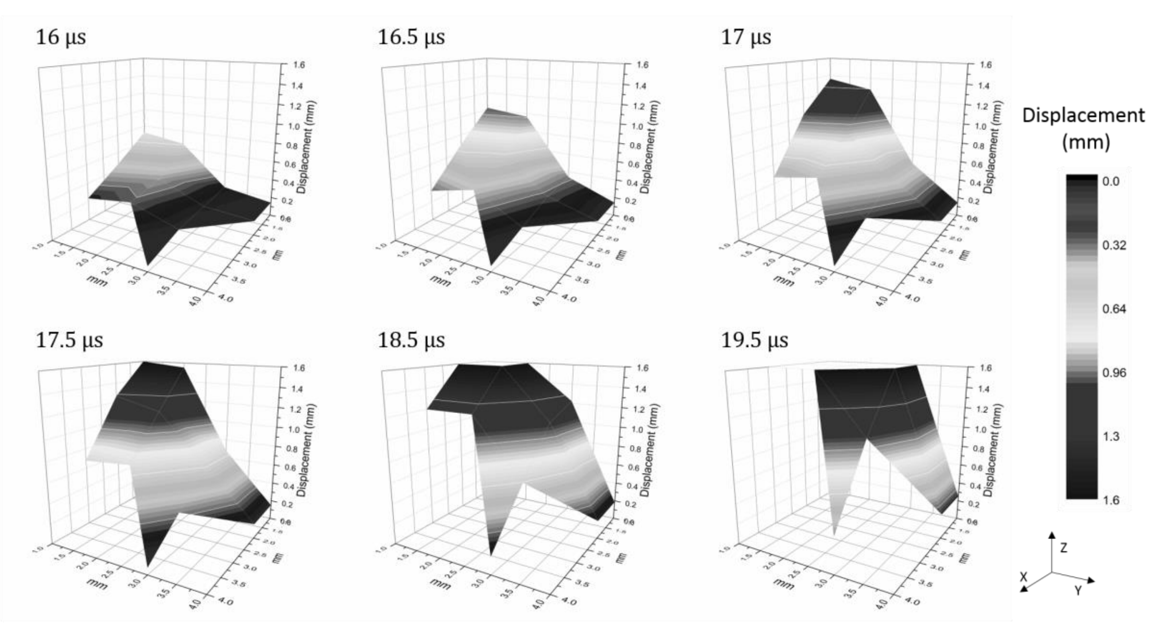

Figure 4: Flyer shape evolution from a VFA spot welding experiment of a 0.8128 mm thick AA 1100 – O flyer plotted using the relative displacements measured by the PDV. The origin is the centre of the flyer before launch. The X-direction is the longitudinal direction of VFA.

As shown in Figure 4, only the data signals obtained from 13 out of 16 probes were strong enough to be digitized for analysis. The intensity of the signals is highly dependent on the surface condition and the power of the laser, and all 16 probes were not optimized for the highest intensity. Nonetheless, the results shown in Figure 4 demonstrates the characterization of the flyer shape evolution within a few microseconds for the first time.

3.3 Process Condition – Structure Relationship

The capability of measuring the collision angle and impact velocities becomes even more meaningful when the analysed process parameters are coupled with microstructures of the corresponding locations. A thorough overview of the microstructural analysis is not provided in this paper, but an example of effects of the process parameters on the weld interface structure is shown in Figure 5. The unique wave-like interface is shown in both Figure 5 (a) and (b) but the amplitude and wavelength of the features are modified by the process condition.

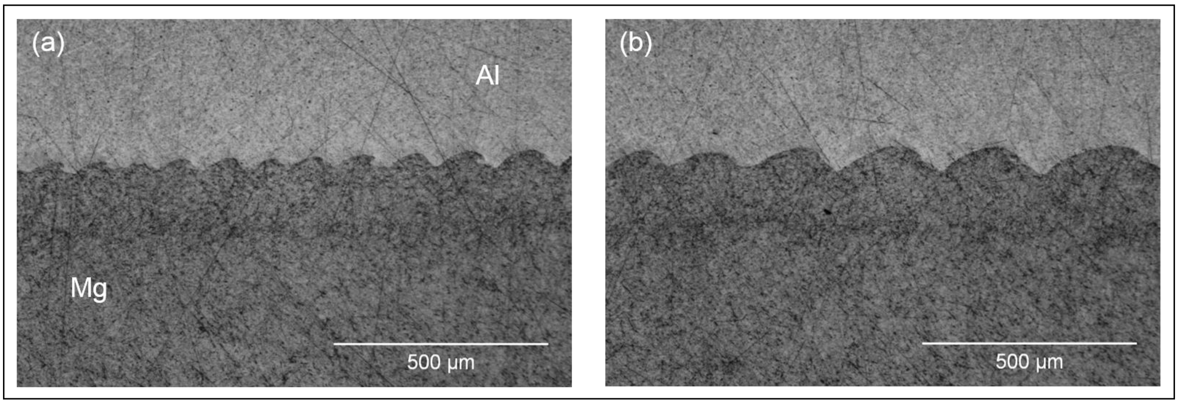

Figure 5: *Weld interface microstructure of an Al-Mg weld made by impact conditions (a) 750 m/s impact velocity – 12 degrees collision angle; (b) 600 m/s impact velocity – 20 degrees collision angle.*

4 Conclusions

Multi-probe Photonic Doppler Velocimetry is a novel and versatile process characterization technique for high speed flyer shape evolution. During impact welding, the flyer shape leads to the unique impact condition and that can be used to predict the interfacial morphology as well as the specific material behaviour of the flyer.

Acknowledgements

This project was supported by the National Science Foundation – Major Research Instrumentation (MRI) and the Grant Opportunities for Academic Liaison with Industry (GOALI) programs.

References

Johnson, J R, G Taber, A Vivek, Y Zhang, S Golowin, K Banik, G K Fenton, and G S Daehn. 2008. “Coupling Experiment and Simulation in Electro- Magnetic Forming Using Photon Doppler.” *3rd International Conference on High Speed Forming,* 35–44. doi:10.2374/SRI08SP160.

Strand, O. T., D. R. Goosman, C. Martinez, T. L. Whitworth, and W. W. Kuhlow. 2006. “Compact System for High-Speed Velocimetry Using Heterodyne Techniques.” *Review of Scientific Instruments* 77 (8): 1–9. doi:10.1063/1.2336749.

Vivek, A., B. C. Liu, S. R. Hansen, and G. S. Daehn. 2014. “Accessing Collision Welding Process Window for Titanium/copper Welds with Vaporizing Foil Actuators and Grooved Targets.” *Journal of Materials Processing Technology* 214 (8). Elsevier B.V.: 1583–89. doi:10.1016/j.jmatprotec.2014.03.007.

Vivek, A, G Taber, J Johnson, and G. S. Daehn. 2015. “Vaporizing Foil Actuator: A Tool for Creating High-Pressure Impulses for Metalworking.” In *60 Excellent Inventions in Metal Forming*, 77–82.