

Development of Fill Impact Welding technique for metal additive manufacturing

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Abstract

Metal additive manufacturing typically utilizes powder as feed. Fill impact welding, uses dime-sized pieces of sheet metal launched at high speeds to impact and weld to the metallic substrate. The driving force can be generated by several means, including vaporizing foil actuators used in this work. A custom impact welding fixture was built to launch 0.5 mm thick and 6.35 mm diameter flat circular metallic disks (flyers) to speeds greater than 500 m/s over a travel distance of 5 millimeters. The flyers impacted target plates placed at fixed relative angles. Fully welded interfaces were observed via cross sectional metallography as well as non-destructive evaluation methods of ultrasonic testing. It was demonstrated that titanium flyers can be reproducibly welded to copper for a certain set of parameters. Furthermore, the impact velocity was found to be controllable and repeatable for various input energies from the capacitor bank power system. For example, for 2.0kJ input energy shots, the average peak velocities of the flyer were measured to be 800 m/s with a variation of less than 3%.

Keywords

Additive, welding, repair, NDE

Introduction

Additive manufacturing (AM) has rapidly expanded across industries such as automotive, aerospace, defense, medical, and consumer goods (Gebhardt, 2011; Guo and Leu, 2013). Fusion-based AM consolidates material through melting via laser, electron beam, or electric arc in inert atmospheres or shielding gas; however, it is often limited by vaporization loss of alloying elements, solidification defects (e.g., porosity, lack of fusion), elemental segregation, and hot cracking (Sames et al., 2016). Thermal cycling can further introduce microstructural anisotropy, residual stress, and distortion (Nycz et al., 2021; Liu et al., 2021).

Solid-state AM technologies reduce or eliminate many fusion-associated defects by minimizing heat input and relying on plastic deformation (Khodabakhshi and Gerlich, 2018). These techniques fall into two main categories: sintering-based (e.g., binder jetting) and deformation-based (e.g., ultrasonic, friction stir, and cold spray) (Tuncer and Bose, 2020). In deformation-based AM, intimate interatomic contact and bonding are achieved through severe plastic deformation that removes surface oxides. Processes like additive friction stir and cold spray are used in large-scale fabrication, cladding, and repair (Khodabakhshi and Gerlich, 2018; Griffiths et al., 2019). MELD, a commercial variant of additive friction stir deposition, enables bulk solid-state metal printing with tailored alloys and composites (Yu et al., 2018), though it requires a large gantry system and faces limitations in overhang angles, tool wear, and resolution.

Cold spray AM uses high-velocity impact to deposit powdered feedstock, removing oxide layers and forming local metallurgical bonds through plastic deformation at particle interfaces (Assadi et al., 2016). This method enables processing of traditionally “unweldable” metals such as 2XXX and 7XXX series aluminum (Mahoney et al., 1998; Brewer et al., 2018; Olea et al., 2013), preserves fine-scale features in metal matrix composites and oxide dispersion-strengthened alloys (Behera et al., 2019; Story et al., 2018), and enables graded compositions (Khodabakhshi and Gerlich, 2018). It also mitigates intermetallic formation at interfaces (Kuo et al., 2019) and operates effectively in ambient air, unlike fusion and sinter-based techniques.

Vaporizing Foil Actuator Welding (VFAW), an impact welding technique similar to explosive welding, uses rapid foil vaporization via capacitive discharge to generate high-pressure plasma that accelerates a flyer sheet into a target at controlled speeds (typically 300–700 m/s) and shallow angles (5° – 20°), enabling oxide removal and bonding (Vivek et al., 2013). VFAW has been used to join a wide variety of dissimilar weld pairs, including Cu–Fe, Al–Fe, Cu–Ti, Ni–Ti, and Ni-based superalloys (Prasad et al., 2020; Liu et al., 2019; Vivek et al., 2014; Gupta et al., 2019; Nirudhoddi et al., 2021). It has also been explored for dynamic impact testing and powder compaction (Prasad et al., 2020).

Building on these capabilities, this work introduces Fill Impact Welding (FIW) as a new solid-state AM process. FIW involves the incremental addition of material to “fill” a three-dimensional space and create a solid object. FIW uses vaporized foil actuators to accelerate sheet or foil feedstocks, eliminating the need for large clamping loads. It operates using only electricity, metal sheets, and sacrificial foils. Compared to powder-based feedstocks, FIW’s sheet inputs are lower in cost and more readily available. Its deposition mechanism preserves more of the original feedstock microstructure than cold spray due to the larger deposited volumes, while

avoiding the extreme cold work characteristic of cold spray, resulting in as-consolidated materials with improved ductility. Though cold spray ductility can be enhanced via heat treatment (Rokni et al., 2018; Story and Brewer, 2018), FIW offers a pathway toward structurally sound builds without additional processing.

This paper presents the fundamental concepts of FIW, system characterization, and a proof-of-concept demonstration using inclined impact filler welding. Non-destructive evaluation (NDE) via ultrasonic imaging was employed to assess weld quality.

Methods

A FIW system was developed, consisting of three parts: a target holding platform, a FIW gun, and FIW cartridges. The target holding platform is a stage isolated from filler launching. It enables accurate control of the impact angle of the target plate. FIW cartridge was developed to launch different sizes of the filler disks as flyers; in this work, filler disk with a diameter of 6.35 mm was equipped in the FIW cartridge. A schematic is shown in **Fig. 1a and 1b**. The FIW gun is connected to a capacitor bank that discharges a high voltage through the FIW cartridge to activate the launch process. With no direct contact between the target holding platform and the FIW gun, those two can be moved independently, making the system suitable for applications involving large and complex components.

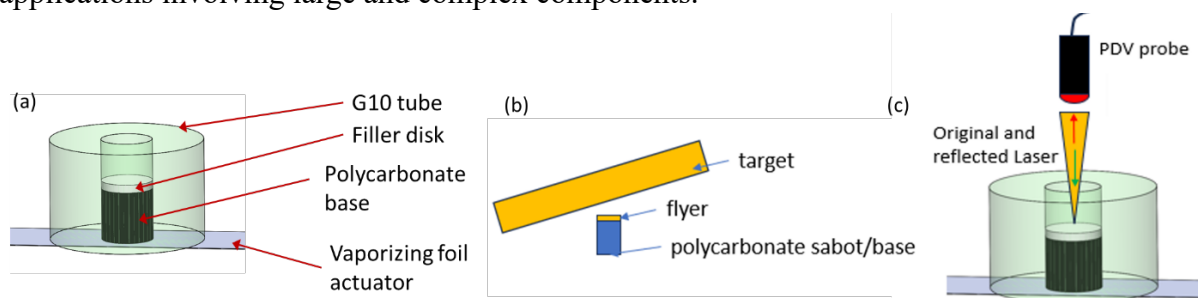


Figure 1: FIW cartridge consisting of actuator and filler flyer (a), schematic of inclined impact between the cartridge and target (b), and velocity measurement of the FIW cartridge and flyer using photonic Doppler velocimetry (c).

By changing the input energy of the capacitor, the impact speed of the filler disk is controlled. System characterization was performed with the speed of filler disk measured with photonic Doppler velocimetry (PDV) and discharging current recording with a Rogowski coil. The PDV experiment set up is shown in Fig. 1c. To test the controllability of the impact speed, filler disks of 0.5 mm thick aluminum sheet of diameter of 6.35 mm were launched at the input energies of 1.0 kJ, 1.5 kJ, and 2.0 kJ. Three samples were launched at 2.0 kJ to evaluate the repeatability of the system. The conditions for welding are mentioned in **Table 1**.

Filler material	Target material	Impact angle	Input energy	Characterization method
0.5 mm Aluminum alloy	N/A	N/A	1.0, 1.5, 2.0 kJ	PDV measurement
0.5 mm CP-Ti	4.76 mm Cu 110	7°, 14°, 21°	2.0 kJ	Ultrasonic imaging, cross-sectional optical microscopy

Table 1: Various materials welded using FIW system.

Welding experiments were conducted using CP-titanium (Grade 2) filler and Cu 110 target with various impact angles and input energy of 2.0 kJ. Ultrasonic imaging as non-destructive testing (NDT) and optical microscopy as destructive were employed testing methods to examine the welding interface and assess the welded area.

Results and discussion

Results of all the PDV tests are shown in **Fig. 2a**, where the 1.0 kJ, 1.5 kJ, and 2.0 kJ input energies generated peak speeds of the disk fillers around 550 m/s, 680 m/s, and 820 m/s, respectively. The velocity-displacement curves estimated by time integration of the velocity-time curve is shown in Fig. 2b. The variation range of the peak velocities of the three repeating experiments at 2.0 kJ was 22.6 m/s, which is less than 3% of the average peak velocity, 821.29 m/s, indicating good repeatability of the FIW system. The recorded current traces are shown in Fig. 2c, which also proves the consistency of the system during the discharging process.

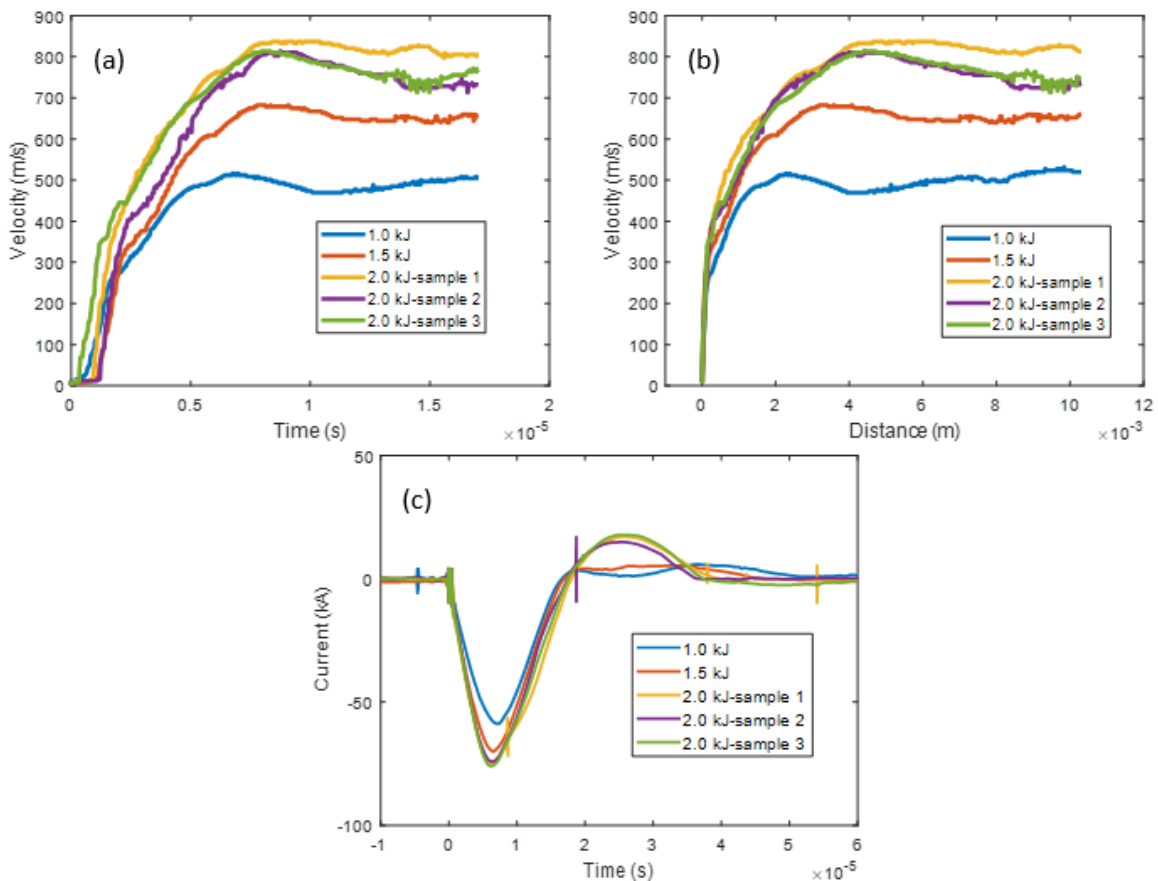


Figure 2: Diagnostics during FIW: (a) velocity-time, (b) velocity-displacement and (c) current-time profiles of the filler disks launched by FIW system.

Dissimilar welds of CP Ti-Cu110 were successfully created at three different impact angles: 7°, 14°, and 21°, shown in **Fig. 3**. Ultrasonic imaging of the CP Ti-Cu110 samples (**Fig. 4**) revealed the following: (1) At the edges of all samples, there were indentations on the target made by the flyer's impact. For the 7° and 14° samples, these regions were located on one side of the weld at the initial impact area, aligning with previously identified impact welding mechanisms. For the 21° sample, unwelded zones appeared around the weld. These unwelded areas can be machined off between welding operations. (2) In the central regions away from the edges, large, 100% welded areas without gaps were achieved for at least one of the impact angles (14°). (3) A wavy interface morphology was observed in all three samples, which are consistent with what has been found for impact welding of Cu-Ti (Vivek et al., 2013).

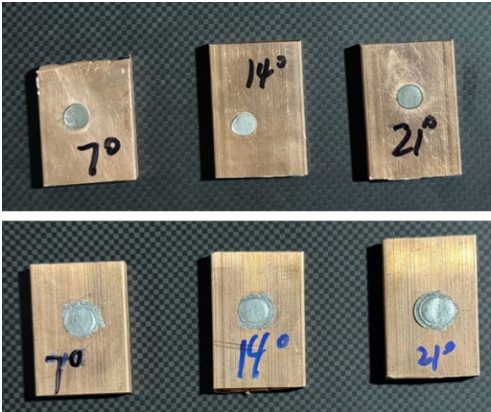


Figure 3: Impact welded CP Ti-Cu110 (upper) and Al3003-Cu110 (lower) at impact angles of 7°, 14°, and 21°.

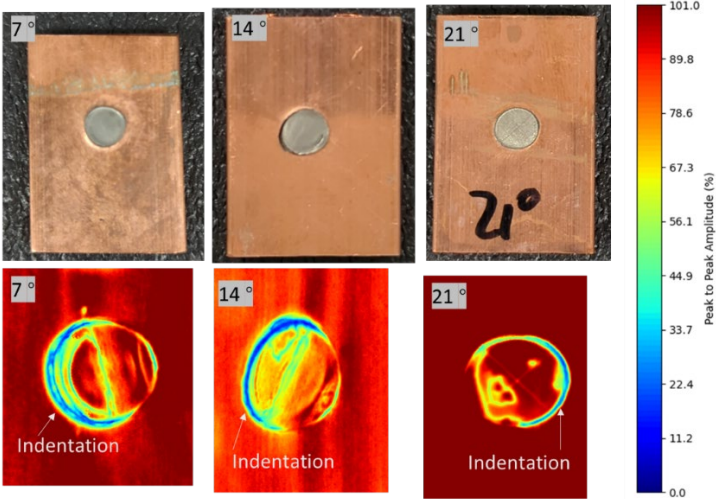


Figure 4: Impact welded CP Ti-Cu110 at impact angles of 7°, 14°, and 21° and ultrasonic imaging results. Red signifies a solid or fully bonded interface, whereas blue represents a gap or unbonded area.

The interface imaged from the diameter of the weld nugget shows near-complete welding in cross-sectional metallography as shown in **Fig. 5**. It revealed a continuous, gap-free weld interface along the entire welding length. The prominent and uniform interfacial waves across the interface indicate a consistently maintained impact angle during the welding process, which is critical for processing parameter control. This is a breakthrough for VFAW, as most previous studies showed inevitable center unwelded zones caused by insufficient impact angles due to welding configurations (Li et al., 2020). The main fully-welded, void-free area, along with the unbonded initial impact region revealed by optical microscopy, aligns with observations from ultrasonic testing, thereby validating the NDE approach.

Experimental measurements of aluminum flyers launched by the FIW system confirmed that the vaporizing foil actuator method can launch flat flyers at speeds adjustable by varying the input electrical energy. The velocity-time curves for the same energy levels nearly overlapped with each other and the flyer left the gun barrel at very similar speeds (within 5%) as shown in Fig. 2. The structure of the weld interface was characterized through ultrasonic testing and cross-sectional metallography (Fig. 4 and 5). All the methods revealed fully or nearly fully welded interfaces when an initial impact angle was set between the target and the flyer. Similar idea was previously demonstrated (Prasad et al., 2020), but this systematic FIW study enables significantly greater control and repeatability, offering scalability for various applications. Testing of the Cu-Ti weld samples revealed a higher amount of waviness. The ability to test weld structure non-destructively was shown for the first time for impact welds made at this size scale.



Figure 5: Cross sectional images of the Cu-Ti weld interface made with a 14° impact angle.

Therefore, it is proved that 1) the process, structure and performance of impact welding are reproducible and 2) that impact welds can be made with minimal to no voids. These two breakthroughs are key to transitioning the technology to a commercial process while opening weld configuration avenues that have not previously been achieved with impact welding.

There are certain aspects of the FIW process and system that need to be improved upon. While void-free welds have been successfully created by inclining the target and flyer, adding the next layer remains a challenge. The previous layer needs to be machined to provide an impact angle within the welding window of that material being welded. More flexible and

precise relative positioning methods such as use of robotic arms should be employed for better aiming of the filler disks.

Conclusions

1) For the first time, VFA was used to launch horizontal flyers in a way that allows for independent control over the positioning of the launch mechanism and the target holder.

2) The process is stable and yields a consistent impact velocity, which is needed for a reproducible welded structure and performance.

3) By controlling the process conditions, this impact welding method can be used as an additive technique where nearly all of the consumable metal (flyer) is added to the target plate.

4) Non-destructive evaluation methods such as ultrasonic testing can be utilized for assessing the impact welded region.

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