Enhancement of Laser Impact Welding for Joining Thicker Aluminium Sheet

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Abstract

This study critically examines the efficacy of Augmented Laser Impact Welding (ALIW) in achieving high-quality welds by leveraging the effects of laser-induced plasma and controlled impact forces. Therefore, various Gunpowder Nitromethane (GPN) compositions were examined. The results demonstrated that the incorporation of 0.1 g of micro-air bubbles into a mixture of 1 g smokeless powder and 10 g of 95% nitromethane significantly enhances the flyer velocity. Moreover, the usage of Sapphire instead of borosilicate glass as a confinement layer can be a great alternative due to its damage resistance after each laser shot. Furthermore, the refined GPN composition was employed in experiments with a 1 mm Al 6061-T6 flyer, where different spot sizes and varying GPN thicknesses were tested to determine the optimal conditions for this specific flyer thickness. The findings revealed that the maximum flyer velocity was achieved when using 0.54 mm of GPN-3 in conjunction with a 5.22 mm laser spot size.

Keywords: Augmented Laser Impact Welding (ALIW), Photonic Doppler Velocimetry (PDV), Impact Welding, and Detonation Energy

1. Introduction

Laser impact welding (LIW) has emerged as a promising technique, distinguished by its superior mechanical strength, precision, and operational efficiency (Thurston et al., 2023). This process leverages high-energy laser pulses to induce shock waves at material interfaces, facilitating bonding through plastic deformation (Daehn & Lippold, 2011). This method is particularly advantageous for welding varying thicknesses of dissimilar materials, a domain where conventional welding techniques often struggle due to the formation of brittle intermetallic compounds (Sen & Puri, 2022).

In LIW technique, the flyer material gains momentum due to the optical vaporization of a thin surface layer. This vaporization generates plasma, which in turn exerts pressure on the flyer. To enhance propulsion efficiency, a transparent confinement layer is incorporated, which confines the plasma and optimizes the energy transfer (Swift et al., 2005). Typically, LIW utilizes laser pulses with energy levels of a few Joules, directed onto surface areas measuring a few millimeters in diameter (H. Wang et al., 2015). However, the process faces inherent limitations in laser energy transmission. In particular, when optical energy densities surpass approximately 10 GW/cm^2, air ionization occurs, impeding further energy delivery. This phenomenon poses a significant challenge to the efficiency and scalability of LIW, thereby restricting its wider industrial application (Thurston et al., 2023).

Therefore, many studies were conducted to enhance the energy released by utilizing various ablative layers. For example, Picatinny Liquid Explosive (PLX), a mixture of 95% nitromethane combined with 5% ethylene diamine, has been widely utilized in impact welding due to its high detonation velocity of 6200 m/s and explosive yield exceeding TNT by 134% (Yoshida et al., 1985). However, regardless of these advantages, PLX presents significant safety concerns, including high sensitivity to impact, as demonstrated by its detonation risk in drop tests. Additionally, its short shelf life—spanning merely seven days— in a sealed glass bottle—further restricts its practical application. Given these limitations, there is a pressing need to develop a safer, more stable explosive suitable for industrial and laboratory use without compromising safety and reliability. Consequently, Thurston et al. (2023) introduced Gunpowder Nitromethane (GPN) as a novel chemical explosive, formulated by blending 10 g of 95% nitromethane with 1 g smokeless pistol powder, which contains various energetic compounds such as nitroglycerin and nitrocellulose. Given its high nitromethane content, GPN is expected to exhibit characteristics similar to Picatinny Liquid Explosive (PLX). While its precise oxygen balance could not be determined due to the unfamiliar composition of the smokeless powder, GPN demonstrates notable advantages over PLX, including a significantly extended shelf life of up to 1.5 years and improved impact resistance (Thurston et al., 2023). These attributes suggest its potential as a more stable alternative; however, further research is necessary to optimize its composition and enhance plasma energy output. Therefore, investigations should focus on refining the formulation through controlled variations in concentration and compounds, ensuring improved sensitivity and greater detonation efficiency.

On the other side, the confinement layer is a critical component in laser impact welding, as it directs and concentrates detonation energy onto the materials being joined while also serving as a medium for laser energy transmission. Several materials, involving glass, water, polycarbonate, and quartz, have been employed as confinement layers, each offering distinct advantages and limitations (Berthe et al., 1997). Glass, for instance, is highly effective due to its optical transparency and minimal laser beam distortion, but it fractures upon repeated laser exposure (H. Wang et al., 2015). Polycarbonate, though resistant to fracture, suffers from optical damage, limiting its reuse. Water, commonly utilized in laser shock peening, has shown promise in LIW applications, while quartz has demonstrated superior pressure generation at equivalent laser power densities (Q. Wang et al., 2023). Despite its absence in previous LIW studies, sapphire presents a compelling alternative due to its high optical transmittance, exceptional mechanical durability, and resistance to deformation under extreme thermal and pressure conditions. However, its feasibility as a confinement layer requires further evaluation, particularly concerning surface reflection and energy absorption characteristics, which could impact welding efficiency.

Finally, this study seeks to advance the foundational work of Thurston et al. (2023), who investigated the use of chemical augmentation to enhance the LIW process. Building on their research, this investigation critically examines the effects of diverse augmentation chemistries and introduces the use of three distinct confinement layers to systematically evaluate their impact on system performance. In addition, an evaluation was performed on a case study involving 1 mm Al 6061-T6 to demonstrate the effect of the improved GPN on thicker flyers.

2. Materials and Methods

In this study, an Nd:YAG laser system (Powerlite™ Precision II Scientific System from Continuum Lasers, Milpitas, CA, USA) was utilized, operating at an energy of 3 J, a wavelength of 1064 nm, a pulse width of 8 ns, and a spot diameter of 5.22 mm. To comprehensively analyze this study, two aluminum alloys, Al 2024-T3 and Al 6061-T6, both with a thickness of 0.5 mm, were selected as flyer materials. The samples were precisely cut into 25 × 25 mm dimensions.

A critical aspect of this research involved investigating the role of gunpowder nitromethane (GPN) as an ablative layer in augmented laser impact welding. This remains an underexplored area, as the optimal compositions for maximizing detonation efficiency are not yet well-defined. Consequently, an empirical approach based on trial and error was adopted, involving modifications to the original GPN composition which consisted of 1 g of smokeless gunpowder mixed with 10 g of 95% nitromethane. The study explored the effects of introducing aluminum powder and micro-air bubbles into the GPN mixture to assess their influence on detonation energy and, subsequently, on the flyer velocity. A detailed breakdown of the different GPN compositions is presented in the corresponding **Table 1**. To ensure the precise evaluation of GPN performance, a controlled layer of 0.37 mm GPN was applied to the sample surface, as shown in **Figure 1**. This was secured using multiple layers of clear tape to maintain a consistent stand-off gap. To quantify detonation energy and measure the flyer velocity, Photonic Doppler Velocimetry (PDV) was employed, with each scenario being tested three times to obtain an averaged dataset on the flyer deformation.

On the other side, an investigation was conducted into the effect of different confinement layers on flyer velocity, aiming to identify a viable alternative to borosilicate glass, which exhibited a tendency to fracture following each laser pulse. Three confinement materials were tested: **(i)** borosilicate glass with a thickness of 9 mm, **(ii)** a sapphire cube with a thickness of 1 inch, and **(iii)** a thin layer of running water approximately 1 mm thick. The primary factor influencing the selection of these materials was their optical transmission properties, which directly affect the proportion of laser energy reaching the flyer. Hoon et al. (2009) reported that for an 8 mm thick borosilicate glass at a wavelength of 1064 nm, the transmission rate was 87%. In contrast, previous studies indicated that sapphire exhibited a slightly lower transmission rate of 83% under the same conditions (Esco Optics Inc.). These findings suggest that, at a wavelength of 1064 nm, borosilicate glass and sapphire share comparable optical transmission characteristics, making both viable candidates for confinement in augmented laser impact welding.

Table 1 *Various compositions of ablative layers*

Ablative Layer	Compositions
GPN-1	1 g Gunpowder + 10 g Nitromethane (Original GPN)
GPN-2	2 g Gunpowder + 10 g Nitro.
GPN-3	1 g Gunpowder + 10 g Nitro. + 0.1 g Micro-air Bubbles
GPN-4	1 g Gunpowder + 10 g Nitro. + 0.2 g Micro-air Bubbles
GPN-5	1 g Gunpowder + 10 g Nitro. + 0.05 g Micro-air Bubbles + 0.05 g Aluminum Powder
GPN-6	1 g Gunpowder + 10 g Nitro. + 0.1 g Micro-air Bubbles + 0.05 g Aluminum Powder
GPN-7	1 g Gunpowder + 10 g Nitro. + 0.1 g Micro-air Bubbles + 0.1 g Aluminum Powder

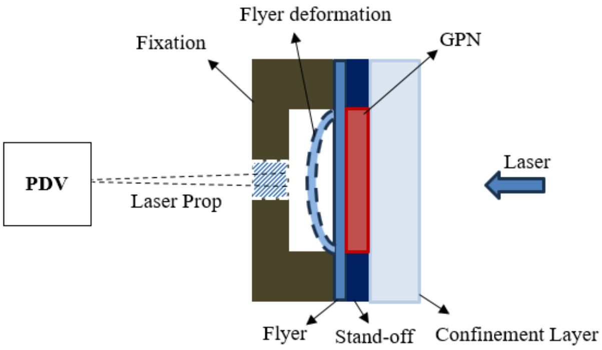


Figure 1 *Schematic of the Augmented Laser Impact Process Setup to measure flyer velocity using PDV*

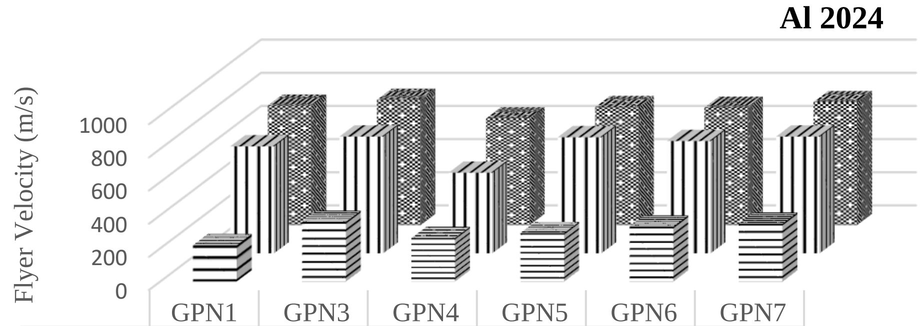
3. Results and Discussion

3.1. The Influence of adding Aluminium Powder and Micro-Air Bubbles:

According to PDV measurements, the detonation energy for GPN-2 was lower than GPN-1, as discussed clearly during previous work (Abdelmaola et al., 2025). Hence, this GPN composition will be excluded from further investigation.

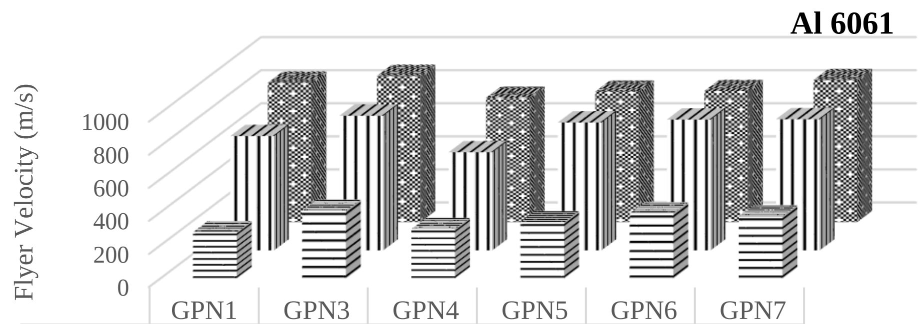
Figure 2-**Figure 3** present the highest flyer velocities recorded across all experimental conditions. The interaction of various additives—including gunpowder, aluminum powder, micro-air bubbles, and nitromethane—produced a complex effect on detonation energy and, consequently, flyer velocity. Notably, the incorporation of micro-air bubbles (GPN-3 scenario) significantly influenced energy enhancement through multiple mechanisms (Yamada et al., 2022). Firstly, micro-air bubbles promote better mixing between the explosive materials and surrounding gases or reactants, facilitating a more uniform and complete reaction that improves energy output. Secondly, they play a role in reducing shock wave attenuation by acting as cavitation nuclei, thereby enhancing shock wave propagation and amplifying explosive energy. Additionally, under certain conditions, micro-air bubbles can trigger cavitation effects, where the rapid formation and collapse of vapor cavities generate localized high pressures and

temperatures, further supporting explosive reaction initiation (Shan et al., 2023). Finally, when a shock wave interacts with a micro-air bubble, it can focus and amplify the surrounding energy, effectively lowering the energy threshold required for detonation and improving overall sensitivity (Ishii & Watanabe, 2019). However, excessive micro-air bubble inclusion (GPN-4 scenario) may reduce available detonation energy, as the bubbles occupy a portion of the explosive's volume, leading to diminished performance.



	GPN1	GPN3	GPN4	GPN5	GPN6	GPN7
Water	219	360	262	292	331	349
Sapphire	645	704	486	700	677	704
Glass	720	755	643	711	707	741

***Figure 2** The highest flyer velocity with respect to various GPN compositions, using different confinement layers; water, sapphire, and borosilicate glass, for 0.5 mm thick Al 2024-T3*



	GPN1	GPN3	GPN4	GPN5	GPN6	GPN7
Water	280	410	299	340	394	376
Sapphire	691	814	593	773	791	793
Glass	843	884	752	789	793	859

***Figure 3** The highest flyer velocity with respect to various GPN compositions, using different confinement layers; water, sapphire, and borosilicate glass, for 0.5 mm thick Al 6061-T6*

On the other hand, for scenarios of GPN-5,6,7 the incorporation of aluminum powder, functioning as a metal particle explosive, contributed to an increase in detonation heat due to its exothermic oxidation process. However, this modification resulted in a reduction in detonation energy and, consequently, a decrease in detonation velocity. This effect is attributed to the damping influence of Al powder, which absorbs a portion of the energy during oxidation, as previously discussed (Dong et al., 2021; Sielicki et al., 2022). Zhang et al. (2022) provided a comprehensive analysis of the impact of Al powder on both detonation heat and velocity. Their findings indicate that with increasing content of Al powder in RDX-based explosives, there is a notable decline in detonation velocity, whereas the detonation heat exhibits a rising trend. Thus, the results presented in **Figure 2**-**Figure 3** confirm that the highest flyer velocities, across all experimental conditions, were accomplished with the GPN-3 composition, which contained 0.1 g of micro-air bubbles into the original GPN-1 formulation.

3.2. The Influence of Various Confinement Layers:

Figure 2-**Figure 3** depict flyer velocity variations across different confinement layers, particularly borosilicate glass, sapphire, and water. Across all GPN compositions, borosilicate glass exhibits the maximum flyer velocities, with only a marginal difference compared to sapphire, followed by water. However, despite its superior performance, borosilicate glass is not a viable option for industrial applications due to its high susceptibility to fracturing and shattering, making it economically impractical. Conversely, sapphire displayed markedly superior hardness and durability compared to borosilicate glass, throughout the welding process (Chen et al., 2022). However, its high cost and susceptibility to cracking present significant challenges for implementation in industrial applications. As discussed before, both borosilicate glass and sapphire exhibit similar transmission characteristics at a 1064 nm wavelength. Considering the flyer velocity results across all cases and the minimal deviation in performance compared to borosilicate glass, sapphire emerged as a highly effective confinement layer. It achieves sufficient-flyer velocities while eliminating the need for frequent replacement due to damage, making it a more practical and sustainable choice for industrial applications.

3.3. Optimization of ALIW parameters for 1 mm Al 6061-T6 as a flyer

The performance of a flyer in an augmented laser impact process is significantly influenced by the thickness of both the flyer material and the augmented layer. The interaction between the laser energy, explosive layer, and flyer material determines the maximum velocity achieved during impact. Therefore, to investigate the impact of GPN-3 on thicker flyers, experiments were conducted using a 1 mm thick Al 6061-T6 flyer. The study examined various laser beam diameters (4 mm, 5.22 mm, and 6 mm) and different GPN-3 thicknesses ranging from 0.27 mm to 0.63 mm, to identify their effects on flyer velocity. The measured velocities (average of 3 samples for each case, with scattering +/- 2%), obtained using Photonic Doppler Velocimetry (PDV), are presented in **Table 2**. Additionally, **Figure 4** illustrates the resulting flyer deformation for each experimental condition, revealing that the most pronounced dimple deformation was observed under specific parameters.

Table 2 *Max. Flyer Velocity of 1 mm Al 6061 at various parameters*

Spot Diameter (mm)	**GPN-3 Thickness (mm)**				
	0.27	0.36	0.45	0.54	0.63
	Max. flyer Velocity (m/s)				
4	333	403	415	442	429
5.22	369	438	449	451	433
6	328	358	324	276	246

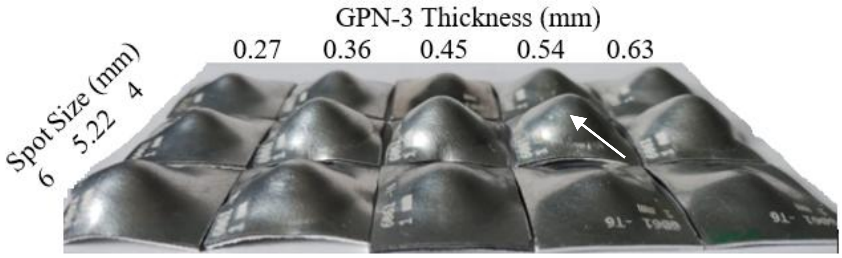


Figure 4 *Flyer deformation of 1 mm Al 6061 at various GPN thicknesses and spot sizes showing the highest deformed dimple at 5.22 mm spot size and 0.54 mm GPN thickness*

Experimental findings, shown in **Figure 5**, indicate that when employing a 1 mm thick Al 6061 flyer, the maximum velocity is reached at a 0.54 mm GPN-3 thickness with a 5.22 mm spot diameter, compared to previous studies (Abdelmaola et al., 2025) that found a 0.37 mm GPN thickness to be optimal when utilizing thinner flyer of a 0.5 mm thick at same spot size. This variation in optimal GPN thickness can be attributed to the interplay between various characteristics; Inertia and Momentum Considerations, Energy Absorption and Shockwave Propagation, and Stress Wave Attenuation and Dissipation. Firstly, the flyer velocity is a result of the momentum imparted by the explosive-driven shockwave. Given that momentum depends on both mass and velocity, a thicker flyer has a greater mass, requiring a proportionally higher impulse to achieve the same velocity. Since a thicker flyer has more mass, it resists acceleration more than a thinner one, necessitating a larger explosive layer to generate sufficient impulse.

Secondly, the explosive layer generates a shockwave that propagates through the flyer. Thicker flyers require a higher energy input to fully transmit this shockwave through the material and maintain an optimal pressure gradient for acceleration. A smaller explosive thickness may not provide enough sustained force for the necessary impulse transfer, leading to suboptimal flyer acceleration. Moreover, as the shockwave moves through the flyer, some of its energy is dissipated due to wave reflection and attenuation. In thicker flyers, a greater proportion of the energy is absorbed before reaching the opposite surface, reducing the efficiency of momentum transfer. Increasing the explosive thickness compensates for this energy loss, ensuring that sufficient pressure is maintained for accelerating the flyer to its maximum velocity.

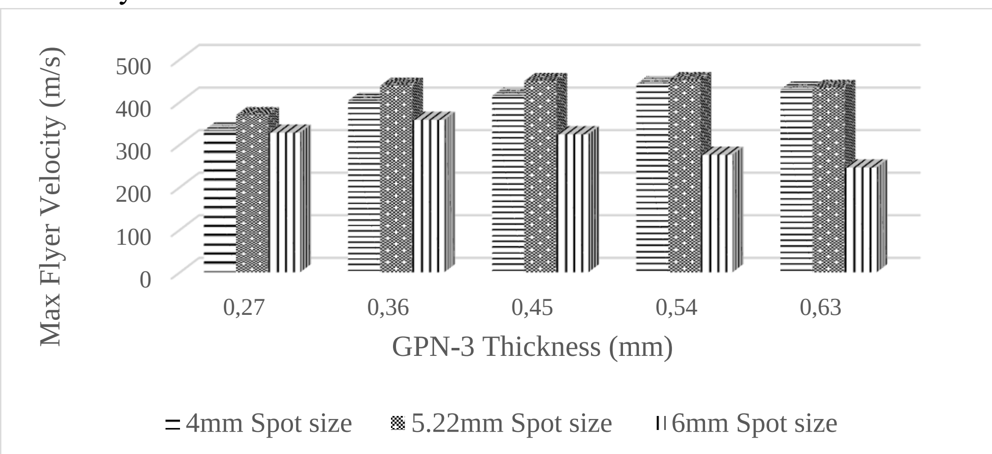
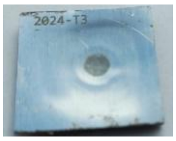
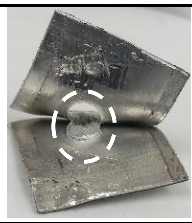


Figure 5 *Maximum flyer velocity of 1 mm Al 6061 flyer at different GPN-3 thicknesses and various spot sizes, during ALIW process using borosilicate glass as confinement layer*

To evaluate the effect of the optimized parameters on the Augmented Laser Impact Welding (ALIW) process, welding trials were performed using two distinct configurations: (1) a normal setup with a flat gap arrangement between the flyer (1 mm Al 6061) and target (1 mm Al 1100), and (2) an angled setup with a 15° collision angle. **Table 3** summarizes the variable parameters for each configuration. Peel testing confirmed successful bonding, revealing a fully bonded weld nugget in both cases.

Table 3 *ALIW Parameters to join Al 6061 as a flyer to Al 1100 as a target with different setup*

Materials (Thickness)	**Ablative Layer**	**Confinement layer**	**Energy (J)**	**Spot Size (mm)**	**Setup**		**Peel Test**
6061/1100 (1mm/1mm)	GPN-3	Glass and Sapphire	3	5.22	Stand-off (0.5mm)		
6061/1100 (1mm/1mm)					Angle 15°		

4. Conclusion

Augmented Laser Impact Welding presents a highly promising alternative to traditional joining methods, particularly due to its superior advantages, which make it a viable replacement for rivets in various industries. A key factor in the process is the augmented layer, which significantly enhances the sensitivity of detonation energy, thereby improving overall performance. The key findings of this study are as follows:

- The incorporation of 0.1 g of micro-air bubbles into the original GPN formulation enhances detonation energy, leading to an increase in flyer velocity.
- The use of borosilicate glass as a confinement layer is limited by its tendency to fracture after each laser shot. As a result, sapphire is proposed as a more durable alternative to extend the operational lifespan.
- GPN-3 has demonstrated effectiveness with thicker materials, specifically 1 mm Al 6061-T6, with optimized process parameters identified at a 5.22 mm spot size and 0.54 mm GPN-3 thickness, ensuring the highest flyer velocity.
- Sound joints with welded nuggets were created using 1 mm thick Al 6061-T6 as a flyer and 1mm thick Al 1100 as a target by utilizing the optimized parameters for ALIW found in this work, as emphasized by the peeling test shown in Table 3

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