

Article

Influence of Augmentation Compositions and Confinement Layers on Flyer Velocity in Laser Impact Welding

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Abstract: Small-scale impact welding may have several advantages over rivets: the strength can be higher, it can be applied right at the edges in lap joints, and it can be lighter and more easily installed if simple systems can be developed. Laser Impact Welding (LIW) is compact and simple, adapting the technologies of laser shock peening. It is limited in terms of the energy that can be delivered to the joint. Augmented Laser Impact Welding (ALIW) complements optical energy with a small volume of an exothermic detonable compound and has been shown to be an effective welding approach. The scope of this study is extended to build upon previous work by investigating varied augmentation chemistries and confinement layers, specifically borosilicate glass, sapphire, and water. The evaluation of these compositions involved the use of two aluminum alloys: Al 2024 and Al 6061. Photonic Doppler Velocimetry (PDV) was utilized to measure the flyer velocity and assess the detonation energy. The findings indicated that adding micro-air bubbles (GPN-3 scenario) to the original GPN-1 enhanced the flyer velocity by improving the sensitivity, which promoted gas release during detonation. Hence, employing 1 mm thick Al 2024 as a flyer with GPN-3 enhances the flyer velocity by 36.4% in comparison to GPN-1, thereby improving the feasibility of using 1 mm thick material as a flyer and ensuring a successful welded joint with the thickest flyer ever welded with laser impact welding. When comparing the confinement layers, sapphire provided slightly lower flyer velocities compared to borosilicate glass. However, due to its higher resistance to damage and fracture, sapphire is likely more suitable for industrial applications from an economic perspective. Furthermore, the lap shear tests and microstructural evaluations confirmed that GPN-3 provided higher detonation energy, as emphasized by the tendency of the interfacial waves to have a higher amplitude than the less pronounced waves of the original GPN-1. Consequently, this approach demonstrates the key characteristics of a practical process, being simple, cost-effective, and efficient.

Keywords: augmented laser impact welding (ALIW); gunpowder nitromethane (GPN); photonic doppler velocimetry (PDV); detonation sensitivity; impact welding; explosive welding



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1. Introduction

Traditional fastening methods, such as rivets, have long been relied upon for joining materials in various industries. However, their limitations, including added weight, the potential for structural weaknesses, and difficulty in application at edges, highlight the need for innovative alternatives, such as refill friction stir spot welding [1,2]. Laser impact welding emerges as a transformative solution, offering superior strength, precision, and efficiency [3].

Laser impact welding (LIW) employs a high-energy laser pulse to generate a shock wave at the interface of two materials, enabling their bonding through plastic deformation [4]. This method is particularly notable for its ability to weld dissimilar materials of varying thicknesses—an area where traditional welding methods often encounter difficulties because of the formation of Intermetallic Compounds [5–7]. In LIW, flyer materials are propelled by the optical vaporization of a thin surface layer. The resulting plasma exerts pressure on the flyer, as shown in Figure 1, and the process is enhanced by a transparent tamping layer, which confines the plasma to increase the propulsion efficiency [8]. LIW commonly utilizes laser energy pulses of a few joules over areas of a few millimeters in diameter [9,10]. However, the technique is constrained by the energy that is deliverable through laser impulses. When optical energy densities exceed approximately 10 GW/cm^2 , ionization of the air obstructs further energy transmission, posing a significant limitation to the process's efficiency and scalability [11]. Consequently, the primary challenge in LIW lies in the limitations of energy delivery. This study is extended to build on the work of Thruston et al. [3], who explored the use of chemical augmentation in their research. To build upon their findings, this investigation critically evaluates the effects of varied augmentation chemistries and incorporates the use of three different tamping layers to further assess the enhancement in system performance.

The broad importance of this work is that it may provide a new method to cost-effectively achieve solid-state welds. Solid-state welds are outstanding and may provide replacements for rivets in aircraft [12] because they (1) possess high strength, (2) have no heat-affected zone, (3) can join wildly dissimilar metals, and (4) can weld metals without destroying their microstructure or temper. Vaporizing Foil Actuator Welding (VFAW) has been shown to be quite effective [12]; however, the physical configuration of the system is cumbersome. A system based on a small laser, an appropriate transparent confinement or tamping layer, and an appropriate exothermic augment layer could be very inexpensive to deploy.

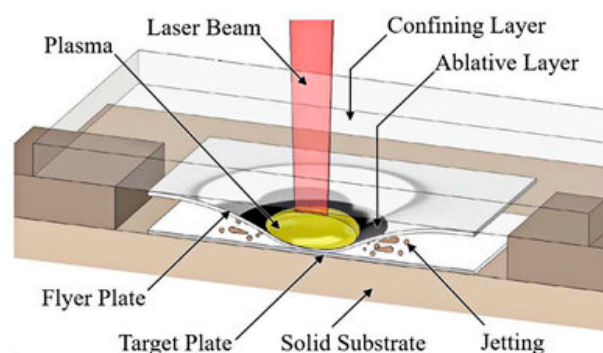


Figure 1. Schematic of laser impact welding configuration showing the plasma generated to accelerate the flyer toward the target. Reprinted with permission from ref. [13].

The subsequent background section discusses two critical parameters: augmented layers and confinement layers. It highlights the transition of augmented layers from Picatinny Liquid Explosive (PLX) to Gun-powder Nitromethane (GPN). Additionally, various confinement layers were utilized to evaluate their influence on the delivered energy.

1.1. Augmented Layer

The augmented layer is crucial in laser Impact welding, affecting several key aspects of the process. Its primary function is to absorb laser energy and convert it into thermal energy, leading to rapid vaporization. This vaporization produces a high-pressure plasma

plume that exerts force on the flyer material, propelling it towards the target material at high velocity.

Based on the literature [3,14], Picatinny Liquid Explosive (PLX), which consists of 95% nitromethane and 5% ethylene diamine, was commonly used in impact welding due to its high performance. It has a detonation velocity of approximately 6200 m/s and an explosive yield that is 134% greater than that of TNT, as evidenced by ballistic mortar tests [14,15]. The addition of 5% ethylene diamine enhanced the oxygen balance of PLX to -48% , compared to -39% for pure nitromethane, thereby improving its stability and performance [14]. Upon detonation, nitromethane decomposes into CO_2 , CO, NO_2 , and NO [16]. Furthermore, experimental data indicate that the minimum diameter required for PLX detonation propagation at $20\text{ }^\circ\text{C}$ is around 18 mm, based on studies using an elongated glass tube [17].

Despite its advantages, PLX has significant drawbacks, including high sensitivity to impact. A drop test with 2 kg in weight from a height of 1 m demonstrates this sensitivity, posing handling challenges and increasing the risk of accidental detonation during the welding process. Additionally, PLX has a limited shelf life, lasting a maximum of one week when stored in a sealed glass bottle. Therefore, it is crucial to develop a safer and more stable chemical explosive that can be reliably used in conventional industrial and laboratory environments without posing a heightened safety risk.

Nitromethane is classified as a high explosive due to its unique properties and characteristics. It has a high energy density, which enables it to release a significant amount of energy upon detonation, making it suitable for applications that require powerful force generation [18]. Its ability to rapidly and efficiently propagate explosive reactions makes it effective in explosive welding. In this context, Thurston et al. [3] introduced Gunpowder Nitromethane (GPN) as a chemical explosive, consisting of a mixture of nitromethane and gunpowder. This blend is prepared by combining 95% nitromethane with smokeless pistol powder, which contains nitroglycerin, nitrocellulose, ethyl centralite, diphenylamine, rosin, and polyester. The composition of GPN includes one gram of gunpowder mixed with ten grams of nitromethane. The general characteristics of GPN are anticipated to resemble those of PLX due to the high nitromethane content in both formulations. Although formal sensitivity tests for GPN were not conducted, rudimentary tests were feasible. The oxygen balance of GPN is expected to be comparable to that of PLX; however, the precise oxygen balance cannot be calculated due to the unknown proportions of nitrocellulose and nitroglycerin in the smokeless pistol powder. The authors emphasized GPN's notable attributes, such as its extended shelf life of up to one and a half years and its impact resistance, positioning it as potentially more stable than PLX. However, further research is needed to determine the optimal composition and configuration of GPN to maximize plasma energy. Therefore, it is essential to experiment with various concentrations and compounds to validate and improve the augmented layer, enhancing its sensitivity to laser beams and increasing detonation energy.

1.2. Confinement Layer

The confinement layer plays an essential role in laser impact welding by directing and concentrating the detonation energy onto the materials being joined. This transparent layer serves as a barrier between the laser source and the workpieces, controlling the energy distribution during the welding process. Additionally, the confinement layer serves as a medium for transmitting the laser energy, ensuring that it reaches the workpieces with optimal intensity and distribution.

Various materials, including glass, polycarbonate, water, quartz, and tape, have been used as tamping layers [11,19,20]. Glass, due to its optical transparency, low absorption

at specific wavelengths, and minimal laser beam scattering or distortion, enables efficient energy transfer from the laser to the flyer, making it highly effective for this purpose [11]. However, glass tends to fracture with each laser shot. Polycarbonate is fracture-resistant but susceptible to optical damage, which limits the repeated use of the same spot for laser shots. Water is commonly used as a confinement layer in laser shock peening and has recently been studied in LIW [21,22]. Quartz has shown superior performance in generating higher peak pressures compared to water when used as a tamping layer at equivalent laser power densities [23]. The authors have not identified any prior LIW investigations using sapphire. However, its high optical transmittance facilitates the efficient delivery of laser energy to the target. Its exceptional mechanical durability and high hardness enable it to withstand the extreme pressures and thermal stresses generated during the welding process without deformation or damage. Therefore, it is necessary to evaluate the feasibility of using sapphire as a confinement layer due to its resistance to fracture under laser exposure. However, potential challenges may arise due to variations in surface reflection, optical characteristics, and energy absorption characteristics among various materials.

Understanding how augmentation compositions interact with confinement layers to influence flyer velocity is pivotal for optimizing weld quality and efficiency. Therefore, researchers can enhance energy transfer mechanisms and tailor process parameters to meet specific industrial needs. This research area not only contributes to scientific knowledge but also paves the way for innovative engineering solutions, enabling the development of stronger, more reliable, and cost-effective welded structures. For instance, augmented laser impact welding (ALIW) represents a transformative technique for joining aerospace alloys that are traditionally considered to be unweldable. It offers superior performance compared to rivets and other mechanical fasteners [3], making it potentially highly advantageous for aerospace applications.

2. Materials and Methods

In this study, the impact of different augmentation compositions and confinement layers on flyer velocity was investigated using Photonic Doppler Velocimetry (PDV) (built at The Ohio State University, Columbus, OH, USA). In this investigation, a Nd laser system (Powerlite™ Precision II Scientific System from Continuum Lasers, Milpitas, CA, USA) was used, with the laser parameters detailed in Table 1. The pulse reached a peak energy of 3.0 J/pulse, with a pulse width of 8.0 ns and a wavelength of 1064 nm, as previously detailed by Wang et al. [11]. To clarify the effects observed in this investigation, 25 mm × 25 mm × 0.5 mm samples of Al 2024 and Al 6061 were employed as flyers.

Table 1. Laser parameters.

Power Density (GW/cm ²)	Energy (J)	Wavelength (nm)	Pulse Width (ns)	Spot Size (mm)
1.34	3.14	1064	8	5.22

As Gunpowder Nitromethane (GPN) is a relatively recent development in laser impact welding (LIW) technology, its precise concentrations and composition are not yet optimized. Hence, modifications were made to the original GPN composition, which consisted of 1 g of smokeless gunpowder mixed with 10 g of 95% nitromethane. The optimal configuration of the ablative (augmentation) layer can be identified by conducting trial experiments with different compositions and compounds, as detailed in Table 2. GPN was applied in the gap between the confinement layer and the flyer, with the gap thickness controlled by the use of double-sided tape layers. In this study, two GPN thicknesses, 0.2 mm and 0.37 mm, were

investigated based on the work of Thurston et al. [3]. This analysis was further reinforced by examining various GPN thicknesses and spot sizes.

Table 2. Different GPN compositions.

Name	Compositions
GPN-1	1 g Gunpowder + 10 g Nitromethane (Original GPN)
GPN-2	2 g Gunpowder + 10 g Nitromethane
GPN-3	1 g Gunpowder + 10 g Nitromethane + 0.1 Micro-air Bubbles
GPN-4	1 g Gunpowder + 10 g Nitromethane + 0.2 Micro-air Bubbles
GPN-5	1 g Gunpowder + 10 g Nitromethane + 0.05 Micro-air Bubbles + 0.05 Al Powder
GPN-6	1 g Gunpowder + 10 g Nitromethane + 0.1 Micro-air Bubbles + 0.05 Al Powder
GPN-7	1 g Gunpowder + 10 g Nitromethane + 0.1 Micro-air Bubbles + 0.1 Al Powder

To evaluate the detonation energy obtained from each GPN composition and their effect on the flyer velocities, Photonic Doppler Velocimetry (PDV) was utilized (average of 3 repeated trials for each case) to evaluate the flyer deformation for each scenario, as shown in Figure 2. A PDV system operates by reflecting a laser beam off a moving flyer sheet. The reflected light is combined with the original laser beam and directed to a detector. Functioning as a displacement interferometer, the system generates a beat frequency proportional to the displacement of the flyer. Specifically, a displacement of half the laser wavelength results in a complete beat cycle at the detector. Consequently, the frequency of these beats is directly related to the flyer's velocity [24].

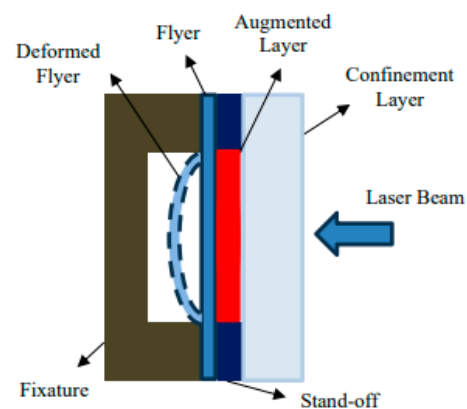


Figure 2. Schematic of the process setup.

To clearly illustrate the effect of various GPN compositions on flyer velocity, three confinement layers were utilized: borosilicate glass (9 mm thick), sapphire (25 mm thick), and water (approximately 1 mm thick) for comparison. During this study, several factors must be considered when evaluating these confinement layers for laser impact welding. Sapphire is significantly harder and more durable than borosilicate glass, making it less prone to damage such as scratching or cracking during the welding process [25,26]. This enhanced durability contributes to the reliability and extended lifespan of the confinement layer. A critical aspect in choosing between these materials is their surface reflection at the sapphire/air interface and through the bulk material, as well as their ability to absorb or dissipate laser energy within the confinement layer. The sapphire surface reflection was measured, determining that most of light loss occurs due to surface reflection, approximately 5.9%. In contrast, transmission loss through the material itself is minimal, with only 0.057% lost per millimeter of thickness. For a 25 mm thick sapphire cube transmitting

3 J of energy, the estimated loss amounts are 0.177 J from surface reflection and 0.04 J due to bulk absorption. Further investigation is necessary to facilitate a comparative analysis between sapphire and borosilicate glass. Table 3 lists properties that highlight the differences between borosilicate glass and sapphire. Moreover, Hoon et al. [27] elucidated the optical transmission curve for borosilicate glass, demonstrating the relationship between transmission percentage and various wavelengths. The authors showed that, for 1064 nm wavelength and 8 mm thick borosilicate glass, the transmission percentage was approximately 87%, while sapphire's curve indicated around 83% transmission [28]. Therefore, both materials exhibit very close transmission levels at a wavelength of 1064 nm.

Table 3. Characteristics of various materials utilized as confinement layers.

Material	Properties	Density (g/cm ³)	Light Transmission Range (μm)	Refractive Index	Hardness	
					(Moh's)	Knoop
Borosilicate Glass		2.2–2.6	0.3–2.5	1.47–1.5	5.5	418
Sapphire		4	0.17–5.5	1.8	9	2000

To analyze and evaluate the joint characteristics, a mechanical lap shear test was conducted to display the load–displacement curves for the welded joints. This test was performed using an MTS electromechanical load frame (MTS Systems Corporation, Eden Prairie, MN, USA), with 1 mm/min as controlled velocity. Additionally, the welded joints were cut through the cross-section using an EDM machine and mounted on epoxy resin for microstructure analysis and examination of the interfacial waves of the same point, with a distance of 1.5 mm from the center of the weld for each scenario. These samples were then ground and polished up to 1 micron. Keller's etchant was applied for 15 s to clearly elucidate the interfacial waves.

3. Results and Discussion

3.1. PDV Measurements

This study is focused on examining the effects of different GPN compositions on flyer velocity across various confinement layers using PDV. Figure 3 presents examples of these measurements, depicting the relationship between flyer velocity and displacement using 0.37 mm of GPN-1 (the original GPN) and GPN-3 (with an addition of 0.1 g of micro-air bubbles). This analysis was conducted using 0.5 mm Al 2024 as the flyer material, with borosilicate glass employed as the confinement layer. The following section will be divided into three segments based on the varying GPN compositions.

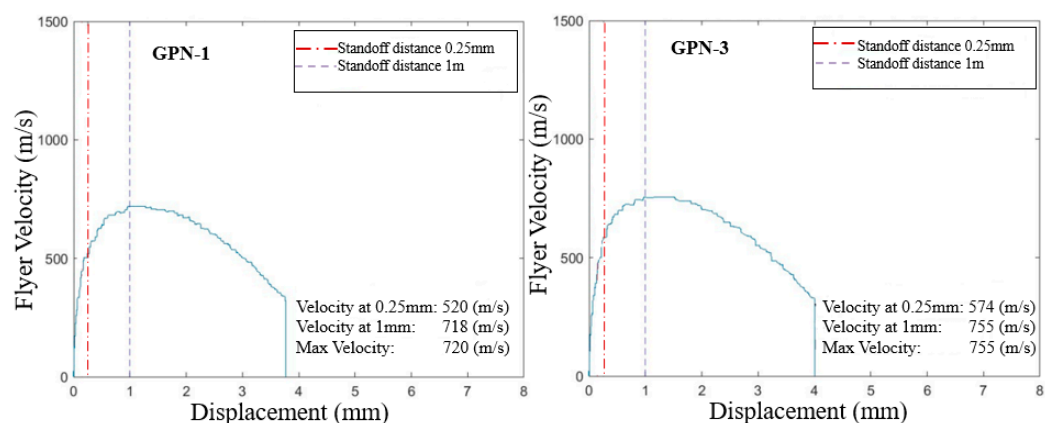


Figure 3. Flyer velocities with respect to displacement according to 0.37 mm of GPN-1 and GPN-3 on 0.5 mm thick Al 2024 as a flyer, using borosilicate glass as the confinement layer.

3.1.1. Effect of Adding Aluminum Powder

The primary focus here is the volume of gases generated by the detonation, which propel the flyer. Adding aluminum powder, which consumes a portion of the energy to form aluminum oxides, increased the detonation heat because it acted as a metal particle explosive. However, this addition reduced the detonation energy and consequently the detonation velocity due to the damping effect caused by the aluminum powder, as discussed previously [29–34]. Zhang et al. [35] summarized the effect of Al powder on detonation heat and detonation velocity. The authors demonstrated that, as the aluminum powder content in the RDX-based explosive increases, the detonation velocity decreases, while the detonation heat shows an upward trend. During the current study, this effect was evident in the GPN-II scenario when 0.5 g of aluminum powder was mixed alone with the original GPN-1. Therefore, the flyer velocities derived from this mixture were included in Table 4 but excluded from the subsequent comparative analysis. Conversely, incorporating micro-air bubbles played a pivotal role and increased the gas content of the mixture [36]. As a result, increasing the amount of micro-air bubbles enhanced the sensitivity of the detonation, as will be explained later.

Table 4. Flyer velocities for eliminated GPN compositions per m/s.

Material (0.5 mm Thick)	GPN-1 (1 g G.P.+ 10 g Nit.)		GPN-II (1 g G.P. + 10 g Nit. + 0.5 g Al Powder)		GPN-2 (2 g G.P. + 10 g Nit.)	
	Sapphire	Water	Sapphire	Water	Sapphire	Water
Al 2024	540	230	486	191	529	226
Al 6061	595	274	513	239	556	221

3.1.2. Effect of Adding More Smokeless Gunpowder

Adding more smokeless powder has no effect on increasing the detonation energy. On the contrary, the flyer velocities decreased upon increasing the gunpowder to 2 g instead of 1 g, as shown in the case of GPN-2. Therefore, the values of the flyer velocities during this scenario, as indicated in Table 4, were also eliminated from the upcoming comparison. The detonation energy decreased when more smokeless gunpowder was added to the augmentation mixture for several hypotheses. Firstly, smokeless gunpowder often contains stabilizers and inert materials that do not contribute to the explosive energy, diluting the active components and reducing the overall energy release. Secondly, excessive gunpowder can create overpressure conditions, leading to inefficient combustion and incomplete detonation. Moreover, the reaction kinetics may be disrupted by the added gunpowder, causing the burn rate to become either too fast or too slow for optimal detonation. Additionally, smokeless gunpowder can absorb heat during detonation, lowering the peak temperature and pressure. Negative chemical interactions between the gunpowder and other components can also reduce energy efficiency. Furthermore, the physical properties of the mixture, such as density and homogeneity, may be compromised, leading to poor energy distribution. Thus, maintaining an optimal balance of components is crucial for achieving maximum detonation energy.

3.1.3. Effect of Adding Micro-Air Bubbles

Table 5 presents the maximum flyer velocity values for all the cases. These combinations of different compositions and components, smokeless gunpowder, aluminum powder, micro-air bubbles, and nitromethane, had a complex impact on the detonation energy and, consequently, on the flyer velocity. Adding micro-air bubbles (GPN-3 scenario) can signifi-

cantly influence the augmentation energy in various ways, as rationalized before [37,38]. Firstly, they can enhance the mixing of explosive materials with surrounding gases or other reactants, leading to a more homogeneous and complete reaction that maximizes energy release. Secondly, micro-air bubbles can reduce shock wave attenuation by acting as nuclei for cavitation, thereby improving the shock wave propagation through the medium and increasing the overall explosive energy. Moreover, micro-air bubbles can induce cavitation effects under specific conditions, where the rapid formation and collapse of vapor cavities generate intense localized pressures and temperatures, contributing to the initiation of the explosive reaction [39]. Additionally, these bubbles can increase the sensitivity of explosive materials to initiation by serving as sites for localized high temperatures and pressures when exposed to external stimuli, making explosions easier to initiate. Lastly, when a shock wave encounters a micro-air bubble, it can focus and amplify the shock energy around the bubble, lowering the energy threshold required to initiate the explosive reaction and enhancing the overall sensitivity [40]. On the contrary, adding more micro-air bubbles (case GPN-4) could potentially reduce the available energy as the bubbles occupy a portion of the explosive's volume.

Table 5. Maximum flyer velocity (m/s) according to different GPN compositions with respect to various confinement layers (glass, sapphire, and water).

Material (0.5 mm)	GPN Thickness (mm)	GPN-1 (1 g GP + 10 g Nit.)			1 g GP + 10 g Nit. + 0.1 g Micro. Bubbles)			GPN-4 (1 g GP + 10 g Nit. + 0.2 g Micro. Bubbles)			GPN-5 (1 g GP + 10 g Nit. + 0.05 g Micro. Bubbles + 0.05 Al Powder)			GPN-6 (1 g GP + 10 g Nit. + 0.1 g Micro. Bubbles + 0.05 g Al Powder)			GPN-7 (1 g GP + 10 g Nit. + 0.1 g Micro. Bubbles + 0.1 g Al Powder)		
		Glass	Sapphire	Water	Glass	Sapphire	Water	Glass	Sapphire	Water	Glass	Sapphire	Water	Glass	Sapphire	Water	Glass	Sapphire	Water
		Flyer Velocity (m/s)																	
Al 2024	0.2	604	545	207	629	611	346	592	365	217	593	561	244	577	565	310	590	570	342
	0.37	720	645	219	755	704	360	643	486	262	711	700	292	707	677	331	741	704	349
Al 6061	0.2	700	539	267	814	777	399	704	470	248	728	720	301	604	590	351	695	662	372
	0.37	843	691	280	884	814	410	752	593	299	789	773	340	793	791	394	859	793	376

Figures 4–7 demonstrate that the highest flyer velocities, in all the scenarios, were achieved with GPN-3, which incorporated 0.1 g of micro-air bubbles into the original GPN-1 composition.

To clarify the effect of various confinement layers, Figures 4–7 also depict the flyer velocities across different materials: borosilicate glass, sapphire, and water. It is evident that, for all the GPN composition scenarios, borosilicate glass yielded the highest flyer velocities, with a slight difference compared to sapphire, followed by water. Despite this, the tendency of borosilicate glass to fracture and shatter made it an economically unsuitable choice for industrial applications. In contrast, sapphire exhibited substantially higher hardness and durability than borosilicate glass, making it less prone to damage, such as scratching or cracking during the welding process [26]. In addition to the previously mentioned aspects, the transmission percentage curves at the 1064 nm wavelength for both borosilicate glass and sapphire are indicative of close behavior. Therefore, given the flyer velocity values across all the cases and the minor deviation from glass, sapphire emerged

as a significant confinement layer that offers high-flyer velocities without the need for frequent replacement due to damage.

In all the scenarios, the higher flyer velocity observed in Aluminum 6061 compared to Aluminum 2024 regarding these different combinations of LIW is primarily due to differences in their physical and mechanical properties. Aluminum 6061 has a slightly lower density, enabling it to achieve greater acceleration for the same energy input. Additionally, its lower yield strength and greater ductility make it more responsive to deformation, facilitating better conversion of laser energy into kinetic energy. In contrast, Aluminum 2024's higher density, increased yield strength, and greater hardness make it less efficient at absorbing and converting energy. These factors, combined with potential differences in surface characteristics and energy absorption behavior, explain why Al 6061 consistently achieves higher flyer velocities than Al 2024 under similar welding conditions [41].

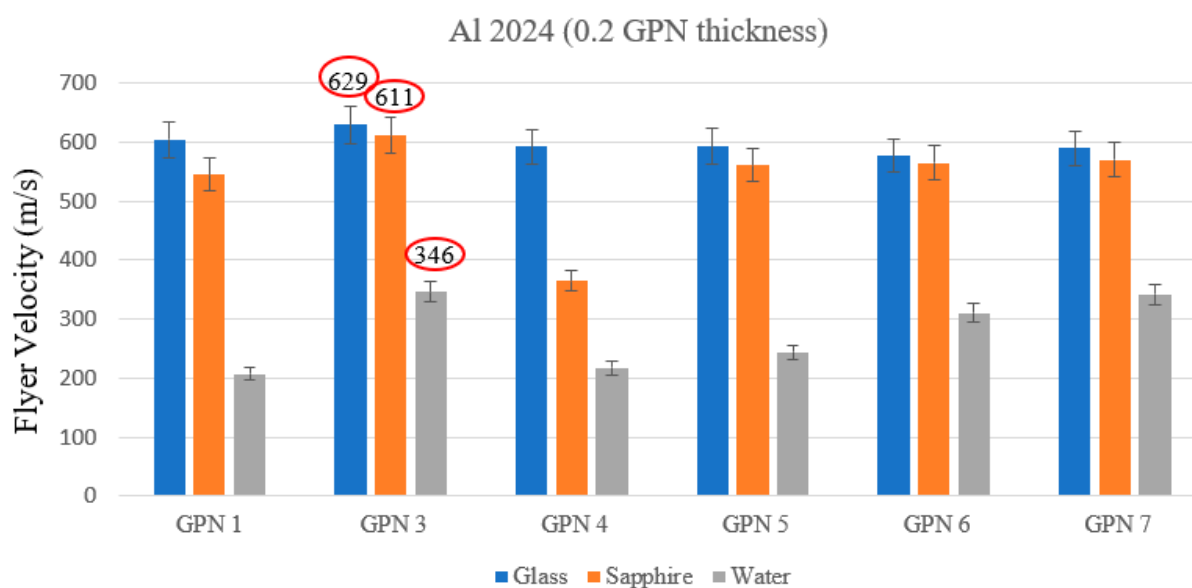


Figure 4. Maximum flyer velocity values for various GPN compositions with different confinement layers for Al 2024 with 0.2 mm GPN thickness.

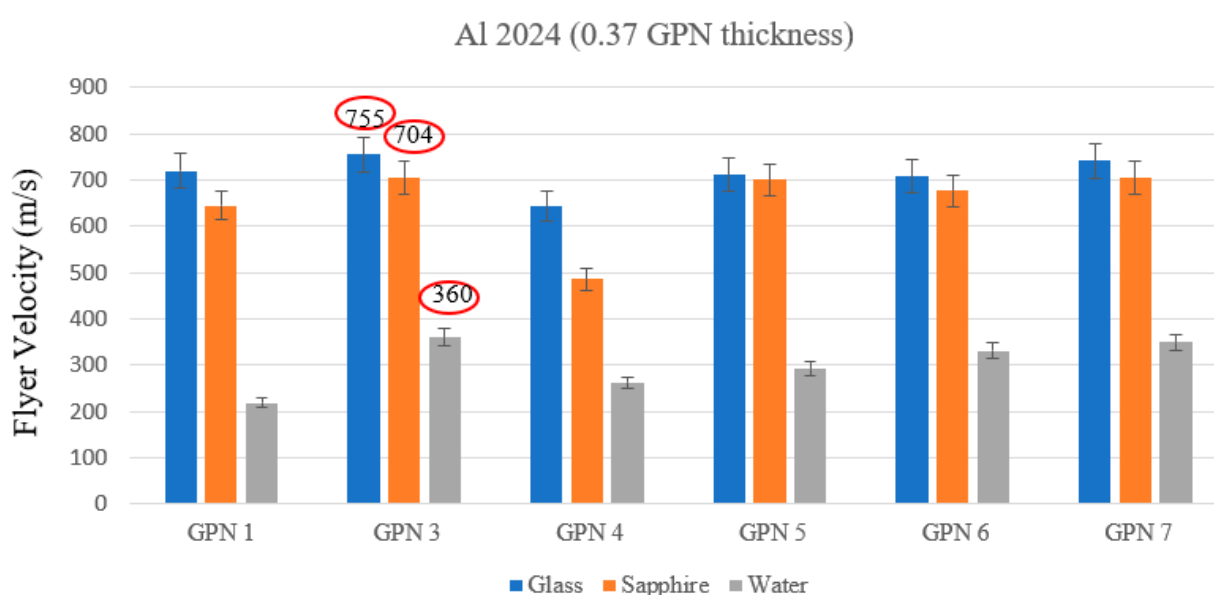


Figure 5. Maximum flyer velocity values for various GPN compositions with different confinement layers for Al 2024 with 0.37 mm GPN thickness.

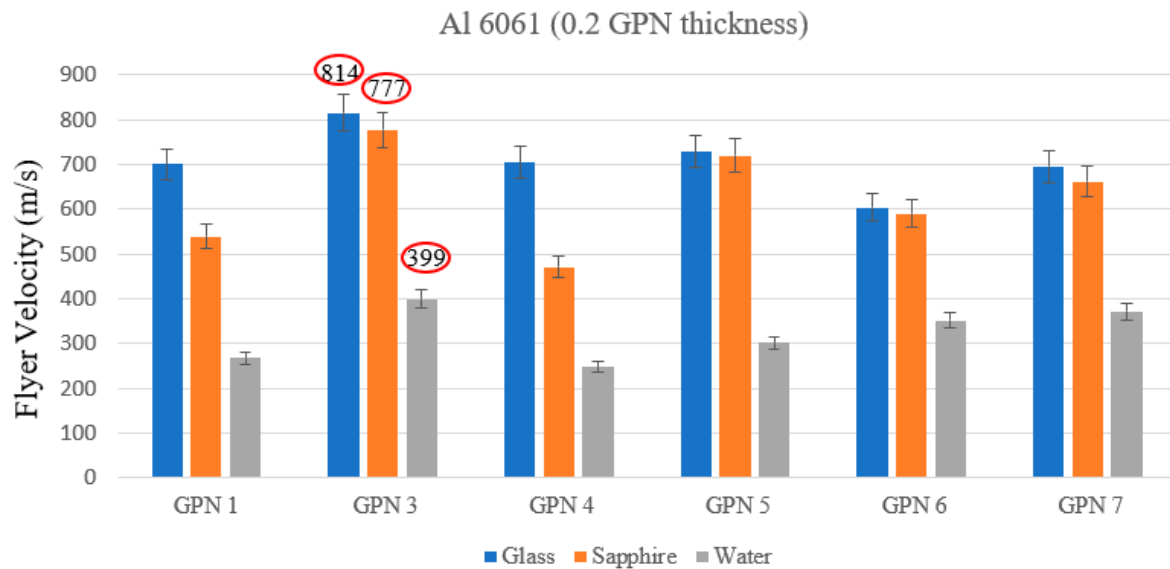


Figure 6. Maximum flyer velocity values for various GPN compositions with different confinement layers for Al 6061 with 0.2 mm GPN thickness.

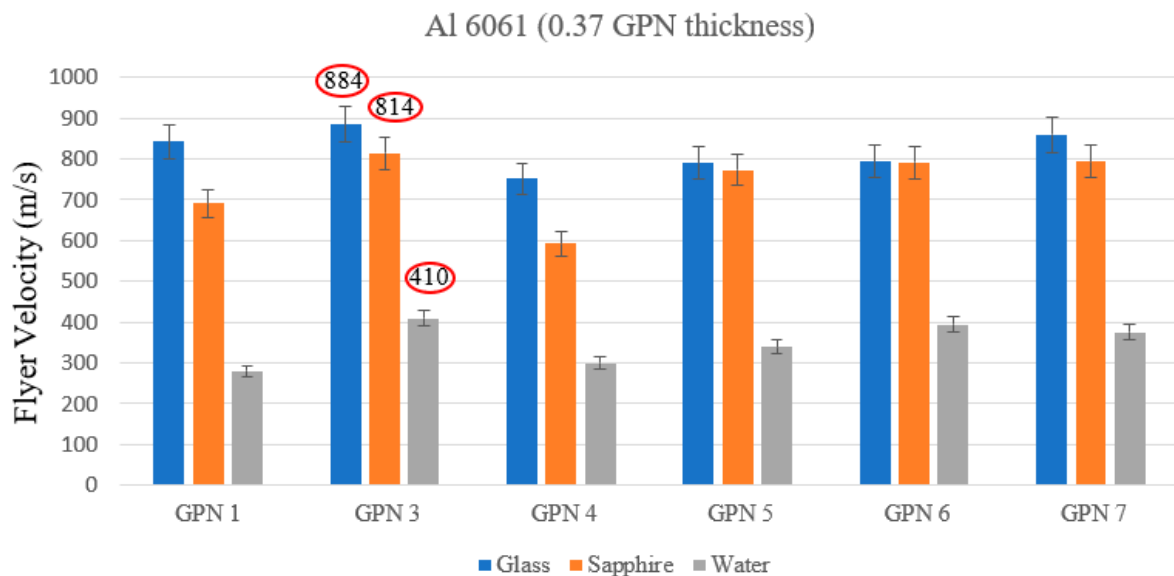


Figure 7. Maximum flyer velocity values for various GPN compositions with different confinement layers for Al 6061 with 0.37 mm GPN thickness.

3.2. The Lap Shear Test

To highlight that GPN-3 delivered the highest detonation energy, a lap shear test was conducted. The performance of GPN-3 was compared to the original GPN-1. For this evaluation, three aluminum alloys, Al 1100, Al 2024, and Al 6061, each with a thickness of 0.5 mm, were utilized. Moreover, Al 1100 was joined with Al 2024 and Al 6061 in different configurations, serving alternately as the flyer and the target. In addition, sapphire was employed as the confinement layer during this evaluation. Figures 8 and 9 display the load–displacement curves for the welded joints of these combinations. These figures demonstrate that, in all the scenarios, GPN-3 provided a higher load than GPN-1. This can be attributed to the previous explanation involving cavitation and gas release from the addition of micro-air bubbles to GPN-1, which influenced the detonation energy. Moreover, failure never took place between the welded components but consistently occurred on

the Al 1100 base material side, which indicated as the weakest link in all the cases and consequently demonstrating the high strength of the joints, as shown in Figure 10.

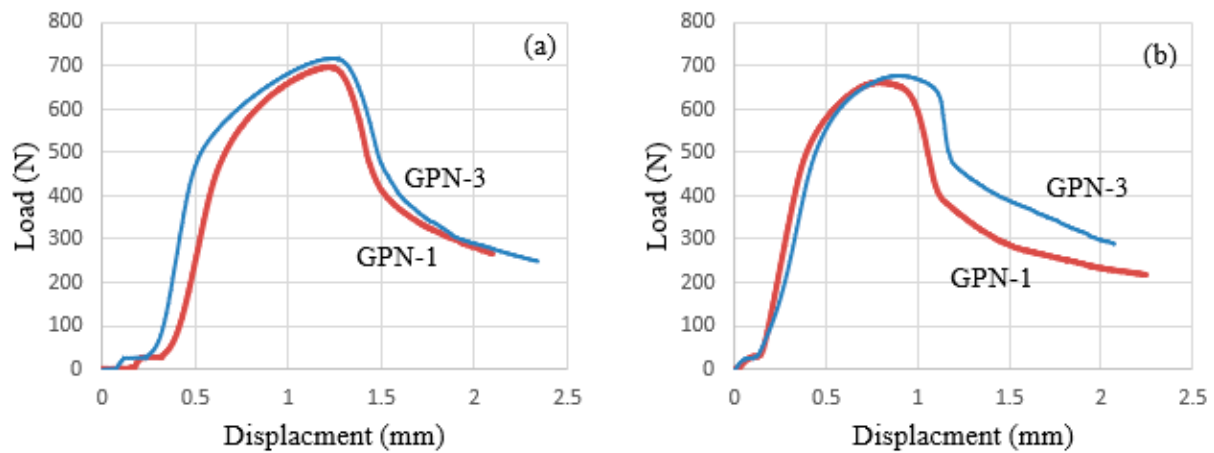


Figure 8. Load–displacement curves for lap shear tests of welded samples, with 0.5 mm stand-off according to different GPN compositions: (a) Al 1100 as a flyer and Al 2024 as a target; (b) Al 2024 as a flyer and Al 1100 as a target.

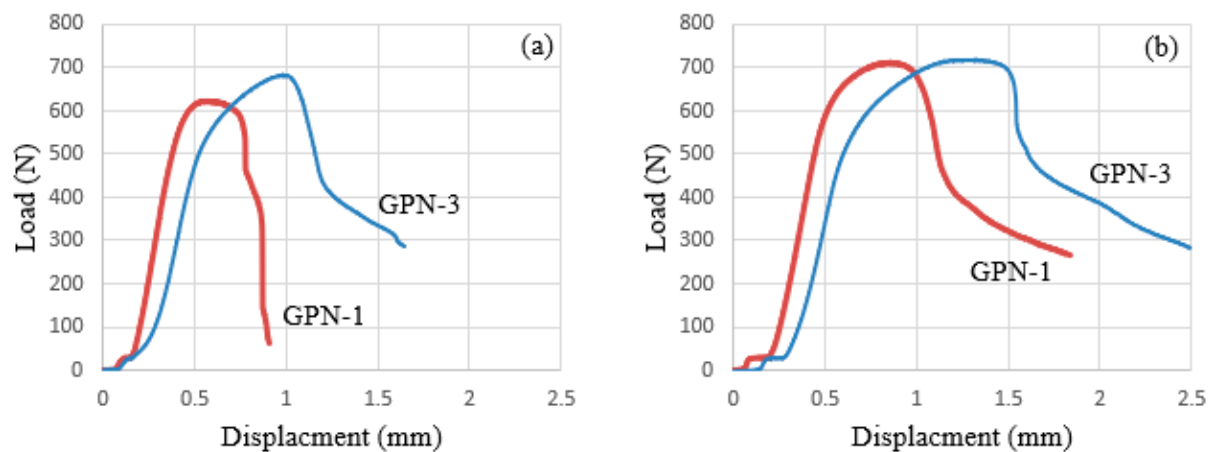


Figure 9. Load–displacement curves for lap shear tests of welded samples, with 0.5 mm stand-off according to different GPN compositions: (a) Al 1100 as a flyer and Al 6061 as a target; (b) Al 6061 as a flyer and Al 1100 as a target.

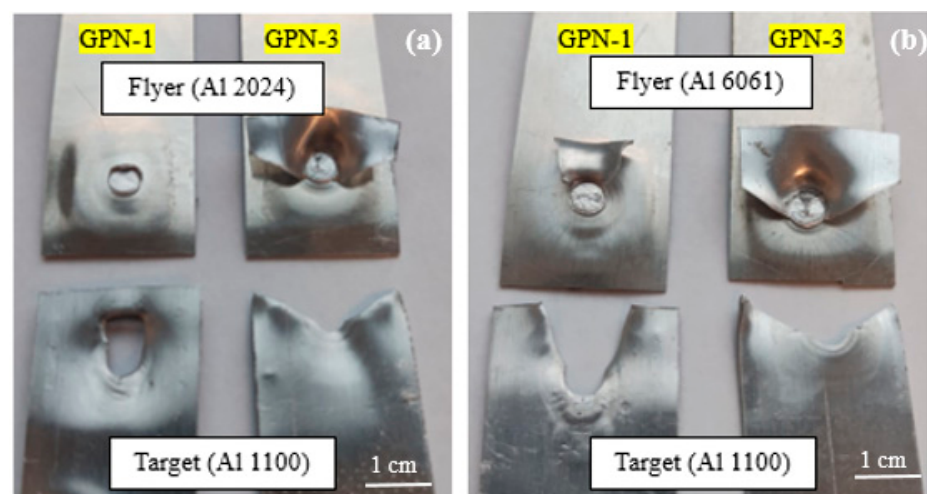


Figure 10. Failure of lap shear tests of welded samples: (a) Al 2024 as a flyer to Al 1100 as a target; (b) Al 6061 as a flyer to Al 1100 as a target, using GPN-1 and GPN-3.

3.3. Microstructure Analysis

According to the results from the PDV measurements, GPN-3 exhibited higher detonation energy compared to the original GPN-1. Consequently, there were differences in the behavior of the interfacial waves between the welded joints using these GPN compositions. Figure 11 depicts the interfacial waves of the welded joints with GPN-1 and GPN-3 across various combinations of materials regarding Al 1100 and Al 2024, which were used as flyers and targets. It was evident that the interfacial waves in all the scenarios using GPN-1 were less pronounced than those using GPN-3, which were more wavy. Therefore, the wavelengths and amplitudes of the interfacial waves were higher in the GPN-3 cases. This can be explained by the higher shock waves and detonation energy that were released from the detonation of GPN-3, which was mixed with the addition of micro-air bubbles to the original GPN-1. Moreover, Carvalho et al. [42] highlighted that increasing the ratio of density or acoustic impedance between the flyer and target materials leads to shorter wavelengths and reduced amplitudes of interfacial waves. This phenomenon is clearly illustrated in Figure 11, where using Al 1100 (lower density) as the flyer material and Al 2024 (higher density) as the target resulted in higher interfacial wave amplitudes compared to the reverse scenario with Al 2024 as the flyer and Al 1100 as the target.

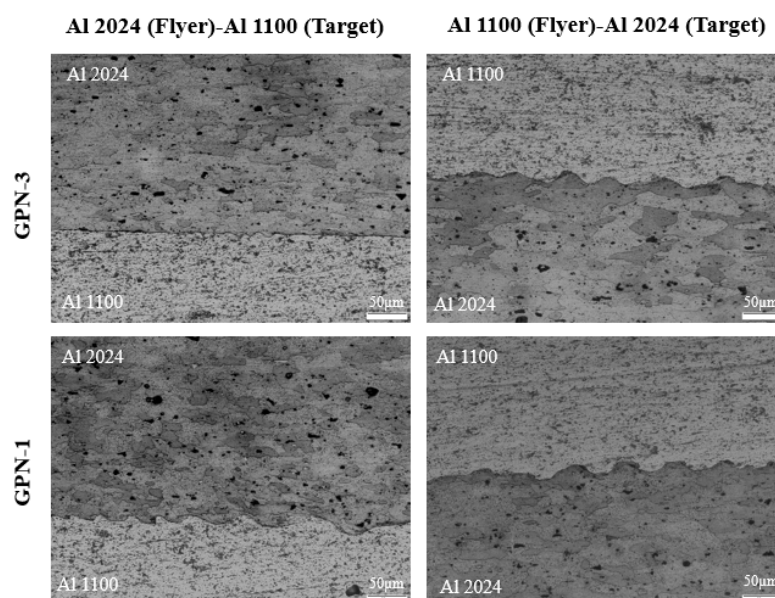


Figure 11. Interfacial waves at 1.5 mm from the center of the weld for different combinations of welded samples from Al 1100 and Al 2024 using different compositions of GPN with 0.5 mm stand-off.

4. Case Study to Emphasize the Effect of GPN-3

Building on Thurston's study [3], which demonstrated that, for 0.5 mm thick Al 2024, the highest flyer velocity was achieved using a 0.37 mm GPN-1 thickness and a 5.22 mm laser spot size, the current research explored a range of GPN-3 thicknesses from 0.27 mm to 0.63 mm under varying laser spot sizes (4 mm, 5.22 mm, and 6 mm). Figure 12 illustrates the dimple deformation observed on 0.5 mm Al 2024 flyers for each parameter combination with respect to flyer velocities. The findings confirmed that employing a 0.37 mm GPN thickness and a 5.22 mm spot size, coupled with borosilicate glass as the confinement layer, yielded the highest flyer velocity of 755 m/s. This emphasized the identification of the same maximum location for augmented thickness and laser spot size as observed in Thurston's original study [3], which utilized GPN-1. As a result, these parameters were adopted as a reference for all the trials.

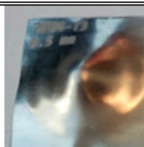
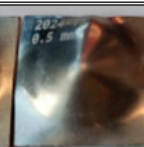
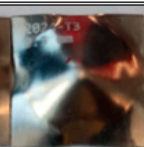
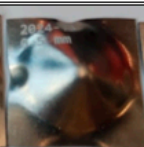
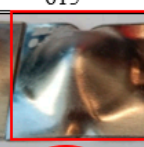
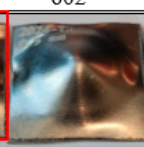
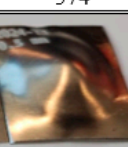
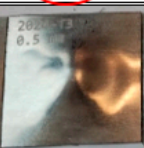
		GPN-3 Thickness (mm)				
		0.27	0.37	0.45	0.54	0.63
Spot Size (mm)	4 mm					
	Velocity (m/s)	556	615	602	595	574
	5.22 mm					
	Velocity (m/s)	442	755	622	536	486
Spot Size (mm)	6 mm					
	Velocity (m/s)	271	326	283	253	212

Figure 12. Flyer velocities at different combinations of GPN-3 thickness and laser spot sizes.

To critically assess the impact of GPN-3 on achieving higher detonation energy and, subsequently, greater flyer velocities, experiments were conducted using thicker flyer materials. Specifically, 1 mm thick sheets of Al 2024 and Al 6061 were employed as flyers, with 1 mm thick Al 1100 serving as the target material. Two process configurations, as shown in Figure 13, were examined: a standard setup with a 0.5 mm stand-off distance between the flyer and the target and an angled configuration with a 15° inclination between the two materials, as outlined in the accompanying Table 6.

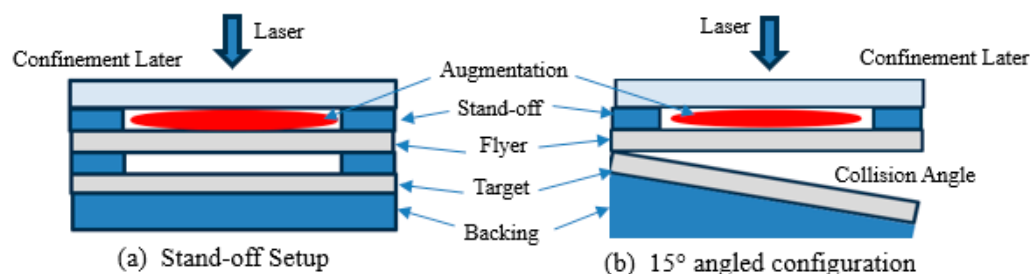


Figure 13. Schematic of ALIW process configuration: (a) standard stand-off setup and (b) 15° collision angle between flyer and target.

Table 6. Welding setup parameters for different combinations of 1 mm of aluminum.

Material (Thickness)	Ablative Layer	Confinement Layer	Energy (J)	Setup	Spot Size (mm)	Note
2024/1100 (1 mm/1 mm)	GPN-3	Sapphire and Glass	3	Stand-off (0.5 mm)	5.22	Successful Welded Joints
6061/1100 (1 mm/1 mm)						
2024/1100 (1 mm/1 mm)				Angle 15°		
6061/1100 (1 mm/1 mm)						

The PDV measurements revealed that the use of GPN-3 increased the flyer velocity of 1 mm thick Al 2024 by 36.4% compared to GPN-1. Therefore, the results demonstrated the formation of robust joints for the stand-off configuration and angled setup, as illustrated in Figure 14. Notably, the ability to successfully bond 1 mm thick materials as flyers underscores the effectiveness of the process.

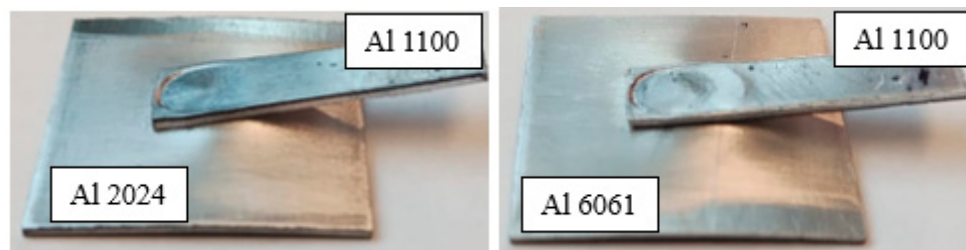


Figure 14. Welded joints using 15° angle between 1 mm Al 2024 (left) and Al 6061 (right) as flyers to Al 1100 as a target, with GPN-3 and sapphire as confinement layers.

5. Conclusions

Laser impact welding (LIW) utilizes augmentation to generate a plasma plume from detonation, enhancing welding quality. This study was conducted with the aim of optimizing a system that was initially proposed by Thruston et al. [3]. Several variations of the augmenting chemistry with different confinement layers were studied to determine the maximum detonation sensitivity, with the following results:

While the addition of aluminum powder increased the heat sensitivity, it decreased the detonation energy and dampened the flyer velocity. In contrast, incorporating micro-air bubbles into the original GPN-1 improved the detonation sensitivity and increased the flyer velocity.

GPN-3 (the one with the addition of 0.1 g of micro-air bubbles) is superior to the original GPN-1 in terms of achieving a better launch speed (4–16% for borosilicate glass, 9–40% for sapphire, and 45–65% for water) while using 0.5 mm thick Al 2024 and Al 6061, suggesting about a 20% increase in the available kinetic energy.

Utilizing GPN-3 enhanced the flyer velocity of 1 mm thick Al 2024 by 36.4% compared to GPN-1.

The ability to achieve a successful weld using 1 mm thick Al 2024 and Al 6061 as flyers is attributed to the high detonation energy produced when using GPN-3 during augmented laser impact welding (ALIW).

Although borosilicate glass as the confinement layer produced the highest flyer velocity, its susceptibility to fracture and damage with each laser shot renders it unsuitable for industrial applications. Conversely, sapphire exhibited slightly lower flyer velocity but demonstrated superior resistance to damage and fracture, making it more suitable for industrial use.

The microstructural analysis revealed that the interfacial waves in the GPN-3 scenarios were higher than those in GPN-1, underscoring the positive effect of micro-air bubbles on detonation sensitivity and flyer velocity. Furthermore, the lap shear tests highlighted this effect, with failures occurring on the Al 1100 side, showing higher curves for GPN-3 compared to GPN-1 in every case.

The use of tactical solid-state welding through augmented laser impact welding (ALIW) demonstrates great promise to replace spot welds or rivets. The process produces high strength without destroying material temper and can be easily and inexpensively practiced. The development of a commercial workflow is the next step.

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