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Article

Optimization of Gas Metal Arc Welding Parameters on the Structural Integrity of Al7075-T651 Welded Joints for Space Applications

Optimización de los parámetros de soldadura por arco metálico con gas en la integridad estructural de las uniones soldadas Al7075-T651 para aplicaciones espaciales

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Abstract

This study optimized Gas Metal Arc Welding [GMAW] parameters for Al-7075-T651 aluminum, crucial for aerospace due to its strength and corrosion resistance. While GMAW offers high-quality welds, Al-7075-T651's high zinc content challenges integrity via bubble formation. Six samples were welded under varied current, voltage, arc length, and gas flow, then analyzed via SEM. Optimization minimized bubble formation and improved weld uniformity. However, residual bubbles remain a concern for long-term strength in harsh space conditions. This research highlights GMAW's potential, especially with robotic systems, for durable spacecraft welds. It proposes a model for optimal parameters, enhancing reliability, reducing launch weight, and improving fuel efficiency. Findings underscore the necessity for continuous welding process refinement to meet evolving space exploration demands.

Aerospace, Aeronautics, Gas Metal Arc Welding.

Resumen

Este estudio optimizó los parámetros de la soldadura por arco metálico con gas (GMAW) para el aluminio Al-7075-T651, crucial para la industria aeroespacial debido a su resistencia y resistencia a la corrosión. Si bien la GMAW ofrece soldaduras de alta calidad, el alto contenido de zinc del Al-7075-T651 pone en peligro la integridad debido a la formación de burbujas. Se soldaron seis muestras con diferentes valores de corriente, tensión, longitud del arco y flujo de gas, y luego se analizaron mediante SEM. La optimización minimizó la formación de burbujas y mejoró la uniformidad de la soldadura. Sin embargo, las burbujas residuales siguen siendo una preocupación para la resistencia a largo plazo en las duras condiciones espaciales. Esta investigación destaca el potencial de la GMAW, especialmente con sistemas robóticos, para soldaduras duraderas en naves espaciales. Propone un modelo de parámetros óptimos que mejora la fiabilidad, reduce el peso de lanzamiento y mejora la eficiencia del combustible. Los resultados subrayan la necesidad de perfeccionar continuamente el proceso de soldadura para satisfacer las crecientes exigencias de la exploración espacial.

Aeroespacial, aeronáutica, soldadura por arco metálico con gas

Area: Promotion of frontier research and basic science in all fields of knowledge

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Introduction

Space exploration is a rapidly evolving field that necessitates significant technological advancements to ensure the safety and efficiency of spacecraft [1]. A critical aspect in constructing these vehicles is joining high-strength and durable materials, such as aluminum alloy 7075-T651 [2]. This material is extensively utilized in the aerospace industry due to its exceptional strength-to-weight ratio and corrosion resistance [1].

The harsh environment of space poses significant challenges to spacecraft design. For instance, Mars exhibits temperatures ranging from -140°C to 20°C within a single day [3]. Furthermore, ionizing radiation from space, including X-rays and gamma rays, can compromise electronic components, while abrasive space dust can damage surface materials and robotic mechanisms [4], [5], [6], [7].

Developing efficient and reliable welding techniques for joining high-strength and durable materials is crucial to address these challenges. Gas Metal Arc Welding [GMAW] is a widely employed technique for joining aluminum alloys, but it requires meticulous parameter selection to achieve high-quality welds [2]. Optimal welding parameter selection is vital to ensuring the structural integrity of spacecraft and preventing catastrophic failures during launch or orbit.

The Al-7075-T651 aluminum alloy is renowned for its exceptional strength and durability, attributed to its chemical composition and thermal treatment [8], [9]. Several authors have highlighted its application in spacecraft construction. Heidari et al. [10] utilized Al-7075-T6 to fabricate rocket fins, demonstrating outstanding results and reduced deformation. Similarly, Enes et al. [11] mentioned its use in constructing telescopes, such as the Hubble Space Telescope.

However, this material presents challenges, including difficulties in machining due to its highly resistant properties. Its low weldability, primarily attributed to its high zinc content [12], is a significant concern. Welding this material, particularly in corner joints, requires precise parameter selection to ensure weld quality.

GMAW welding is challenging to perform manually, especially in inaccessible locations. Therefore, implementing this technique in a robotic mechanism is crucial. The KUKA KR QUANTEC offers excellent advantages, including high-quality welds, accessibility to hard-to-reach areas, and precise weld seams [15]. Reducing spacecraft weight is vital for improving fuel efficiency and lowering launch costs. GMAW welding can facilitate this using lighter materials, such as Al-7075-T651, reducing component mass and production costs.

Space exploration demands advanced and reliable welding techniques for joining high-strength and durable materials. GMAW welding is a promising technique that can address welding challenges in the aerospace industry.

This research aims to investigate optimal GMAW welding parameters for joining Al-7075-T651 corner joints, enhancing spacecraft efficiency and reliability. Currently, rovers like Curiosity and Perseverance employ rivets and bolts in their suspension, wheels, structure, and specialized analysis arm. However, this joining technique poses risks in deployment and terrain navigation, as other planetary surfaces are replete with obstacles and inclines that can compromise these joints [16], [17], [18].

Therefore, this research proposal is viable for mitigating these risks and enhancing spacecraft efficiency and reliability. The study seeks to optimize welding parameters to minimize defects and maximize joint quality through simulation and experimentation of welding parameters, such as current, speed, and shielding gas pressure. Using Gas Metal Arc Welding [GMAW] for its advantageous properties, including slag removal, flux reduction, and compatibility with most commercial alloys [13]. Additionally, its continuous electrode surpasses the start-stop cycle of Shielded Metal Arc Welding [SMAW] and enables fewer discontinuities and greater deposition ranges [14].

Methodology

The aluminum alloy 7075-T651 [Al7075-T651] used in this study is a commercially available precipitation-strengthened Al-Zn-Mn-Cu alloy commonly used in the aerospace industry for structural components [19].

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The designated tempering process, Al7075-T651, includes solution treatment, stretching, and artificial material aging at 120°C for 24 hours [20]. The complete composition of this material is shown in Table 1.

Box 1

Table 1

Material components properties Al7075-T651

Chemical element	Quantity
Al	87.1 - 91.4 %
Cr	0.18 - 0.280 %
Cu	1.20 - 2.0 %
Fe	<= 0.50 %
Mn	2.10 - 2.90 %
Mg	<= 0.30 %
Si	<= 0.40 %
Ti	<= 0.20 %
Zn	5.10 - 6.10 %
Other	<= 0.15 %

The samples used for this research were prepared from a plate measuring 23 cm in length, 3.5 cm in width, and 1.2 cm in thickness to obtain 6 samples. The KUKA KR QUANTEC robot arm was developed especially for the automotive field since its load capacity is up to 300 kg and a maximum length of 3.9 meters long. This arm has different optimized movement modes that together with its maximum flexibility give us excellent results when adapting its torch module to weld by the GMAW method [22]. When using this arm, we have a level of reliability when welding since human error is eliminated in the welding process where it effectively maintains the welding line called bead.

In conjunction with its Fronius module with the technology called "Special two-stroke"[23] allows us to have a clean weld without sputtering and good penetration and fusion with the filler material, plus a fundamental part in which the piece of Al-7075-T651 is not necessary to heat it to break the layer of alumina when welding, this is extremely important because by other methods it is necessary to heat the aluminum parts thus damaging excessively the heat treatment that can carry the piece.

For this research we tested a different electrode than the one recommended by the manufacturers, what is recommended for this specific alloy is ER5356 because it is an aluminum-magnesium alloy that is more in accordance with the composition of this 7XXX aluminum series, but instead we used ER4043 which is an aluminum-silicon alloy because its properties improve the fluidity of the molten material as well as reduce the susceptibility to hot cracking during solidification [24].

Before welding, the plate was cleaned with xylene, acetone, and methanol to remove grease residue. Table 2 presents the working parameters for welding each of the samples.

Box 2

Table 2

Working parameters for Fronius "Special two-stroke"

Sample	Current [A]	Voltage [V]	arc length [mm]	Filament feed [m/min]	Gas flow L/min
1	104	9.6	1.9	5.6	13
2	134	19.6	3.8	6.4	13
3	151	51.6	4.7	7.1	13
4	161	22.4	5.3	7.6	13
5	170	23.2	6	8.1	13
6	181	23.4	6.5	8.6	13

Figure 1 displays the welds obtained from samples 1 to 6. Each sample was cut transversely to expose the welds. Then, metallographic grinding was carried out with water sandpaper of grit sizes 320, 600, 800, and 1200; this was succeeded by polishing a Dremel brand moto-tool set at 5000 rpm and employing 0.3 μm alumina polish. The grinding and polishing times were 10, 5, 5, 5, and 2 minutes, respectively, performed horizontally relative to the workpiece.

Box 3

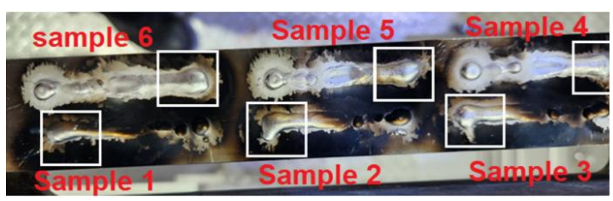

Figure 1

Al7075-T651 plate with 6 welding samples

The samples were characterized by Scanning Electron Microscopy [SEM] using Jeol JSM-5400 operated at 3 kV, WD 22 mm, and X50 to observe the morphology of the welding samples.

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Results

Figure 2 shows SEM micrographs of Sample 1, captured under the following conditions: current of 104 A, voltage of 9.6 V, arc length of 1.9 mm, filament feed rate of 5.6 m/min, and Ar-100% gas flow. Bubbles with minimum diameters of 10 µm and maximum diameters of 135 µm are observed in this sample. The presence of black spots is attributed to the sanding process. Figure 2B displays the right corner of the weld, while Figure 2C shows the central part, both with a scale of 100 µm. Although a perfect joint is observed, bubbles could create potential breakpoints [21].

Box 4

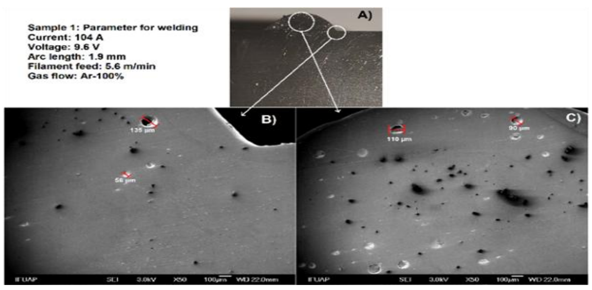

Figure 2

Sample 1 A] shows the cross-section of the weld, B] shows the right corner of the weld, and C] shows the central part

Figure 3 shows SEM micrographs of Sample 2, obtained with the following parameters: current of 134 A, voltage of 19.6 V, arc length of 3.8 mm, filament feed rate of 6.4 m/min, and Ar-100% gas flow. Bubbles with diameters ranging from 10 nm to 288 µm are identified. As in Sample 1, the visible black spots result from the sanding process.

Figure 3B shows the left corner of the weld, and Figure 3C shows the central part, both with a scale of 100 µm. Although the weld appears uniform, bubbles with large diameters could weaken the joint.

Box 5

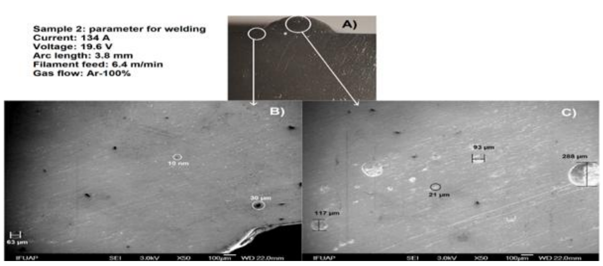

Figure 3

Sample 2 A] shows the cross-section of the weld, B] shows the left corner of the weld, and C] shows the central part.

Figure 4 shows SEM micrographs of Sample 3, captured with a current of 151 A, voltage of 51.6 V, arc length of 4.7 mm, filament feed rate of 7.1 m/min, and Ar-100% gas flow. Numerous bubbles are identified in the weld, with diameters ranging from 8 µm to a maximum of 321 µm.

This sample exhibits many bubbles of various sizes, making it unsuitable for achieving a solid weld. The black spots observed are attributed to the sanding process. Figure 4B shows the right corner of the weld, and Figure 4C shows the central part, both with a scale of 100 µm.

Box 6

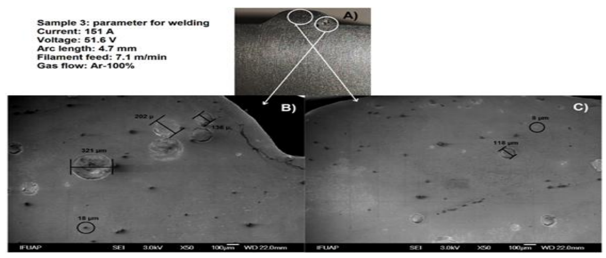

Figure 4

Sample 3 A] shows the cross-section of the weld, B] shows the right corner of the weld, and C] shows the central part.

Figure 5 presents SEM micrographs of Sample 4, obtained under the following conditions: current of 161 µA, voltage of 22.4 V, arc length of 5.3 mm, filament feed rate of 7.6 m/min, and Ar-100% gas flow. A uniform weld with few bubbles is observed; however, a bubble with a diameter of 441 µm is identified in the cross-section.

The black spots present are attributed to the sanding process. Figure 5B shows the left corner of the weld, and Figure 5C shows the central part, both with a scale of 100 µm. Although the reduced number of bubbles suggests an adequate weld, the bubble size may significantly weaken the joint.

Box 6

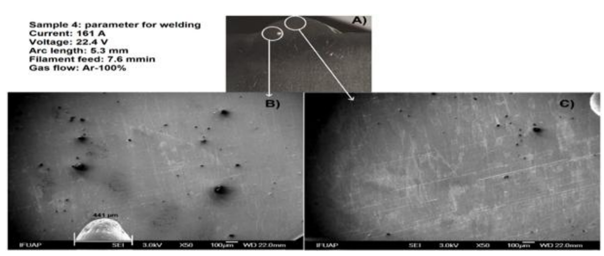

Figure 5

Sample 4 A] shows the cross-section of the weld, B] shows the left corner of the weld, and C] shows the central part

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Figure 6 shows SEM micrographs of sample 5 with the following parameters: current 170 A, voltage 23.2 V, arc length 6 mm, filament feed 8.1 m/min, and gas flow Ar-100%. A uniform weld with few bubbles is observed; however, the bubble observed in the cross-section is 15 µm. The presence of black spots is attributed to the sanding process. Figure 5B shows the left corner of the weld, while Figure 5C shows the central part, with a scale of 100 µm. The few bubbles could indicate a good weld. However, the size of the bubbles will significantly weaken the weld.

Box 7

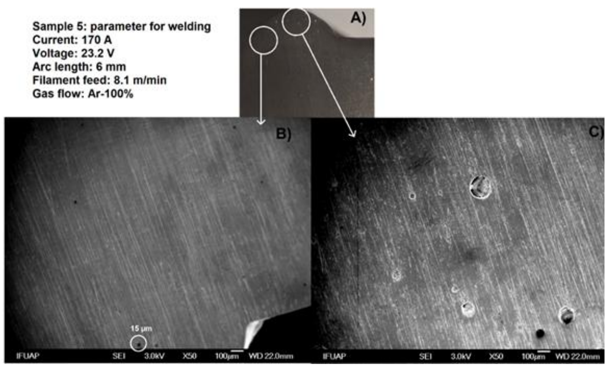

Figure 6

Sample 5 A] shows the cross-section of the weld, B] shows the left corner of the weld, and C] shows the central part.

Figure 7 shows SEM micrographs of Sample 6, obtained under the following parameters: current of 161 µA, voltage of 22.4 V, arc length of 5.3 mm, filament feed rate of 7.6 m/min, and argon gas flow at 100%. The image reveals a weld with a uniform appearance and a minimal amount of bubbles, suggesting improved joint integrity.

However, bubbles up to 10 µm in diameter are identified in the cross-section, which could impact the weld's long-term strength. The black spots in the micrograph are attributed to the sanding process and do not indicate weld defects. Figure 7B shows the right corner of the weld, while Figure 7C displays the central part, both with a scale of 100 µm. Although the reduced number of bubbles suggests a suitable weld, the bubble size may still weaken the joint, especially under stress or load conditions.

Box 8

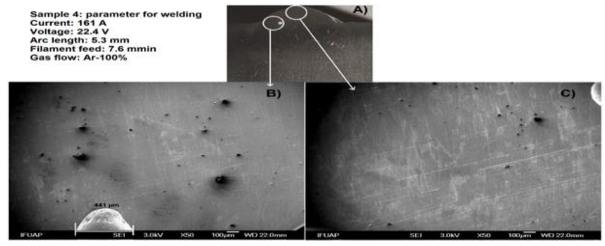

Figure 7

Sample 6 A] shows the cross-section of the weld, B] shows the right corner of the weld, and C] shows the central part

Conclusions

This study demonstrates the potential and challenges of applying Gas Metal Arc Welding [GMAW] to join Al-7075-T651 aluminum alloy in aerospace applications. Al-7075-T651's high strength-to-weight ratio and corrosion resistance make it an ideal material for spacecraft components; however, its welding challenges, particularly its susceptibility to bubble formation and reduced weldability, necessitate careful parameter optimization.

The study establishes a link between welding parameters and weld quality by analyzing six samples prepared under different welding conditions. Specifically, the current, arc length, and shielding gas pressure affect bubble formation and the uniformity of the weld.

The findings reveal that although GMAW can achieve uniform, high-quality welds, the presence of even tiny bubbles, as identified in this study, can weaken joints; this is critical given the extreme environmental conditions of space, where welded structures must withstand severe thermal cycles, ionizing radiation, and abrasive space dust. The study's results underscore that parameter optimization is crucial for achieving welds that maximize durability and reduce potential failure risks. The selection of optimal parameters for GMAW also enhances cost-efficiency by minimizing material waste and reducing the need for additional components, such as rivets or bolts, which add weight and complexity to spacecraft.

Furthermore, integrating GMAW with robotic mechanisms, such as the Kuka robotic arm, proves advantageous. Robotics enhance precision in difficult-to-reach areas and reduce human error, critical in spacecraft manufacturing, where consistency and reliability are paramount.

This approach addresses the limitations of manual GMAW and presents a path for the aerospace industry to adopt advanced automated welding processes, improving spacecraft assembly quality while lowering manufacturing costs.

GMAW shows promise as a viable welding method for Al-7075-T651 alloy in aerospace applications. However, future research should focus on further refining GMAW parameters and exploring alternative methods for quality assessment, such as in-situ monitoring during welding.

The continued advancement of welding techniques will be essential for the next generation of spacecraft, where reducing weight, enhancing durability, and ensuring reliability remain paramount. This research contributes a foundational model for welding parameter selection, paving the way for aerospace manufacturing improvements that support the demanding requirements of space exploration.

Abbreviations

A: Amps
Al: Aluminum
Al7075: Aluminum Alloy 7075
Ar: Argon
CONAHCYT: *Consejo Nacional de Humanidades, Ciencias y Tecnologías* [National Council for Humanities, Sciences, and Technologies]
Cr: Chromium
Cu: Copper
ER4043: Aluminum-Silicon welding wire
ER5356: Aluminum-Magnesium welding wire
Fe: Iron
GMAW: Gas Metal Arc Welding
kV: Kilovolt
L: Liters
m: Meters
Mg: Magnesium
min: Minutes
Mn: Manganese
mm: Millimeters
rpm: Revolutions per minute
SEM: Scanning Electron Microscope
Si: Silicon
SMAW: Shielded Metal Arc Welding
T651: Thermal Treaty 651
Ti: Titanium
V: Volts
WD: Working Distance
Zn: Zinc
µm: Micrometer

Declarations

Conflict of interest

The authors declare no interest conflict. They have no known competing financial interests or personal relationships that could have appeared to influence the article reported in this article.

Author contribution

SANTIAGO VARGAS, ERICK RENE, and CUATE-GOMEZ, Diego-Hernan will conduct the development, experimentation, different Characterizations, and article writing. GARZÓN-ROMÁN, Abel, and SANTIAGO VARGAS, EDNA PATRICIA, helped with the correction of the manuscript.

Availability of data and materials

The data that support the findings of this study are available from the corresponding author, Santiago Vargas, upon reasonable request.

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