



Nikola Knezović¹, Angela Topić¹

ADVANCES AND THE FUTURE TRENDS IN WIRE AND ARC ADDITIVE MANUFACTURING (WAAM)

NAPREDAK I BUDUĆI TRENDovi ADITIVNE PROIZVODNJE ŽICOM I ELEKTRIČNIM LUKOM (WAAM)

Professional paper / Stručni rad:

Author's address / Adresa autora:

¹Fakultet strojarstva, računarstva i elektrotehnike Sveučilišta u Mostaru, Mostar, BiH

Paper received / Rad primljen:

November 2023.

Paper accepted / Rad prihvaćen:

December 2023.

Keywords: wire and Arc Additive Manufacturing, welding, alloys, functionally graded materials

Ključne reči: aditivna proizvodnja žicom i električnim lukom, zavarivanje, legure, funkcionalno graduisani materijali

Abstract

Over the past three decades, extensive research has been conducted on WAAM (Wire and Arc Additive Manufacturing), a production technology that traces its origins back almost a century with its initial patent. This technology has garnered increasing attention due to its capability to fabricate large near-net-shape metal products. The utilization of existing welding equipment for the heat source and material feedstock in WAAM offers the advantage of lower initial investment costs. Originally gaining prominence in the aerospace industry, it primarily focused on the utilization of lightweight metal alloys. However, recent advancements have broadened the scope of WAAM to encompass numerous products, including functionally graded materials (FGMs) and the combination of diverse alloys. This study seeks to unveil the latest breakthroughs and potential avenues in WAAM technology, offering valuable insights and recommendations for future research endeavors.

Rezime

Tokom protekle tri decenije, sprovedeno je opsežno istraživanje o Aditivnoj proizvodnji žicom i električnim lukom WAAM-u (Wire Arc Additive Manufacturing), proizvodnoj tehnologiji koja svojim početnim patentom vodi svoje poreklo skoro jedan vek unazad. Ova tehnologija privlači sve veću pažnju zbog svoje sposobnosti da proizvede velike metalne proizvode približnog oblika i dimenzija konačnog proizvoda. Korišćenje postojeće opreme za zavarivanje za izvor toplote i potrošnog materijala u WAAM-u nudi prednost nižih početnih troškova ulaganja. Postupak je prvobitno stekao značaj u vazduhoplovnoj industriji, prvenstveno se fokusirao na korišćenje lakih metalnih legura. Međutim, nedavni napredak proširio je obim WAAM-a kako bi obuhvatio brojne proizvode, uključujući funkcionalno graduisane materijale (FGMs) i kombinaciju različitih legura. Ova studija nastoji da otkrije najnovija otkrića i potencijalne puteve u WAAM tehnologiji, nudeći vredne pristupe i preporuke za buduće istraživačke poduhvate.

The paper was published in its original form in the Proceedings of the International scientific and professional conference: Welding connecting - "Welding and welded structures 2023" held in Sarajevo, BiH, from October 25 to 27, 2023.



1. Introduction

The constant evolution of the industry serves as a driving force, compelling researchers to always explore novel production technologies. In recent times, additive manufacturing technologies have gained significant popularity due to their ability to fabricate intricate components with enhanced efficiency. However, until the extensive development of Wire and Arc Additive Manufacturing (WAAM), the majority of additive manufacturing methods were unable to effectively produce metal parts. WAAM is the easiest to describe as a fusion of welding and additive manufacturing. It harnesses an electric arc as the primary heat source and employs welding wire as the feedstock material, all while being guided by robotic hands or CNC machines for precise movement [1]. Although the first patent related to WAAM dates back to 1925 [2], it wasn't until its potential for reducing raw material waste in the aerospace industry was discovered that researchers began to show heightened interest in this technology [3]. Consequently, much of the experimentation and research in the field has been concentrated on the production of aerospace components, thereby dictating the choice of materials predominantly used, such as titanium, aluminium, nickel-based alloys, and so forth [4].

Thanks to wider use and interest from researchers all over the world, more and more different metals and alloys are being produced using this technology. For example, one of the abilities which distinct WAAM from conventional technologies is production of functionally graded materials (FGM) - composite materials that exhibit a gradual variation in their composition, microstructure, or properties over their volume [5]. Unlike traditional homogeneous materials, they are engineered to possess tailored and smooth transitions from one constituent material to another, resulting in unique and desirable properties along the gradient. Furthermore, valuable insights have emerged from studies focusing on thermal management during the WAAM process, stress relief, and post-processing machining techniques. These endeavors aim to facilitate the production of parts that not only match the characteristics of conventionally manufactured counterparts but potentially surpass them in terms of quality and performance.

2. Latest findings and advances in WAAM

2.1. Stainless steels

Researchers are increasingly intrigued by stainless steels due to their versatile applicability. Wire Arc Additive Manufacturing (WAAM) presents a potential solution for various challenges encountered in traditional production processes.

Paper [6] presents the use of a TIG method with a novel current waveform comprising a mixture of AC and DC for the production of stainless steel components. An austenitic welding wire (G 18 8 Mn) was employed as an additional material. The current modes were varied, ranging from 100% DC to a combination of 70% DC and 30% AC, with the AC ratio gradually increasing. The microstructure exhibited refinement as the AC ratio increased, leading to a transformation in the morphology of austenite from columnar dendrites to equiaxed dendrites. Consequently, the average grain size decreased, indicating an enhanced degree of refinement with a higher AC ratio. Moreover, it resulted in improved tensile properties in both directions, likely attributable to the grain refinement effect.

One of the parameters that can be manipulated during research is the interpass temperature, as demonstrated in [7]. Super-duplex stainless steel wire ER2594 (25 9 4 N L) was used to fabricate two "walls." While all other parameters remained constant, the interpass temperature for the first wall was set at 150 °C, whereas for the second wall it was adjusted to 100 °C. As a result, the second wall exhibited a lower ferrite content, approximately 10% less, which subsequently led to higher maximum fatigue limit stresses. These findings are proof that even minor alterations to process parameters can exert a significant influence on the final product.

Fatigue life was an important characteristic for the authors of paper [8]. They compared their product with the forged 13Cr4Ni martensitic stainless steel typically employed in hydro turbine runners. Welding wire uses was ER410NiMo (G 13 4). For WAAM-produced component, fatigue strength of 10^7 cycles at room temperature was 468 MPa, surpassing the forged part's fatigue strength of 370 MPa. Furthermore, the WAAM part exhibited higher yield strength and ultimate tensile strength when compared to the forged counterpart.



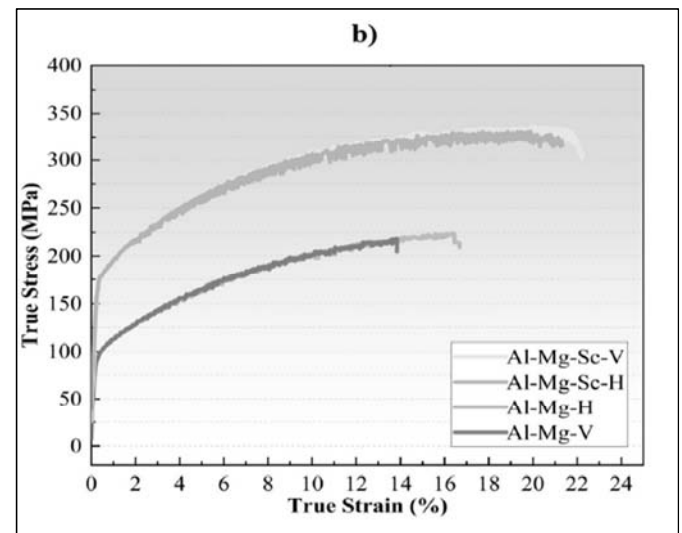
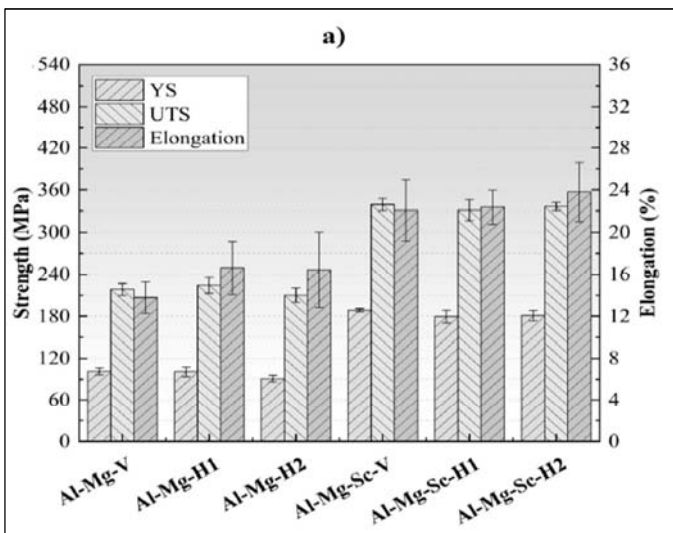
2.2. Aluminium

As previously mentioned, the aircraft industry has played a significant role in driving the development of Wire Arc Additive Manufacturing (WAAM). Given that aluminium is extensively utilized in the aircraft industry, it is not surprising that numerous research papers focus on this material.

In paper [9] a study is presented focusing on two aluminium alloys: Al-Mg and Al-Mg-Sc alloy. The inclusion of Sc was chosen due to its ability to refine grains and convert non-heat treatable strengthened alloys into heat-treatable strengthened alloys. Additionally, Sc enhances fatigue strength and resistance against microcrack growth in Al-Mg alloys. Following the production process, an additional heat treatment was applied. The addition of Sc was found to be crucial in increasing the nucleation rate and reducing the grain size. Depending on the heat treatment temperature, the grain size was reduced by 86-

93%. The uniform precipitation of Al_3Sc particles during deposition through WAAM significantly impeded dislocation motion, leading to further improvements in the strength of the deposited Al-Mg-Sc alloy. The mechanical properties such as yield strength, ultimate tensile strength, and elongation were also enhanced, which was attributed to the refined grain structure and precipitation strengthening. Although there was only a slight improvement in hardness observed through heat treatment due to the absence of supersaturated Sc available for precipitation, the heat treatment temperatures did not have a significant influence on the mechanical properties, as shown in Picture 1.

The differences in mechanical properties among Al-Mg alloys with varying heat treatment temperatures were minimal, and the same trend was observed for Al-Mg-Sc alloys. However, significant differences in mechanical properties were attributed to the presence of Sc.



Picture 1. Mechanical properties of a) Al-Mg alloys and b) Al-Mg-Sc alloys

Slika 1. Mehaničke karakteristike a) Al-Mg legura i b) Al-Mg-Sc legura

Optimization of parameters to produce aluminium alloy of good quality was presented in the paper [10]. The MIG method was employed with a new hybrid arc technology that combined cold metal transfer and pulse transfer. The AA2024 filler wire was used in the process. Three key parameters were varied: wire-feed speed (WFS), travel speed, and the CMT/P ratio, which represents the ratio of the number of cold metal transfer stages to pulse stages in a cycle. Among the parameters studied, the wire-feed speed had the most significant influence on porosity. Initially, the porosity decreased with increasing WFS, but beyond a certain point, it started to increase again.

Lower porosity levels were achieved with lower travel speeds, indicating higher heat input. Surface roughness was also greatly affected by the WFS and travel speed. Higher WFS resulted in lower surface roughness, while the relationship between surface roughness and travel speed was more complex, initially decreasing and then increasing with higher travel speeds. The CMT/P ratio played a major role in the formation quality of the parts. The best formation quality was achieved when the CMT/P ratio was in the middle range. With a higher ratio, surface roughness began to increase. In conclusion, the study demonstrated the importance of optimizing parameters such as WFS, travel



speed, and CMT/P ratio to produce aluminium alloy parts of superior quality, ensuring minimal porosity, lower surface roughness, and better formation quality.

In paper [11], a similar investigation to that in paper [9] was conducted to study the impact of an alloying element on the characteristics of an aluminium alloy, with copper (Cu) being the element of interest. Three different welding wires with varying copper percentages (5%, 5.65%, and 6.3% Cu) were used in the study. Copper acts as the strengthening element, precipitating the θ' phase after solution ageing to enhance the mechanical properties of the alloy. The number and size of θ phases precipitated from the as-deposited Al-Cu alloy increased with higher copper content. However, when the Cu content exceeded 5.65%, larger remaining θ phases were observed under the solid solution treatment condition. Upon subjecting the alloy to T6 heat treatment, the mechanical properties reached their highest level at a Cu content of 5.65%. This suggests that an optimal balance is achieved with this specific copper percentage for obtaining desirable mechanical characteristics. An important consideration for limiting the Cu percentage to not exceed 5.65% is the anisotropy of mechanical properties. For parts produced with the welding wire containing 6.3% Cu, the vertical specimens exhibited a change in fracture mode from ductile to brittle fracture. Therefore, to maintain improved mechanical properties and avoid issues related to anisotropy, it is advisable to keep the copper content at or below 5.65%.

An interesting idea was suggested in the paper [12], where steel strip was inserted in the middle of the aluminium part. This steel strips serve as smart parts providing information to the user thanks to an embedded device. The study explored various combinations of steel strips and welding torch offset distances to assess their performance. The deterioration of the bimetallic interface was evaluated using X-ray tomography to generate thickness maps. To analyze the bonding quality between the steel strip and the aluminium alloy, scanning electron microscopy (SEM) and energy-dispersive X-ray spectroscopy (EDS) were employed. The results indicated that welding with an offset equal to or less than 2.0 mm led to a degradation of the steel strip, rendering it unsuitable for creating a high-quality bond. Upon observing the side view of the samples, it was found that an offset of 3.0 mm resulted in a bead and a strip separated by significant void space.

Therefore, using an offset of 3.0 mm or more was also considered inappropriate. On the other hand, when an offset of 2.5 mm was employed, a bimetallic layer was identified through EDS analysis, indicating a sign of strong bonding between the steel strip and the aluminium part. In conclusion, the study highlighted that an offset of 2.5 mm proved to be the most appropriate for embedding a steel strip within an aluminium part, ensuring a robust and well-bonded connection, while offsets of 2.0 mm or less and 3.0 mm or more were not suitable for achieving the desired bonding quality.

2.3. FGM - Functionally Graded Materials

As it is already said, researches of FGM are gaining increased interest, since WAAM offers a viable and promising solution for the fabrication of components composed of two or multiple distinct materials in a gradual and continuous manner.

An intriguing approach was shown in paper [13], where the welding wire "3Dprint AM 718," (composed of Inconel 718 alloy) was deposited onto a substrate made of steel grade S275. Three sets of specimens were collected at different stages: without any heat treatment (referred to as AB, as build), solution-treated (ST), and aged (STA). The AB sample exhibited a considerable presence of the Laves phase on the deposited side, which was only partially dissolved even after the solution annealing process. Unfortunately, the solution treatment resulted in undesired grain coarsening in both the substrate and the deposited "wall." However, the ageing treatment did not show any noticeable grain growth. The hardness of the substrate decreased by more than half, and this reduction remained unchanged after ageing. On the other hand, the "wall" exhibited increased hardness only after ageing treatment. The elastic and shear moduli showed an increase at greater distances from the interface (first layer) for all treatment conditions. This behavior can be attributed to the relatively lower mixing of the alloying elements in this region.

Paper [14] also presents combination of an Inconel alloy with steel, but this research used Inconel 825 and austenitic stainless steel 316L (1.4404). Building manner was slightly different – the Inconel alloy served as the substrate, and then twenty layers of Inconel were deposited before an additional twenty layers of stainless steel were placed on top. The resulting structure formed the middle part, which represented the Functionally Graded Materials (FGM), as illustrated in Picture 2.



Picture 2. Building of the FGM with WAAM

Slika 2. Izradjen FGM sa WAAM-om

To evaluate the mechanical properties, specimens were extracted from all three sections for tensile testing. For fracture toughness testing, specimens were specifically taken from the middle part at the FGM interface. Tensile testing results did not exhibit significant differences among the sections, as all of them demonstrated plastic deformation, indicative of ductile fracture behavior. The Crack Tip Opening Displacement (CTOD) values were found to be similar, measuring 0.853 mm for the Inconel side and 0.873 mm for the stainless steel side. These comparable CTOD values imply that this FGM configuration could be effectively employed in tough and demanding environments.

In research [15] a distinct approach was taken, involving the production of a complex CoCrFeMoNiV alloy using flux-cored welding wire. The shell of the material was composed of FeNi36, while the other alloying elements were present in the filling. The study encompassed chemical and microstructural analysis, mechanical properties testing, and an examination of the material's behavior under abrasive wear using the G75 test. Chemical composition analysis revealed minimal differences between the nominal composition of the welding wire and the final product, with minor burn-off of Cr, Mb, and Co, which was expected during the manufacturing process. The material exhibited an average Young's modulus of 246 GPa, a yield strength of 530 MPa, and a tensile strength of 560 MPa. The hardness values ranged between 252 HV10 and 270 HV10. The most significant and

noteworthy finding was the result of the G75 test, demonstrating that this material exhibited wear resistance comparable to cobalt-based alloys commonly used for producing wear-resistant claddings. The wear loss in the G75 test was approximately 110 mm³, further indicating the promising potential of this complex CoCrFeMoNiV alloy for wear-resistant applications.

Other complex alloy, Fe-Mn-Si-Cr-Ni-V-C, was used in the paper [16]. This alloy is shape memory alloy (SMA). The resulting fabricated component underwent a comprehensive characterization, focusing on microstructure, mechanical properties, and functional behavior assessment. The fabrication process exhibited desirable features, including low porosity and high deposition efficiency, leading to minimal surface waviness and reduced post-processing machining requirements. The measured mechanical properties were exemplary, with a yield strength of 472 MPa, fracture stress of 821 MPa, and elongation of 26%, indicating excellent material performance. These mechanical characteristics render the alloy and the manufacturing process suitable for various construction applications. Cyclic testing was performed, revealing a repeatable mechanical response, high levels of absorbed energy and maximum stress with low irrecoverable strain. These findings highlight the material's potential for applications in civil engineering, particularly in seismic systems, due to its ability to withstand repetitive loading and maintain its functional properties effectively.



3. Conclusions

The constant evolution of the industry has driven researchers to explore novel production technologies, leading to the growing popularity of additive manufacturing methods, particularly WAAM. The technology's potential for reducing raw material waste in the aerospace industry sparked heightened interest, resulting in much research focusing on aerospace applications and materials like titanium, aluminum, and nickel-based alloys. However, WAAM's versatility has enabled its expansion to various metals and alloys, including stainless steels and functionally graded materials (FGM), offering tailored material gradients with unique properties.

Studies have revealed valuable insights, such as the optimization of process parameters to achieve better part quality, the influence of alloying elements on mechanical properties, and the integration of steel strips as smart components. Additionally, the application of WAAM in producing complex alloys like Co-Cr-Fe-Mo-Ni-V and Fe-Mn-Si-Cr-Ni-V-C has shown excellent mechanical properties and wear resistance, offering potential for wear-resistant claddings and civil engineering applications.

Future work suggestions would be numerous, but some of the most important are:

- further material exploration: continue exploring the compatibility of WAAM with a broader range of materials, including specialized alloys for specific industrial applications, to expand the technology's potential in diverse fields;

- multi-material FGM development: research the production of complex FGM structures combining various materials with tailored properties, exploring new designs for enhanced performance in specific applications;

- industrial adoption and standardization: promote the adoption of WAAM technology in industrial sectors and collaborate on establishing standardized procedures and guidelines to ensure consistent quality and reliability of WAAM-produced components;

- integration of smart components: investigate the integration of more sophisticated smart components, beyond steel strips, to add additional functionalities to WAAM-produced parts for real-time monitoring and feedback systems;

- quality assurance: improvement of in-situ NDT techniques allow for real-time monitoring during the

manufacturing process, helping to detect any defects or anomalies as they occur, leading to improved part quality and reduced scrap rates.

By addressing these future research areas, the potential and applicability of WAAM can be further advanced, contributing to the continuous improvement and growth of additive manufacturing technologies in the industry.

3. Zaključci

Konstantna evolucija industrije navela je istraživače da istražuju nove proizvodne tehnologije, što je dovelo do sve veće popularnosti metoda aditivne proizvodnje, posebno WAAM-a. Potencijal tehnologije za smanjenje otpadnih sirovina u vazduhoplovnoj industriji izazvao je povećano interesovanje, što je rezultiralo velikim fokusom istraživanja na primenama u vazduhoplovstvu i na materijalima kao što su titanijum, aluminijum i legure na bazi nikla. Međutim, WAAM-ova svestranost je omogućila njegovu ekspanziju na različite metale i legure, uključujući nerđajuće čelike i funkcionalno graduisane materijale (FGM), nudeći prilagođene gradijente materijala sa jedinstvenim svojstvima.

Studije su otkrile bitne stvari, kao što su optimizacija parametara procesa za postizanje boljeg kvaliteta delova, uticaj legirajućih elemenata na mehanička svojstva i integracija čeličnih traka kao pametnih komponenti. Pored toga, primena WAAM-a u proizvodnji složenih legura kao što su Co-Cr-Fe-Mo-Ni-V i Fe-Mn-Si-Cr-Ni-V-C pokazala je odlične mehaničke osobine i otpornost na habanje, nudeći potencijal za obloge otporne na habanje i primenu u građevinarstvu.

Predlozi za budući rad bi bili brojni, ali neki od najvažnijih su:

- dalje istraživanje materijala: nastaviti da se istražuje kompatibilnost WAAM-a sa širim spektrom materijala, uključujući specijalizovane legure za specifične industrijske primene, kako bi se proširio potencijal tehnologije u različitim oblastima;

- razvoj složenih FGM materijala: istraživanje proizvodnje složenih FGM struktura koje kombinuju različite materijale sa prilagođenim osobinama, istražujući nove dizajne za poboljšane performanse u specifičnim primenama;

- industrijsko usvajanje i standardizacija: promovisati usvajanje WAAM tehnologije u industrijskim sektorima i sarađivati na uspostavljanju standardizovanih procedura i



smernica kako bi se obezbedio dosledan kvalitet i pouzdanost komponenti koje proizvodi WAAM;

- integracija pametnih komponenti: istražiti integraciju sofisticiranijih pametnih komponenti, u kombinaciji sa čeličnim trakama, da bi se dodale dodatne primene delovima proizvedenim WAAM-om za sisteme za praćenje i povratne informacije u realnom vremenu;

- osiguranje kvaliteta: poboljšanje in-situ NDT tehnika omogućava praćenje u realnom vremenu

tokom procesa proizvodnje, pomažući da se otkriju bilo kakvi nedostaci ili anomalije kada se pojave, što dovodi do poboljšanog kvaliteta delova i smanjene stope otpada.

Baveći se ovim budućim istraživačkim oblastima, potencijal i primenljivost WAAM-a mogu se dalje unaprediti, doprinoseći stalnom poboljšanju i rastu tehnologija aditivne proizvodnje u industriji.

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