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Analysis of the Bimetallic Joint of a Hot-Forged Crosshead Composed of ASTM B221 6060 Aluminum and AWS A5.36 E110C-G M Low Alloy Steel Obtained by Localized Fusion Additive Manufacturing

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In this study, the development of a bimetallic crosshead produced by additive manufacturing (AM) is discussed, evaluating the joint region between the two metals. The focus was on investigating the metallurgical aspect of this hybrid part, particularly the effect of warm forging at the interface, which combines attributes of two different metal alloys. Fabrication of the crossheads involved metal deposition, resulting in a wear-resistant outer layer using AWS A5.36 E110C-G M welding wire and an inner layer filled with ASTM B221 6060 rolled aluminum. The analyses showed that the intermetallic region had good adhesion properties after warm forging, although excessive formation of iron oxides could compromise the ductility of the joint. The results indicate that, with the formation of intermetallic phases minimized, additive manufacturing makes it possible to create complex high-performance components with customized properties, serving as a guide for evaluating the viability of this approach in further studies.

Keywords: *Warm forging, Additive Manufacturing, Crosshead, 3D printing, Bimetallic forging, Bimetallic joining.*

1. Introduction

3D printing, or additive manufacturing, has transformed the production of mechanical parts, bringing new design and customization options. The terminology Additive Manufacturing (AM), often referred to as Rapid Prototyping, refers to production methods that allow the rapid creation of an initial model or prototype, which will serve as the basis for the development of other models and the final product in its definitive version[1]. This method is considered innovative and substantially reduces the manufacturing time of models and prototype parts and also reduces the error rate during the production process[2]. Among the AM techniques, the wire arc directed energy deposition (WA-DED) technique, also known as wire arc additive manufacturing (WAAM) is attracting interest due to its high deposition rate[3-5] and used to produce parts from various structural alloys such as Ni-based superalloys and stainless steels[6-10].

Altering the design of components already present in vehicles and aircraft has provided superior performance. This is done by replacing materials in non-critical areas with lighter alternatives, reserving high-performance materials only for the areas that really demand this quality[11]. To make this transformation effective, various research and development activities are conducted to create appropriate technologies, such as improving automotive efficiency and reducing weight, which can be achieved by changing the material used[12].

Weight reduction is an essential strategy for reducing fuel, energy, and machining costs in the aerospace and automotive sectors. According to Bandivadekar et al.[13], combustion engine vehicles with a 10% weight reduction can achieve fuel savings of 6.9%, with acceleration from 0 to 60 mph improved by 7%. Similarly, electric vehicles with the same weight reduction can achieve a 5.1% increase in fuel efficiency and a 13.7% increase in range. Lighter alternative materials such as aluminum alloys, carbon fiber, composites and fiberglass composites are viable options for the production of automotive parts, and can reduce weight by 30-60%, 50-70% and 25-35%, respectively, compared to steel[14]. However, the strength, durability, and rigidity of lightweight alloys face challenges such as higher manufacturing costs and the need for more complex manufacturing processes[15].

For components facing high stress, it is common to opt for materials with superior mechanical properties, and for these parts subject to high stresses, materials with high mechanical properties are commonly accepted as the only alternatives[16].

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Therefore, this study will analyze the joining region of a hot-forged bimetallic crosshead produced by additive manufacturing, highlighting the impact of this technique on the metallurgical characteristics involved in the process.

Steel is known for its strength and durability, making it essential for transmission parts subject to heavy loads and adverse conditions. Aluminum, on the other hand, due to its lightness and thermal dissipation capacity, can improve performance in systems where weight reduction is important[15]. Additive manufacturing makes it possible to create parts with complex structures, integrating both materials in a precise and personalized way[17]. This technology offers the opportunity to optimize properties in a single part, adjusting the characteristics of the crosshead to meet specific performance requirements.

Seeking to understand the phenomena that occur at the interface of such different materials, the research combines visual and metallographic analysis to evaluate the bonding conditions between the two materials. Aspects such as the analysis of the structure and profile of the joint of the metals involved were investigated to understand how the combination and arrangement of materials can influence the overall behavior of the component. The ability to manufacture complex parts with optimized characteristics can result in significant advances in various industrial sectors, from automation to aerospace. A detailed understanding of the benefits and challenges associated with the additive manufacturing of bimetallic crossheads contributes to the advancement of engineering practices and promotes continuous innovation in the development of high-performance mechanical components..

In the manufacture of bimetallic components – such as crossheads combining steel and aluminum, the complementary properties of these materials can be exploited, improving the performance of mechanical elements in applications requiring strength and lightness.

In this work, the authors developed and analyzed a bimetallic crosshead manufactured by additive manufacturing, using a combination of aluminum and steel, with the aim of evaluating the feasibility and performance of joining these materials. Visual and metallographic analyses of the interface region were carried out, investigating the structural integrity and phase distribution resulting from the warm forging process. The results indicated good cohesion between the metals, with controlled formation of transition zones and no significant evidence of discontinuities, demonstrating the technique's potential for applications requiring both mechanical strength and weight reduction.

2. Materials and Methods

To manufacture the test pieces, samples were produced using a welding machine adapted by UniSATC, consisting of an axis coupled to a table with X, Y, and Z degrees of freedom. A numerical control system was adapted to operate automatically, so that the torch height could be controlled linearly, ensuring uniform material deposition. A semi-automatic SMASHWELD 250E welding machine from the manufacturer ESAB was used. The machine performs the MIG/MAG welding technique; for this study, the MAG welding process was applied, using a gas mixture of 85% Argon and 15% CO2. The details of the equipment are presented in Figure 1.

The design follows the approximate dimensions shown in Figure 2a, and the matrix used is shown in Figure 2b. The toolpath program was developed in G-code (Figure 2c), using Mach3 software for computer numerical control. The toolpath was designed based on the dimensions of the arms of the crosshead, running in a clockwise direction, and then supplemented with a circle with a diameter of 30 mm, to reinforce the connection between the arms and fill the body of the part. Six layers were applied alternately according to the diagram shown in Figure 2d. A Ø 10 mm hole was drilled in the center of the part to create a uniform surface and allow the 3/8" aluminum bars to fit in.

The deposition parameters used in the WAAM process are shown in Table 1.

The temperature at the time of material deposition was measured using an OPTRIS thermal camera, model PI 08M, with a temperature range between 575 and 1,900 ºC, enabled the monitoring and recording of temperature variations during

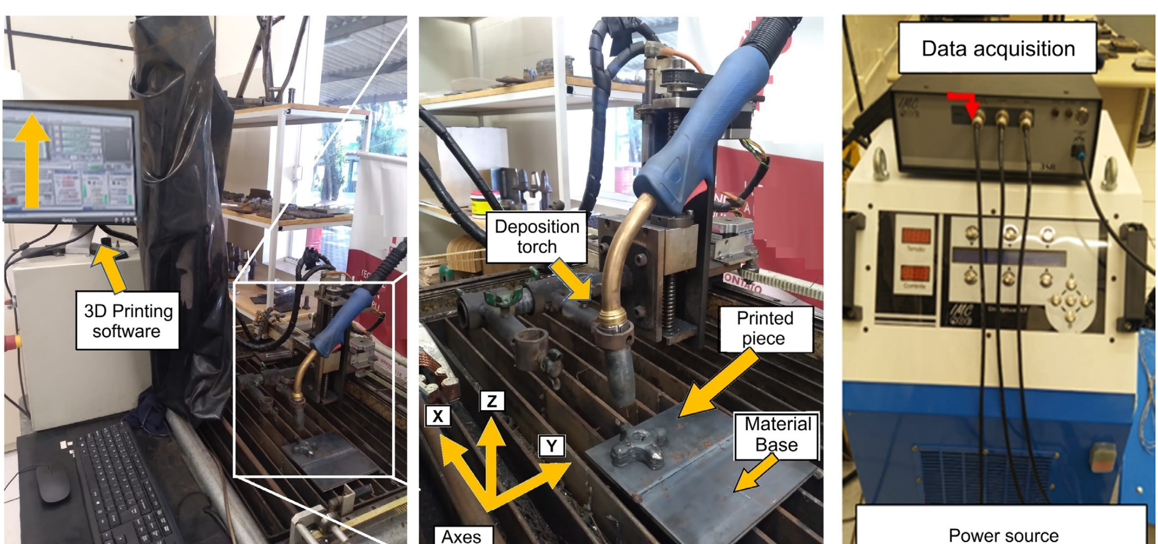


Figure 1. Welding machine used in the experiment.

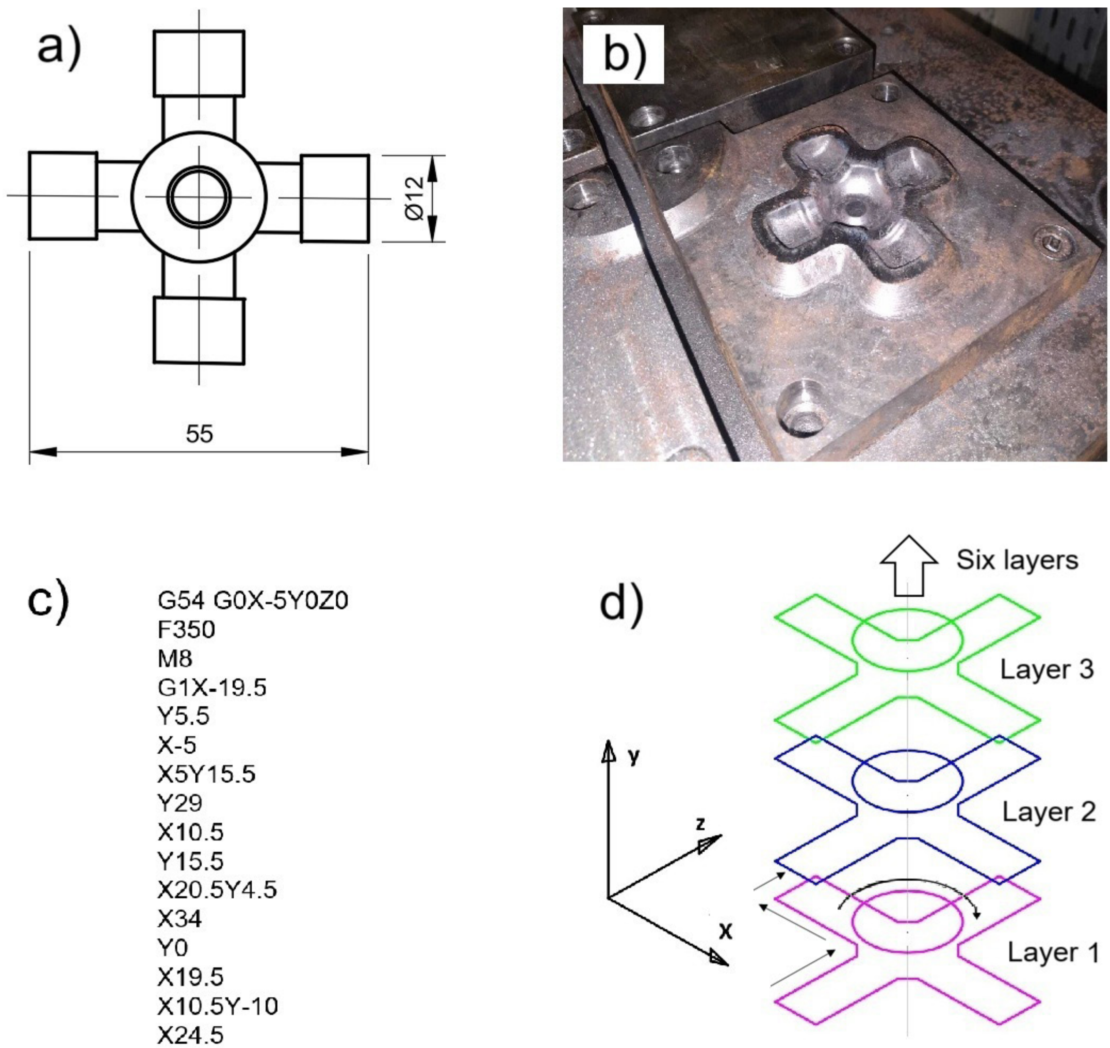


Figure 2. Crosshead design (a), forging die (b), manufacturing program (c) and deposition steps (d).

the printing of the steel element. Figure 3 shows a recorded temperature of 1,401.5 ºC during the crosshead printing process.

Table 2 presents the chemical composition of the alloys used in the manufacture of the bimetallic crosshead.

The steel samples were placed in a furnace preheated to 900 ºC and maintained at a plateau temperature to minimize the effects of surface oxidation. The temperature of 900 ºC was adopted based on the work of Meng et al.[20] and considering that higher temperatures could cause the aluminum core to melt during forging. The aluminum core, in contrast, was placed at room temperature when the crosshead was positioned in the die.

Forging was carried out in a single step using a hydraulic press with a capacity of 100 tons, belonging to Unisatc's mechanical forming laboratory. A temperature drop was observed due to the movement of the steel piece from the furnace to the press, as well as the exchange of temperature with the press tooling. Figure 4 shows the temperature of the crosshead recorded at the time of forging.

In Figure 5a and 5b, one can see the outside of the printed crosshead, while Figure 5c displays the aluminum bars that will fill the crosshead's core, and Figure 5d depicts the forged sample with the aluminum in its core.

Table 1. Setting parameters for the printing machine.

Parameters	Amount
Average electricity current (A)	144.0
Electrical voltage (V)	19.0
Electrical power (kW)	2.7
Gas flow (L/mm)	13.9
Wire feeding (kg/h)	1.0
Welding speed (mm/min)	200.0

3. Results and Discussion

Initially, samples were selected based on a visual analysis of the bimetallic joint to identify those most suitable for further analysis.

To analyze the joint, the sample was cut along the axis, as shown in Figure 6a. In its cross-section (Figure 6b), the

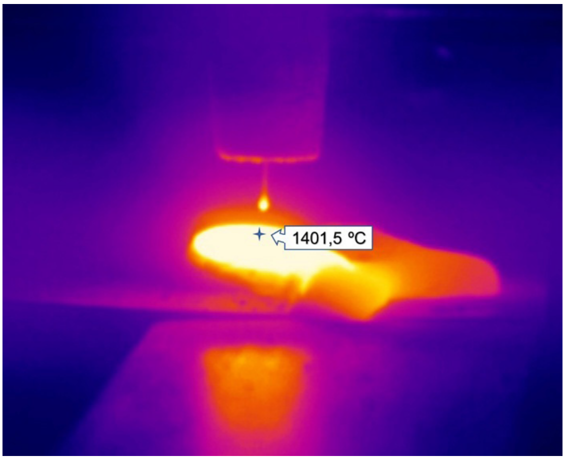


Figure 3. Print thermography.

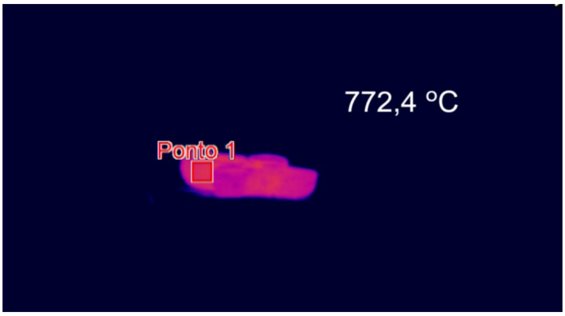


Figure 4. Crosshead temperature during forging.

curling of the aluminum core inward can be observed caused by the stresses that deform the steel and the ductility of the aluminum. This behavior is similar to that observed in the experiments by Politis et al.[21]. The deformation resulted in a mechanical interlock between the two materials, enhancing the bimetallic bond. A similar phenomenon was also reported in Xusheng et al.'s[22] studies.

The boundary between the two metals can be seen in Figure 7a, and in Figure 7b, it can be observed that surface fusion of the aluminum occurred due to contact with the steel heated during forging, a condition similar to that reported by Chang et al.[23].

According to the analysis, it was visually evident that there was no perfect adhesion between the metals at the bimetallic boundary, due to the differing characteristics of the two metals. Among the factors that may have influenced this separation is the press's load limit of 100 tons, the sawing process, and the differing expansion and contraction behavior between steel and aluminum. This behavior was also observed by Wang et al.[24].

Optical microscope analysis also revealed the presence of material fragments in the bonding region. These particles may have resulted from slippage between the surfaces during forging or to the thermal contraction process, which affects steel and aluminum differently.

Forging also led to the rupture and separation of oxide films, which, due to the flow of material, migrated to the aluminum matrix. This situation was reported in the study by Politis[25] and demonstrates the relevance of using the temperature processing window diagram for aluminum and steel to avoid metal separation, as shown in the work by

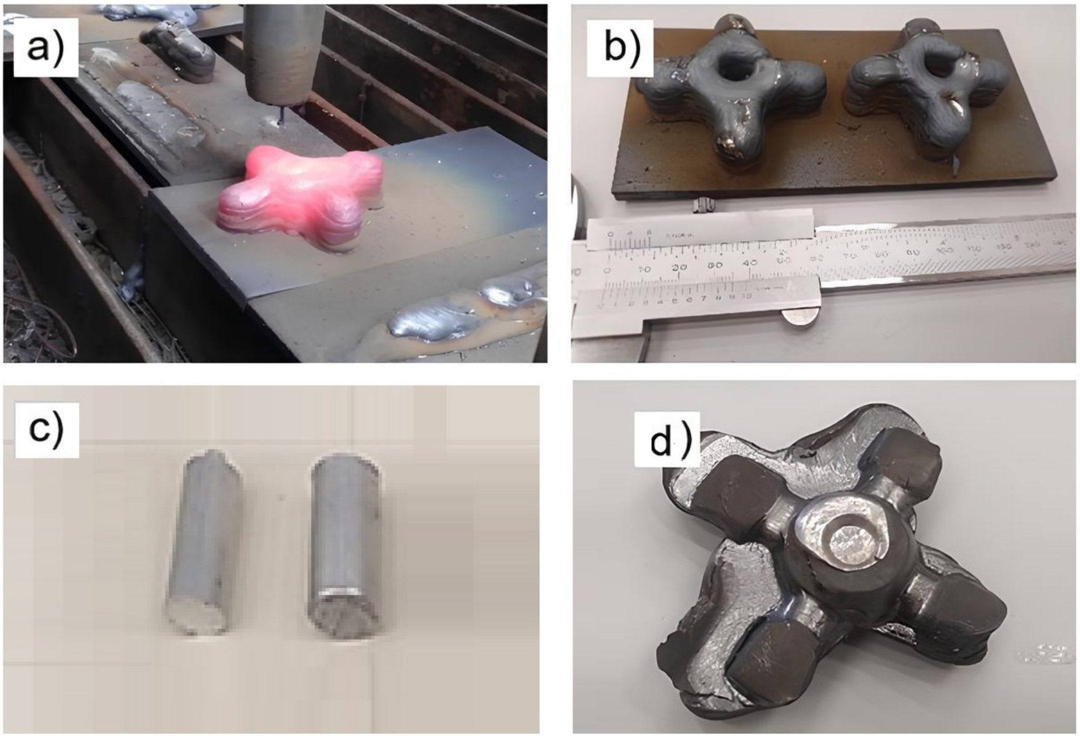


Figure 5. a) External part of the crosshead on the welding machine; b) printed samples; c) 3/8" rolled aluminum bar d) forged bimetallic crosshead.

Table 2. Chemical composition of materials[18,19].

Material	Al	Mg	Si	Mn	Ti	Zn	Cu	Fe
ASTM B221 Alloy 6060	97.42	0.58	0.59	0.01	0.013	0.02	0.10	0.20

Material	C	Mn	Si	P	S	Cr	Ni	Mo
AWS A5.36 E110C-G M	0.07	1.57	0.42	0.01	0.01	0.41	1.49	0.34

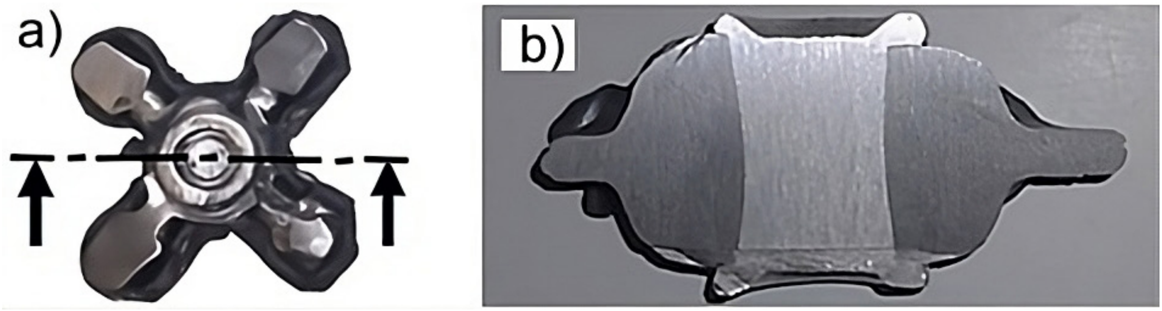


Figure 6. a) Sample cutting plane (b); cross-section sample.

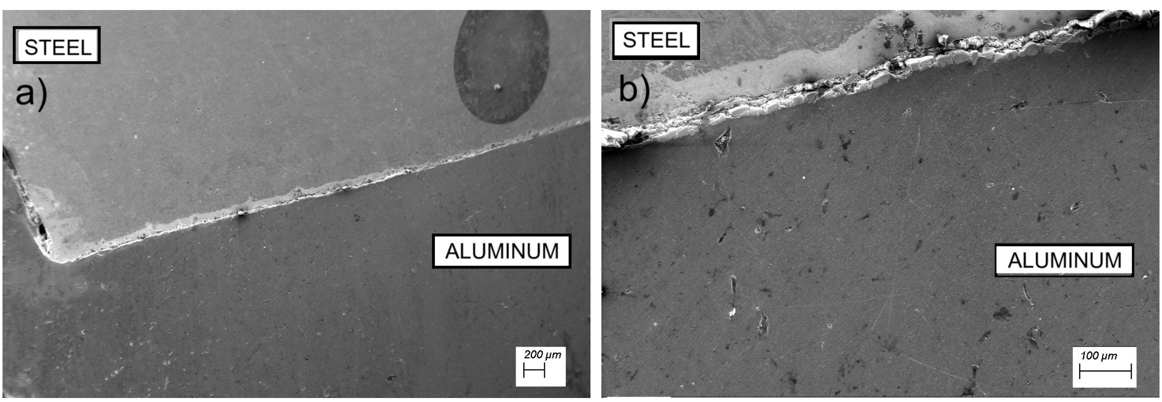


Figure 7. The boundary between the two metals. Etchant: Nital 2%.

Politis et al.[26]. Details of the gap and fragments of material can be seen in Figure 8.

The relatively low temperature of the steel did not lead to significant changes in its structural constituents, which were more pronounced in the region of the bimetallic joint, where there was heat exchange between the metals during cooling. According to Wang et al.[24], heat transfer and the incompatibility of mechanical properties between the two materials are the main reasons for this behavior. This process resulted in a coarser grain morphology near the joint, as shown in Figure 9 and detailed in Figure 9b.

For the hardness measurement, the piece was cut in the axial direction and nine measurements were taken using a 1 kgf load (HV1) and a dwell time of 10 seconds. The indentations were made at linear intervals with an increment of 0.5 mm, starting from the zero point located at the junction between the two materials. The diagram showing the measurement pattern is presented in Figure 10.

The results obtained showed that there were no significant changes in the properties of the materials. The measurements taken on the aluminum exhibited very consistent values, with a maximum of 62 HV and a minimum of 60.31 HV. These two measurements were taken at the points closest to and furthest from the joint, respectively.This result indicates that there was no evidence of a change in the hardness of the aluminum at

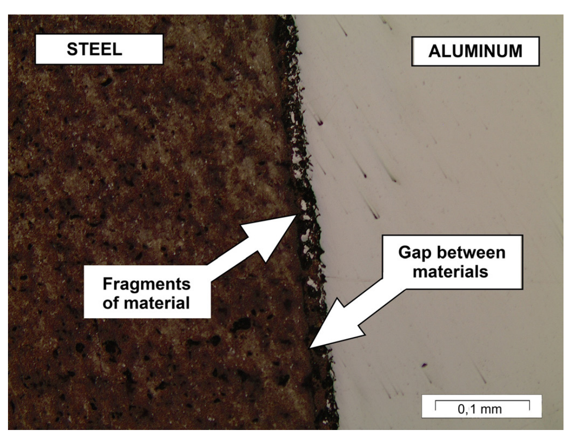


Figure 8. Fragments of material in the gap between steel and aluminum. Without attack.

Table 3. Microhardness values in the bond region between the materials.

Material	Point	increase (mm)	Distance from Zero-point (mm)	hardness (HV)
Aluminum	4	0.5	2.0	62.83
	3	0.5	1.5	60.46
	2	0.5	1.0	60.31
	1	0.5	0.5	62.09
Border	0	0	0	307.66
Steel	5	0.5	0.5	266.00
	6	0.5	1.0	282.86
	7	0.5	1.5	279.92
	8	0.5	2.0	292.31

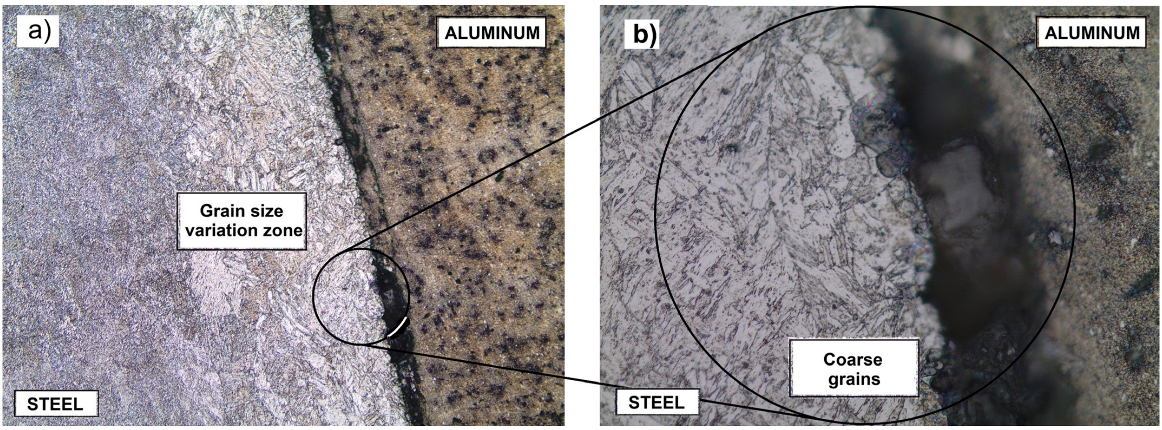


Figure 9. Variation in grain size within the HAZ of steel. Etchant: Nital 2%.

the interface due to exposure to high temperatures in contact with the heated steel, corroborating the study by Politis[25]. Thus, the aluminum does not appear to undergo changes due to its proximity to the steel during forging, or the affected zone may be smaller than the resolution of the test equipment.

The microhardness measurement in the steel region showed similar behavior, with a minimum hardness of 266 HV and a maximum hardness of 292.31 HV, indicating that no compositional transition zone was formed as a result of the forging process.

The microhardness test values are presented in Table 3, and the corresponding graph is shown in Figure 11.

Regarding surface oxidation, traces of these elements were identified, albeit in reduced form, corroborating the findings of Wang et al.[24]. One of these constituents can be seen in Figure 12.

Using EDS analysis, the elements present in the joint between the two materials were identified. The chemical composition consists mainly of Fe and O, indicating the presence of steel oxides throughout the region, as shown in Figure 13. These oxides were formed during the heating of the steel portion of the crosshead. According to Chen et al.[27] the presence of oxides can be detrimental to the formation of a reliable interface between materials.

EDS analysis, used to determine the relative concentration of each material, not only revealed a greater quantity of oxides at the metallurgical junction but also detected presence of chromium, manganese, molybdenum, and silicon. The percentage of each element and the quantification table are presented in Figure 14.

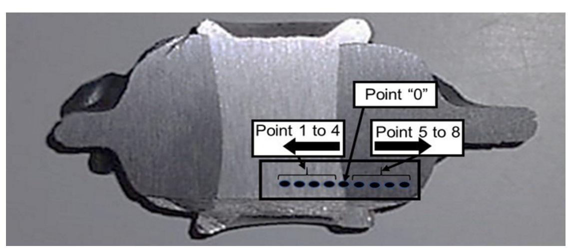


Figure 10. Hardness measuring points.

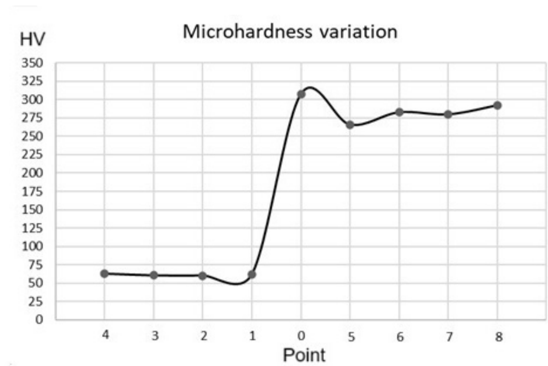


Figure 11. Microhardness graph.

For better visualization, the elements of the bimetallic joint were isolated, and EDS mapping was performed, as shown in Figure 15.

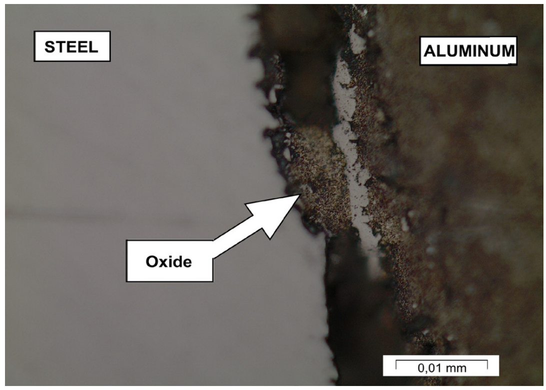


Figure 12. Evidence of surface oxide from heating. Without etching.

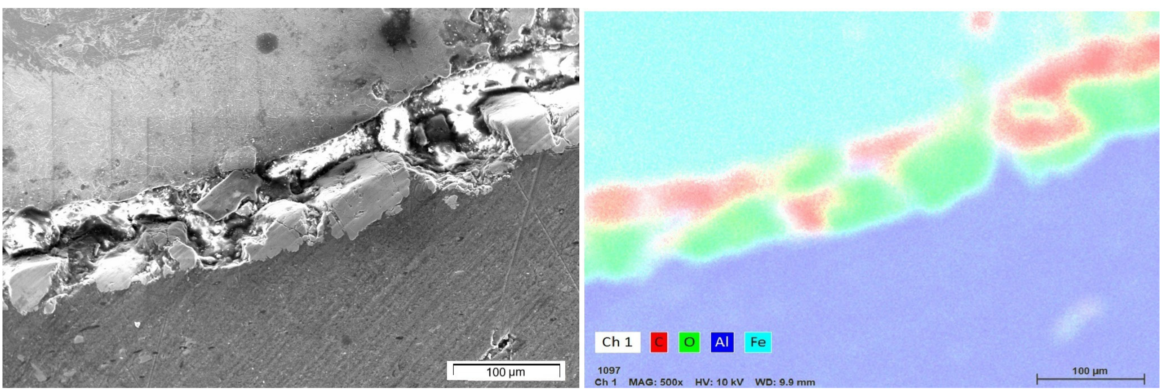
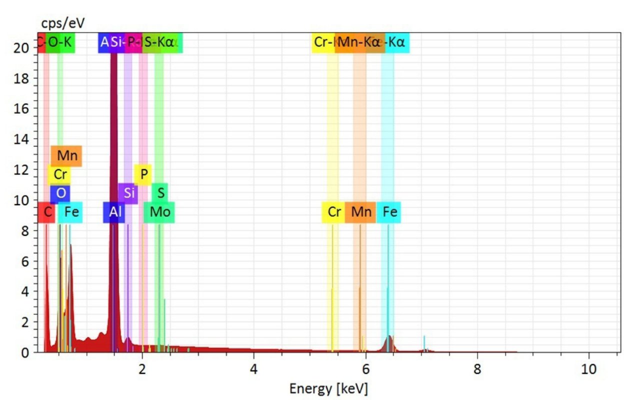


Figure 13. Energy dispersion analysis of the bonding region.



Map

Element	At. No.	Netto	Mass [%]	Mass Norm. [%]	Atom [%]	abs. error [%] (1 sigma)	rel. error [%] (1 sigma)
Aluminium	13	15694034	44.77	41.23	37.46	2.03	4.53
Iron	26	657491	35.72	32.90	14.44	1.58	4.41
Carbon	6	1141133	18.88	17.39	35.48	1.99	10.54
Oxygen	8	1269021	8.59	7.91	12.12	0.92	10.69
Silicon	14	142942	0.62	0.57	0.50	0.05	8.16
Manganese	25	0	0.00	0.00	0.00	0.00	1.96
Chromium	24	0	0.00	0.00	0.00	0.00	1.71
Molybdenum	42	0	0.00	0.00	0.00	0.00	1.54
Phosphorus	15	0	0.00	0.00	0.00	0.00	1.77
Sulfur	16	0	0.00	0.00	0.00	0.00	1.56
		Sum	**108.57**	**100.00**	**100.00**		

Figure 14. Qualitative microanalysis of chemical elements present in the sample.

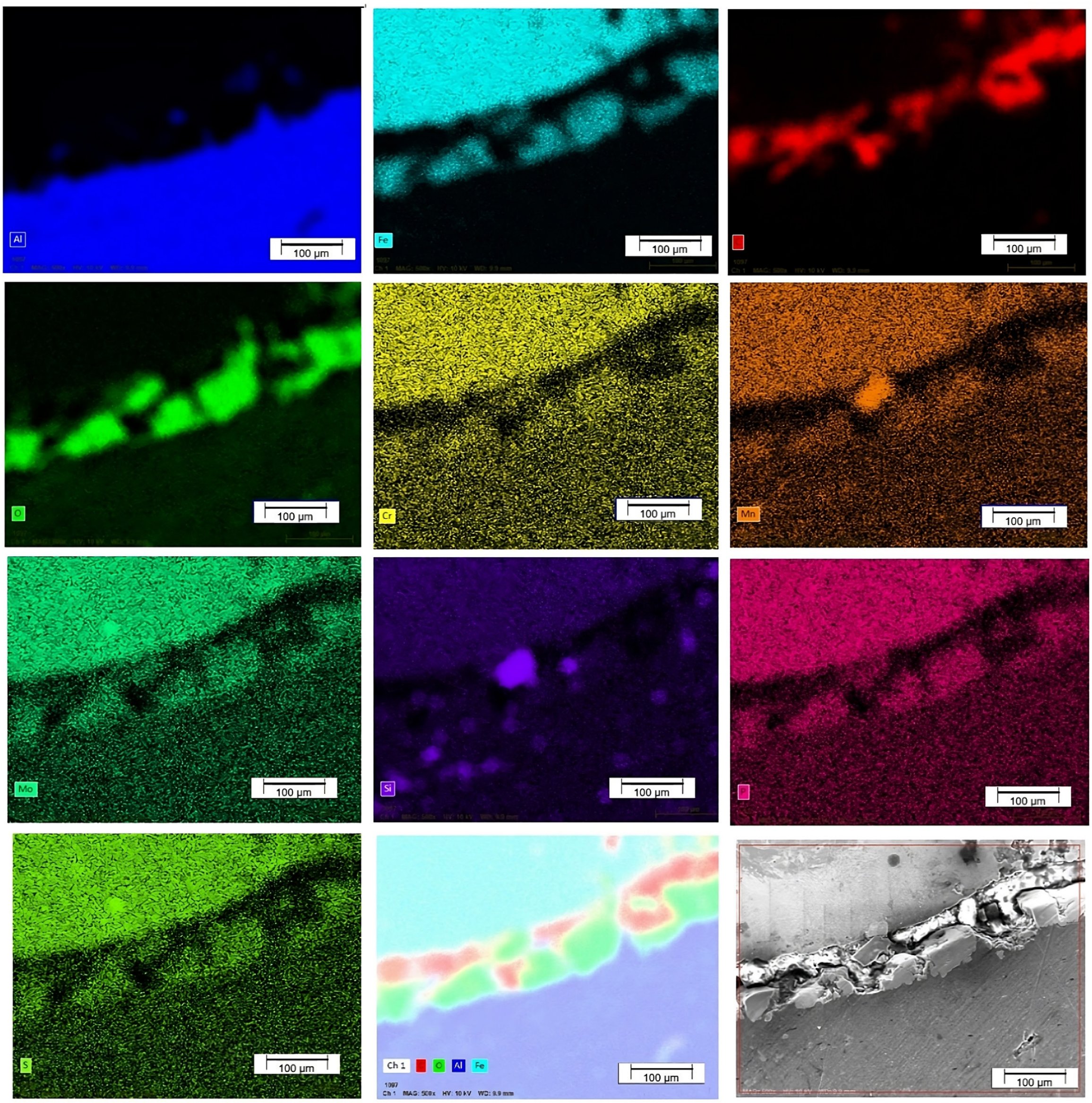


Figure 15. EDS images with isolated elements.

4. Conclusions

The purpose of this study was to preliminarily investigate the interface of forged bimetallic joint in a crosshead developed from an AWS A5.36 E110C-G M low-alloy steel body and a 6060 aluminum core produced by WAAM. Experimental analysis of the interface of bimetallic steel and aluminum parts led to the following conclusions:

- Forging the crosshead with the steel region heated to 900 ºC and with the core at room temperature maintained the main metallographic characteristics.
- The joint between the two materials visually revealed a region of cracking, which may have resulted from due to the sample being cut by a saw or due to the unequal contraction of the materials during cooling. This reveals the incompatibility of mechanical properties between the two materials.
- Surface oxidation was seen along the boundary between the two materials, even when the pieces were placed in the furnace after reaching the pre-established temperature.
- Fragments of material were found in the gaps, possibly from dragging between the surfaces during forging. The oxide layers of the steel were also broken and transported to the aluminum matrix.
- The low alloy steel underwent microstructural changes in the regions close to the bimetallic boundary, as a result of heating and temperature exchange between the metals during cooling.
- The work represents a preliminary investigation and future work is recommended using different materials and temperature combinations to evaluate the formation of oxides and the occurrence of atomic diffusion in the boundary zone between the materials. A powder

flux, such as borax, could also be applied to reduce the oxide layers

5. References

1. Gibson I, Rosen D, Stucker B. Additive manufacturing technologies: 3D printing, rapid prototyping, and direct digital manufacturing. 2nd ed. New York: Springer; 2014. http://doi.org/10.1007/978-1-4939-2113-3.
2. Garcia LHT. Desenvolvimento de processo de fabricação de compósitos de fibras longas através da tecnologia de Manufatura Aditiva. [dissertation]. São Carlos: Universidade de São Paulo. 2016.
3. Çam G. Prospects of producing aluminum parts by wire arc additive manufacturing (WAAM). Mater Today Proc. 2022;62(1):77-85. http://doi.org/10.1016/j.matpr.2022.02.137.
4. Guler S, Serindag HT, Cam G. Wire arc additive manufacturing (WAAM): recent developments and prospects. Engineer and Machinery. 2022;63(706):82-116.
5. Cam G, Gunen A. Challenges and opportunities in the production of magnesium parts by directed energy deposition processes. J Magnes Alloy. 2024;12(5):1663-86. http://doi.org/10.1016/j.jma.2024.05.004.
6. Günen A, Gurol U, Kocak M, Cam G. Investigation into the influence of boronizing on the wear behavior of additively manufactured Inconel 625 alloy at elevated temperature. Prog Addit Manuf. 2023;8(6):1281-301. http://doi.org/10.1007/s40964-023-00398-8.
7. Kocaman E, Gurol U, Gunen A, Cam G. Effect of post-deposition heat treatments on high-temperature wear and corrosion behavior of Inconel 625. Mater Today Commun. 2025;42:111101. http://doi.org/10.1016/j.mtcomm.2024.111101.
8. Bölükbaşı OS, Serindag T, Gurol U, Gunen A, Cam G. Improving oxidation resistance of wire arc additive manufactured Inconel 625 Ni-based superalloy by pack aluminizing. CIRO J Manuf Sci Technol. 2023;46:89-97. http://doi.org/10.1016/j.cirpj.2023.07.011.
9. Gürol U, Altinay Y, Gunen A, Bolukbasi OS, Kocak M, Cam G. Effect of powder-pack aluminizing on microstructure and oxidation resistance of wire arc additively manufactured stainless steels. Surf Coat Tech. 2023;468:129742. http://doi.org/10.1016/j.surfcoat.2023.129742.
10. Günen A, Gurol U, Kocak M, Cam G. A new approach to improve some properties of wire arc additively manufactured stainless steel components: simultaneous homogenization and boriding. Surf Coat Tech. 2023;460:129395. http://doi.org/10.1016/j.surfcoat.2023.129395.
11. Silva JPSC, Erberelli JPSC, Miyauchi ET, Hatimine E. Appling polymeric material in engine cooling system. In: Simpósio Internacional de Engenharia Automotiva – SIMEA; 2022; São Paulo. Anais. São Paulo: Associação Brasileira de Engenharia Automotiva; 2022.
12. Politis DJ, Lin J, Dean TA, Balint DS. An investigation into the forging of Bi-metal gears. J Mater Process Technol. 2014;214(11):2248-60. http://doi.org/10.1016/j.jmatprotec.2014.04.020.
13. Bandivadekar A, Bodek K, Cheah L, Evans C, Groode T, Heywood J, et al. On the road in 2035: reducing transportation's petroleum consumption and GHG emissions. Cambridge: MIT Laboratory for Energy and the Environment; 2008.
14. U.S. Department of Energy [homepage on the Internet]. Lightweight materials for cars and trucks. Washington, DC: Office of Energy Efficiency & Renewable Energy; 2015 [cited 2025 Apr 26]. Available from: https://www.energy.gov/eere/vehicles/lightweight-materials-cars-and-trucks
15. Bentes F, Cavalieri M, Ramos S. Bloco de motor em liga de alumínio. Projectus. 2023;8(4):1-14. http://doi.org/10.15202/25254146.2023v8n4p1.
16. Graf M, Härtel S, Binotsch C, Awiszus B. Forging of lightweight hybrid metallic-plastic components. Procedia Eng. 2017;184:497-505. http://doi.org/10.1016/j.proeng.2017.04.120.
17. Domingues WV, Arce RP, Frose LR. Additive manufacturing and computational simulation: a review of integrated technologies and applications. In: Simpósio Internacional de Engenharia Automotiva – SIMEA; 2023; São Paulo. Anais. São Paulo: Associação Brasileira de Engenharia Automotiva; 2023.
18. ASTM: American Society for Testing and Materials. ASTM B221: standard specification for aluminum and aluminum-alloy extruded bars, rods, wire, profiles, and tubes. West Conshohocken: ASTM; 2021.
19. AWS: American Welding Society. Specification for carbon and low alloy steel flux cored electrodes for flux cored arc welding and metal cored electrodes for gas metal arc welding. Miami: AWS; 2010.
20. Meng Z, Jia X, Feng W, Zhuang W, Wu M. Investigation on interfacial bonding characteristics of steel/aluminum bi-metal gears by hot forging processing. Metals. 2022;12(8):1244-4. http://doi.org/10.3390/met12081244.
21. Politis D, Lin J, Dean T. Investigation of material flow in forging Bi-metal components. In: 14th International Conference on Metal Forming; 2012 Sep 16-19; Krawkov. Proceedings. Krawkov: John Wiley & Sons; 2012. p. 231-4.
22. Xusheng C, Gang C, Hongming Z, Fei H, Weiwei W, Zhiming D. Simulation and verification for thixotropic-core compound forging formation of aluminum-steel bimetal components. Special Cast Nonferr Alloy. 2021;41(6):760-8.
23. Chang X, Chen G, Wang B, Chen Q, Zhang H. Thixotropic-core compound forging for aluminum-steel bimetal gears. J Mater Process Technol. 2021;299:117371. http://doi.org/10.1016/j.jmatprotec.2021.117371.
24. Wang W, Politis NJ, Wang Y, Zhou X, Balint D, Jiang J. Solid-state hot forge bonding of aluminium-steel bimetallic gears: deformation mechanisms, microstructure and mechanical properties. Int J Mach Tools Manuf. 2022;180:103930. http://doi.org/10.1016/j.ijmachtools.2022.103930.
25. Politis NJ. Forging lightweight bimetal gears [dissertation]. London: Imperial College London; 2017.
26. Politis DJ, Politis NJ, Lin J. Review of recent developments in manufacturing lightweight multi-metal gears. Prod Eng. 2021;15(2):235-62. http://doi.org/10.1007/s11740-020-01011-5.
27. Chen Q, Chang X, Qi L, Zheng J, Xie C, Chen G. Interface heterogeneity of aluminum-steel bimetal parts manufactured via thixotropic-core compound forging. J Mater Process Technol. 2022;306:117648. http://doi.org/10.1016/j.jmatprotec.2022.117648.

Data Availability

The datasets used and/or analysed during the current study are available from the corresponding author on reasonable request.