

Welding and wire arc additive manufacturing using FSE solid-state recycled wires: Challenges and future perspectives

Gustavo H.S.F.L. CARVALHO^{1,a} *, Gianni CAMPATELLI^{1,b}, Gianluca BUFFA^{2,c}

¹Department of Industrial Engineering, University of Florence, Via di Santa Marta 3, 50139 Firenze, Italy

²Department of Engineering, University of Palermo, Via delle Scienze, 90128 Palermo, Italy

^agustavo.carvalho@unifi.it, ^bgianni.campatelli@unifi.it, ^cgianluca.buffa@unipa.it

Keywords: Wire Arc Additive Manufacturing (WAAM), Circular Economy, Material Extrusion

Abstract. Friction stir extrusion (FSE) is an interesting process for recycling aluminium chips. It significantly reduces waste and energy consumption by recycling materials without remelting. The possibility of producing continuous wires by FSE allows the possibility of using it as an input material in welding processes, which can significantly improve the sustainability of aluminium manufacturing. This study explores the use of FSE-recycled wires in welding and their feasibility for wire arc additive manufacturing, investigating the potential, challenges, and improvement methods for developing the process. The results show that the FSE-recycled wires can be effectively used for welding deposition. However, improving chip cleaning treatments is crucial for reducing hydrogen and oxides to further improve this application. With some improvements, potential applications and fitness for purpose can be envisioned for the process, offering an interesting circular approach in aluminum manufacturing.

Introduction

In the last few decades, environmental sustainability has become a primary concern in engineering, including manufacturing and processing. One approach to mitigating a process's environmental footprint is to employ materials with a lower environmental impact as input feedstocks, such as recycled materials in engineering and manufacturing.

The characteristics of aluminium, such as its low density (yielding a high strength-to-weight ratio), excellent thermal and electrical conductivity, and outstanding corrosion resistance [1], are leveraged in a broad spectrum of applications, from the automotive, maritime, and aerospace sectors to structural and architectural projects, storage vessels, and a variety of consumer goods [2]. Furthermore, the inherent recyclability of aluminium is essential in reducing ecological strain and preserving the Earth's natural resources. These alloys, especially those with compositions close to commercially pure alloys, experience very low or insignificant property degradation during recycling. Therefore, they maintain similar characteristics through repeated cycles and are a leading candidate for material recycling [3].

However, using recycled materials in engineering is not straightforward because virgin raw materials are usually recommended to guarantee the quality and repeatability of components with stringent requirements.

Friction Stir Extrusion (FSE) is gaining attention as a promising option for aluminium recycling, particularly for machining chips and scraps. FSE is a solid-state process that generates heat through the frictional forces between a rotating tool and workpiece. This frictional heating softens the aluminium chips within the chamber in contact with the rotating tool. The softened metal is then forced through a die to create wires, rods, and other profiles [4]. It finds a use for machining chips that are usually regarded as waste by-products of component manufacturing, and

the process occurs in a solid state, which obviates the need for material melting for their recycling. This substantially curtails primary energy consumption compared with conventional remelting followed by wire drawing techniques, achieving energy reductions on the order of more than 70% [5].

With the capability of producing uniform and continuous products, such as wires, FSE opens up the possibility of creating materials that can be used as inputs for manufacturing components, such as welding and Wire Arc Additive Manufacturing (WAAM). Therefore, using FSE as an input for filler metal for welding and WAAM represents a remarkable possibility for reducing the environmental impact of manufacturing [6].

The possibility of using solid-state recycled wire in WAAM and welding, especially for aluminium alloys, carries several challenges that still need to be studied, defined, and overcome. For this type of application, the Gas Tungsten Arc Welding (GTAW) process is considered the most suitable because it allows the use of wires, can adapt to small variations in the wire/rod, and the feed of the filler material can be adjusted independently from electrical parameters, allowing for a more isolated evaluation of the wire [7]. Also, using alternating current (AC) is effective in mitigating the surface oxide layer issue, which has a significantly higher melting point than aluminium (approximately 2040°C compared to the 660°C of aluminium [8]).

In addition, aluminium is highly susceptible to porosity, and its high thermal conductivity leads to a more challenging deposition [8–10]. As widely reported in the literature, porosity is a prevalent defect in fusion-based welding and additive manufacturing, negatively affecting ductility, corrosion resistance, and thermal/electrical conductivity [11]. For aluminium alloys, the issue arises from the notable difference in hydrogen solubility between liquid and solid aluminium, which leads to excess dissolved hydrogen in the liquid phase being trapped during solidification [12,13].

Previous studies [7,14] have also shown that when using FSE-derived wires for welding or WAAM, multiple potential hydrogen sources exist throughout the process, making it significantly challenging to achieve components with low levels of porosity. Therefore, a comprehensive understanding of the challenges associated with using these wires, coupled with strategies for process improvement and fitness for purpose, is crucial to making the process viable and suitable for use in engineering.

This study investigates the novel application of FSE-recycled wires in GTAW-based welding and the feasibility for WAAM by comparing two conditions of solid-state recycled wires from a process perspective. Wires produced by FSE using chips directly from machining and chips that had undergone a cleaning treatment before the FSE process were tested. The depositions were evaluated from a process perspective and macroscopically characterised and analysed using high-resolution computed microtomography (micro-CT).

Materials and Methods

Several series of AC GTAW-based weld and WAAM depositions were performed using wires recycled by FSE in an automatic deposition process. The deposition system is shown in Fig. 1, it consists in a conventional GTAW welding using AC, with an independent feeding system, detailed in [14]. The deposition parameters are presented in Table 1 and were constant for all samples studied in the present work, and are a result of previous parameter optimization.

Table 1. GTAW welding parameters.

Current (A)	Voltage (V)	Wire feed speed (m/min)	Travel speed (mm/min)
160	13.0	0.6	120

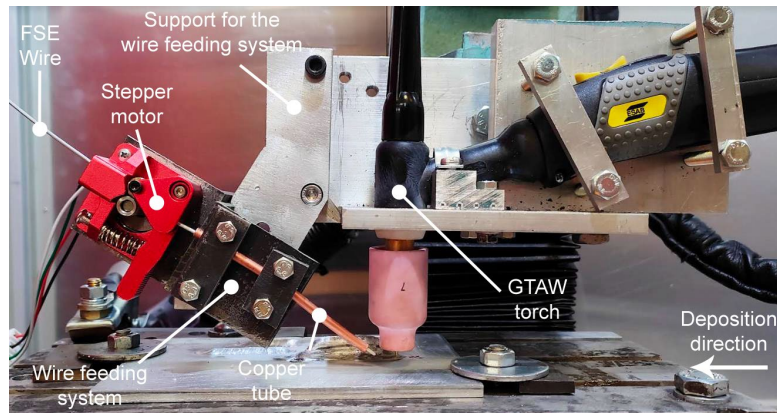


Fig. 1. GTAW-based automatic system used for the depositions.

The FSE filler wires were produced according to the procedure detailed by Buffa et al. [15], with process parameters of 500 RPM and 18 kN force, to produce wires of 1 mm diameter. The chips used for the FSE were collected from machining a 6082 aluminium bar under two different conditions: using chips directly from the machining to represent the worst condition scenario, and chips subjected to a cleaning process after machining before FSE processing. The chips present variable dimensions. This cleaning involved immersing the chips in acetone to remove moisture, grease, and other contaminants that are invariably present after typical machining operations. The milling operation that generated the chips was performed conventionally, mirroring standard industrial practices. AA1050 plates served as deposition substrates for all experiments and have a thickness of 5 mm. Table 2 shows the chemical compositions of the substrate and the bar that generated the chips for the manufacturing of the wires (unless otherwise specified, the values indicate the maximum allowed percentages).

Table 2. Nominal chemical composition of filler metal and substrate (% weight) [16].

	Mg	Si	Mn	Fe	Cu	Cr	Ti	Zn	V	Al
Substrate AA1050	0.05	0.25	0.05	0.40	0.05	-	0.03	0.05	0.05	99.5 min
AA6082 (~wires)	0.6-1.2	0.7-1.3	0.40-1.0	0.50	0.10	0.25	0.10	0.20	-	Bal

The internal porosity of the depositions was investigated using high-resolution 3D micro-computed tomography (micro-CT) employing a Skyscan 1172 high-resolution micro-CT scanner. Two-dimensional X-ray projections were acquired with a rotation increment of 0.9964° between the slices. Three-dimensional models were reconstructed and visualised using CTVox and CTVol software. Several cuts were performed using the tomography technique, such as longitudinal and transverse, to evaluate them internally.

Results

First, the wires were analysed macroscopically to determine whether there were significant differences. Fig. 2 shows the general aspect of a wire produced with chips, with and without cleaning. The main differences lie in the roughness of the external appearance. Disregarding the FSE process marks (small transverse regularly spaced lines along the wire), the wires manufactured with uncleaned chips (Fig. 2a) have a rougher surface compared to the wire manufactured with cleaned chips.. Another noteworthy feature is that the wires produced with uncleaned chips are slightly more irregular (curved) in terms of wire shape and straightness.

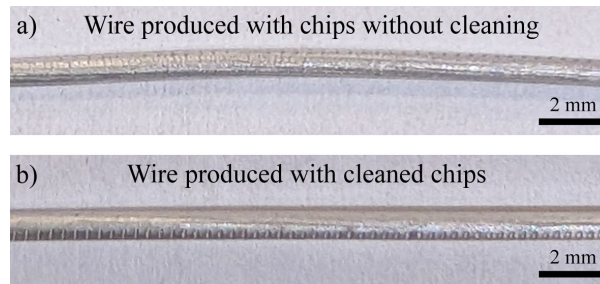


Fig. 2. External aspects of the wires produced by FSE.

The depositions were performed using a bead-on-plate approach to understand the effect of deposition in a simple, regular area and direction using the optimized parameters in Table 1. Therefore, the deposition was performed in the flat position (the easiest and simplest one) to discard the effects of the welding position, rectilinear and 70 mm in length.

Fig. 3 shows the top view of the two depositions performed with the two types of wires. Although the differences in the external appearance of the wires were not highly significant (Fig. 2), the depositions were entirely different. When using wires without chip cleaning (Fig. 3a), the deposition exhibited irregularities along its path, irregularities in shape, and a significant presence of oxides as dark zones. Observing the outer edge of the bead using wires produced with cleaned chips (Fig. 3b), there was a much more substantial path regularity and only small shape variations. However, the main difference observed, especially when considering the deposition of aluminium alloys, is the amount of oxides, impurities, and surface porosity observed in the deposition with wires with uncleaned chips. The amount of dark-coloured oxides was substantial, and below these oxides, there was the presence of porosity that arose on the surface. With the wire with cleaned chips, despite some oxidation, it was substantially less.

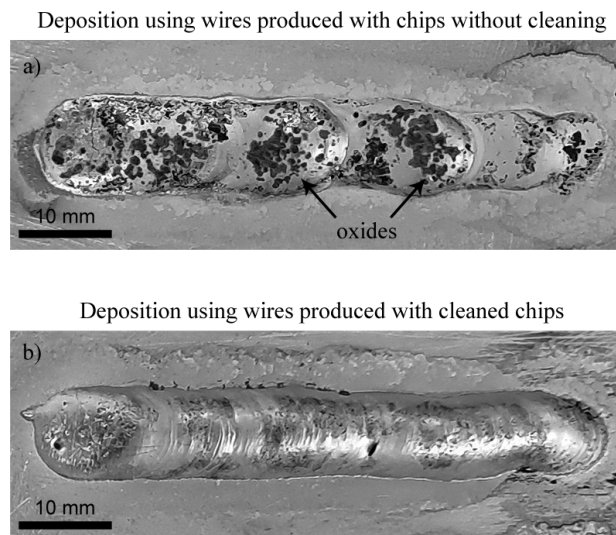


Fig. 3. Aspects of depositions performed with the two types of wires.

Several computed tomography tests were performed to understand the reasons for the notable difference between the depositions and to analyse the depositions internally. First, tests were conducted on the wires used in the depositions. Fig. 4 and Fig. 5 show the results of the tomography.

The wires produced with uncleaned chips (Fig. 4) have a rougher surface and some internal discontinuities (arrows). On the other hand, the wires produced with cleaned chips (Fig. 5) do not have internal defects and have a smoother external surface. For alloys such as aluminium, which

are very sensitive to impurities and moisture (due to hydrogen), these defects may cause significant problems during deposition because they may carry impurities and humidity from the chips to the deposition area. The deposition results in Fig. 3a indicate that many impurities and hydrogen sources were present, resulting in poor deposition. Using cleaned chips as the input material for the FSE process significantly improved the external and internal qualities of the manufactured wires.

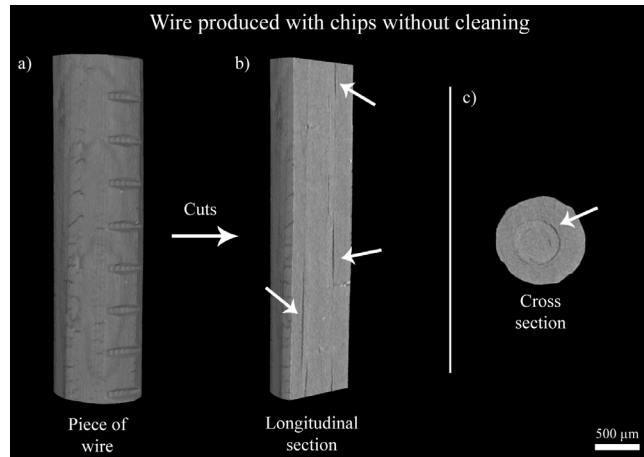


Fig. 4. Microtomography of wires produced with chips without cleaning (from left to right: wire aspect, longitudinal cut, and wire cross section). The small arrows indicate the discontinuities found inside the wires.

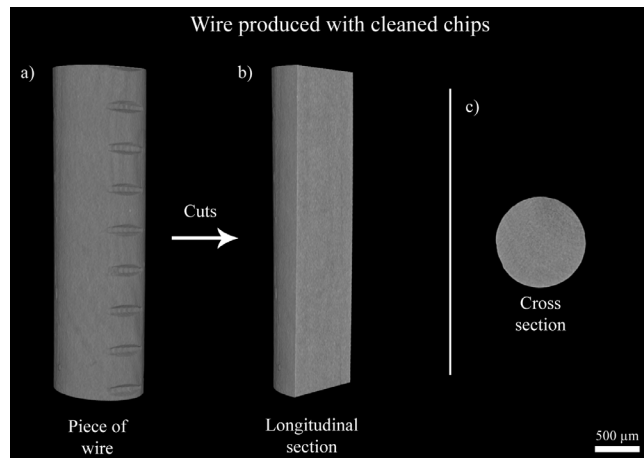


Fig. 5. Microtomography of wires produced with cleaned chips (from left to right: wire aspect, longitudinal cut, and wire cross section).

Fig. 6 and Fig. 7 present the microtomography analysis of the deposited beads. The aluminium metallic part is represented in white (to which a 40% transparency was applied to see the interior), while the red part represents the voids/pores. A significant presence of pores was observed in both depositions, regardless of the wire type. However, some significant differences should be noted. First, several pores appeared on the surface when using the wire with uncleaned chips (Fig. 5a), whereas the same did not occur when the wire with cleaned chips was used (Fig. 6b).

There was also a significant difference in the porosity. Fig. 7 shows the top views of the samples. The lower images show only the pores in detail, where it is possible to see that the wire produced with uncleaned chips generated a much larger number of pores. Not only is the quantity greater, but the size of the pores is much larger, and some of them are concentrated in some zones,

which is even more harmful to the material's properties. When using wires produced with cleaned chips, the pores were smaller and more evenly distributed.

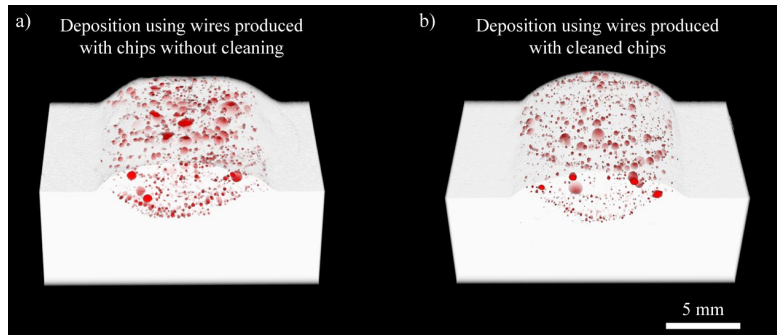


Fig. 6. Microtomography of depositions. Aluminium is represented in white, and voids/pores are represented in red.

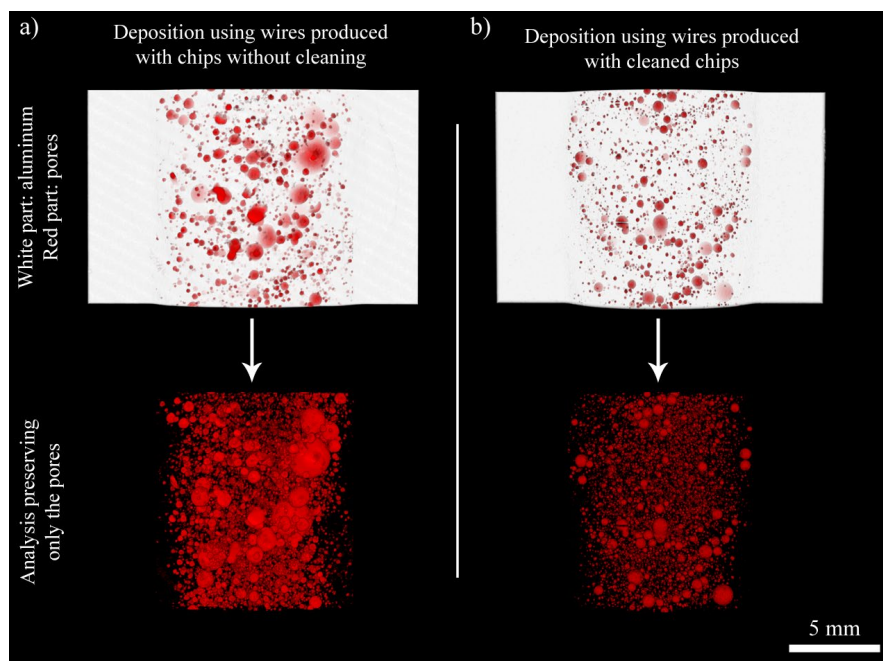


Fig. 7. Top view of microtomography. The images at the bottom show only the porosity isolated from the materials. Aluminium is represented in white, and voids/pores are represented in red.

The use of wires recycled by FSE for WAAM deposition is feasible and presents interesting perspectives for the manufacturing industry. The results proved that consistent beads can be formed without electric-arc instability. The rationale for utilising recycled materials in manufacturing is compelling: it offers a pathway to resource conservation, reduces reliance on virgin material extraction, and contributes to a circular economy model.

However, the porosity found suggests that the current cleaning protocols need to be improved. Therefore, further research is required to optimise and develop more effective cleaning treatments and detect the possible sources of hydrogen that could be introduced in the process. This could involve exploring different cleaning agents, cleaning durations, and temperatures or employing multiple cleaning stages. In addition to chip cleaning, the welding environment plays a crucial role in controlling porosity. The moisture in the surrounding atmosphere can contribute to the hydrogen pick-up by molten aluminium. Therefore, the overall care in the WAAM process with FSE wires should be greater than that in conventional aluminium deposition.

Conclusions

This study explored the feasibility of utilising FSE-derived recycled rods for material deposition and identified the key challenges associated with this process. The following conclusions were drawn:

- The results show that using FSE solid-state recycled wires as filler material in WAAM and welding is feasible and effective.
- Pre-FSE cleaning of machining chips is essential to minimise impurities and potential hydrogen sources in the resulting wire. Porosity was observed in depositions made with both cleaned and uncleaned chip-derived wires, but significantly improved results were obtained using wires with cleaned chips.
- Despite pre-FSE chip cleaning, some porosity persisted in the deposited material, indicating the need for further optimisation of cleaning protocols and investigation of impurity sources to enhance the overall deposition quality. Further refinement of the welding parameters and control of the welding environment may also prove beneficial.

Acknowledgments

This study was carried out within the activity of project “PERPETUAL 100% Material utilization using sOLID sTate recycling and Additive Manufacturing for productIOn and repairing of aluminum components (PERPETUAL MOTION)”, funded by the European Union - Next Generation EU, Mission 4 Component C2, Project: 20224H9YC9, CUP: B53D23005510006.

References

- [1] R.N. Lumley, *Fundamentals of Aluminium Metallurgy: Production, Processing and Applications*, 1st ed., Woodhead Publishing Limited, 2011.
- [2] X. Yang, R. Li, T. Yuan, L. Ke, J. Bai, K. Yang, A comprehensive overview of additive manufacturing aluminum alloys: Classifications, structures, properties and defects elimination, *Mater. Sci. Eng. A*. 919 (2025) 147464. <https://doi.org/10.1016/j.msea.2024.147464>
- [3] S.N.A. Rahim, M.A. Lajis, S. Ariffin, A Review on Recycling Aluminum Chips by Hot Extrusion Process, *Procedia CIRP*. 26 (2015) 761–766. <https://doi.org/10.1016/j.procir.2015.01.013>
- [4] Y.M. Altharan, S. Shamsudin, S. Al-Alimi, Y. Saif, W. Zhou, A review on solid-state recycling of aluminum machining chips and their morphology effect on recycled part quality, *Heliyon*. 10 (2024) e34433. <https://doi.org/10.1016/j.heliyon.2024.e34433>
- [5] D. Baffari, A.P. Reynolds, A. Masnata, L. Fratini, G. Ingarao, Friction stir extrusion to recycle aluminum alloys scraps: Energy efficiency characterization, *J. Manuf. Process*. 43 (2019) 63–69. <https://doi.org/10.1016/j.jmapro.2019.03.049>
- [6] G. Ingarao, M. Amato, A. Latif, A.D. La Rosa, R. Di Lorenzo, L. Fratini, Life Cycle Assessment of aluminum alloys chips recycling through single and multi-step Friction Stir Consolidation processes, *J. Manuf. Syst*. 68 (2023) 651–659. <https://doi.org/10.1016/j.jmsy.2023.05.021>
- [7] G.H.S.F.L. Carvalho, G. Campatelli, L. Fratini, Feasibility study of using friction stir extruded recycled aluminum rods for welding and additive manufacturing, *Manuf. Lett*. 42 (2024) 52–55. <https://doi.org/10.1016/j.mfglet.2024.10.007>
- [8] T. Anderson, B.E. Anderson, F.G. Armao, P. Berube, T. Burns, D.M. DePauw, J. Ginder, B.W. Hemmert, R.B. Hirsch, C. Hsu, M.S. Kadlec, S.F. McCleary, M.A. Palmer, S.E. Pollard, M.J. Russell, D.J. Spinella, M.P. Vandenberg, K.L. Williams, J. Zhang, J.H. Myers, Aluminum

and Aluminum Alloys, in: A. O'Brien (Ed.), AWS Weld. Handb. Vol. 5 - Mater. Appl. Part 2, 9th ed., American Welding Society, Miami, USA, 2015: pp. 1–135.

[9] M. Arana, E. Ukar, I. Rodriguez, A. Iturrioz, P. Alvarez, Strategies to reduce porosity in Al-Mg WAAM parts and their impact on mechanical properties, *Metals (Basel)*. 11 (2021). <https://doi.org/10.3390/met11030524>

[10] R. Fu, S. Tang, J. Lu, Y. Cui, Z. Li, H. Zhang, T. Xu, Z. Chen, C. Liu, Hot-wire arc additive manufacturing of aluminum alloy with reduced porosity and high deposition rate, *Mater. Des.* 199 (2021) 109370. <https://doi.org/10.1016/j.matdes.2020.109370>

[11] S. Chandra, J. Radhakrishnan, S. Huang, S. Wei, U. Ramamurty, Solidification in metal additive manufacturing: challenges, solutions, and opportunities, *Prog. Mater. Sci.* 148 (2025) 101361. <https://doi.org/10.1016/j.pmatsci.2024.101361>

[12] N. Trometer, B. Chen, M. Moodispaw, W. Cai, T. Rinker, S. Kamat, Z. Velasco, A.A. Luo, Modeling and validation of hydrogen porosity formation in aluminum laser welding, *J. Manuf. Process.* 124 (2024) 877–890. <https://doi.org/10.1016/j.jmapro.2024.06.052>

[13] G. Mathers, *The Welding of Aluminium and its Alloys*, 1st ed., Woodhead Publishing Limited, Cambridge, England, 2002. <https://doi.org/10.1007/s13398-014-0173-7.2>

[14] G.H.S.F.L. Carvalho, G. Campatelli, B.S. Cota, D. Campanella, R. Di Lorenzo, Development of a NC-Controlled GTAW-Based Wire Arc Additive Manufacturing System for Using Friction Stir Extrusion Recycled Wires, *Machines*. 13 (2025) 10. <https://doi.org/10.3390/machines13010010>

[15] G. Buffa, D. Campanella, M. Adnan, U. La Commare, G. Ingarao, L. Fratini, Improving the Industrial Efficiency of Recycling Aluminum Alloy Chips Using Friction Stir Extrusion: Thin Wires Production Process, *Int. J. Precis. Eng. Manuf. Technol.* (2024). <https://doi.org/10.1007/s40684-023-00573-w>

[16] J.R. Davis, *ASM Speciality Handbook: Aluminum and Aluminum Alloys*, 4th ed., ASM International, Materials Park, Ohio, USA, 1998.