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Towards the wire-feed friction stir extrusion-based additive manufacturing of aluminum alloys

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Abstract. In this work, wire-feed friction stir extrusion-based additive manufacturing (FSE-AM) was studied to assess its potential for multi-layer deposition of aluminum alloys. FSE-AM is a novel technology devoted to avoiding fusion-related defect formation for large-scale additive manufacturing. Using AA1070 feedstock, features of the layer formation were observed, as well as the mechanical properties of the material were analyzed. Energy characterization was carried out to assess the energy efficiency of the proposed method.

Introduction

Additive manufacturing (AM) of aluminum alloys is one of the most significant scientific and engineering topics due to the unique properties of these materials, such as corrosion resistance, a high strength-to-weight ratio, and other advantageous characteristics, making them widely used in various industrial applications [1, 2]. At the same time, many additive technologies are based on fusion, leading to several challenges that impede their adoption [3].

Using common fusion-based technologies, such as Laser Powder Bed Fusion (LPBF), issues such as porosity and hot cracking in aluminum alloys have been observed [4]. Porosity can form due to gases trapped during melting-solidification cycles, especially in alloys containing elements such as Mg, which tend to evaporate due to their relatively low boiling temperature [5, 6]. This defect significantly affects the mechanical properties of additively manufactured materials and limits their industrial applications. Hot cracking is another significant defect caused by high thermal gradients and residual stresses during additive manufacturing. It is particularly prevalent in high-strength aluminum alloys, especially dispersion-hardened ones [7, 8].

To address these issues, alternative AM approaches have been developed, some of which are based on frictional interaction and occur in the solid state [9, 10]. The primary advantage of these methods is that they operate below the melting point of the material (approximately 0.6–0.8 of melting temperature) [11]. By avoiding melting, it is possible to eliminate defect formation, such as porosity and cracking, thereby improving the mechanical properties of aluminum alloy components [3]. These techniques are generally based on friction stir welding (FSW), a well-known method for joining various aluminum alloys [11]. A variation of this, friction stir additive manufacturing, was the first attempt to adapt FSW for AM purposes. However, this method requires layer-by-layer welding of plates, resulting in very high material costs [12].

As an alternative, friction surfacing-based deposition [13] and additive friction stir deposition [14] have been developed to utilize consumable tools and significantly reduce metal scrap. The authors of [15] demonstrated that such techniques provide high-quality deposition for aluminum alloys, although the mechanical properties are slightly lower than expected compared to the parent material. An additional issue with these methods is discontinuous deposition due to the use of

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consumable rods with a limited length. At the same time, for large-scale additive manufacturing, continuous deposition—as seen in Wire Arc Additive Manufacturing (WAAM) and similar techniques—would be more beneficial [16].

For this reason, new technologies based on friction stir extrusion are being developed to enable continuous solid-state deposition. These approaches offer high material versatility, allowing the processing of a wide range of aluminum alloys in the form of wire [17], rods [18], and powder [19]. More than that, it enables suitability for high-strength alloys, such as aluminum and titanium alloys, which suffer from solidification defects, residual stresses, and distortion in conventional AM. In [20], the authors demonstrated that this approach can be implemented with a robotic setup, broadening the possibilities and applicability of wire-based solid-state deposition techniques for large-scale manufacturing. As a near-net-shape process, friction stir extrusion-based methods can significantly reduce material waste compared to other AM techniques aligning with global sustainability goals [21]. Moreover, by combining these methods with friction stir extrusion recycling, it might be possible to significantly decrease their environmental impact [22]. However, the development of these techniques is still in its preliminary stages, necessitating urgent investigation of challenges like material and feedstock form compatibility, process scalability, and tool wear to enable widespread industrial implementation.

In this way, this study aims to investigate the feasibility of solid-state deposition of AA1070 aluminum alloy using wire-feed friction stir extrusion-based additive manufacturing, to investigate the characteristics of layer formation and the mechanical properties of the produced material, as well as to preliminary assess sustainability and material efficiency of the proposed technology.

Materials and methods

In this work, technically pure aluminum AA1070 wires (ESAB OK Tigrod 1070) with a diameter of 2.4 mm were used as a feedstock for wire-feed friction stir extrusion-based additive manufacturing.

AM process was performed on dedicated friction stir welding machine ESAB Legio 3ST. For this purpose, a special tool system was designed (Fig. 1). The system consists of two parts: rotary tool (1) and stationary shoulder (2). The first part is designed to serve as an extrusion chamber and a shoulder during deposition. At the same time, the second part is plasticizing the feedstock material fed through the channel (3) and transporting it into the deposition area, where it is stirred by pins. The following process parameters were selected by preliminary experimental campaign: rotation speed of 1400 rpm, wire feeding and tool travel speed of 600 mm/min, and pin plunge depth of 0.2 mm. The last parameter responsible for the layer thickness and the force applied by the stationary shoulder: the lower the plunge depth, the higher the gap between substrate and shoulder and, subsequently, the lower the loading force during the deposition process. As a result of the experiment, samples with one layer and two layers of deposition were produced.

During the FSE-AM process, the electrical energy used by the equipment was recorded using a power and energy quality analyzer Chauvin Arnoux C.A 8331 connected to the input of the ESAB Legio.

After the deposition, cross-section and longitudinal section of samples were cut out for metallography and microhardness measurement. Sections were mechanically grinded, polished, and then etched to reveal features of material flow. Microhardness was measured using Remet HBV-30A tester with a loading force of 0.5 kg and indentation time of 15 seconds. Metallographic analysis was performed using Olympus GX51 optical microscope.

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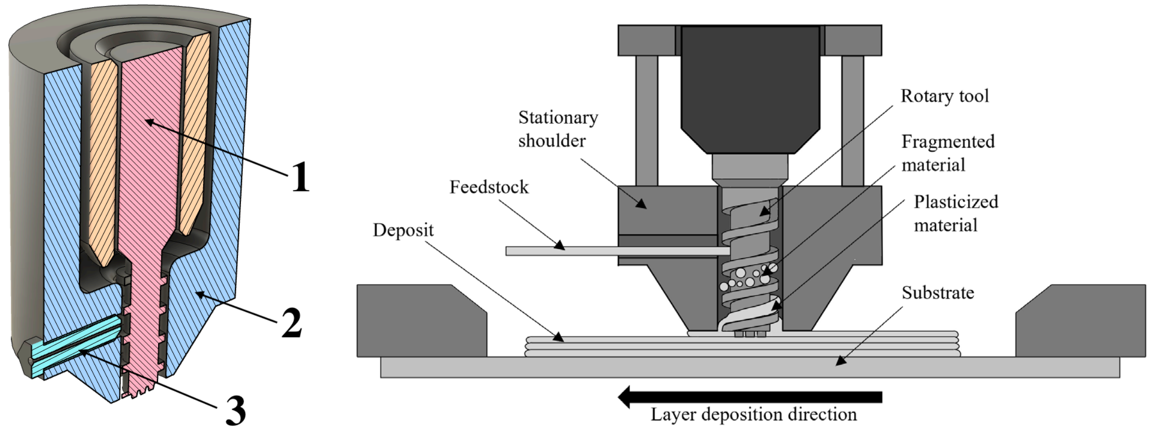


(a) *(b)*

Fig. 1. (a) Cross-section of the FSE-AM tooling system CAD-model and (b) scheme of the FSE-AM process. 1 – rotary tool, 2 – stationary shoulder, 3 – wire-feeding channel

Results and discussion

During the experimental campaign preliminary process parameters selection has been carried out to achieve stable material deposition. As shown in Fig. 2, when process parameters are not correct, the deposition occurs with irregular shape and thickness (Fig. 2 (a, b, c)), while using appropriate mode, layer shape irregularities eliminate (Fig. 2 (d)). Due to a high adhesion of pure aluminum to steel, there is a detachment effect leading to unbonding of the layer in starting and ending positions. Despite that, there are no visible defects in the main body of the deposit shown in Fig. 2 (d), which was selected for detailed analysis.

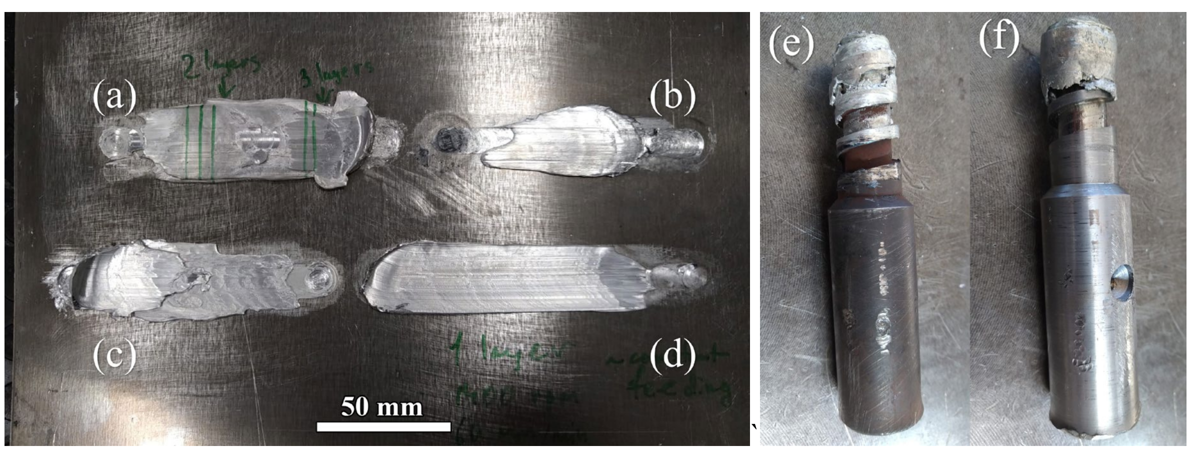


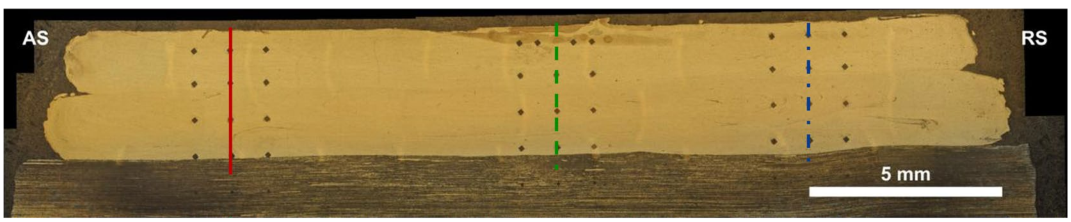
Fig. 2. Samples made by FSE-AM during preliminary parameter selection. (a – c) – defective samples, (d) – sample with acceptable deposition quality produced with rotation speed of 1400 rpm and tool travel speed of 600 mm/min, (e – f) – rotary tools after process

High aluminum adhesion also affects the rotary tool, leading to the formation of a coating on its surface. It is clear from Figure 2 that the material fills the grooves of the tool and, depending on the production mode, it can be partially (Fig. 2 (e)) or fully (Fig. 2 (f)) covered by aluminum. In fact, this coating is the material plasticized but not effectively transferred to the substrate, and to avoid this effect, some dwell time after the deposition can be suggested to empty the extrusion chamber.

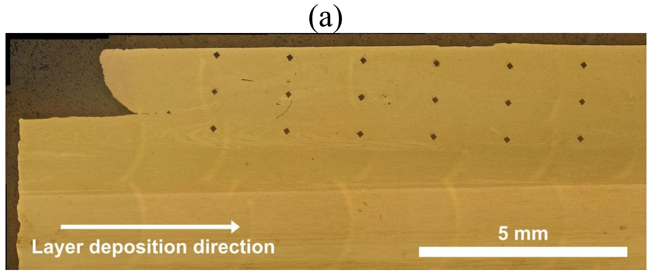
In Fig. 3, the cross-section of a single layer discussed above is shown. It is visible from the figure that the deposited volume contains no defects such as pores, voids, and cracks. However, on both the advancing and retreating sides of the sample, there is a lack of bonding. Such defects occurred only in the stationary shoulder effect area. It must be noted that on the advancing side, such an effect is considerably low in comparison to the retreating one. Such behavior can be connected to the heat distribution in the deposition area, as it was shown for the friction surfacing method [23], but it will be studied in future research. The main body of the deposited layer is well bonded with the substrate due to the presence of pins.

Fig. 3. Cross-section of FSE-AM single layer of AA1070 alloy

Further deposition of the second layer leads to an improvement of the previously deposited layer bonding (Fig. 4 (a)), while there are still some edge defects in the interface between the layers. It is also visible that the second layer has a lower width than the first one, but at the current development stage, the difference is acceptable. The longitudinal section, in turn, shows that the defect-free structure can be observed over the whole length of the sample in the layer deposition direction.



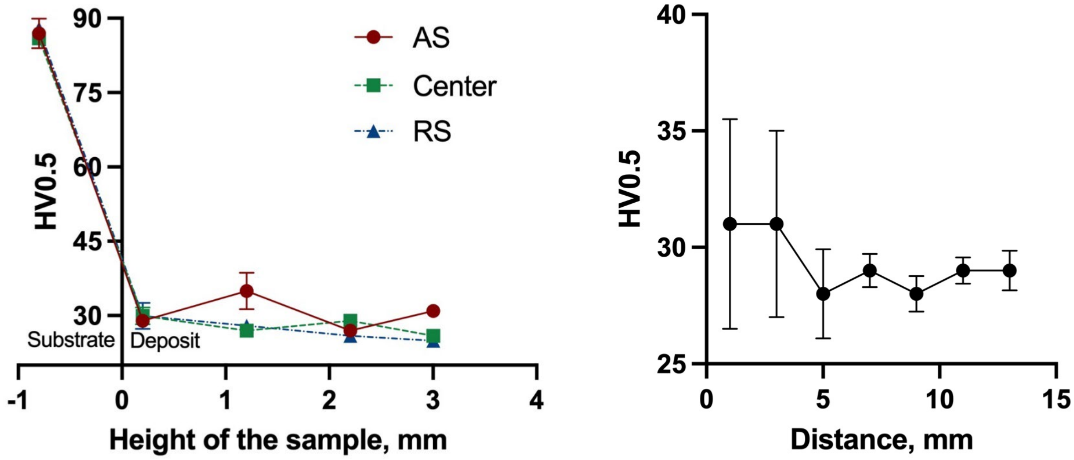
(a)



(b)

Fig. 4. (a) Cross-section and (b) longitudinal section of multi-layer FSE-AM sample of AA1070 alloy with traces of microhardness measurements. Colored lines are showing corresponding colors of hardness profiles in Fig. 5

Microhardness measurements show that there is no significant anisotropy of mechanical properties along the height of the FSE-AM AA1070 sample, while it occurs when comparing different sections of the sample. In a cross-section, Vickers value averages at about 30 MPa level, although on the edges it slightly decreases (Fig. 5 (a)). In the longitudinal section, the average value is about 29 MPa, leading to an anisotropy level of about 4 %, which is extremely low in comparison to fusion-based methods [24].



(a) (b)

Fig. 5. Microhardness distribution in (a) cross-section and (b) longitudinal section of multi-layer FSE-AM sample of AA1070 alloy

Obtained results show that wire-feed friction stir extrusion-based additive manufacturing is well suitable for operating with aluminum alloys. Proper parameter selection leads to a stable and efficient material deposition with no critical defects which can affect the performance of the sample. However, obtained hardness values show that the material after the deposition faces a reduction in mechanical properties. In work [25], authors show the microhardness of AA1070 alloy on a level of 35 MPa. At the same time, as-built FSE-AM material achieves a maximum of 30 MPa, which is about 15% lower than the parent material. Because of the complex thermo-mechanical action of the tool during the deposition, the material must undergo significant microstructural changes, leading to a hardness decrease effect. Similar material behavior was observed in related solid-state additive processes [15], making this a common problem of friction-based techniques. In this way, it is necessary to deeply analyze the microstructural changes, which will be the aim for future works connected to this method.

To investigate the process from the environmental point of view, electric energy was studied along with the deposition rate. The electric power trend was analyzed, demonstrating three main stages of the FSE-AM process (Fig. 6): tool plunge, during which pins penetrate the substrate; dwell-time accompanied by initiation of wire feeding; and deposition stage with the tool moved along the welding line. It is visible that maximum power is achieved only about halfway through the deposition stage. This fact is because of the filling of the extrusion chamber by plasticized material. The weight of a single layer was measured, and the deposition rate was calculated to be 0.42 g/s. To assess the energy required for the deposition process, Specific Energy Consumption was found out at a level of 5.14 kWh/kg. In this way, the proposed method is able to meet competition with other solid-state additive manufacturing. For example, the Additive Friction Stir Deposition method, which can be used for additive manufacturing with various aluminum alloys, demonstrates from 3.8 to 4.6 kWh/kg depending on the material used at a similar deposition rate [26].

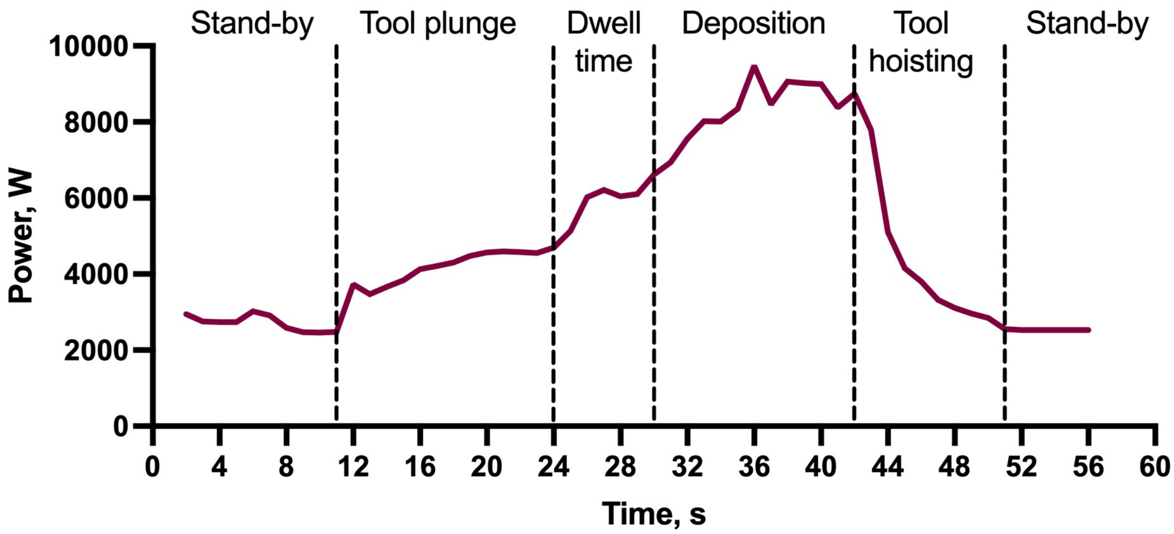


Fig. 6. Electric power trend of FSE-AM single layer deposition

In this way, the FSE-AM technology demonstrates high potential for aluminum additive manufacturing purposes, providing high quality of layer deposition with relatively low energy demand required for the deposition. Flexibility of this technology can also enable metal scrap recycling, significantly increasing its sustainability [22]. This effect can reduce the environmental impact of the method, although full life-cycle assessment analysis must be performed to get detailed data.

Conclusions

As a result of the experimental campaign on the FSE-AM of AA1070 aluminum alloy carried out, the following conclusions have been made.

- If wrong process parameters are used, geometrical irregularities during the deposition occur. After the proper mode selection, it is possible to achieve a stable deposition process.
- FSE-AM samples show well-bonded layers formed with no internal defects like voids or cracks. However, edges of the samples consist of defects known as lack of bonding. Further layer deposition, in turn, improves the quality of previous layer bonding to the substrate.
- Additive AA1070 alloy demonstrates microhardness on a level of 30 MPa, which is 15 % lower than the parent material. At the same time, the anisotropy of mechanical properties is significantly low and does not exceed 4%.
- The method demonstrates a high deposition rate on a level of 0.42 g/s and Specific Energy Consumption of 5.19 kWh/kg, which are of the order of other solid-state techniques.

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