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Reviewed Paper

Enhancing Deposition Rates in Additive Friction Stir Deposition: A Comprehensive Review.

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Abstract:

Growing demand for high-speed, defect-free additive manufacturing has led to increased exploration of solid-state processes like Additive Friction Stir Deposition (AFSD), which eliminate melting and mitigate solidification-related defects common in conventional methods. This study introduces strategies to improve the build rate of AFSD by optimizing process parameters, tool design, or material feed mechanisms. Key factors influencing deposition efficiency, such as rotational speed, traverse speed, and feed rate, are analyzed to enhance material flow and reduce defects. Tool geometries and multi-material feed systems are investigated to maximize deposition efficiency while maintaining structural integrity. The findings provide valuable insights for scaling AFSD for high-rate production applications in the aerospace, automotive, and defense industries.

Keywords: additive manufacturing, additive friction stir deposition, build rate, defects, Friction Heating, process parameters

Introduction:

Additive manufacturing (AM) has transformed modern manufacturing by enabling the fabrication of complex geometries layer by layer, thereby improving design flexibility, reducing material waste, and increasing production efficiency. It also has the advantage of processing softer and low-melting alloys [1]and is actively introduced into the automotive, aerospace, biomedical, and defense industries, showing massive importance compared to the traditional manufacturing processes[2]. Unlike additive manufacturing, subtractive methods shape parts by removing material, often generating substantial waste.

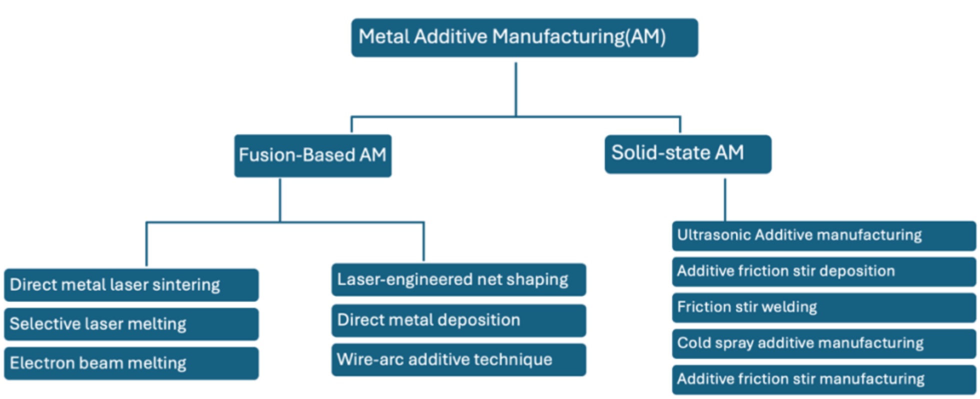


Fig 1. Overview of Metal AM Techniques

Additive manufacturing (AM) processes are classified into seven categories: material extrusion, directed energy deposition, powder bed fusion, binder jetting, sheet lamination, vat photopolymerization, and material jetting. These categories encompass a wide variety of feedstock types and energy sources across polymers, metals, and ceramics, highlighting the broad scope of the AM industry. While this review acknowledges the diversity of AM technologies, its focus is on metal-based solid-state AM, particularly Additive Friction Stir Deposition (AFSD), which is distinguished from fusion-based methods by eliminating melting and reducing solidification-related defects. The peak temperature is typically in the range of 50-90% of the melting temperature of the feed material[3]. Under this condition, the print head's material is expected to have minimal permanent deformation during printing, ensuring refined microstructures, enhanced mechanical properties, and minimized thermal distortion[3] [4]. They produce components with low porosity, improved fatigue resistance, and superior interlayer bonding, making them attractive for repair, coating, and high-performance applications. Fusion-based AM processes rely on localized melting and solidification of the feed material in the form of powder or wire, unlike solid-state processes. Examples of Fusion-Based AM processes are Laser Powder Bed Fusion (LPBF), Electron Beam Melting (EBM), and Directed Energy Deposition (DED)[5] [6][7][8]. They provide high precision and the processing of a wide range of materials, but introduce solidification-related defects, residual stresses, and anisotropic microstructures, which can compromise mechanical integrity or desired print properties[2] [9].

Additive friction stir deposition (AFSD) is a breakthrough in the solid-state AM processes, which evolved from the Friction Stir Welding (FSW) process, originally developed to join aluminum alloys. FSW involves joining metallic materials through plastic deformation under high shear stress. AFSD integrates a material feeding mechanism, allowing for continuous deposition without melting. AFSD uses a tool that rotates and is a non-consumable shoulder applying axial force and creating frictional heat to soften feed material during the process. AFSD has gained traction for its ability to process hard-to-weld materials such as aluminum, titanium, and nickel-based superalloys. AFSD enables high deposition rates, defect-free bonding, and superior mechanical performance, making it a compelling alternative to conventional AM techniques. The open environment process feature of AFSD without a chamber or powder bed system gives it a no-size limit for its final print compared to other AM processes. Another importance of AFSD is its final print having the final properties required with no need for post-processing such as hot isostatic pressing (HIP) therefore reducing time and energy use.

The final properties of the print through AFSD are influenced by several process variables such as layer height, rotational speed of the tool, transverse speed of the tool, actuator speed acting as the feed rate of the process, temperature, and feedstock characteristics[10] [11][12]. Layer height has been investigated showing an influence in the final tensile property of the print. In this investigation, thinner layers (1mm) showed lower fracture strains and ultimate tensile strengths compared to thicker layer heights (2mm to 3mm)[13]. The rotational speed of the tool also has an impact on the heat generated through frictional contact with the substrate. Higher rotational speed increases the heat input for the plastic deformation of the feed material leading to large grain sizes and reduced tensile strength and hardness. Aside from layer height and rotational speed, transverse speed also influences the printing process by increasing the grain and decreasing recrystallization therefore increasing the tensile strength in some materials such as aluminum alloy 6061[14].

Some problems encountered using fusion-based AM processes such as powder bed fusion, direct energy deposition, and wire arc AM have been addressed with AFSD to produce final prints with desired and expected properties. The inferior quality of in-situ TiB_2 /7XXX composites using fusion-based processes due to vaporization of Mg/Zn elements, hot cracking, and porosity during rapid solidification was addressed using AFSD which led to reduced grain size, aspect ratio, and mechanical properties[10] [15]. Nonweldable alloys such as AA7050 which undergo hot cracking during rapid solidification during fusion-based AM were successfully produced showing forging-like tensile properties with no chemical modifications[16]. Valuable insights into the development of more reliable and efficient metal additive manufacturing techniques, emphasizing improvements in the mechanical properties of processed metals and the potential applications in various industrial sectors were investigated. The key findings included how specific methods such as the addition of ceramic particles or enhanced cooling techniques, lead to finer microstructures and improved mechanical properties in aluminum alloys, elaborating on the evolution of friction stir processes that allowed for better integration and stabilization of metal parts in industrial applications. A study also aimed to determine the suitability of the as-deposited material of AA2219 aluminum alloy for use in NASA's Space Launch System vehicle construction. This delved into the evolution of precipitates in the AA2219 alloy and the process parameters controlling the quality of the deposited material. It also presents the results of a parametric study to determine the local optimal AFS-D AA2219 process parameters, microstructure, tensile response, and strain-life fatigue response[17].

This paper provides a comprehensive overview of the Additive Friction Stir Deposition (AFSD) process, focusing on its fundamental working principles, key process parameters, and tool head design. It also highlights the advantages of AFSD over traditional fusion-based additive manufacturing methods, particularly in terms of microstructural integrity and mechanical performance. Furthermore, the paper explores recent research developments in the field and discusses potential future directions for expanding the application of AFSD in advanced manufacturing.

2.0 The mechanism of AFSD

AFSD is a solid-state manufacturing process that was patented by Aeroprobe Corporation (now MELD Manufacturing)[18], which integrated friction stirring with a material feeding process to manufacture site-specific components[19].

Problems such as pores and cracking haven't been resolved using fusion-based additive manufacturing methods. Different solid-state AM methods have been used to deposit Aluminium and it was concluded that AFSD was the most comparable in terms of mechanical performance[19]. Almost a non-porous structure can be produced using AFSD making if an area of great interest and direction in AM[18]. Since the commercialization of this AM process, there have been intense academic and industrial studies carried out for several materials such as aluminum alloys, magnesium alloys, steel, and titanium alloys.

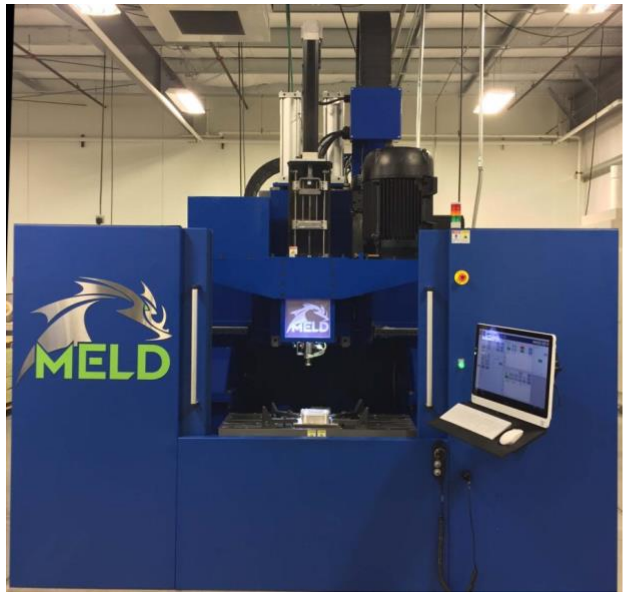


Fig 2. The equipment developed by MELD Corporation[20]

AFSD's speed is 10 times faster than fusion-based methods[21] and its ability to deposit without post-processing as compared to other AM processes is also a crucial advantage over other AM methods[22]. It utilizes a feed-rod which is fed through a rotating tool head with a hollow center and a diameter of about 38.1 mm. The feed rate is set at 35 mm/min, and forces can reach up to 100 kN. The feed-rod and tool head assembly rotate at speeds ranging from approximately 10^2 to 10^3 rpm. Fig 2 shows AFSD process consists of two main stages: initial material feeding and steady-state deposition[23]. During the initial feeding stage, the rotating tool moves downward toward the substrate, leaving a small gap between the two surfaces. An actuator engages with the feed rod, which is then inserted at a low rate. As the rod contacts the substrate, it experiences intense frictional heating and axial force, leading to plasticization[24]. The softened material fills the gap between the tool and the substrate, setting the stage for continuous deposition. The combination of compressive forces and shearing forces causes the softened material to mix with the substrate surface. Features on the tool surface, such as protrusions, further enhance frictional heating and material mixing.

Once the material has been sufficiently plasticized, the steady-state deposition stage begins. At this stage, the tool moves relative to the substrate along a predefined trajectory, continuously depositing the material. This stage is divided into intra-layer deposition, where a single layer is deposited, and inter-layer deposition, which involves multiple layers. The latter can introduce cyclic heating effects, which influence the microstructure and mechanical properties of the previously deposited layers[25][26].

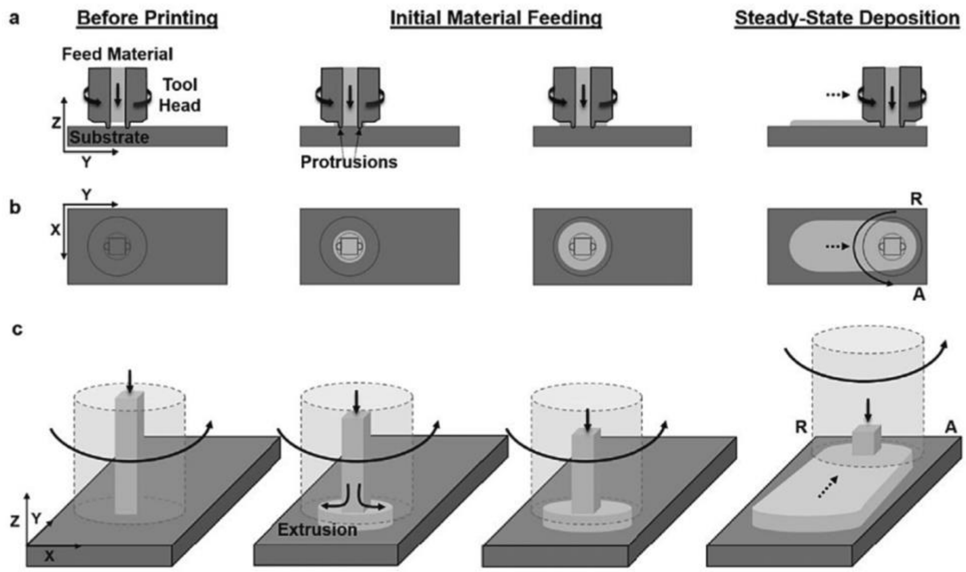


Fig 3. Schematic diagrams showing the main AFSD processing steps (from left to right): before processing, initial material feeding, and steady-state deposition. This includes (a) side view, (b) top view, and (c) isometric view.[23]

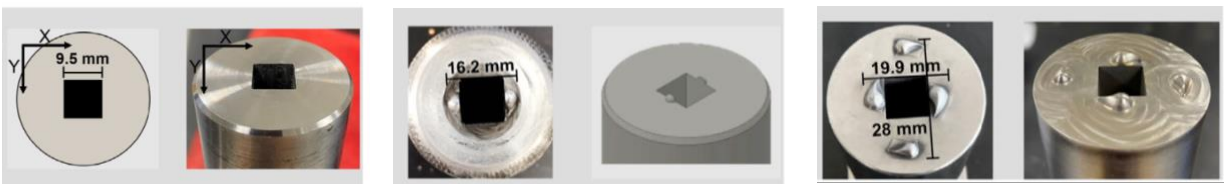
2.1Print tool head

The print head for AFSD must have a melting temperature higher than that of the print material to prevent deformation of the print head during friction. The peak temperature is typically in the range of 50-90% of the melting temperature of the feed material[27]. Under such conditions, the print head material is preferred to have minimal permanent deformation. Table 1 below shows the type of print head material used to print feed materials with given examples[7][28].

Table 1: shows appropriate tool head material for various types of feed materials, with examples of build materials.

Material property (to be printed)	Examples	Type of print head
Low Temp. Materials	Al, Cu, Mg Alloys	Steel tool head
High Temp. Materials	Ni-based superalloys, Ti-6Al-4V, etc.	Lanthanated Tungsten tool head.

A flat tool with no features at the bottom, except the central feed rod channel for material feed, was first used in this process. Thinner layers are achieved using flat tools, while the tool head with teardrops normally produces deep material mixing. Advanced studies were made, which led to an improvement of the tool to two small protrusions, which finally improved to 4 protrusions called teardrops. For the 4 protrusions, two protrusions are near the edge of the feed-rod channel, while the other two are located at a radius further away towards the outside surface protrusions have a maximum height of 2.3 mm. Adopting surface features(teardrops) on the print head, the flash width is reduced, the vertical material mixing is enhanced, and more complex 3D features are formed across the interface, such as the serrations, fins, and lobes.



a) b) c)

Fig 4: shows the adopted tool surface features. a) tool with a flat surface and no feature at the bottom. b) tool with two small protrusions (height- 1.5 mm) on the bottom surface near the edge of the feed-rod channel. c) A tool with four teardrop-shaped protrusions. Two protrusions are near the edge of the feed-rod channel, while the other two are located at a radius further away towards the outside surface protrusions have a maximum height of 2.3 mm.[29]

2.2 Process parameters.

The efficiency of this process depends on several factors. AFSD process parameters are critical to deposit quality, with variations significantly impacting thermal parameters. Microstructural factors like grain size, texture, and second-phase particles are influenced by these parameters, affecting the alloy's mechanical properties.

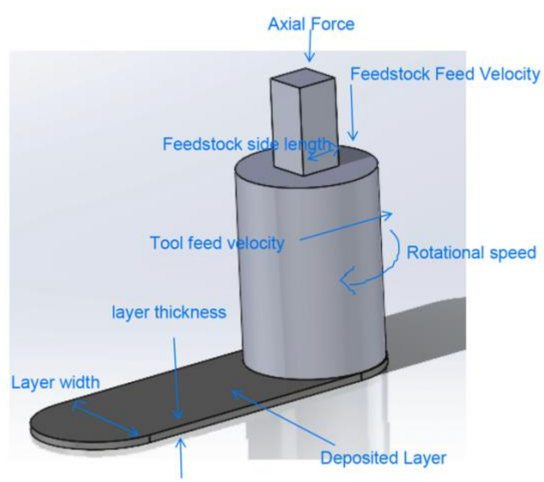
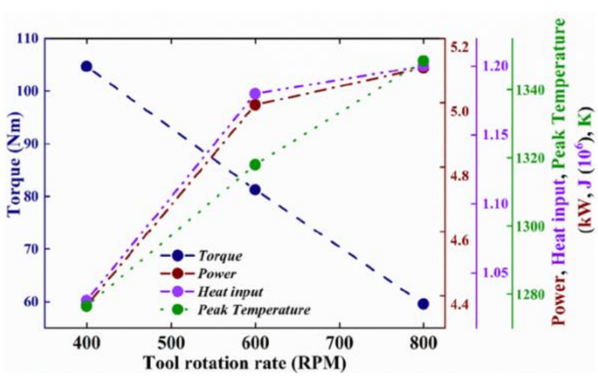


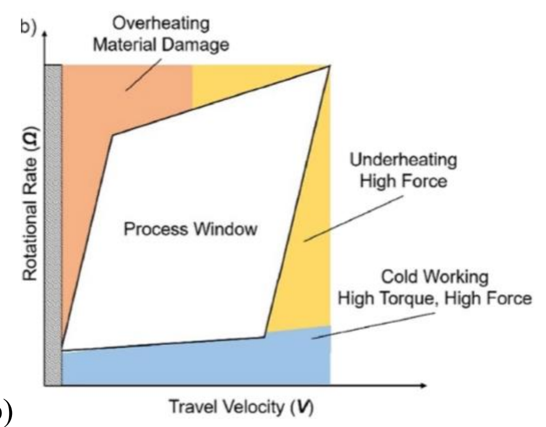
Fig 5: Schematic of AFSD showing the process parameters.

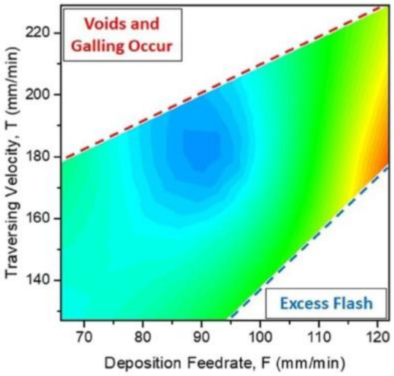
A successful model requires a thorough understanding of process variables. The main process parameters for the AFSD are tool rotating speed (ω), feed rate (FR) or axial force (AF), tool traverse velocity (V), and single layer height (H). Layer Height represents the distance between the underside of the tool and the substrate. To ensure strong bonding among the substrate, feed material, and successive layers, an appropriate layer height is typically established, allowing the tool protrusion to be inserted into the substrate[4][3][11]. In a study using Aluminium, AFSD was deposited at various thicknesses (1 mm, 2 mm, and 3 mm) and results showed a significant reduction in *Z*-axis tensile performance with increasing thickness. It is beneficial to use thicker layers over very thin layers since they have the benefit of shorter build times[10]. There is a maximum layer thickness beyond which mechanical properties degrade due to reduced mixing with previous layers as layer height increases.

The temperature of the plasticized material is affected by rotational speed. Higher rotational speed results in higher heat input as compared to lower rotational speed which may affect the mechanical properties of the final print. The feed rate or axial force is affected by the spindle torque during rotation. The importance of FR or AF is to help push the feed rod downwards through the tool. When there is higher axial force, it leads to better adhesion of the deposit; but excessive AR can also cause an increase in flash formation which affects the thickness of the final deposit[11]. Studies have been done to show how the actuator force and spindle torque are affected by the rotational speed of the tool and it showed that actuator speed and spindle torque decreased with rotational speed. Lower tensile strength and hardness of the components were produced with high rotational speed compared to better properties produced with lower speed(400rpm).

After the feed material has been plasticized, the material is supposed to be deposited in a predetermined path as required to obtain the final print. The transverse speed of the tool is responsible for this and influences the final properties of the product. It has been investigated, and the transverse speed is said to influence the heat required and the microstructure of the final print. A faster transverse speed in AA6061-T6 was studied and it led to an increase in grain size and decreased the degree of recrystallization, leading to an increase in the tensile strength for AA6061-T6[30].

a) 

b) 



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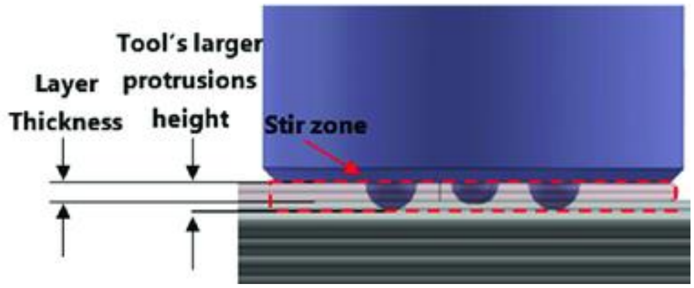

d)

Fig 6: a) Variation of torque, power, heat input, and peak temperature with tool rotation rate. b) Feasible process window defined by rotational rate and travel velocity[28]. c) The processing boundaries between the actuator deposition feed rate and traversing velocities[31]. d) layer height and thickness in AFSD[10].

The conclusions that were drawn from Fig.1. were:

- The rise in deposit temperature with increasing tool rotation rate is expected to lower the flow stress of the deposited layers and reduce the coefficient of friction between the tool and the deposited material. The variations in thermal conditions and plastic flow behavior with processing parameters contribute to microstructural differences.
- At a constant material feed rate and traverse speed, power consumption and heat generation during processing increase with the tool rotation rate.
- As power input and heat generation rise, the peak processing temperature also increases due to unchanged thermal boundary conditions and heat transfer mechanisms.
- Spindle torque and the corresponding actuator force decrease as the tool rotation rate increases.
- An additional effect of increasing the tool rotation rate is the change in strain rate. Higher tool rotation rates lead to an increased strain rate during shear deformation; however, the extent of this effect depends on the strain rate sensitivity of the deposited material.

3.0 Optimal process parameters

Optimal process parameters are the carefully selected conditions that maximize efficiency, quality, and performance in a manufacturing or engineering process. Identifying and controlling these factors is essential for achieving repeatability, minimizing defects, and optimizing resource utilization. Table 2 below shows the key process parameters for various materials; their impact on manufacturing outcomes, and strategies for determining the optimal conditions for various applications are also investigated.

Table 2: shows optimal experimental parameters obtained using AFSD with the deposited material type

Deposited Material	rotational speed (rpm)	feed rate(mm/min)	transverse speed(mm/min)	layer height(mm)	Build rates(cm^3/hr)	REF
AA2219	200	88.9	101.6	1	481.4	[17]
AA2024	300	51	120	1	276.2	[32]
AA5083-H131	200	69.8	127	1	378	[33]
AA6061-T6	300	66	127	1	357.4	[30]
AA6061	300	152.4	254	1	825.2	[34]
AA60617651	300	69.9	127	1	378.5	[35]
AA7075-T651	225	50.8	50.8	1	275.1	[36]
AA7050-T7451	225	50.8	50.8	1	275.1	[37]
Cu110	275	-	127	1	-	[38]
AZ3 1B	300	51	102	1	276.2	[39]
WE43-T5	325	63.5	152.4	1	343.9	[40]
304 stainless Steel	800	6.6	51	0.25	35.7	[41]
AISI 316L	500	30	102/108	0.5	162.5	[42]
SS316	400/600/800	25.2	202.8/253.8	0.5	136.5	[12]
IN625	600	16.2	76.2	0.5	-	[43]

Notably, each material suitable for AFSD has a distinct process window, making it essential to thoroughly evaluate the AFSD process window from multiple perspectives, including volume defects, surface quality, and mechanical properties[44]. Mostly parametric studies are made to ensure the right process parameter combinations are chosen to prevent wasted material and poor mechanical properties of the final print. [45] was the first to report on the optimized process parameters of AFSD-AA2219 and the final mechanical properties when compared to the wrought AFSD-AA2219. A deposition tool with 4 teardrops was used in this study, which aided in mixing and heat generation. In their parametric study, ten process parameter sets were created with tool rotational speed varying from 175- 300 rpm, and transverse speed varying from 88.9 mm/min to -139.7 mm/min. A constant feed rate of 88.9 mm/min was used for each set of parameters. The optimized process parameter was determined by ranking each build based on microhardness and grain size measurements. Vickers micro-indentation was used to assess the hardness, serving as a screening tool for strength. A process parameter map revealed a local maximum microhardness of 83 Hv at (200 rpm, 101.6 mm/min), significantly lower than the 145 Hv of the as-received material, identifying this as the optimal parameter set. The above is how almost all the optimized process parameters were obtained, strongly taking into consideration the desired properties of the final product for various applications. Although increasing feed rate and rotation speed can improve the build rate, these optimizations often come at the expense of mechanical strength and microstructural integrity, an area still not thoroughly investigated in existing AFSD research.

3.1 Contributing factors to select build rates for different materials

Several factors contribute to different build rates for different materials. Thermal conductivity of the build material, melting point and thermal softening temperature, hardness and strength, viscosity and flow behavior, and microstructural characteristics are among other factors that contribute to different build rates. Materials with high thermal conductivity such as copper dissipate heat quickly, which can reduce the localized softening required for effective deposition. This may necessitate slower processing speeds or higher energy inputs to maintain the necessary temperature, potentially reducing the build rate. Materials with higher melting points such as tungsten, require more energy for processing, which can limit the maximum build rate, and also softer materials such as aluminium alloys are generally easier to deform and deposit, which can lead to faster build rates. The viscosity and flow behavior of the material at elevated temperatures influence how easily it can be deposited. Materials that maintain a low viscosity and good flow characteristics during processing can be deposited more smoothly and quickly, enhancing the build rate. Fine-grained or homogeneous materials may deform more uniformly, aiding in a consistent build rate, while coarse-grained or heterogeneous materials may present challenges.

3.2 Microstructure and Properties of AFSD Parts at High Deposition Rates

High deposition rates in AFSD also play a critical role in determining the microstructure and mechanical performance of the final build. Increased deposition speeds alter the thermal cycles and strain rates on the material, affecting grain refinement, precipitation behavior, and bonding quality. Studies have reported on aluminum alloys that higher traverse and feed rates can promote finer, equiaxed grains due to enhanced dynamic recrystallization; although excessive heat from elevated rotational speeds may result in grain coarsening and reduced hardness [34,10]. Also, faster deposition conditions influenced residual stress distributions in AA6061, underscoring the link between process rate and microstructural stability [30]. Similarly, in SS316, deposition parameters significantly affect microstructure evolution, where higher strain rates resulting from faster deposition improved refinement but introduced anisotropy in the mechanical response [12]. In copper systems, it's demonstrated that deposition rate influenced recrystallization kinetics and texture development, directly affecting conductivity and strength [38]. For titanium alloys, AFSD builds yielded fine "α–β" lamellar structures with enhanced hardness and yield strength compared to slower builds through fast deposition [7]. Overall, while high deposition rates can enhance productivity and promote grain refinement, they must be carefully optimized to avoid heterogeneity, anisotropy, or localized soft zones.

4.0 Problems encountered by fusion based Additive manufacturing processes solved using AFSD

Several challenges associated with fusion-based additive manufacturing (AM) processes have been addressed using additive friction stir deposition (AFSD). For instance, printing aluminum matrix composites reinforced with nanoparticles such as SiC and Al_2O_3 is difficult using conventional beam-based techniques due to issues like poor dispersion and interfacial reactions. Alloys such as AA7050, which are categorized as "non-weldable" due to their susceptibility to hot cracking during rapid solidification, pose significant difficulties in fusion-based processes[46]. Materials like copper and Al-Mg-Si alloys, which are also challenging to print via laser or electron beam-based AM methods, have shown improved processability through AFSD. In particular, aluminum alloys in the 2xxx and 7xxx series, which are known for being non-weldable, can be more readily formed using AFSD compared to fusion-based approaches[21]. Moreover, in-situ composites like TiB_2/7xxx produced through fusion processes suffer from poor quality due to vaporization of alloying elements such as Mg and Zn, hot cracking, and high porosity during rapid solidification[16]. There are some challenges also encountered using this process. Flash formation is a major challenge that is caused by too much heat overly plasticizing the feed material causing it to flow out of the deposition zone. This reduces the efficiency of the amount of deposited material to the overall amount of feed material. The diameter of the print head is large making small features with precise geometry difficult to print making minor machining and surface finishing very necessary[18].

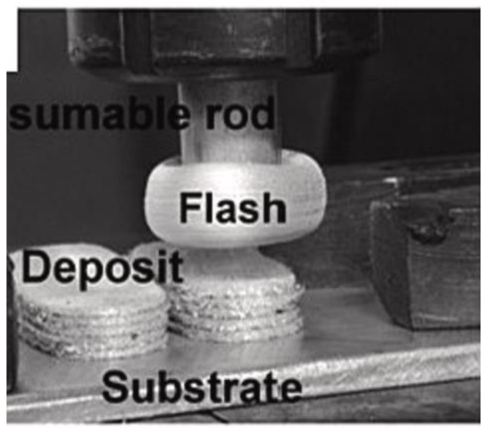

Fig 7. Flash formation in the Additive Friction Stir Deposition Process [18].

5.0 Conclusion and Future Recommendations

AFSD has the potential to process a wide range of materials and is being actively explored for its applications in Additive Manufacturing, coating, repair, joining, and composites. However, several avenues can be explored to enhance the performance and efficiency of AFSD. One promising approach is the preheating of feed material before deposition, which could help reduce thermal gradients and minimize the time required to plastically deform the material solely through frictional heating. Additionally, in-situ heating during the printing process, achieved by incorporating embedded heating elements in the print head may promote more uniform deformation and improved bonding between layers. Advancements in hardware, such as the development of novel print heads like double tool configurations, could significantly increase deposition rates and simplify the process for industrial-scale applications. Another area with potential is powder-based AFSD, where powdered feedstock, though currently underexplored could open pathways to higher build rates and expanded process capabilities.

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