A Study on Process Parameters and Scope of Material Flexibility in Friction Stir Additive Manufacturing, a Sustainable Technology

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Abstract- To keep up with the pace of Industry 4.0, Metal Additive Manufacturing(MAM) is revolutionizing its course from fusion-based MAM to the recently developed Solid State Friction Stir MAM. Fusion-based MAM has numerous drawbacks, especially due to solidification issues and inferior shear strength. Friction Stir Additive Manufacturing (FSAM) has variant novel techniques, it works on the governing principle of Friction Stir Welding (FSW) to build components layer after layer. Friction Stir Deposition is a very recent development in which the feed material, which is in form of powder, rod, or in form of machine chips (recycled) sustains in situ self-generated heating (by Friction stir mechanism).Due to the development of high strain rates, the feedstock binds to the substrate by extensive global plastic deformation leading to dynamic recrystallization giving fully dense bindings without any porosity, hot cracks, and inclusions. Being a solid-state thermo-mechanical process, it overcomes the drawbacks of Binder Jetting, Direct Energy Deposition, Sheet Lamination, and other MAM Techniques by giving, not only defect-free but also a microstructure, which is even better than the wrought, superior mechanical and structural properties, tight tolerances, proper bindings locally as well as globally, but lacks the ability for excessively complex parts. Owing to equiaxed and uniform refined microstructure, high energyefficiency, scalability, a wide range of material (Al, Ti, Ni, Mg) usage, reduced part distortion, its ease of use, superior quality, variety in feed materials, and minimal post-processing needed, it is amongst the best suited MAM for industries like aerospace, automotive, military, biomedical and maritime which require to manufacture high-strength, low-weight pure bulk metals, laminates, composites, biocomposites, alloys, and coatings. This paper outlines the mechanism of various FSAM techniques, studies the Process Parameters, the scope of Material Flexibility, defect detection, and the difficulties involved in enhancing the microstructure and efficiency. The paper concludes by analyzing its future trends.

Keywords- Friction Stir Deposition (FSD), FSAM, Process Parameters, Materials, Recycling machine chips, 3D printing

1. INTRODUCTION

Ere the industrial revolutions, livelihood was subjected to craftsmanship and agriculture. With time the urge to develop newer materials and manufacturing processes came up and people wanted to use better quality products and enhance their lifestyle. This started research for newer materials and fabrication methods, which could be more effective and fast compared to the traditional ones. This trend made the country's economy dependent on its industrial growth via large-scale production and mechanized tooling. Four stages in the industrial revolution are seen as (a) Stage 1: A shift in manufacturing from manual to the steam-driven, which continued up to 1835, (b) Stage 2: Vast-scale manufacturing by high-end energy resource development, which continued up to 1945, (c) Stage 3: Shift from mechanically driven era to a technology-driven era of Computer, Digital data, and Internet, it continued up to 2015, (d) Stage 4: Integrates advanced manufacturing processes especially Additive Manufacturing(AM) with the Simulation and Optimization,Big data, Internet of Things, Augmented Reality, Robotics and AI to create computer-aided manufacturing systems which not only interpret but also use data by Machine Learning to manage numerous intelligent movements back in real-world pacing towards complete automation [1]. Hence the industry is benefited from the flexible product modification, product development, market entrance, reduced cost, and operational unification achieved.

The six primary steps of AM are (a) building a 3D model via Software packages, (b) tessellating, (c) stacking, (d) configuring and calibrating the machine, (e) producing prototypes, and (f) post-processing and strength analysis. As new technologies and techniques for fabrication are developed, design and production research is redefining the boundary of conventional methods. Earlier termed as rapid prototyping (in the 1980s), this process faced advancements and is now termed as Additive manufacturing. Feedstock is used, which is in the form of a powder or wire. It may be fused, heated, or build as stacks by multi-dimensional computer-aided process planning and manufacturing system [2]. With minimum homo sapiens interaction, it eliminates all needs to remove or mould material further into the shape of a product [3]. Additive manufacturing (AM) is the formal industrial nomenclature, but 3Dprinting is recognised frequently common alternative, owing to a joint effort by the ISO-International Standards Organization with ASTM-American Society for Testing and Materials [4].

Due to its capacity to create complicated geometries, decrease waste, increase design flexibility, and lower the cost of customization, metallic 3-d printing (MAM) is among the most key techniques employed in the manufacturing business [5,6]. For example, some titanium surgical implants have recently been printed using it. Boeing 777 with engine GE9X uses a heat exchanger system, consisting of 300 individual pieces. Owing to AM evolution, it just requires one, which also happens to be 25% cheaper and 40% lighter. SpaceX has used MAM components to cut down on production time and weight for its Super Draco and Raptor engines, and NASA plans to do the same for the Space Shuttle's primary engine in the near future. Made of 308LSi austenitic stainless steel (SS), the world's 1st additively manufactured metallic bridge is at De Wallen, Amsterdam, it stretches 10.50 meters over the Oudezijds Achterburgwal canal [7-10].

Binder jetting (BJ), Sheet Lamination, Material Extrusion (ME), Direct energy deposition (DED), Vat Polymerization, and Powder bed fusion (PBF) are the six main types of MAM processes defined by ASTM/ISO 52900:2017 [4]. Metals are involved in just four of these six processes. Acknowledging advancements in AM, metal, polymer, ceramic, composite,and bio-compatible materials are just a few examples that can be used [11].

Binder Jetting results are analogous to those of printing text on paper. When metal powdered granules bond to one another through a liquid binder,it creates a solid material layer. This printing process normally takes place at room temperature, this assists in avoiding thermally induced errors such as undesired grain development and distortion which are common in other MAM techniques that rely on a heat source [12-16]. The base material also acts as a substitute support structure while the permanent one is being built. Waste is reduced since there is no need for framing [17,18].

Direct Energy Deposition (DED) is a method that, like welding, employs a concentrated heat source to melt materials that are placed via a nozzle. It accounts for 16% of the overall MAM market and is mostly used for producing fairly close parts and fixing or making improvements to existing parts [20-22]. The DED method makes use of a heat source that may melt a feedstock (wire and powder) to a liquid state [23]. It is touted as being more efficient than competing technologies since it doesn't need the use of powerful lasers. In addition to being more cost-effective than PBF (Powder Bed Fusion) by 60-80%, it is simpler to run too. Fused deposition modelling (FDM) was developed for additive production of polymeric as well as composite layers [24-26]. The bound powder and ceramic release substance, are held on separate spools in a sealed container, and extruded by a conventional Material Extrusion machine. When using polymer binders, the 3d printer must raise the temperature of the feed higher than its melting point [27-30]. When using an electron or laser beam, PBF melts the material, allowing for the deposition of several coatings of material at once [31,32]. Metal direct laser sintering is being used to create bigger mechanical components like turbine blades, it has the potential of creating thick multi-layered substances but has a massive operational expense [33]. PBF falls into a similar category. Similarly, electron beam melting necessitates a vacuum during the production of functional components, whereas selective laser heating has higher operating costs than the aforementioned AM techniques [34-36].

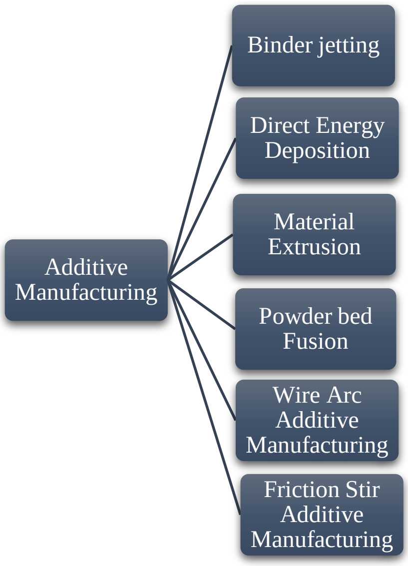

Fig.1 Types of Additive Manufacturing

Calvert et. al [37] declared that elevated temperatures and gradients developed in electron beam welding caused accelerated grain growth, a decrease in isotropic behaviour, a decrement in levels of stress dilution, and other typical cast defects. He also explained that it required some machining within every succeeding layer for a better connection surface. The traditional subtractive production process for fabrication involved around 85 percent wastage of base material. The AM process requires lesser material bulk volume and concurrently improves the strength-to-weight ratio. Some of its latest techniques that are extensively used are selective laser sintering, cold spray AM, electron beam welding, layered friction stir AM, etc. Mukhopadhyay et al. [38], Sing et al. [39] declared that selective laser melting fabricated components with remarkable defects along with porosity. Mertens et al. [40] observed that the enormous laser energies utilised in laser beam AM would lead to more material loss due to evaporation, unnecessary spatter, and degradation of exterior nature by baling. SMD (shape metal deposition) has an extensive build rate but inferior surface quality and bad dimensional tolerance, this issue was resolved by the application of LBAM. The parts made had better properties but had a tremendous cost of operation, slow build rates, and moderate bulk volume. Making metal parts by AM got commonly restrained to fusion-based methods where the powder substrates have to be heated above the melting point and, as the laser or beam moves forward, the consequent molten metal pool tempers down, getting solidified according to the scanning tool path followed by the laser or beam [41]. Like in fusion welding and casting, fusion-based MAM unavoidably negotiates in quality control of the material; cooled material suffers from hot cracking (especially in pure aluminium), porosity (especially in LBAM-made parts), residual stresses, and other defects. These defects get elevated due to the improper grain structure formed by the swift cooling rate and a sharp temperature gradient. Even after years of research, the quality of fusion-based components still lacks. Even in Cold Spray AM, which is the most researched AM in recent times, FSP has to be followed after deposition due to the porosity, micro-cracks, and improper bindings in some places [42-45]. Thus, there has to be post-processing done on FSP machines, this increases the cost of the component as it undergoes two different exclusive machine setups. These limitations cause the emergence of friction stir-based AM processes.

Friction stirring has been used to extrude or plastically distort metal by causing it to generate heat before it reaches its melting point. Force is applied axially across a tool, and the tool is rotated while moving in a translational direction to provide the desired effect. Originally created in 1991 at The Welding Institute (TWI), it is a solid-state bonding technology [46-48].It originated as a skill for joining aluminium and its alloys, a material that is notoriously hard to weld using traditional techniques. Friction Stir Welding (FSW) is successfully applied for aluminium alloys in industries[49-52]. Various businesses, including those involved in production and shipping, as well as the military, aviation, and automobile sectors, benefit from FSW. The procedure surpassed lap welding, spot welding, and submerged welding because of the fine, uniform microstructure achieved by grain refining [53-56]. The FSW principle is further refined and used in a variety of different production processes, including brazing, cladding, shaping, alloying, and so on [57-59]. In Friction Stir based Brazing, the absence of a tool pin eliminates the defects. At times, the process of FSW is followed by Friction Stir Cladding (FSC) in order to increase the corrosion resistance of the material [60,61]. Different researchers have contributed towards this process: White in 2002 patented friction-based solid state joining [62], Thomas in 2005 highlighted the scope of FSW as a method of AM [63], Rajiv S. Mishra in 2008 got a US

Patent by stating the working mechanism of Friction stir technique for getting superior strength and superplasticity [64], by Boeing's study they explained the eminent advantages of FSAM over other MAM [65,66], Calvert in 2013 published a thesis on AFS for WE43 alloy's structural characteristics [67], and Liu in 2018 got a US Patent on Hybrid friction stir technology for dissimilar materials by electro plastic deformation route [68].

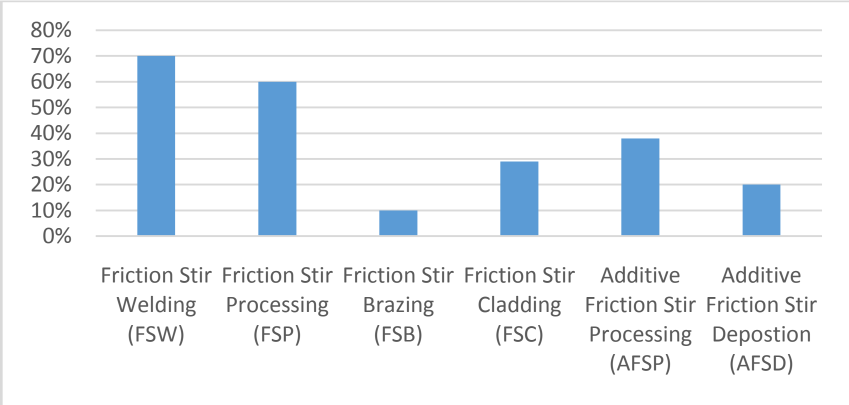

Fig.2 Contribution of Friction Stir Technologies in Research

FSAM is capable of resolving the drawbacks and overcoming the challenges faced in conventional AM, like defects, porosity, inclusions, high residual stresses, hot cracks due to hasty cooling after fusion, a large post-processing need, improper bindings, distortion, micro-cracks, high energy consumption in costly beam-based AM, and partially dense and non-uniform columnar microstructure in selective laser melting. It can print near-net shapes, almost defect-free, using a variety of composite materials, including metals, polymers, alloys, and even biocomposites. FSAM includes a massive variety of rewards like dynamic refined microstructure, high build rates, structural integrity, good scalability, and capability for high-strength, and low-weight parts. Hence, it has applications in a wide gamut of aspects and sectors like aerospace, automotive, military, biomedical, and maritime. Figure 3 explains the milestones in the evolution of this technique[69-79].

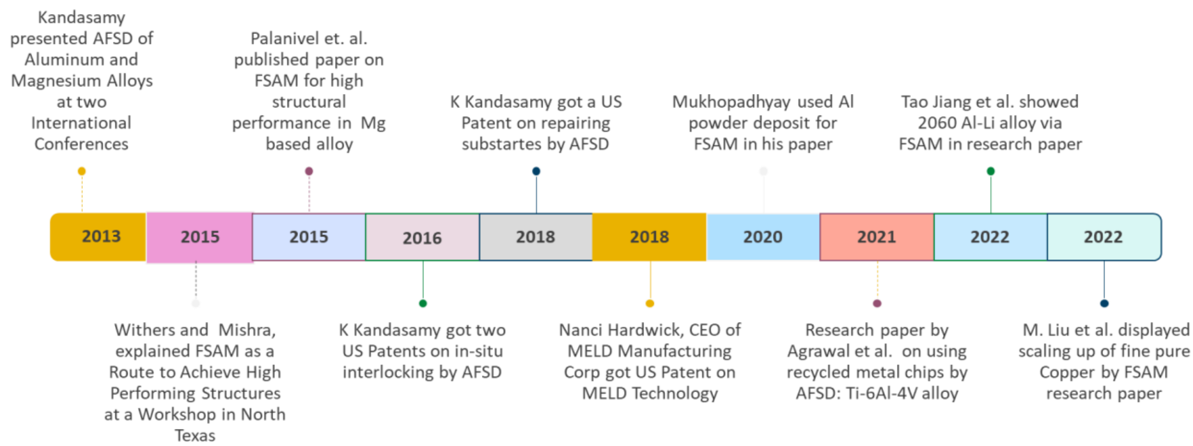

Fig.3 Milestones in process evolution

2. PROCESS METHODOLOGY

2.1 Mechanism

Using the notion of solid-state FSP to fabricate multilayer components through layer-by-layer blending gives enhanced microstructure. Traversing to dynamic recrystallization, exceptional mechanical properties are achieved by the grain refining process due to the development of tremendous strain rates of around 200/sec. The properties of a metal are enhanced by extreme localised as well as global plastic deformation with a refined isotropic uniform equiaxed grain structure of material. The shoulder comes into contact with the work surface, which is held on the table by jigs and fixtures from all sides. Downward normal forces and rotational forces are used to create in-situ frictional heat by rubbing the substrate. This increases the temperature of the stirred zone, and flow stress droops. Pins or protrusions seep inside the material, the tool is revolved at an eminent rpm and transversed along the planned tool path, and the flexible material is churned about the pin.

Feed material can also be introduced by hollow tool in AFSD for reinforcements, repairs of grooves, coatings, and even for complete layer building. The process has many characteristics, like solid-state processing, wrought behaviour, and flexibility in feed materials. There is a slight variation between the properties of the advancing and retreating side, like in FSW. The natural peculiarities of FSAM, like reheating, feedstock additions as rod or powder through the hollow tool head or externally, as done by Mukhopadhyay [38], global plastic deformation instead of local deformation, and resintering, distinguish it from FSW. The two techniques are: Additive Friction Stir Processing (AFSP) and feedstock based additive friction stir deposition (AFSD).

2.2 Types

2.2.1 Additive Friction Stir Processing (AFSP)

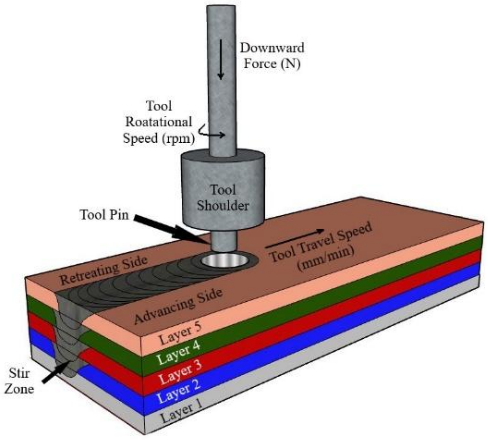

Fig. 4: Additive Friction Stir Processing

It works on layer-by-layer bonding of materials, and is a derived technique of friction stir welding (FSW) [44]. The protruding pin length is typically kept higher compared to the build layer so that proper binding of the material sheets can happen at a time. Here, the temperature is raised by generating heat by stirring the tool shoulder base against the top of the plates and also by the churning of the tool pin, which penetrates within the material, as depicted in Figure 4. This type has been extensively used in the automotive industry for composite fabrication, the sheet metal industry for lamination, and even for alloys with a higher melting point and higher hardness materials like Ti and Ni. Mishra et. al proposed for the structural frames of the airplane wings, and high-performance stringer/stiffener assemblies, in his patent and research paper [58].

2.2.2 Additive friction stir deposition (AFSD)-It was first suggested by Liu [59]and Stelt [60,61] to use hollow rotary tooling of the Friction Stir Cladding (FSC) technique in AFSD, and then Kandasamy got two US patents on AFSD in 2016 [73,74]. In 2018, AFSD became popular under the name of MELD when Aeroprobe Corp. introduced its AM branch as MELD Manufacturing Corporation [75,76], as listed in Figure 3. Here, the hollow tool has protrusions made on the base of the tool's shoulder. Its rotation and rubbing on the deposited material or substrate generate heat. As the tool doesn't contain a pin that could dip inside the material, so protrusions serve the purpose of the pin. The feed material contained in the hollow shoulder is in the form of recycled chips, consumable solid rods, or powder and is directly fed to the stirred zone. By topographical studies, the mechanism of temperature rise caused by friction is studied. The feed material is melded, stirred, and plastically deformed locally as well as globally, binding the deposited layer on the substrate plate fully.

This is extensively used for fabricating pure bulk metal (like Al and Cu), cladding, surface composites by adding SiC, and also in repair works for grooves and apertures. Unlike other AMs, no issues of porosity and other defects occur while fabricating Al in bulk from its powder. Hartley et. al [80] presented research on the cladding of Al-Mg-Si sheets of a very low thickness (in micrometres) for the automotive industry. AFSD has a high level of tolerance for feedstock due to its strong material deformation and binding mechanism. The deposited material may nonetheless have improved mechanical properties even when the feedstock is not totally dense (in the form of recycled machined chips containing oxide impurities) [81]. In many cases, solid rod feed is preferred to powder feed for fabricating composites, as it has a lower chance of impurities embrittlement and better ductility. Mukhopadhyayet. al [38] stated that feed could also be given externally to prevent the blocking of the tool outlet.

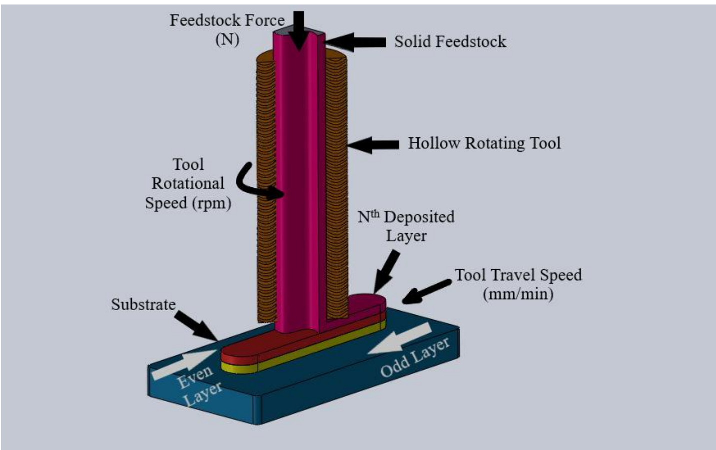

Fig 5: Additive Friction Stir Deposition

3. Comparative study of Optimized Process Parameters-

Various process parameters affect the process, and each has their individual contribution, these are: -

- Tool Travel Speed (TTS)
- Tool Rotational Speed (TRS)
- Shoulder geometry along with its features like Tool Shoulder Diameter (TSD)
- Tool Tilt Angle (TTA)
- Probe Geometry and its features like Tool Pin Length (TPL) and Tool Pin Diameter (TPD)
- Tool Plunge Depth
- Sideways Tilt Angle
- Vertical Pressure Applied
- Temperature of Nugget Zone

Among the following process parameters, it is observed that the parameters which have the maximum impact on the dynamic grain refinement are TRS, TTS, TSD, TTA, TPL, and TPD, their study is optimized and discussed in Table 1.

Table 1: Major Process Parameters in FSAM

Author [Ref]	Process	TRS in rpm	TTS in mm/min	TSD in mm	TTA in degree	TPL in mm	TPD in mm
Rodelas[82]	AFSP	100, 150	114, 51	-	-	-	-
Bo Li et al. [83]	AFSP	500	90	15.0	0	2.23	6.00
Calvert et al. [37]	AFSD	600, 1000	60	-	-	-	-
Guoqiang H et al. [84]	AFSP	1350	55	15.0	2.52	3.40	4.50
Roodgari et al [85]	AFSP	600	40,	20	0	0.5	6

			70, 100				
Derazkola et al. [86]	AFSP	850	45	20	2.5	6	6
Akash M et al. [37]	AFSD	170	22	16	0	Pinless	Pinless
Mackenzie Perry et al. [87]	AFSD	300	120	-	0	Pinless	Pinless
Jonathan et al. [88]	AFSD	275	127	-	-	-	-
K.Anderson et al. [89]	AFSD	175, 300	88.9, 139	38.1	0	Pinless	Pinless
Wenya Li [90]	AFSP	1500	30	15	2.5	3.85	4
Stubblefield et al. [91]	AFSD	300	127	38.1	0	Pinless	Pinless
Ardalanniya et al. [92]	AFSP	800, 1250	40, 70, 100	18	3	1.8	6

4. Comparative study of Material Flexibility-

Due to the flexibility of feed material and base material, FSAM gives a better alternative for fabricating alloys, composites, laminates, and even for the metals which are difficult for fusion-based welding and AM. Material Flexibility and findings are stated in Table 2.

Table 2: Material Flexibility and Findings in FSAM

Author (Year)	**Feed Stock**	**Base Material**	**Remarks**
J.Rodelas et al. [82]	Haynes Alloy 282	Alloy 600 (IN600)	Characterization done for Nickel-Based Surface Layers Alloy. Doubled hardness and improved kinematics of the precipitate structure as a result of the accumulated strength from interfacial mixing.
Bo Li et al. [83]	Pure Al	Ti3Alp/Ti6Al4V	By AFSD, fabricated and evaluated Ti3Alp / Ti–6Al–4V Surface Layer. The typical hardness increased to 400 Hv, while the coefficient of resistance dropped down to as low as .20
Calvert et al. [37]	WE43 Mg alloy	WE43-T5	Manufactures WE43 Alloy dense part with a homogenous fine grain structure without the use of any subsequent process. Grain growth was delayed to reduce the mean grain size to 2.0 from 2.4 after quick cooling with liquid N_2.
Hang et al. [93]	Al 6061	Al 6061	Outlined advantages of AFSD as compared to beam-based MAM. Several sensors were activated, allowing in-situ monitoring of thermo-mechanical interactions, faults, and topology topographical research.
Guoqiang H et al. [84]	WC particle	AA5083 H112	Fabricated Al–WC surface composite. Studied the progression of the perpetual dynamic recrystallized structure mechanics, and the retarded grain growth, which resulted in a reduction in grain dimensions.
Joey G. et al.	AA 7075	AA 7075	Worked on Repair of 7075 Aluminum Alloy. Even when the groove is 1.33 times wider

[94]			than feed rod, the feed fills the whole groove volume. In the higher sections, it consistently permits acceptable mixing. Reflected a smooth transition of columnar substrate plate grains to refined, equiaxed grain of the deposited metal, with no abrupt boundary.
Roodgari et al [85]	IF steel	St52 steel	Fabricated 2-layer laminated steel composite in comparison to base, made units have a good Yield Strength (YS) with low extensibility, possess Ultimate Tensile Strength (UTS) that falls between IF and St52 steel value, peak UTS-470 MPa and hardness-225 Hv at the condition 70 TTS, 600 TRS. If compared to core material, the consistent structure combined with the proximity of discrete phases in the built section give a lower UTS.
Derazkola et al. [86]	textile sheet	PMMA and its granules	Evaluated a laminated polymer steel sheet. The X – ray Photo-electron Spectrometry (XPS) method was used to investigate the sample. The formation of dipole-bonds was visible using XPS.
Akash M et al. [37]	AA6061	Al6061-T6	Carried microstructural and mechanical characterization of Al powder deposit. The introduction of granular feedstock in the hollow tool clogs the tool's end, making processing more difficult. Hence, the powdery feed was introduced into the substrate externally in this study to suppress this limitation.
Shirkharkolaei et al. [95]	silica	ABS	Adding Silica in ABS (acrylonitrile butadiene styrene) to improve pits properties. Results by responses surface method (RSM) displayed- value for predicting the error in deflection and bending strength, to be 8.5% and 6.1%.
Mackenzie Perry et al. [87]	AA 2024	AA 6061	Conducted morphological, structural study of non-planar interface. The feedstock is fully recrystallized; substrate sustains partial recrystallization. The material characteristics influence the exploration of interphase and its morphology.
Jonathan et al. [88]	Alloy 110 Cu	Alloy 110 Cu	Study on microstructure development of deposited Cu. It is totally firm outside while compact at the deepest levels. Guarding covering oxide forms on the outside facade of the placed substance.
Hsien Ho et al. [96]	Hydro-xyapatite powder	AZ31B Mg alloy	Biomineralization and biocompatibility of AZ31B Mg alloy hydroxyapatite composites was studied. The formed HA-Mg biocomposites showed better hemacompatibility, cellular adherence, and biocompatibility when compared to the substrate, it also has high surface energy of 46.80 mJ/m^2 and ratio of Calcium to Phosphor in the mineral phase from 1.55 to 1.6.
Anderson et al. [89]	AA2219	AA2219-T87	Carried out characterization of the fatigue behavior. The grain size is five times lower, and the θ'-θ phase is completely absent. The material that was created displayed a substantial portion of essential strengthening states.
Wenya Li [90]	Cu powder	Pure Al	Due to enhanced fine grains, a stronger bonded interface, and strain hardening, the analysis indicate that the adverse effects of particle interface were completely absent, enhancing the mechanical properties of copper. Because of the significant thermomechanical-coupling effect, the efficiency can reach 370 percent.
Stubblefield et al. [91]	AA6061-T651	AA6061	Did computational meshfree framework for the numeric simulation. Smoothed Particulate Dynamics, a distinct Lagrangian simulated method, showed high accuracy with experimental information recorded by the code, like temperature charts. Constructed outlines, strain plastic variation on entire bulk, giving an insight of the underlying mechanism.
Ardalanniya et al. [92]	Cu powder	Al-Zn alloy	Fabricated a laminated AlZnCup/Al-Zn composite. Manufacturing of intermetallic phases, by the emergence of unreacted Cu drops. It is carried out by improving filler

			particles dispersion while restricting flocculation, with increasing traversed and rotational speeds. The buildup of refined grains mostly on outer skin of a tiered composite results in a consistent pattern of minute dimples on the crack surface.
Ilana K. Lu et al. [97]	AA2050	AA2050	Fabricated cast Al alloy, 2050 Al–Cu–Li. The possibility that cast feed metal might be more cost-effective than wrought processed feed was also investigated.

5. Case Study

5.1 AA5083 machine chips deposition in AFS-D [81]

5.1.1 Process-

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Al alloy 5083 (AA5083-H131) plates were reduced in a milling machine to get 2–3 millimeters long segregated flakes through a dry slicing technique in order to get the machine chips for this research. The piling of AA5083 machine chip was accomplished by loading K2 MELD machinery with metal flakes with the help of an auger feed mechanism that force them to drip easily into hollowed 38.10 mm rotary tool onto a 6.35 mm thickness AA5083-H131 base with succeeding layers. The frictional force, and the fluid pressure through the tool, cause complete plastic deformation in the material, due to shear and dynamical recrystallization (DRX). DRX in turn is carried outdue to the matrix orientations across grain boundaries, which are stimulated bythe nucleated crystals. Layersare built up to 2.5 millimeters high, with dense submicron equiaxed grain structure, with completely robust and tight bonding between the chip and the base. The advantage is that the supply chain benefits from fewer logistic links by using in-house machine chips, while the disadvantage is that a lack of available energy in distant areas hinders the thermal decomposition of metallic flakes into granular feed supplies.

5.1.2 Mechanical Properties and Microstructure-

Optical inspection of the material cross-section indicated radial migration of minerals from its central core to its periphery. Electron backscatter diffraction revealed a finer crystalline structure, which has a general grain size of 1.50 µm. Results from a tensile test revealed a lower yield strength of 170.40 MPa. While, UTS was determined to be 368.0 Mpa, affected by strain hardening, in accordance with the Hale-Petch relationship. Average Vickers hardness was 57.7 Hv. The beam-based AM method of Al resulted in prominent oxide deposits and brittle behavior, whereas the stress-strain relation demonstrated ductility [81].

5.2 Sustainable Additive manufacturing by depositing recycled metal chips to get Ti-6Al-4V alloy [77]

5.2.1 Process-

Using AFSD, the authors compressed recycled Ti64 chips into granular feed and pumped them into the hub of the machine. Here it got plasticized due to the high temperatures generated by the frictional stir heating. The size of thecoating was 30 x 135 x 25 mm and the tool material was WC. Such feed rods had a diameter of 9.52 mm, a thickness of 9.52 mm, and a length of 152.4 mm. The test pieces were rotated at 3 different speeds (in RPM), moved at a certain speed (in inches per minute), and feed was given (F in inches per minute). It was determined that the coating height for all 3 deposits was 1.016 mm. The TSL OIM 8 software was used for the analysis of the EBSD data. Wilson's VH3300 Micro hardness test apparatus was used to exert force of 0.5 HV to the specimens to measure their hardness. Energy dispersive spectroscopy (EDS) with Scanning electron microscopy detection using an FEI Quanta 200 instrument was utilized to determine the constitution of the treated sample (Agarwal 2021).

5.2.2 Mechanical Properties and Microstructure-

The characteristics of Ti64 are highly dependent on both the initial particle sizes as well as the lamellar diameter. The manufactured layers contain tiny, equiaxed preceding granules with fragile thin layers. The formed samples had a total plastic extension of 71%, a yield strength of 1050 MPa, and an ultimate tensile strength of 1140 MPa. The majority of grain is refined using DRX. It is shown that the tool transverse speed (V), and tool rotation rate (ω), have a considerable influence on the resulting structure. The increased heating rate during AFSD occurs due to the higher levels of ω^2 /V. Ti64 may be deposited under three various circumstances, each of which can alter the crystalline structure of the thermal conductivity of the high-strength alloy, and thus its tool endurance. Due to its superior tensile properties compared to other 3D printing methods, as well as its ability to provide a homogeneous setup to the required crystal structure, AFSD of recycled items allows the making of great composite structures with lowered power consumption and lowered wastage [77].

6. Microstructure and Mechanical properties

This is recognized that the maximum temperature in FSD for constructed Al Mg Si alloy can be over 450 °C, while the top thermistor only records a transitory maximum temperature of around 135 °C [98]. Anisotropy in strength and plastic flow behaviour are both possible in the process used to make rolled sheet metal [99], although stiffness in the plane variations isoften negligible [100]. Al alloy [101], Inconel [102,103], and Mg alloys have demonstrated that AFSD is characterised by a considerable flow of material and rotation, resulting in virtually isotropic in-plane mechanical features. During cooling, the temperature differential between the build stack and the base leads to global deformations. Cladding Geometry can give impressive residual stress at surface and provide benefits like greater element tiredness [104] as well as fracture resistance. No significant damage or local buckling to the base material is caused by loads. Micro structural development in AA6061 was investigated in response to process variable [105].

The granular structure of the deposited films and the interface of the WE43 magnesium cladded alloy, made by FSAM technology, was analysed by electronic back scattering diffraction (EBSD) assessment map [106,107]. This mechanism method facilitates complete DRX, resulting in the development of a refined crystalline structure having excellent fatigue behaviour. This was evidenced by a comparison of the microstructuresof the FSD produced Inconel 625 superalloy to the commercial plate by Rivera et. al [108,109]. In a related manner, Ti-6Al-4V titanium alloy produces similar results after solid-state deposition and develops a completely dense structure with minimal residual stress and significant strength. It is clear that the extreme shear deformation generated by the spinning tool, greatly reduces the size of the martensitic laths. According to the latest studies, this allows for the deposition of a Ti-6Al-4V dense material with an equiaxed crystalline structure, resulting in a significant improvement in mechanical characteristics [110-112]. S316 L stainless steel undergoes similar enhancements, including structural equation modeling and increased hardness. Interestingly, the ductility of the processed alloy remains unaltered, although the ultimate tensile strength (UTS) and yield stress (YS) are both 25% higher. In another study, UTS is lowered and the elongation is increased by a factor of two, as compared to the stretched and tempered down WE43 magnesium alloy [113,114].

Under 1600 rpm of rotation and 300 mm/min of translation, the FSAM 2060-T3 Al Li alloy had a sound single track. The excessive material flow, and high rotational and translational speeds caused microporous flaws. The optimum slicing rate of 80% integrates the overlapping track. A low slicing rate caused uneven microstructure, and excessive plastic deformation caused flaws [115]. Other additive manufacturing processes have 20–50 HV of microhardness. FSAM eliminated metallurgical flaws by skipping the melting and solidification of the material. FSAM considerably decreased size distribution and texture strength in the single-track and overlap-track stirred zones. Plastic deformation improved dislocation density [78].

FSAM is also capable to form Cu-St bimetallic sheets. The junction has no pores or fractures, indicating a superior quality and reliable FSAM process. The interface's cyclic wave-like structure boosts Cu-St sheet shear strength. Deformation, grain refining, and solid solution enhancement have been found. Test procedure show 435 MPa tensile and 345 MPa shear strengths. These qualities outperform conventional approaches [116]. FSAM allowed scale-up manufacturing of full-dense Ultra fine-grain pure Cu. A relatively homogenous recrystallized microstructure gave bulk Ultra fine-grain pure Cu with outstanding mechanical characteristics. The FSAM approach can be used for many metal and alloy systems, getting massive bulk material fabrication more practical [79]. FSAM can correct the Keyhole on aluminium alloy 7N01. This flaw degrades material mechanical characteristics. Pin-less rotating tools and fillers were offered to tackle the Keyhole issue. The corrected Keyhole was metallographically analysed and mechanically tested. The precise tool design, filler material, and Keyhole repair settings made the technique effective. TRS enhances material characteristics. TRS was 1600 RPM and the steady plunge speed was 2 mm/min. At 1600 RPM, the restored joint's elongation and tensile strength were 7.6 % and 311.5 MPa, respectively, and 96% of a fault-free joint was made[117].

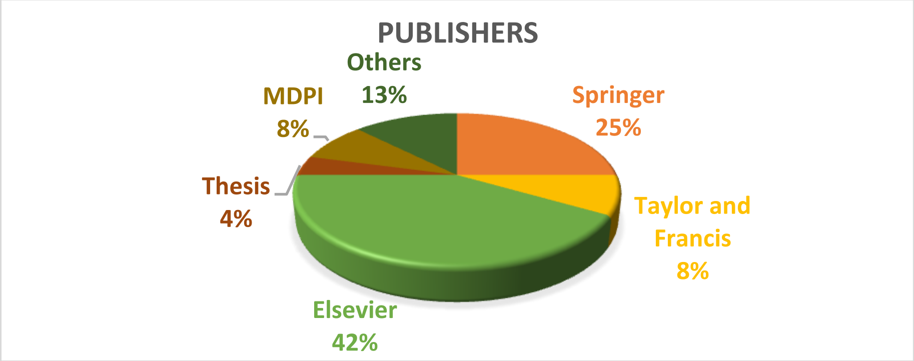

Fig.6 Contribution of various publishers in FSAM

7. Future Trends

For a process to exist, it needs to fulfill basic requirements, but if a process starts to evolve, it reflects the potential of the process. FSW has been prominently present for ages, but owing to its solid state mechanism, it has evolved for cladding, brazing, repairing, alloying, MMCs, and as an AM technique. Various authors have effectively devised and tested the FSAM process; however, it is still in its nascent stages, and much work remains to surmount its limitations. Its cost effectiveness, environmental sustenance, process efficiency, material flexibility, wide applicability, and wrought properties, make it a reliable and industry-ready process. The aforementioned features of the FSAM method make it a better fit for potential industrial projects. Due to the process's adaptability, it can be utilised in a variety of manufacturing areas.By the technique, medical devices and their essential elements were produced in the recent scenario. Based on FSAM's current performance, it is also anticipated that it will leave its mark in all areas of healthcare.Multiple sensors may be employed as well to monitor the process and measure the in-situ rate of cooling. According to the acquired feedback report, process parameters can be modified to reduce the defects, resulting in a substantial enhancement in the robustness, performance, and quality of parts produced using this method.The build capability would also be a focus of future research. Innovative composites or ceramics ought to be employed for the manufacturing of components with excellent strength and an elevated melting point. This is a crucial consideration when utilising AFSD as a composite manufacturing method, as the rigid reinforcement particulates can cause unnecessary tool material deterioration.

8. Discussion and Conclusion

The pie chart in Fig. 6 shows the contribution of various publishers in FSAM. The pie chart in Fig. 7 shows substrate material flexibility in FSAM, sunburst chart in Fig. 8 displays the feed material flexibility in the case of two different tools, one when the tool resembles an FSP tool with a pin, another is the hollow tool having a solid rod or powder feed for deposition. Fig. 9 displays the process capability of FSAM via a pie chart. It is seen that FSAM is highly capable of fabricating sheet metal laminates, pure bulk metals like Al, and Cu with the desired reinforcements, various Composites like nano-material composites, Ti-Al-V composites, Al–WC composites, Al-Zn-Cu composites, biocompatible biocomposites, cladding and repairing of the substrate.

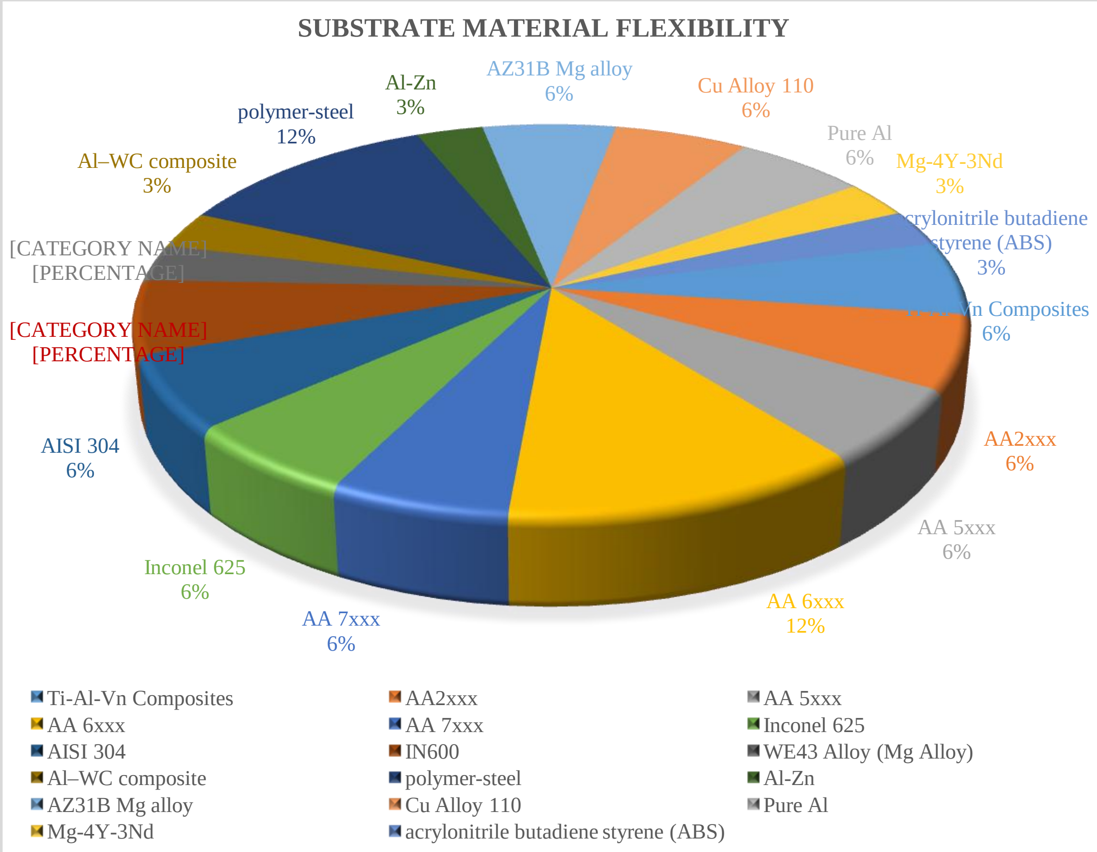

Fig. 7 Substrate Flexibility

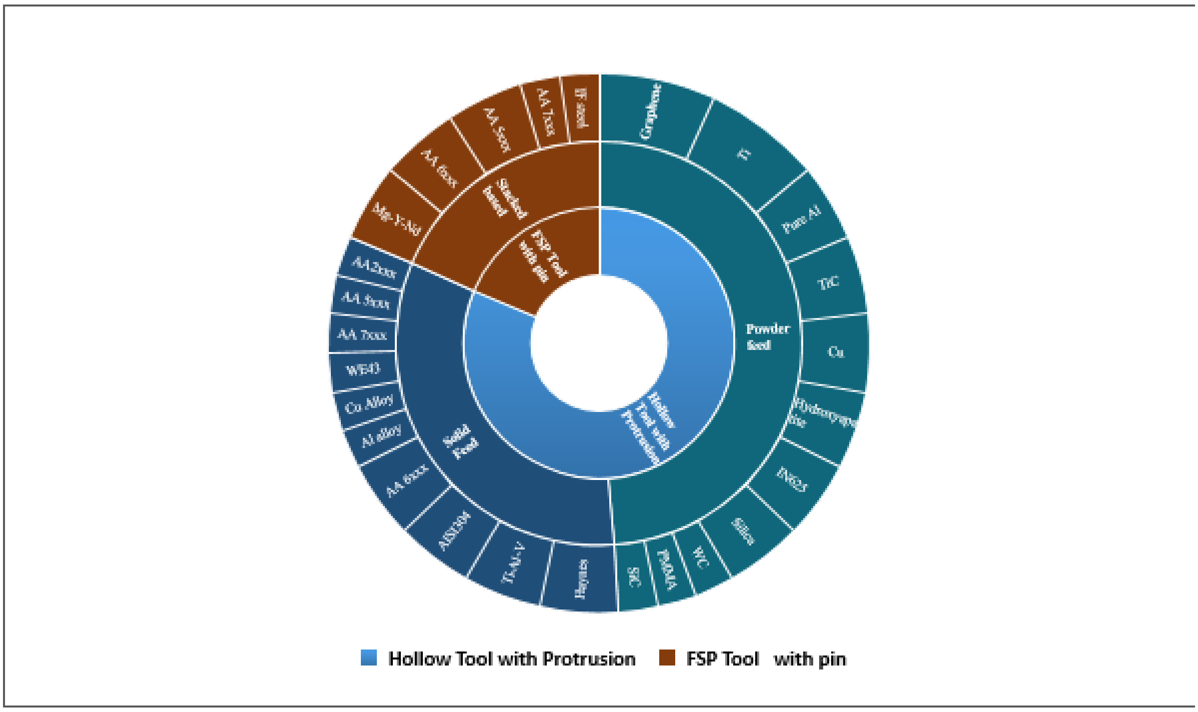

Fig.8 Feed Material Flexibility

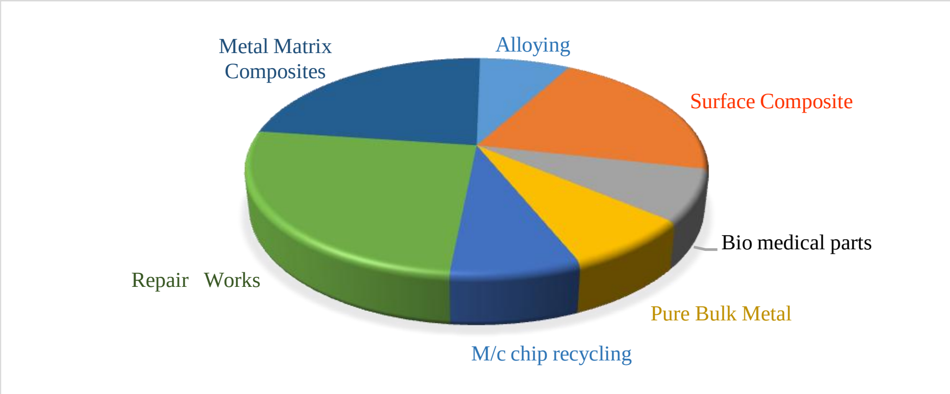

Fig.9 Process Capability of FSAM

In an austere environment, the feed can be given in form of recycled metal chips directly via hollow tool in the stir zone, without much effect on the characteristics of the built metal. FSAM is capable of fabricating the components with negligible hot cracking dilution, particle segregation, internal cavities, porosity, inclusions, etc. owing to its solid-state nature and the computer aided process planning implementation. Some properties of FSAM that make it environment friendly and effective are- negligible emissions, inconsumable tools, no shielding environment needed, large repeatability, and high acceptability for large products and especially for Magnesium, Aluminium, Nickel, Titanium, Copper based alloys.

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