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Assessment of Friction Stir Welding on Aluminium 3D Printing Materials

S.S.S. Abu Bakar, S. Sharif, Mohd Faridh

***Abstract:** This review paper will discuss about the joining process of Aluminium 3D printing materials by using friction stir welding process. Currently, the studies on the joining of 3D printing materials by friction stir welding are very limited. Through this review, the joining materials characteristics such as weld efficiency, hardness and microstructure after friction stir welding process will be discussed to identify the behavior of weld joint materials. Understanding the friction stir welding process on 3D printing materials is importance in order to support the future advancement of 3D printing technology in terms of 3D printing part repairing activity and the secondary process such as the joining of 3D printing parts. In this paper, the fundamental concept of friction stir welding and powder bed fusion 3D printing is discussed. At the end of the review, the summary of friction stir welding process on Aluminium 3D printing materials concluded that the joining process is feasible to weld the materials with joint efficiency 83.3% and modify the base material characteristic of the 3D printing materials.*

***Keyword:** FSW, EBM, SLM, DMLS, 3D Printing.*

I. INTRODUCTION

3D printing metal is one of the Additive Manufacturing (AM) process which has been used in many industries such as automotive [1]–[3], aerospace [4]–[6] and biomedical [7]–[9]. In automotive industries, the demand to reduce the carbon emission and at the same time improve the performance and safety of the car inevitable. **Figure 1** clearly shows the usage of the 3D printing parts in production in U.S and it is predicted to increase from below 5,000 to 100,000 between years 2015 until 2035. Currently, 3D printing technology is used primarily for rapid prototyping of prototype parts. Apparently, the application of the technology would increase if the cycle time and equipment cost could be reduced [1].

In aerospace industries, General Electric (GE) has moving forward by investing in 3D printing technology by open new facilities in Chakan, India to focus on flexibility in part design and production technique. The new fuel nozzle in a GE jet engine has used 3D printing technology for their next generation of LEAP engine. The result from the application of this new technology, the company can reduce the number of the production process, the part become 25% lighter and five times stronger compare to previous manufacturing process. This project ended up saving about $3 million per aircraft, per year [4].

AM process are considered as the most promising technique to fabricate biomaterial such as Ti-6Al-4V alloy for medical applications. The process have also resolve several problem in the manufacturing of porous and unitised components, for instance improving the compatibility of implants and human tissue. The prime advantage of AM is the capability to customized fabricate biomaterial alloy implants to meet individual patient requirement, and manufacture net-shape metallic biomaterials [9].

Nowadays, the demand of 3D printing keep on increasing in order to fulfill the demands in producing parts with complex geometry at a lower development cost. The increasing demands 3D printing parts in industry would eventually lead to the 3D printed parts repairing activity and secondary process such as joining, foaming and cutting. This secondary process need to be developed in order to support the growth of the 3D printing application in the future.

II. FRICTION STIR WELDING

FSW process is known to be a robust process and technique in welding technology for decade. This advancement has given the opportunities to the industries to produce superior welds, improved reliability and increased productivity in joining process technology [10]. FSW has been patent in United State in 24 October 1995 with patent number 5460317. This process initially invented by WM Thomas and his team from The Welding Institute (TWI), Cambridge, United Kingdom [11]. In FSW process, the probe which is harder than the workpiece is used to weld the workpiece together. The probe is allowed to rotate at certain speed and force into the workpiece joint whereby frictional heat is generated as the probe enters the workpiece. The heated workpiece material around the probe becomes plasticized and removing the probe allows the plasticized region to solidify and joining the workpiece together [11].

In order to produce a sound and defect-free weld using FSW, the probe geometry design is an important factor besides the FSW process parameters. These parameter setups include rotation of the probe (in rev/min), travers speed, spindle tilt angle, and target depth as shown in **Figure 2** [12]. FSW process parameters are significant factors which affect the heat generation, material deformation, process effectiveness, welding penetration, product quality as well as productivity [13].

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***** Correspondence Author

Shaik Syahman B. Shaik Abu Bakar*, Faculty of Mechanical Engineering, Universiti Teknologi Malaysia, Johor Darul Takzim, Malaysia. Email: shaiksyahman@gmail.com

Prof. Dr. Safian B. Sharif, Faculty of Mechanical Engineering, Universiti Teknologi Malaysia, Johor Darul Takzim, Malaysia. Email: safian@utm.my

Dr. Mohd Faridh B. Ahmad Zaharuddin, Faculty of Mechanical Engineering, Universiti Teknologi Malaysia, Johor Darul Takzim, Malaysia. Email: faridh@utm.my

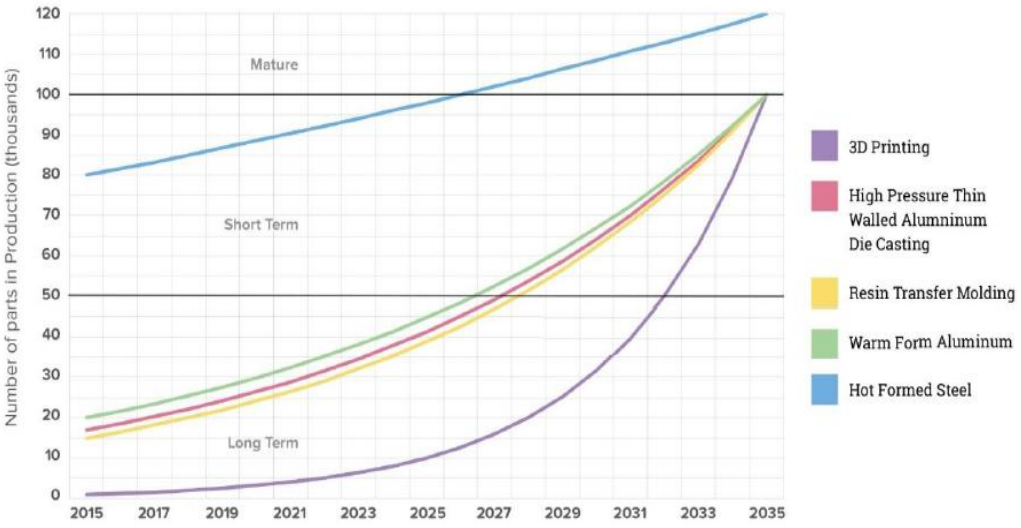

Figure 1. Automotive Emerging Manufacturing Processes and Enablers for Growth, 2015 to 2035 in United State [1].

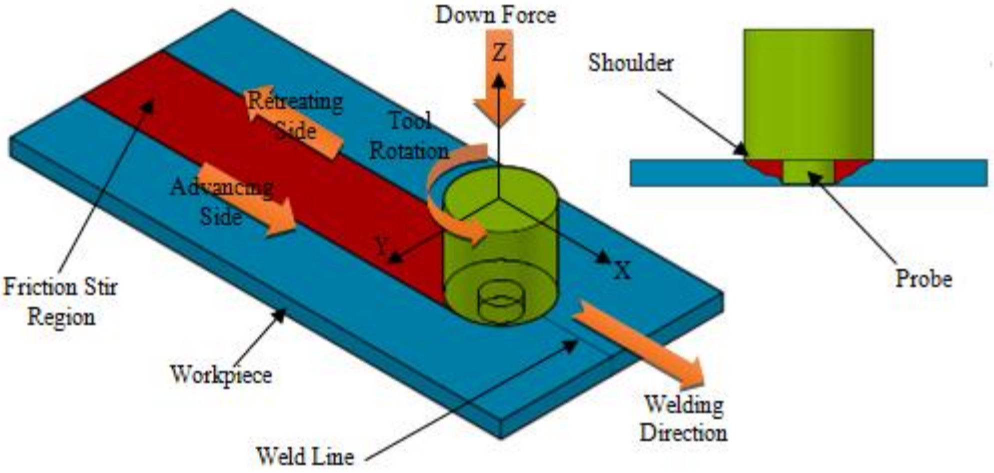

Figure 2: Schematic drawing of friction stir welding

In FSW process, tool or probe rotates and slowly plunged into the workpiece at joining line, until the tool shoulder firmly in contact with the workpiece surface under applied load. The frictional heat is generated from the friction area between the tool shoulder, probe and workpiece. The heat generated at the tool shoulder is higher compared to the heat generated at the probe surface. Once the workpiece material plactized or semi melted, the material experienced severe plastic deformation due to the localised heat generated. At the same instance, the plasticized material flow from the leading face of the probe to the trailing face, where it is forged into the joint [14]. Material flow behaviour during FSW process is a very complex phenomena and very much poorly understood at this moment. The flow characteristic of FSW process has been suggested as an in-situ extrusion process by some researchers [15]. The occurrence of stirring and mixing of weld material only happen at the surface layer of the weld; adjacent to the rotating shoulder of the probe [12].

III. METAL 3D PRINTING TECHNOLOGY

Metal 3D printing technology is one of additive manufacturing (AM) processes that can be categorised under the powder bed fusion 3D printing family. Generally, there are three types of metal 3D printing technology namely; Electron Beam Melting (EBM), Selective Laser Melting (SLM) and Direct Metal Laser Sintering (DMLS) [16].

In EBM process, the parts was produced by melting and solidifying the metal powder on layer-by-layer basis; just like the other version of powder bed fusion technologies. The thermal energy used to melt the powder is converted from the kinetic energy to thermal energy when the high-speed electron strikes the metal powder. Due to that, the metal powder temperature would rise to above the melting point and rapidly liquefy the metal powder. EBM process runs under vacuum environment in order to prevent energy loss and to support the processing of reactive metal alloys such as titanium [17].

Another method of 3D Metal printing technology is SLM technology that was invented by Fraunhofer ILT in mid 1990s. In this technology, the metal powder is heated up using laser beam until it is fully melted. The molten metal powder would fuse together with the layer below. During the process, inert gas such as argon or nitrogen is used to prevent the melt pool oxidation and assist in removing metal vapour. The process which is illustrated in Figure 3, involves a very complex parameter in order to produces full dense, metallurgical sound parts with minimal internal stress. Among the important parameters involved are laser power, scan speed, hatch spacing, powder particle size morphology, distribution, layer thickness, and scan strategy [18].

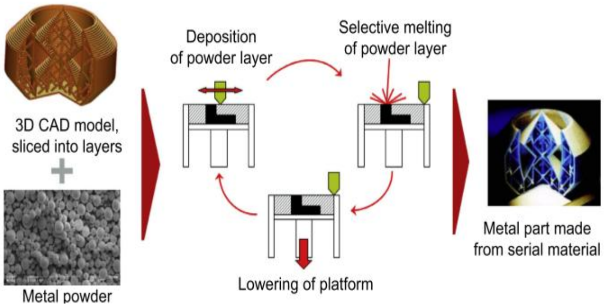

Figure 3: Schematics of the SLM process [18].

One of the most effective 3D metal printing technologies is DMLS, where the related patent for the field of laser-sintering was acquired by EOS in 1997 from 3D Systems [19]. In general, the processes between DMLS and SLM are quite similar in which the parts are developed layer-by-layer by using the laser beam as an energy source to heat the metal powder [16]. However, unlike SLM process, DMLS does not melt the metal powder completely in order to fuse the metal powder particle together. Instead, the metal powder is sintered by laser to fuse it [20]. Since the sintering process occurred at a lower temperature as to compare to fully melting the metal powder, the laser power usage for DMLS is lesser than the SLM process.

IV. FRICTION STIR WELDING OF METAL 3D PRINTING

Zhenglin and team from Singapore has conducted a research of FSW on SLM material in 2018 [21], [22]. The research used a blended metal powder of aluminium powder AlSi10Mg and 2% of nano-sized alumina (nAl2O3). The FSW process was run by using robotic FSW to perform the welding with butt join configuration on 10 mm thickness material. The geometry of FSW tool was 15 mm diameter with conical pin diameter 6.5 mm and 7 mm respectively. The FSW parameter used in this study is tabulated in Table 1.

In this study, the SLM part had been successfully joined by FSW and their weldability, mechanical behaviour and microstructure evolution were investigated. The welded SLM part result was comparable to FSW of wrought AA6061 sheets and FSW fragmented and homogeneously dispersed in weld region. Result from the tensile test for SLM part shows the highest weld efficiency is 83.3% and the lowest is 67% as shown in

Tabale From the FSW experiment result on mechanical and microstructural behaviour for AA2219-O and AA7475-T761 alloy, the researcher found weld efficiency for both materials is 97% and 70% respectively [23]. Meanwhile, the experiment from others researcher for AA6082-T6 and AZ91 Mg alloy result show the weld efficiency is 72% and 75% respectively as shown in

[24].

Table 1: Parameter used in Zhenglin study

Process parameter	Rotation speed, RS (rpm)	Traverse speed, TS (mm/s)	Tilt angle, TA (O)	Downward force (kN)
FSW with high heat input	1200	1	4.5	3.5 – 4.5
FSW with low heat input	600	1	4.5	3.5 – 4.5

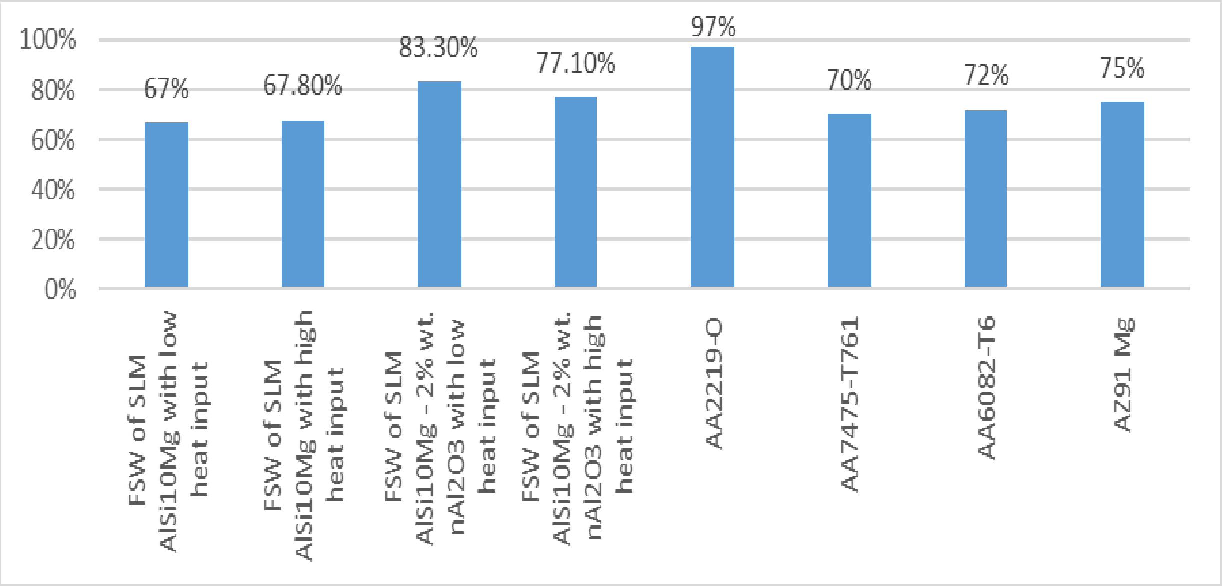

Figure 4: Comparison of weld efficiency for 3D printing materials, aluminium and magnesium alloy.

From Zhenglin observation, the size of the grain increased with the use of high tool rotational speed. However, the fine grains were observed in the nugget zone due to the dynamic recrystallization process. A higher amount of Si was found in the advancing side of the welds due to higher temperature generated in the area where more Si particles were precipitated out. The FSW produced porosity-free macrostructure in welding area compared to SLM part received with 9% porosity and the hardness and tensile strength of weld was reduced due to the precipitation of Si. Besides a higher ration of rotational speed to transverse speed would also lead to larger grain size and lesser hardness.

Table 2: Weld Efficiency of SLM joining by using FSW process [22]

Material and Process	Weld Efficiency (%)
FSW of SLM AlSi10Mg with low heat input	67
FSW of SLM AlSi10Mg with high heat input	67.8
FSW of SLM AlSi10Mg - 2% wt. nAl2O3 with low heat input	83.3
FSW of SLM AlSi10Mg - 2% wt. nAl2O3 with high heat input	77.1

Researchers from Italy, Scherillo, Hassanin and team has reported and conducted an experiment to study microstructure of FSW of Aluminium fabricate by DMLS with same experimental setup [25], [26]. In this research, a 3 mm thickness specimen was fabricated using AlSi10Mg metal powder (**Figure 5**). The FSW parameter used for rotational speed and transverse speed was 800 rpm and 200 mm/min. Compared to Zhenglin's study, the rotational speed used was between the ranges of high and low heat input in Zhenglin's study. However, the transvers speed in this study much higher than the one in Zhenglin's study. The result from the study shows that, AlSi10Mg DMLS parts had been successfully joint with free macroscopic defects and fine grain homogeneous macrostructure observed within the nugget zone. The macro-hardness from Scherillo report in this study also shows that the hardness at nugget zone is higher than the base material hardness (Table 3). This finding contradicts to the result from Zhenglin's study. In which the hardness value within nugget zone is lower than the base material hardness (**Figure 6**). However, there is no result regarding the micro-hardness from Hassanin's report.

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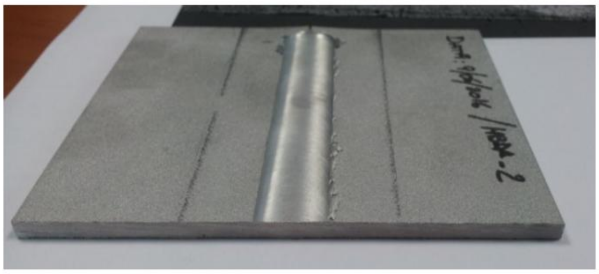

Figure 5: DMLS Aluminium Specimen after joining with FSW method [25].

Table 3: Vickers Hardness of the different zone of the joint of AlSi10Mg DMLS part [26].

Zone	Vickers Hardness (HV)
Base Material (BM)	93 ± 3
Thermal Mechanical Affected Zone (TMAZ)	98 ± 1
Nugget Zone	101 ± 2

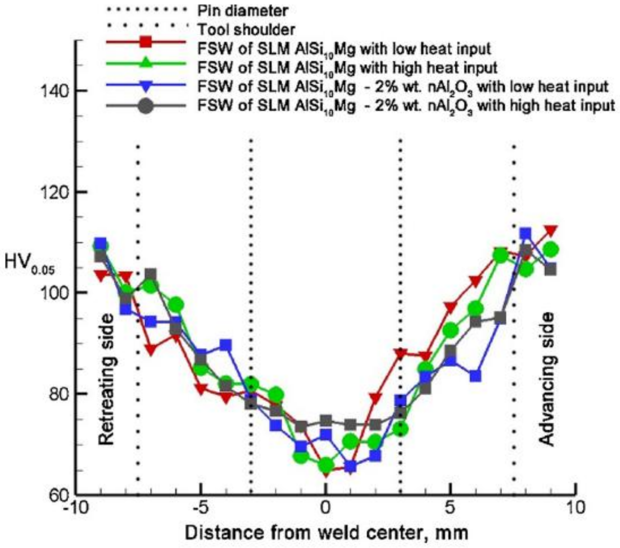

Figure 6: Hardness profile of SLM joining by FSW [22].

The differences of the hardness trend at nugget zone between Zhenglin and Scherillo study also happen for the other grades of wrought aluminium materials. A Finding from an India researcher for AA2219-0 and AA7475-T761 similar and dissimilar join, show that the hardness value at the nugget zone was higher compare to the base material [23].

As compare to a finding from Portugal researcher for AA5083-H111 and AA6082-T6 joining, the hardness trend shows no significant changes for soft tamper material, but the hardness is reduced at nugget zone for base material with higher hardness value due to dissolution of the hardening precipitates [27].

From Table 4, the trend of hardness at nugget show all the SLM material hardness at nugget zone was reduce while for DMLS material was increase. The difference in trend of hardness in nugget zone also can be observe in FSW for wrought aluminium alloy. Although the hardness trend at FSW nugget zone was different from those reported by various researchers, the similar finding from the report shows that the grain size modification had occurred at the FSW weld zone.

Table 4: Comparison of FSW hardness at nugget zone from various study.

Materials	Base Material Hardnes, Hv	Hardnes at weld zone, Hv	Trend	Referance
SLM AlSi10Mg with low heat input	139	68	Reduce	[22]
SLM AlSi10Mg with high heat input	139	67	Reduce	[22]
SLM AlSi10Mg - 2% wt. nAl2O3 with low heat input	124	75	Reduce	[22]
SLM AlSi10Mg - 2% wt. nAl2O3 with high heat input	124	74	Reduce	[22]
DMLS AlSi10Mg	93	101	Increase	[26]
AA 2219-O	85	105	Increase	[23]
AA 7475-T761	145	162	Increase	[23]
AA 5083-H111	80	80	Same	[27]
AA 6082-T6	115	75	Reduce	[27]

The macrograph in Figure 76 shown the cross-section of DMLS parts welded using FSW process. From the figure, it can be seen that parent material (PM), thermal mechanical affected zone (TMAZ), onion ring (OR) and nugget zone are distinguishable. However, heat affected zone (HAZ) is not labelled in the figure like the normal practice by other researchers such as in Figure 87 [28]. From both figures, it can be clearly seen that the weld zone for DMLS specimen and 5A06 aluminium alloy are similar.

The weld join also shows intrinsic asymmetry macrostructure shape with onion ring shape at AS for both figures.

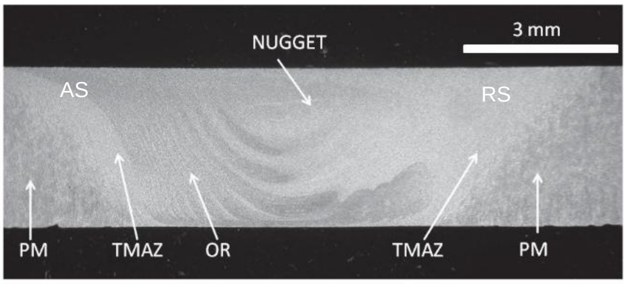

Figure 7: Macrograph of the DMLS parts joint by FSW with highlighted the different zones [26].

Figure 8: Macrograph of 5A06 aluminium alloy joint by FSW with highlighted the different zone [28]

V. CONCLUSION

From the research, FSW is proven able to be used as one of the methods to join the metal 3D printing materials. By using proper FSW tools and correct parameter setting a sound and defect-free weld can be produce in order to joint the metal 3D printing materials. Besides, the FSW tools must be harder than the materials that need to weld. The most important parameters in FSW are the rotation of probe, travers speed, spindle tilt angle and target depth.

Although EBM, SLM and DMLS have been categorized under powder bed fusion, only SLM and DMLS had been reviewed for joining by FSW. This is due to lack of information on EBM joining process by FSW. The weld joint efficiency of FSW on the 3D printing metal can reach up to 83.3% compared to its base materials strength. Meanwhile, the micro-hardness trends cannot be concluded due to the inconsistent result. However, most of the researcher found that FSW process modified the microstructure of the materials by refining the grain structure. The macrograph of FSW 3D printed metal and other aluminium alloys show similar welding zone shape with AS of the weld zone different from the RS.

At this moment, the published research paper for FSW on 3D printing materials are very limited. Due to this matter, the information related to FSW on metal 3D printing material is difficult to be compared and studied. It is hoped that, this present summary could help other FSW researchers to better understand the joining process of metal 3D printing materials using the FSW process.

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AUTHORS PROFILE

Shaik Syahman B. Shaik Abu Bakar M.Sc (2014) in Petroleum Engineering from Universiti Teknologi Malaysia and B.Hons(2002) Universiti Sains Malaysia, working on friction stir welding. Member of Board of Engineer Malaysia and Malaysia Board of Technologies.

Prof. Dr. Safian B, Sharif Prof(2008): Universiti Teknologi Malaysia, PhD (2000): Coventry University, UK: M.Sc.(1991), UMIST, Machester, UK, B.Eng(1986), UTM. Associate Technical Editor, An International Journal of Machining Science and Technology (MST), Tylor & Francis, WOS, Quartile Q3. Malaysia Quality Assurance (MQA) Committee Member for Document Review for Programme Accreditation Compliance Audit.

Dr. Mohd Faridh B Ahmad Zaharuddin PhD(2016), Hanyang University, Seoul Korea. Lecturer in Universiti Teknologi Malaysia, Faculty of Mechanical Engineering.