A Review on metal 3D printing; 3D welding

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Abstract. 3D printing is a well-known method to produce a 3D object and widely used in many types of industries including, mechanical, civil, medical, etc. The technology has been applied in industry for more than 20 years ago, but it is strictly limited to the slow production of small plastic objects, and some special fabric only. As its advancements, the technology of 3D printing becomes broad interest recently. In present industrial, 3D printers are able to produce high precision, quality products of different sizes fast at comparatively low cost. The aim of this paper is to highlight the importance of 3D printing in meeting low and medium production volumes besides having a review on metal 3D printing techniques available. The issue and challenges in producing metal 3D printing also will be discussed extensively in this paper. Suggestions on the subtractive method to complete the 3D printing process according to research interest also explained in this paper.

1. Introduction
3D printing is additive manufacturing (AM) formerly known as a method of reshaping product development in industries. This 3D printing is resulting in the rapid growth in showing the usefulness in design, small-batch production, and potentially distributed manufacturing [1-6]. In general, an AM is a technology that enables the fabrication of 3D parts from 3D data by depositing a thin layer of material layer-by-layer until a semi-finish part is produced. A few decades ago, 3D printing is commonly applied for rapid prototyping only but lately, it is used for actual manufacturing. Frazier [7] and Das et al [8] also addressed that AM has been around over two decades, but it has only recently begun to appear as a significant marketable manufacturing technology. According to Wong and Hernandez [9], the early version of 3D printing is to produce a fast prototype by speeding up the process in model development and shortening lead time between product development and market placement. The requirement to capture the market placement is significant to facilitate the product for not being outdated. In a fraction of time, the company able to produce prototype parts faster compared to conventional manufacturing methods, such as molding, forging, and milling [10]. Few researchers believed that the product produce by AM is unique as well it can be produced in a short time which is surely able to mass customization [11]. This is also considered as the growth of 3D printing where the changes in the uses of 3D printing in presenting the trend of new business model. In the meantime, 3D printing acknowledged as one of the fastest-growing fields in AM.

As a small and medium-sized production company, there are certainly a number of factors to consider in production costs. The total cost of production must include the cost of labor, the process, and the manufacture of a product which is of utmost importance. The importance of 3D printing in this kind of industry is to help in reducing waste. Since AM have a great technology to reduce energy and
material cost, it could be an indicator for the industry in innovative development. The production steps are reduced when the assembly requirement is eliminated. Hence, by having a 3DD printing, practically small and medium companies can reduce production waste [3] as well as the number of workers. The AM process also able to shorter time to market the product with the benefit of lowering down the overall production cost [12]. AM necessarily correspond to the practices in small and medium companies. Few researchers carry out the studies on the importance of 3D printing in various fields such as in design, engineering, analysis and planning, pre-production parts, manufacturing and tooling, aerospace [13], automotive and biomedical [14]. For instance, a brief explanation of the importance and uses of 3D printing in mechanical engineering is done by Madhav et al. [15]. The growing trend in demand for metal-based parts for low and medium production is evident as various companies from the medical and aerospace industries continue to demand the advancement of this technology in meeting their needs [16]. It is vital for a company to comply with the demand to meet the customer’s expectations. Further explanation of metal 3D printing or known as 3D welding, and its challenge, and issues will be discussed in sections 2 and 3 respectively. Suggestions on the subtractive process are discussed in section 4

2. 3D welding
Welding is a process of linking parts by melting the work piece and adding filler material. It is also being defined as a consistent joining technique to assemble metal parts with the heat application [17-18]. 3D welding is described as a constructing up metal beads layered by layer to produce a 3D metal object [20]. The differences between common welding and 3D welding are illustrated in Figures 1 and 2. The cost and productivity are increased to produce, metal volume objects by using the welding method [21]. Not only to produce a new 3D object, but research by Ren et al. [22] has also been done about the 3D repairing technology where surface patching has greatly improved the accuracy, efficiency, and reliability of part repairing. The repair shows it would save more cost than producing a new part to replace the broken part.

![Figure 1. Example of common welding (joint) types: square butt, lap, and T-joint. [19]](image1)

![Figure 2. Example of 3D printing: (a) 3D computer graphic image of a cup object and (b) formed object by 3D Micro Welding. [20]](image2)

Additive welding technology is one of the processes to manufacture 3D parts for metal. The chronology (Figure 3) of development 3D welding for the fabrication of 3D structure has been discussed by Colegrove and Williams [23]. The most common technique for 3D printing consists of Powder Bed Fusion (PBF), Material Extrusion, Sheet Lamination, Directed Energy Deposition (DED), Material Jetting, and Binder Jetting. Material extrusion and Binder jetting methods used to be applied to plastics and ceramics only in the past 20 years, but now being used in metal 3D printing as well due to advancement in additive manufacturing technique. The material used for the metal 3D printing
technique is most likely powder-based and wire-based [24]. A recent article written by Lewandowski and Seifi published about the mechanical properties of materials processed by various AM techniques, including powder bed fusion and directed energy deposition technologies [25].

Three universities named University of Nottingham, Wollongong University and Southern Methodist University in Dallas has conducted research work related to 3D arc welding [26]. According to Korzhik et al. [27], the development of plasma arc melting and welding technologies, as well as the other welding technologies of 3D printing of metal products is being researched by advanced research institutes and industrial corporations of economically developed countries at present. Metal 3D printing can be roughly categorizing into two main groups; Powder Bed Fusion (PBF) and Directed Energy Deposition (DED) based on technologies used. Table 1 shows the list of technology for both groups. Article from Bhavar et al. in 2014 [28] has discussed about this two type of technologies based on their energy source used. However, there are other techniques that have been recently developed, such as binder jetting [14] [29], cold spraying [30], friction stir welding [31], direct metal writing [32] and diode-based processes [33]. Besides Bhavar et al., Some other researchers [34-35] in their review about metal AM also highlight some of the differences between the various processes. A summary of the several AM technologies and the dictate AM equipment manufacturers is presented by Hederick in his review [36].

Table 1. List of Powder Based Fusion and Direct Energy Deposition technologies [28]

| Powder Based Fusion (PBF)               | Direct Energy Diffusion (DED)                      |
|----------------------------------------|---------------------------------------------------|
| Selective Laser Sintering (SLS)        | Laser Engineered Net Shaping (LENS)               |
| Selective Laser Melting (SLM)          | Direct Metal Deposition (DMD)                     |
| Direct Metal Laser Sintering (DMLS)    | Electron Beam Free Form Fabrication (EBFF)       |
| Electron Beam Melting (EBM)            | Arc Based Additive Manufacturing                   |

PBF is the leading technology in the industry which shows it is relevant to metal objects [37]. PBF technologies able to manufacture products with good mechanical properties and complex shapes with high accuracy (±0.02 mm) [38]. According to Berger, DMLS is the most preferred PBF technology for welding 3D printing with short manufacturing time, cost-effective assembly, and wide variety of metal parts. DMLS is a laser-based rapid prototyping and tooling process by means of which net shape parts
are fabricated in a single process. SLM, SLS, and DMLS are always being described as similar process however, the nature of the powder is the main difference. Research on the 3D welding machine is not new and various successful stories were reported from all over the world and had been reviewed by Korzhik et al. [27]. In terms of welding technique, there are various techniques employed e.g. arc-weld [39], laser [40], MIG [41], TIG [42-43], plasma-arc [44] and electron beam [45]. Table 2 shows the list of techniques for 3D welding focusing on metal that has been discussed by Wang et al [46].

Wire-Arc Additive Manufacturing (WAAM) is an arc-based technology considered by high productivity, high energy efficiency, and low raw material cost [47-48]. WAAM shows the high saving in the uses of material where buy to fly ratio compared to traditional welding method is 4.9 including the finishing machining [49]. In producing welded joint and metal layers a few technologies for welding methods such as MX3D, GMAW, GTAW being discussed by Peleshenko et al. [50] as a new level of 3D printing. However, among all additive welding technologies, plasma arc welding is the most promising with the high accuracy of manufacturing and the quality of the surface compared to other arc welding method [50].

Table 2. List of welding technology for metal 3D printing with the advantages [46]

| Technology   | Advantages                                      | Material                        |
|--------------|-------------------------------------------------|---------------------------------|
| TIG          | High quality                                    | Low-alloy structural steel      |
| High frequency TIG | High precision and quality                  | High-strength steel             |
| Pulse MIG    | Simplicity and economic efficiency             | Stainless steel                 |
| Cold Metal Transfer (CMT) | Low heat input, High Stability of the process | Nickel heat-resistant alloys    |
| Tandem Pulsed MIG | High building-up speed                            | Aluminum alloys                 |
| Plasma PTA   | High quality, High speed, Possibility to adjust the width of the build-up layer | Titan, titanium alloys          |
|              |                                                 | Copper and copper alloy         |

3. Issues and challenges on 3D welding

Significant research and further understanding are required in aspects of machine design and process integration, optimization, and level of automation including for process planning to meet future demands. One of the challenges in producing metal 3D printing is the selection of the material. For example, titanium and its alloys are commonly used in various industries due to their high performance [51-52] but it is the long lead time and high machining cost if being performed with conventional. The common steel used in 3D welding are tool steel [53], austenitic stainless steel [54], precipitation hardenable stainless steel [55], and maraging steel [56]. Due to the different properties of each metal, the correct material needs to be chosen in order to enlighten the purpose of AM which is reducing cost, waste, and energy. Besides the differences in properties, other things to be considered are such as the price, method, or technique and the strengthens [24] of the metal itself. Further research about each metal itself will help in selecting the appropriate material. Secondly, the defects after the 3D welding process also are the drawback of this process. The void formation, anisotropic microstructure, and mechanical properties, divergent from design to execution and layer by layer appearance are highlighted [24] as the challenges that are attributed to the nature of AM. High porosity created in product lead to the reduction of interfacial bonding between the printed layer which
also will reduce its mechanical performance [57]. However, it is depending on the method and the type of material used.

Other issues regarding the metal 3D printing are poor surface finish, inaccurate dimensional and the requirement of post-processing (machiing, heat treatment or chemical etching) to complete a part [24]. However, the combination of 3D-printing technology with equivalent manufacturing and subtractive manufacturing will create additional benefits for advanced manufacturing. The effectiveness of combination both process welding and milling was proven by Alhuzaim [58] in his research work. The welding process combined with milling is the conceptual idea presented by researcher from the India Institute of Technology and Automation [27]. The combination with the milling process gave great manufacturing flexibility besides increase surface quality and dimensional accuracy [59]. The residual stress and strain is highly dependent on the strategy of depositing the material which also leads to the constant height that can be measured layer by layer. Most of the available 3D printing machine available in the market is powder-based material. As it is a powder, the strength of the produced parts results in some issues. The post-welding process should not only be focused on the accuracy and the surface finish itself but also need to take into account about the product’s strength.

Welding machine design also becomes one of the issues to perform welding because it is due to the complexity of the parts. Most of the existing machine available is a hybrid machine, where two or more processes were integrated on the same machine. A machine usually will consist main body, tools and mechanism involve to perform tasks (for this case welding), control system, and accessories. The body shape and size may affect the mechanism and arrangement of machine parts. Thus, at design stages, the complex design of the machine should be avoided to elude difficulty during the welding process. Figure 4 shows a few existing machine designs presented in previous researchers.

Figure 4. Solid casted iron body (a), structure wireframe (b) by Rosli et al., (41) and without frame as robotic arm is utilized by Colgrove and William (22) as shown in (c)

For welding operation, two important tools required are the platform and the welding nozzle. The nozzle uses to perform welding need to mount or clamp on a bracket or holder, while the platform is needed to prepare a space where the weld bead is produced. Two options for welding mechanisms to be described, it is either to have a fixed nozzle and moving platform or vice versa. However, it is to be highlighted that the efficient method where a stationed nozzle could reduce machine complexity, as the cable and bulky size will limit the movement of the nozzle. In addition, the moving platform is much easier to control.

4. Suggestions

Traditional manufacturing technologies [60], such as casting, forging, machining, and injection molding are portrayed as a process to make a 3D part in previous years. However, time-consuming for the preparations and waste in the material makes the process is not good compared to additive manufacturing. However, it cannot be simply compared to comparable manufacturing technologies
such as casting, forging, and machining with subtractive manufacturing processes (milling, turning, and grinding); relatively, different manufacturing technologies should be applied where they can be of best use. 3D printing must provide end-use products by fabricating more than just simple structures with sufficient mechanical strength to retain shape in order to become more widely adopted in mainstream manufacturing technology. Through the powder-based technique, the necessary strength is not able to achieve. In future research, the author would like to suggest forging as the subtractive process of 3D welding. Forging, known as the metal forming process, that involves large deformation and can improve part's strength. In addition, time taken is shorter compared to machining and suitable to use due to the suitability for mass production.

Through 3D welding, the pre-form shape can be prepared, and this will reduce waste and can shorten the process steps. The critical issue to be addressed is on part complexity due to forging is not convenient with the harder materials because it is difficult in filling a complex cavity. Limitations of the process include the need to build larger volumes. Further research will be carried out accordingly in order to find the solution to the limitation of the forging process to become a subtractive process in producing 3D objects.

5. Conclusion
This paper presented the surface of 3D printing with the justification of 3D welding technology and technique available. Their relationship was explained based on the review the literatures in this research area. Many publications had explored the importance and techniques of 3D printing including metal 3D printing. However, there is limited research to discuss about strength of parts after welding process.

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