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Additive Manufacturing Using MIG Welding

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***Abstract*— The first step of creating layer by layer a 3D object using computer-aided design was rapid prototyping, developed in the period of 1980's for creating models and prototype parts mainly for industrial purpose only. Recent developments have reduced the cost of 3D printers, thereby expanding its applications in schools, homes, libraries and laboratories. Initially, 3D printing has been extensively used by architects and designers to produce aesthetic and functional core making process without changing the shape or size of the sand mold (core). The process that has traditionally been use to melt and join metals by establishing an arc between a continuously fed filler wire and the base metal. The high deposition rates and ease of implementation are advantages of GMAW based additive manufacturing when compared to laser-based processes (Song et al., 2005), (Karunakaran et al., 2010).This work has sought to build a model that performs a cradle to gate analysis of the energy that would be consumed in an additive-subtractive manufacturing system used to produce steel components using wire-based system and powder-based system as the input to the additive part of the process. Compared with GMAW-based AM process, the surface quality improved significantly by adding laser with other parameters being equal.**

***Index Terms*—3-D Printing, GMAW, Wire-based system, Powder-based system, AM process**

I. INTRODUCTION

The first step of creating layer by layer a 3D object using computer-aided design was rapid prototyping, developed in the period of 1980's for creating models and prototype parts mainly for industrial purpose only. Rapid prototyping is one of the earlier additive manufacturing (AM) processes. But in later years, It allows for the creation of parts (i.e) product that we required, that this process presented to product development are the time and cost reduction, human interaction, and consequently the product development cycle , also the possibility to create almost any complex shape that could be difficult to machine, Since it forms like layer by layer[28]. Now, it is completely modern manufacturing and many other industries with new processes, materials, and applications. In addition to prototypes, complex components, houses, and even human body parts can now be 3D printed. With the rapid advancement of 3D printing and 3D bio-printing technologies, a huge body of research and practical applications exists for these technologies [29]. Now, doctors can build a model of a damaged body to analyze it and plan better the procedure, market researchers can see what people think of a particular new product, and rapid prototyping makes it easier for artists to explore their creativity [28]. The applications of rapid prototyping in sand mold and core printing simply substitute the conventional molding and core making process without changing the shape or size of the sand mold (core). Importantly, 3D printing not only provides an alternate method for conventional manufacturing but also revolutionizes the topological structure design of products 3D printing technology can also bring new elements to casting design and mold design in the casting industry. Kang et al. proposed the application of a hollow mold to aluminum alloy castings according to the idea of a shell-truss mold based on 3D printing technology, and achieved outstanding results [12]. Layered manufacturing of metal frameworks is a promising technology in dental practice. The mechanical properties of metal frameworks fabricated by using different layered manufacturing methods are affected [16]. This technique recently used as tool in medical field for manufacturing of customized implants and bio-models. AM presents capacity of building highly complex geometries directly from a CAD model, which permits fabrication of custom implants from computed magnetic resonance data from a patient. Some advantages of these implants are shorter surgery times, improved bio-mechanical compatibility, reduction in rejection and infection risks, better ergonomic and aesthetic results and increasing the probability of success of the implant [17]. New applications are emerging as novel materials and AM methods are continuously being developed. One of the main drivers for this technology to become more accessible is attributed to the expiry of earlier patents, which has given manufacturers the ability to develop new 3D printing devices. Recent developments have reduced the cost of 3D printers, thereby expanding its applications in schools, homes, libraries and laboratories. Initially, 3D printing has been extensively used by architects and designers to produce aesthetic and functional prototypes due to its rapid and cost-effective prototyping capability. The use of 3D printing has minimized the additional expenses that are incurred in the process of developing a product. However, it is only in the past few years that 3D printing has been fully utilized in various industries from prototypes to products. Product customization has been a challenge for manufacturers due to the high costs of producing custom-tailored products for end-users [24]. On the other hand, AM is able to 3D print small quantities of customized products with relatively low costs.

II. PRINTING METHODS

Methods of additive manufacturing (AM) have been developed to meet the demand of printing complex structures at fine resolutions. Rapid prototyping, the ability to print large structures, reducing printing defects and enhancing mechanical properties are some of the key factors that have driven the development of AM technologies. The most common method of 3D printing that mainly uses polymer filaments is known as fused deposition modelling (FDM). In addition, additive manufacturing of powders by selective laser sintering (SLS), selective laser melting (SLM) or liquid binding in three-dimensional printing (3DP), as well as inkjet printing, contour crafting, stereo lithography, direct energy deposition (DED) and laminated object manufacturing (LOM) are the main methods of AM[24].

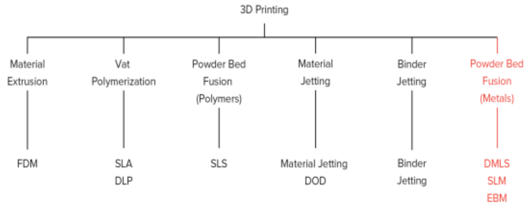

Fig. 1. 3D printing classification

A. *Sterolithography*

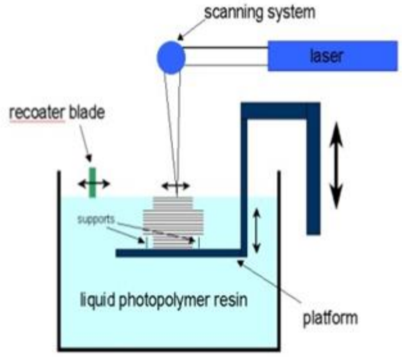

Fig. 2. Stereolithography

Stereo lithography employs photo curable polymer resin which solidifies into solid when exposed to high intensity light. Initially, curing was only possible with UV light, but recently polymers cured with visible wavelengths have been introduced. Highly focused lasers or LED beams with high intensity are used, and the spot size of the light beam determines printing resolution. Each layer of the object is printed as a point-by-point 2D cross section cured by the scanning focused beam onto a printing platform immersed in a photo curable tank that holds the liquid resin. Recently, projection-based stereo lithography has been introduced with promise to decrease print time while maintaining almost the same resolution as line-based stereo lithography. The basic principle of this process is the photo polymerization, which is the process where a liquid monomer or a polymer converts into a solidified polymer by applying ultraviolet light which acts as a catalyst for the reactions; this process is also called ultraviolet curing. It is also possible to have powders suspended in the liquid like ceramics. The energy of the light source and exposure are the main factors controlling the thickness of each layer. SLA can be effectively used for the additive manufacturing of complex Nano composites.

B. *Wire Feed Systems*

A schematic of a wire feed unit is shown in Fig. The feed stock is wire, and the energy source for these units can include electron beam, laser beam, and plasma arc. Initially, a single bead of material is deposited and upon subsequent passes is built upon to develop a three dimensional structure. In general, wire feed systems are well suited for high deposition rate processing and have large build volumes; however, the fabricated product usually requires more extensive machining than the powder bed or powder fed systems do. In summary, there are a large number of diverse AM pieces of equipment commercially available. These may be broadly characterized as powder bed, powder fed, and wire fed systems. There are distinct advantages to each type of system dependent upon the intended applications, e.g., repair and refurbishment, small part fabrication, large part fabrication.

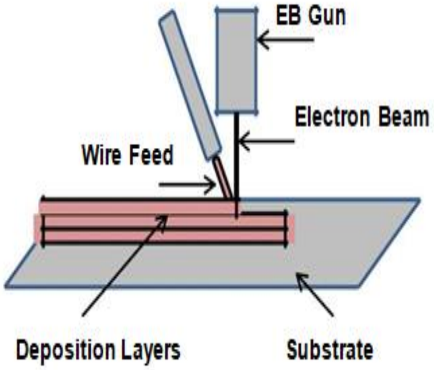

Fig. 3. Generic illustration of an AM wire feed system

C. *Laser Engineering Net Shaping (Lens)*

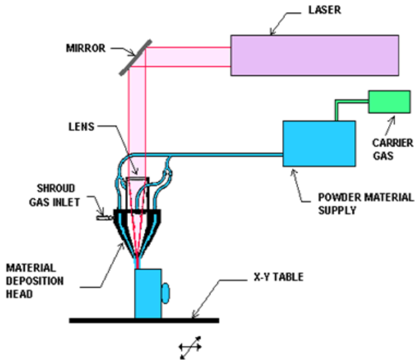

Fig. 4. Lens

In this additive manufacturing process, a part is built by melting metal powder that is injected into a specific location. It becomes molten with the use of a high-powered laser beam. The material solidifies when it is cooled down. The process occurs in a closed chamber with an argon atmosphere. This process permits the use of a high variety of metals and combination of them like stainless steel, nickel based alloys, titanium-6 aluminium-4 vanadium, tooling steel, copper alloys, and so forth. Alumina can be used too. This process is also used to repair parts that by other processes will be impossible or more expensive to do. One problem in this process could be the residual stresses by uneven heating and cooling processes that can be significant in high precision processes like turbine blades repair. Fig. 4, is an illustration of how the part is made in this process.

TABLE I
LENS DEPOSITION SEC DISTRIBUTION

Energy Consumption Factor	SEC (J/kg)
Theoretical Melt Energy	1.19E+06
Melt Efficiency Contribution	2.42E+06
Laser Energy Transfer Efficiency	5.51E+06
Machine and Chillers Contribution	5.11E+07
CNC Worktable	6.70E+06
Total for LENS Deposition	6.69E+07

D. *Wire-based Additive Manufacturing*

Gas metal arc welding (GMAW) was developed in the 1950s, and was formerly known as metal inert gas (MIG) welding. The process that has traditionally been use to melt and join metals by establishing an arc between a continuously fed filler wire and the base metal. The arc and molten weld pool are usually shielded by inert gases (Kou, 2003). Researchers have developed GMAW based additive manufacturing processes and paired them with CNC milling to create a complete additive-subtractive manufacturing system as described in Figure 1, (Song et al., 2005), (Karunakara et al., 2010). These systems deposit a layer of molten wire across a prescribed geometric area using GMAW and the layer is then face milled. Upon completion of the appropriate layer depositions and face milling cycles, finishing machining is performed to attain the desired final dimensions. Highly accurate parts with low surface roughness, as well as acceptable density could be produced using these processes. The high deposition rates and ease of implementation are advantages of GMAW based additive manufacturing when compared to laser-based processes (Song et al., 2005), (Karunakaran et al., 2010).

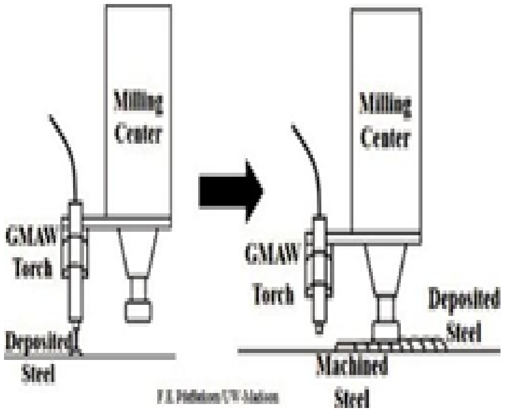

Fig. 5. Simplified wire-based additive manufacturing process diagram

E. *Selecting Laser Sintering*

This is a three-dimensional printing process in which a powder is sintered or fuses by the application of a carbon dioxide laser beam. The chamber is heated to almost the melting point of the material. The laser fused the powder at a specific location for each layer specified by the design. The particles lie loosely in a bed, which is controlled by a piston, that is lowered the same amount of the layer thickness each time a layer is finished. This process offers a great variety of materials that could be used: plastics, metals, combination of metals, combinations of metals and polymers, and combinations of metals and ceramics. Examples of the polymers that could be used are acrylic styrene and polyamide (nylon), which show almost the same mechanical properties as the injected part. It is also possible to use composites or reinforced polymers, that is, polyamide with fiberglass. They also could be reinforced with metals like copper.

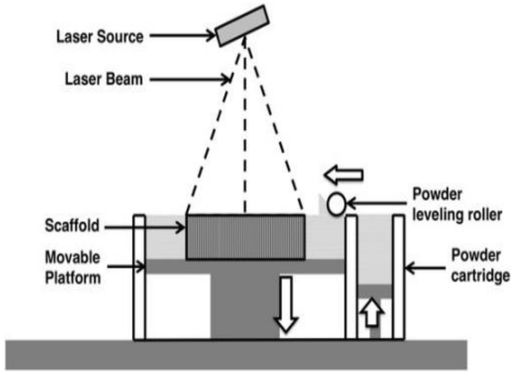

Fig. 5. DMLS

F. *Model Methodology*

This work has sought to build a model that performs a cradle to gate analysis of the energy that would be consumed in an additive-subtractive manufacturing system used to produce steel components using wire and powder as the input to the additive part of the process. The entireties of the processes included in this analysis.

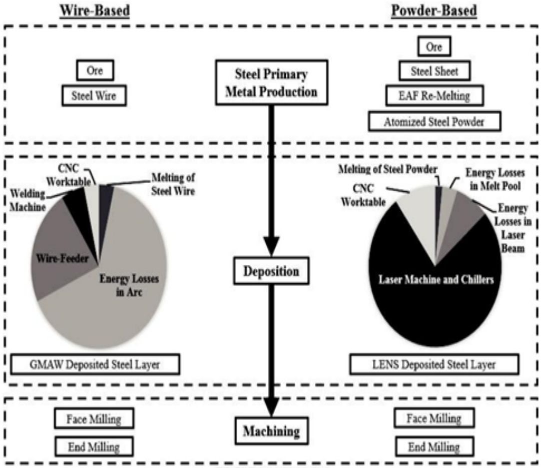

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Fig. 6. Process flowchart of energy consumption in wire-based and powder-based additive-subtractive manufacturing

III. PRINTING MATERIALS

Materials in additive manufacturing technology systems are defined by the fabrication processing technology. Each 3D printing technology transforms material through external heat, light, lasers and other directed energies. The ability of a material's mechanical composition to react positively to a certain directed energy marries that material to a technology which can deliver the desired change. These material-technology partnerships will expand as materials are advanced and material chemistry explored. Advancing technologies encourages more positive material reactions, layer by layer, to directed external energies. The mechanism of material change-unique to individual 3D printing technologies and processes-defines the material in terms of state changes, final mechanical properties and design capabilities. By extension, developments in 3D printing materials correspond with developments in 3D manufacturing; as the build process improves to encourage more positive reactions from materials, material selections will expand. The 3D printing materials are available in different material types and states such as powder, filament, pellets, granules, resin etc.

A. Plastics

Nylon, or Polyamide, is a strong, flexible, reliable and durable plastic material commonly used in powder form with the sintering process or in filament form with the Fusion Deposition Modeling (FDM) process. It is naturally white in color but it can be colored pre -or post-printing. This material can also be combined (in powder format) with powdered aluminum to produce another common 3D printing material for sintering- Aluminize. ABS is another strong plastic used for 3D printing, in filament form. It is available in a wide range of colors useful option for some applications. Lay Wood is a specially developed 3D printing material for entry-level extrusion 3D printers.

This special filament is a composite material of recycled wood and polymer parts that can create wood-like objects that have the look, feel and even the smell of wood. It can be printed between 175-2500^{O}C. It is available in light and dark color wood.

B. Metals and Alloys

The most common metals and metal composites are titanium, aluminum and cobalt derivatives. Metal additive manufacturing is showing excellent perspectives of growth. It is also used in the biomedical, defense and automotive industries. Metal AM provides great freedom for manufacturing complex geometries with special connections compared to conventional manufacturing methods. In particular, multi-functional components can be developed to provide solutions to structural, protective engineering and insulation problems at the same time. Many metallic materials such as stainless and tool steels, some aluminum alloys, titanium and its alloys, and nickel-based alloys can be manufactured using PBF-based AM processes. PBF technologies can manufacture components with good mechanical properties and complex shapes with high accuracy (±0.02 mm).Titanium and its alloys, steel alloys, a few aluminum alloys, nickel alloys, and some cobalt-based and magnesium alloys have been optimized for AM. In particular, titanium and its alloys are high-performance materials commonly used in various industries. They are characterized by high machining costs and a long lead-time based on conventional manufacturing methods.

C. Ceramics

Ceramics are a relatively new group of materials that can be used for 3D printing with various levels of success. The ceramic parts need to undergo post-processing processes same as any ceramic part made using traditional methods of production — namely firing and glazing. Extrusion of ceramic paste or filament is also known as extrusion free-forming of ceramics (EFF), fused deposition modeling of ceramics (FDC) or rapid prototyping (RP). The main methods of post-curing for extruded ceramics are phase changing (i.e., crystallization of liquid phase by freezing or freeze-drying), evaporation of water or solvent and UV or heat curing. Besides the particle size distribution and packing of particles in the paste, the liquid to solid ratio, air-entrapment, temperature, drying and de-binding procedure, solidification kinetics and inter-layer adhesion can affect the properties of 3D printed ceramics. Stereo lithography, in spite of being developed for 3D photo polymerization (UV, laser or LEDs can also be used) of monomer into polymers, has been extended.

D. Experimental System

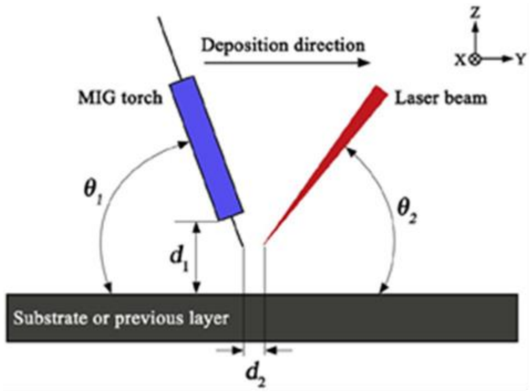

Fig. 7. Schematic diagram of low power pulsed laser assisted MIG based AM system

The L-M based additive manufacturing system, which mainly consisted of a welding work flat, a MIG welder (type OTC WB-P500L) and a laser generator (type Riton LWS-800FK). The welder is a kind of unified welder, in which the wire feed speed varies with the welding current. The laser generator can provide a maximum average output power at 800 W; it is a kind of pulsed laser, and the pulse waveform of laser beam is shown in Fig. 3. The pulse time of laser is 2 ms and the pulse frequency of laser is 30 Hz. The MIG welder and laser generator are connected to each other by a welding robot (type OTC FD-V20). The robot is responsible for executing several following functions: control of the MIG welder and laser generator on/off, adjustment of related parameters of GMAW process, control of the movement of the MIG torch and laser torch, and other necessary information can be designed by the human-machine interface. During the L-M deposition process, thin-wall parts were deposited layer by layer in an alternative direction along the centerline of the substrates as shown in Fig. 2. The MIG torch and laser torch are fixed together, moving together to change the arc striking points through the robot's rotation. Based on a number of experiments, the relative position of two torches above the base metal is depicted in Fig. 3. The detailed angles and distances are demanded as follows: d_1 ¼ 12 mm, d_2 ¼ 1 mm, q_1 ¼ 75, q_2 ¼ 60. After a layer is deposited, the two torches are lifted a certain distance together in Z direction controlled by the robot program. In the deposition process, the angle of two torches, and the distance be-tween the torches and the substrate or the underlying layer was almost consistent.

E. Arrangement of the Experiments

In this experiment, the ER5356 aluminum alloy wire with a diameter of 1.2 mm was fed into the molten pool to form the deposited layers on the 6061 aluminum alloy plates with dimension of 300 mm 300 mm 5 mm. The gas mixture of AR (95%) and CO2 (5%) was applied for the shielding gas of MIG torch, with a flow rate of 20 L/min. With the purpose of analyzing how the laser power influences the forming characteristics of thin-wall parts, the paper carried out the four groups of experiments for fabricating thin-wall components under the same welding current 120 A in different laser powers: (1) P ¼ 0 W, (2) P ¼ 200 W, (3) P ¼ 400 W,P ¼ 600 W (the laser powers are all average value). As stated in Table 2, the experimental parameters were kept constant except the laser power. As introduced in Section 4.1, the wire feed speed varies with the welding current. As a result, the deposition rate of each layer was the same in the condition of the same welding current and the same deposition velocity. The inter-layer temperature was controlled at 100 C measured by an infrared thermometer (type UT305C), and the process was paused between each layer until the temperature of the previous layer fell to 100 C. Every layer was deposited 160 mm length, and the thin-wall part of each experiment group combined 20 layers.

TABLE II
EXPERIMENTAL PARAMETERS OF L-M BASED AM PROCESS

Parameter	Value
MIG current	120 A
Wire feeding speed	6.5 m/min
Deposition velocity	600 mm/min
ER5356 wire electrode diameter	1.2 mm
Size of 6061 aluminum alloy substrate	300 mm*300 mm
Deposition length	160 mm
Total layer number of thin-wall part	20

IV. CONCLUSION

1. The low power pulsed laser induced MIG (L-M) based AM system was proposed, the practicability and high stability for fabricating metal products has been verified.
2. The dimensions of the deposited thin-wall part were influenced by the laser power. The width decreased with the increasing of the laser power within a certain range of laser power, and the height increased proportionally under the equal deposition rate.
3. Compared with GMAW-based AM process, the surface quality improved significantly by adding laser with other parameters being equal. The width and height difference reduced obviously while adding the low power laser, both the standard deviation decreased by more than 50% when the laser power was 400 W.
4. The coefficient of utilization in materials reached 91.12%, and increased about 15% using L-M to fabricate thin-wall parts under a proper laser power.
5. A model was created to estimate the energy consumption from cradle to gate in wire-based and powder-based additive-subtractive manufacturing processes. The model relied on published SEC values for primary metal production of wire and powder. Deposition process components from the literature and experimentation were utilized to find SEC values for deposition.

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