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Advances in High Temperature Materials for Additive Manufacturing

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Abstract. In today's technology, additive manufacturing has evolved over the year that commonly known as 3D printing. Currently, additive manufacturing have been applied for many industries such as for automotive, aerospace, medical and other commercial product. The technologies are supported by materials for the manufacturing process to produce high quality product. Plus, additive manufacturing technologies has been growth from the lowest to moderate and high technology to fulfil manufacturing industries obligation. Initially from simple 3D printing such as fused deposition modelling (FDM), poly-jet, inkjet printing, to selective laser sintering (SLS), and electron beam melting (EBM). However, the high technology of additive manufacturing nowadays really needs high investment to carry out the process for fine products. There are three foremost type of material which is polymer, metal and ceramic used for additive manufacturing application, and mostly they were in the form of wire feedstock or powder. In circumstance, it is crucial to recognize the characteristics of each type of materials used in order to understand the behaviours of the materials on high temperature application via additive manufacturing. Therefore, this review aims to provide excessive inquiry and gather the necessary information for further research on additive material materials for high temperature application. This paper also proposed a new material based on powder glass, which comes from recycled tempered glass from automotive industry, having a huge potential to be applied for high temperature application. The technique proposed for additive manufacturing will minimize some cost of modelling with same quality of products compare to the others advanced technology used for high temperature application.

1. Introduction

Additive manufacturing (AM) is an industrial revolution technology which currently being promotes among the engineering sector. The technology was most often known as 3D printing which allows the process to create complex geometries with customizable material properties. Additive manufacturing terms were used recurrently as widening appeal of rapid prototyping which is notably within the manufacturing industry while 3D printing is the general public terms at large scale. At earlier of additive manufacturing process, rapid prototyping was aimed at creating printed parts, not just models but its verify, fit and function the created parts as in a second compare to the others conventional technologies[1]. Additive manufacturing make a huge market turning as the process are becoming

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more relevant to the manufacturing industry around the world. The process present definite advantages which is flexible to complex shapes and shades of printed part, less cost and manufacturing were required for the process, and less material waste produced when only needed material used during for the additive manufacturing [2]

The development of additive manufacturing technology has been evolved over the year can be obviously spotted on automotive, aerospace and medical industries [3]. Advances of additive manufacturing for automotive industries have opened doors for newer designs, cleaner, lighter, and safer products, shorter lead times and lower costs that will benefit production within the automotive industry [4]. In aerospace industry, the technologies might be applied throughout all processes from the design concept to near-end-of-life repairs. Its then drives additive manufacturing deeper into related processes, making it multi-purpose to the industry [5]. In medical industry, additive manufacturing capabilities align well with the needs of medical devices such as hearing aids, dental crowns, and surgical implants, which are pretty small in size and therefore, additive manufacturing technology were convenient for the production [6]. United States lead the expanding of additive manufacturing technology in as the most pioneering company such as Stratsays, Zcorp, and 3D System are base there [7]. However, new companies appeared from outside the United States has placed their market which becoming more competitive and has met considerable in developing technique, software tools, and material to support the technology for manufacturing industry [8].

2. Current Technologies

Additive manufacturing does not require any mould, every single product may have its own exclusive and aesthetic characteristics. The technology use an additive process where the material was added layer by layer to build part, compare to conventional manufacturing that using a variety of tooling and machines. Basically, additive process performed basic procedures which create the model of the part using computer-aided design (CAD) software. By using CAD, solid modelling system will able to interpret and represent three dimensional objects more precisely even for complex object [1]. However, the process were differ depending on the material and machine technology used. Table 1 below shows the classification of current additive manufacturing technologies.

Table 1 Classification of current additive manufacturing technologies[9].

Categories	**Technologies**	**Material**	**Source**
Powder Bed Fusion	Selective Laser Sintering (SLS)	Polyamides /Polymer	Thermal Energy
	Direct Metal Laser Sintering (DMLS)	Atomized metal powder (17-4H stainless steel, cobalt chromium, titanium Ti6Al-4V), ceramic powder	High-powered Laser Beam
	Selective Laser Melting		
	Electron Beam Melting (EBM)		Electron Beam
Material Extrusion	Fused Depositon Modelling (FDM)	Thermoplastics, Ceramic slurries, Metal pastes	Thermal Energy
	Contour Crafting		
Vat Photopolymerisation	Stereolithography (SLA)	Photopolymer, Ceramics (alumina zirconia, PZT)	Ultraviolet Laser

Material Jetting	Polyjet/ Inkjet Printing	Photopolymer, Wax	Thermal Energy /Photocuring
Binder Jetting	Indirect Inkjet Printing (Binder 3DP)	Polymer Powder (Plaster, Resin), Ceramic powder, Metal powder.	Thermal Energy
Sheet Lamination	Laminated Object Manufacturing (LOM)	Plastic Film, Metallic Sheet, Ceramic Tape	Laser Beam
Directed Energy Deposition	Laser Engineered Net Shaping (LENS) Electronic Beam Welding (EBW)	Molten metal powder	Laser Beam

Most recently, ASTM International has classified additive manufacturing technologies into seven categories which is powder bed fusion, material extrusion, vat photopolymerization, material jetting, binder jetting, sheet lamination, and directed energy deposition [9]. These technologies are presented via an overview of technology evolutions and research reviews over the last two decades for commercially available additive manufacturing systems.

3. General Flow Process of Additive Manufacturing

In general, a typical process is performed by the following basic procedures using computer-aided design (CAD) software. By using CAD, solid modelling system will able to represent three-dimensional, then, converting the CAD model to STL format as it was the standard format for additive manufacturing process. STL generally referred as “Standard Triangle Language” or “Standard Tessellation Language”, generates triangular facets to represent CAD model [10] as in figure 1. Its states that the facets are each designated by the X-Y-Z coordinates of their three vertices and a surface normal vector that indicates the orientation of the facet and which side of it faces out. The format also includes rules to make sure that the triangles are all appropriately connected at the nodes[11]. The process continued with slicing the STL file into thin cross-sectional layers. The pre-processing software slices the STL model into a number of layers with the thickness depending on the build technique. The thickness can be from several micrometres until several hundred micrometres. The process of slicing of this model digitally starts from the bottom of the design and finishes at the highest point [10].

Fig. 1 (1) Surfaces are represented by triangle, (2) Faceted STL file translated with coarse tolerance, (3) File translated with fine tolerance [12].

Then, construction of the model begins with stacking the materials layer by layer at a time, usually from polymer, metal, alloy, ceramic, or composite powders until three dimension object were formed. Each shaped layer represents a cross-section of the sliced model. Most additive manufacturing machine is a kind of autonomous and requires minimum operation from human.
The finishing step is the post-processing, which involve removing the prototype from the machine and detaching any support. Post processing operation include machining, peening, grinding polishing, surface treatment and heat treatment[13].

4. Common Materials used in Additive Manufacturing

Materials for additive manufacturing assign to build absolute parts that are complex enough for prototyping, practical testing, fitting, and most importantly until end use. In additive manufacturing, the early state of material can be in the form of solid, liquid and powder state, depending on the technique. The most common material for additive manufacturing is polymer such as Acrylonitrile Butadiene Styrene (ABS), Polyamide, Polycarbonate (PC), Poly-lactic Acid (PLA) and Polyvinyl alcohol (PVA) as they are among the cheapest materials in the industry. The polymer material comes in form of pellets or filament. Many of these materials are toughened to improve impact and fracture performance, but it is not clear whether additive manufacturing takes full advantage of these properties[14]. Polymers are widely utilized for prototyping model and low performance parts, however, there is still high demand for developing polymers as based material for advanced application.

According to Swiss Federal Laboratories for Materials Science and Technology [15], materials for additive manufacturing met some confront on properties such as fast heating and cooling rates, hot cracking, thermal residue, pressed and saturated phases transformation and also segregation. Better understanding of the link between microstructure, processing, and properties for fabricated parts, as well as developing an additive manufacturing materials database are obliged. Like others conventional manufacturing process, the initial choice of material was tied to the constraint of the process. For example, thermoplastics for fused deposition modelling, low-viscosity binder for inkjet printing, adhesive paper for laminated object manufacturing, photosensitive epoxy resin for stereo-lithography and powdered crystalline and semi-crystalline polymers for laser sintering [3].

Ceramic also be used for additive manufacturing and it usually come in the form of powder. The mechanical properties of ceramic parts produce by additive manufacturing technology were close to the conventional product as they have no cracks or large pores[16].

There is another type of materials used for additive manufacturing which is conductive ink [17]. Conductive ink usually used for inkjet printing technologies and there are different type of inks include colloidal suspensions of nanoparticle, organometallic compounds in solution and conductive polymers [18]. Inkjet printing involves the ejection of droplet of ink from a print head on to a substrate. The technology has great value for printing purpose as can be used for pharmaceutical, bio-medical and for 3D printing for architecture modelling [19].

5. High Temperature Materials in Additive Manufacturing

Development of additive manufacturing these days, drive to a significant number for the processes. As the expanding figure of new technology, new materials were constantly developed and analysed in terms of their feasibility of materials that suitable for the layered manufacturing.

A thermoplastic material, ULTEM 9085 developed mainly for the aerospace industry and also has applications in the marine and other niche industries. By using fused deposition Modelling (FDM) technique, ULTEM 9085 produce a strong, lightweight, flame-retardant thermoplastic part and widely used in aircraft interiors. The material has a V-Zero rating for flame, smoke and toxicity (FST). ULTEM 9085 is certified for use on commercial aircrafts, which will allow manufacturers to bypass a lengthy certification process. The heat deflection temperature for this material is 320° F / 160° C [20] so that, it increase the potential of the material as an ideal candidate for functional prototyping and end use parts applications in the aerospace and marine industry.

Poly(etherketoneketone) that has the lower processing temperature limit and peak melting temperatures at range 359ºC to 362ºC [21], is a semi-crystalline thermoplastics material. It is an additive manufacturing material that present certain advantages over amorphous thermoplastics in terms of higher range of continuous use temperature, the ability to use the material at temperatures even above glass transition temperature (T_g) for short spans without much loss in modulus [22], better resistance to creep deformation [22], and able to resist chemical and wear. Stratasys & Co. develop this material for spacecraft and other launch vehicle to help them address the environmental conditions in space, and protect the delicate electronics in their satellites from the dangers of extreme temperatures and the risks of electrostatic discharge [23].

Inconel 718 is another advanced material used in additive manufacturing for high temperature application. Inconel 718 represent super alloy since it can used permanently above 600ºC and possesses good strength and toughness at high temperature application. Inconel 718 was more convenient and well preserved material properties leads great application in the industries due to its excellent properties with holding its superior mechanical properties in a wide range of temperatures. Firstly, Inconel 718 is a nickel-chromium–based alloy with first-rate creep properties, good tensile strength, fatigue strength, and rupture strength, which makes it widely employed in many applications, includes nuclear reactors and liquid fueled rockets. Second, it has excellent oxidation resistance and hot corrosion resistance [24], which ideal for the application at a high temperature up to 700ºC and where the atmosphere is highly carburizing and oxidizing, such as combustion chambers and turbine blades, components for rings, aircraft, and land-based gas turbine engines. Due to tool over-wear and poor workpiece surface integrity [25], its high hardness and low thermal conductivity characteristics make it very hard to manufacture finished products using conventional machining methods, especially for those having complex structures. The laser-based additive manufacturing such as Selective Laser Sintering (SLS) and Direct Metal Laser Sintering (DMLS) technologies will have great applications for Inconel 718 in the industry, especially for the aerospace components [26].

AISI 4140 is another type of high temperature material for additive manufacturing materials and has been applied by using laser powder bed fusion (L-PBF) technique[27]. AISI 4140 is material from steel alloy which are most commonly used for high tensile material with wide range application for heavy industry [28]. The mechanical properties such as yield strength, tensile strength, elongation and the toughness of the material were excellent when compared to conventional technique. Based on the initial microstructural characterization, the formation of small solidification grain and ultrafine cell structures on the additive manufacturing samples, AISI 4140 steel alloy have better result compare to the conventional one [27].

Ti-6Al-4V is a metal materials has the specification calls for post additive manufacturing thermal processing, HIP or thermal anneal treatment. The HIP cycle is nominally 100 MPa and 926 ºC for 2-4 hours and furnace cooled below 427ºC. The thermal anneal is nominally 913 ºC for 2-4 hours and furnace cooled below 427 ºC. It is worth noting that both the HIP temperature and the thermal anneal temperatures are within the α-β phase field close to the β-transus temperature of 1000 ºC [29]. Moreover, several Ti-6Al-4V parts were manufactured using Arcam-based electron beam melting (EBM) process. More specifically, these parts were manufactured using Arcam Model EBM SI2 machine at the Boeing Aerospace, St. Louis, MO, facility under a separate collaborative project sponsored by the Air Force Research Laboratory [30].

6. Application of High Temperature Materials in Additive Manufacturing

It seems that the present state of additive manufacturing is rapidly changed to make the technology significant for manufacturing industry. For high temperature application, it is adequate for heavy industries such as aerospace and automotive sectors and the ability of additive manufacturing process to manufacture parts

In NASA, they have printed tiny, wafer-like satellites that will be used to reasonably transmit research data back to Earth. Their goal is to put 3D printing into space to make astronauts more self-sufficient by printing out whatever parts they might need. A 3D printer has been built and tested that can work in zero gravity [31]. In others, E3000 is the first satellite 3D printed project features using aluminium as based materials and it is commercial satellite system to make use of lithium-ion batteries to keep it powered up during eclipses [32].

Formula one (F1) is the utmost technically advanced sport in this era. New cars have been developed every year and then endlessly developed until the course of the year. F1 is usually a solid barometer of the car industry as a whole and the teams have to build the same things, but faster, lighter, stronger and better. By using 3D printers, WilliamsF1 has revealed a few central details after making a collaboration with German industry giant EOS. The collaboration allowed them to print any part of WilliamsF1 including full gearbox assemblies for functional testing and production aero parts [33].

Besides, one of the early adopters taking advantage of 3D technology was Hendrick Motorsports in the world of NASCAR. Hendrick uses rapid prototyping and 3D printing to "make mistakes in plastic" to cut down on cost. They also produce some non-essential equipment such as mirror mounts for use directly on the cars. Their goal was to produce a fully functional intake manifold in a short time period in order to test a new design while working together with Magneti Marelli, Brazil. A custom-designed material, WindformGF2.0, was utilized [31]. It is a polyamide-based powder reinforced with glass fibers and aluminum. It was chosen because the manifold needed to resist high temperatures (to 130°C) and be fully fused to resist vacuum loss or leaks [34].

7. Proposal of New Material for Additive Manufacturing

The overview from various study about material in additive manufacturing showing that the material are still limited on basic polymer for low cost technology of additive manufacturing and widely used of metal powder by high technology of additive manufacturing for advanced function of product. For high temperature application, there are some disadvantages on investing more energy and cost on the modelling by additive manufacturing technologies. Besides, there are some complex technique on the preparation of material which the common materials used is metal powder and composite.

For the new proposed material for additive manufacturing is glass powder which originated from wasted tempered glass from automotive industry which has some issue on their disposal problem. In order to maintain the sustainability of the environment, the wasted glass was reused and processed into the form of powder to be developed into new material for additive manufacturing especially for high temperature application. The properties of the glass itself can withstand the higher temperature with melting point of 1600 °C and very hard material. Moreover by using glass powder material, it can minimize the use of natural source such as other metal which is needed to be preserved.

By mixing the powder glass with the suitable binder which comes from organic based binder, it works as vehicles that can hold the particles of glass powder in their shape until the process of sintering. The mixed powder glass and the organic binder were processed into the form of filament by extrusion process. Then, it will be printed in 3D geometry via additive manufacturing known as fused deposition modelling (FDM) technique.

The simple technique of additive manufacturing were used for this material which is FDM as it can minimize cost and not too complicated like the other technologies of additive manufacturing for high temperature material.

Sintering process is one of the crucial processes needed to remove the binder particles from the sample. During the sintering process, the temperature is high enough to melt and remove the binder however it is still low to melt the glass material so that it can maintain the shape of the sample. After the sintering, the properties of the sample were test in terms of hardness, strength, melting point and also the microstructure of the sample by using scanning electron microscopy (SEM).

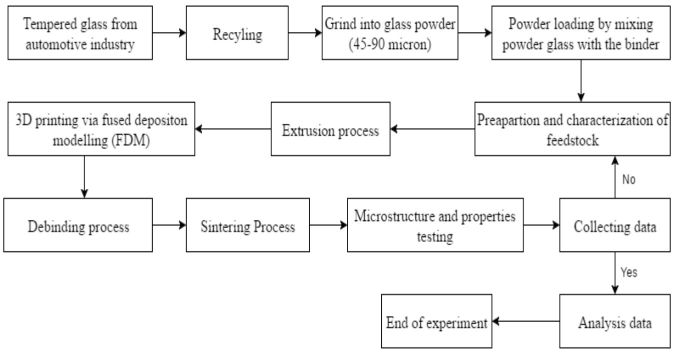

Fig. 2 Flow chart process of proposed material for high temperature application.

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