Technical Report

Synopsis: “Metal Additive Manufacturing: A Review”

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The following is a synopsis of William Frazier's technical report "Metal Additive Manufacturing: A Review" published in the Journal of Materials Engineering and Performance.

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Overview

This article examines the state of what is becoming a rapidly emerging manufacturing technique called additive manufacturing, with specific focus given to its application in manufacturing metal components. First it goes through defining what additive manufacturing (AM) is in general, the metal materials it covers, and the advantages & potential pitfalls which previous studies have identified. These are then examined in greater detail as the current techniques / systems available are reviewed, current technological challenges, concerns regarding qualification and control systems, business model considerations, and the environmental impact are all reviewed. The general conclusion is that while there are certainly plenty of benefits to be had from this technology, and a path to rectifying the current pitfalls, a larger scale breakthrough of sorts is needed to truly make this a more generally adopted option in production manufacturing.

Background

Here AM is defined as "a process of joining materials to make objects from 3D model data, usually layer upon layer, as opposed to subtractive manufacturing methodologies." This is a technique which has been around for decades, but has recently been gaining momentum with strong consideration of the advantages being given as early as 2009. In general it has been widely acknowledge that this is potentially a high transformative technology, but one which much more investigation into is needed. Much of the previous publications or meeting on the topic have been centered on outlining the unknowns, or potential risks, so that future research can be focused on understanding these in greater detail to either eliminate them as concerns or develop the framework to overcome them. The major themes which were highlight in these efforts were refining the process for efficiency, metrology and part variance, need for a physical model of the process to understand the material science, and a need to standardize the process.

Techniques / Systems

There are 3 main types of systems in use today which are Power Bed Systems, Powder Feed Systems, and Wire Feed Systems. The power bed system has the material spread across the work area with a scanning head sweeping the laser source across the work area to melt the material into the desired shape. As it solidifies more material is spread across the work area and the process is repeated until the 3D component is created. The advantages are the ability to produce high resolution structures, internal passages, and high dimensional control.

Powder Feed Systems similar materials are used, but now the material is deposited through nozzle into the path of the beam. Here the work piece can either still remain in place with the beam scanning an area to create the 3D component, or the part is self can sit on stages which moved the component. The advantage to this technique is it more easily scales up in larger lot sizes, and it can be used to rework parts as well. However this comes at the cost of some precision. Wire Feed Systems operate based on a solidified material being feed into the beam path to create droplets which are deposited to create the 3D component. This process presents an even greater increase in throughput, however, it requires further post-processing.

Technological Challenges

A lot of what is holding back this technology really gaining more production traction is related to technical challenges and unknowns that are present. In particular the list of available metals that can be used for this process is not that extensive currently, there is currently no real-time process monitoring, limits in the mechanical properties, and there are surface roughness, porosity, & fatigue concerns.

Currently there are a limited number of Titanium, Aluminum, Tool Steels, Super Alloy, Stainless Steel, and Refractory alloy options available which are compatible with AM processing. Of these Titanium alloy Ti-6Al-4V is the one which has been the most extensively researched. Studies have been performed to examine the effects the rapid solidification of the material, directional cooling, and phase transformations will induce in the final bulk material that is produced. The rapid solidification reduces elemental partitioning and extends solid solubility. The directional heat extraction may result in preferred directionality in grain growth. The repeated thermo cycling and phase transformations seem to have a complex effect as well which is not completely understood today. The typical defects that are associated with this are micro-porosity as a result of gas entrapments from the rapid cooling.

The porosity of the final fabricated parts typically is less than 50um. This can be improved through thermal annealing which eliminates residual porosity and improves the physical properties of the material. The fatigue strength in the Z direction increases by 24%, and by 27% in X and Y directions. The surface finish also affects the fatigue performance. Recent studies have directly correlated and increase in surface roughness to a decrease in fatigue life leading to rolled materials have greater fatigue life. Additionally investigation into the microstructures produced in electron beam systems vs laser beam systems shows that the laser based system yield irregular pores where electron beam systems yield spherical pores. Another area of consideration is the build rate and feature definition required for a part. These are closely related to the final surface quality. In general high build rates lead to lower feature definition and hurt surface finish. So for parts which are manufactured at a high build rate added post processing may be need to meet a high quality final surface finish.

In general when processed correctly the mechanical properties of AM materials are comparable to traditionally manufactured ones. The high cooling rates help to reduce partitioning and reduce grain sizes. However, what we do see is that AM processed materials do exhibit microstructures which can reduce the strength of the material. This can be compensated for via thermal annealing.

Qualification and Controls

It is clear that in order for the method to become more accepted and consider viable for higher end production manufacturing an improvement is need in terms of in-process control and metrology. Specifically the model of material structure evolution needs to be further developed so that requirements of what is needed in terms of process control can be defined. Certainly it clear that the process could lead to potential microstructure anomalies not seen in solid materials used in traditional manufacturing techniques. What need to be determine from the model is what of the many variable in the process are most sensitive to the final performance of the material, whether it be the droplet size, feed rate, scanning rate, power stability, etc. have a great effect on the final material properties and part-to-part variances. In order to be widely accepted the process controls must reach a level such that the variance part-to-part & machine-to-machine is low in order to instill confidence in repeatability. This is key for gaining adoption into industries which will have the demand needed to truly drive the innovation of the technique.

Business Considerations

Currently AM looks to have been accepted on a prototyping quantity level, however, further advancements are needed in order to become more viable in high production volumes. In small volume prototype situations the rapid turnaround and reduction in non-recurring engineering costs make AM very attractive. However, as the volume increase the fact that the materials used are more expensive, the metrology need more time consuming, and lack of standards are holding back its adoption. Advancements are need to reduce these recurring cost drivers before the business case for AM in volume will make sense. What is not well understood currently, and could be a justification for investment into making these advancements is the positive effect AM could have on the supply chain. The ability to run small lot sizes without losses in efficiency would enable companies to reduce inventory costs and improve the logistics of maintaining component availability.

Environmental Impacts

This is one of the area which seems to be the least understood. The majority of what has been done is not necessarily directly tied to AM and more inferred, with hard data somewhat lacking. Things like reduced energy consumption of the equipment is mentioned. However, the biggest impact is expected to come in reduction in the weight of the final components. The assumption here is the AM being and additive process will lead to less material in the final parts as the component is being built by adding just enough material, as opposed to traditional manufacturing which will lead to removing just enough. For components used on transportation equipment the reduction in the weight of those vehicles and it potential impact on the reduction in the energy consumption seems clear. Also, even just the reduction in energy consumption for shipping all AM parts would stand to make some impact as well. What is not clear however is if this potential conservation of the material used will have any adverse effects to the performance of the components made. There is also a need to quantify the actually reduction in weight that will be observed, and steps put in place to ensure designers are not oversizing parts to offset this.