Developments in Metal Additive Manufacturing

An examination of the past, present, and future of additive manufacturing research

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The ASTM F42 technical committee defines additive manufacturing (AM) as the "process of joining materials to make objects from three-dimensional (3D) model data, usually layer upon layer, as opposed to subtractive manufacturing methodologies" (Ref. 1). This is a broad definition that includes different types of technologies and materials including polymers, metals, and ceramics. Additive manufacturing is also known as additive fabrication, additive processes, additive techniques, additive layer manufacturing, direct digital manufacturing, rapid prototyping, rapid manufacturing, and freeform fabrication (Refs. 2–4).

Three Benefits Additive Manufacturing Brings

Additive manufacturing offers many advantages over conventional manufacturing in that it can overcome some geometric constraints and compositional barriers, as well as improve production time (Refs. 5–10). AM has the ability to create complex geometries that are difficult to achieve using conventional methods. Designers also have the ability to create lighter, more functional components made of fewer parts through additive manufacturing methods (Refs. 11, 12). For example, the medical field is creating porous implants for bone in-growth to improve bone regeneration (Ref. 13). In the aerospace industry, the geometry of cooling channels for components such as turbine blades has conventionally been limited to shapes attainable by drilling and capping (Ref. 12). These cooling channels can be designed closer to the walls of a part, which can improve coolant flow and reduce weight. Multicomponent parts can be made into one single part without tooling constraints from traditional manufacturing methods (Ref. 11). Traditionally made from multiple components, fuel nozzles can be made as a single piece with additive manufacturing as shown in Fig. 1A and an Airbus bracket has been designed with AM to reduce

A Ti-6Al-4V turbine cooling test bed size, measuring 365 × 365 × 320 mm with a complex internal structure, is able to be additively produced on a Farsoon Technologies FS421M system in one piece. (Courtesy of Farsoon Technologies.)

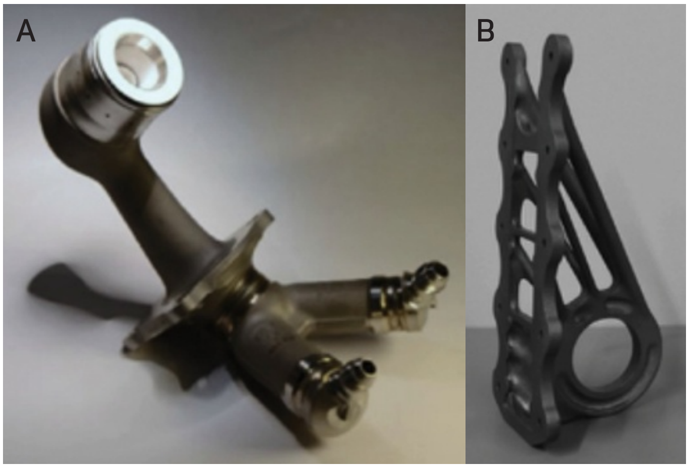

Fig. 1 — Additive manufactured components produced by laser beam melting: A — Fuel nozzle built as one piece with optimized interior channels; B — Ti-6Al-4V Airbus bracket with reduced weight (Ref. 14).

weight as shown in Fig. 1B (Ref. 14).

The second advantage is the ability to produce a part in a relatively short amount of time. Additive manufacturing initiates with the creation of a 3D model using a computer program that can be converted to a file format that calculates the slices taken to produce the AM component, layer by layer. These simplifications mean that a component can be made within hours or days compared to traditional methods. Atzeni and Salmi (Ref. 9) found additive manufacturing can reduce the time and cost from the design phase to manufacturing because there is no investment in designing and fabricating tooling and fixtures.

The third advantage is the cost savings because additive manufacturing is material and resource efficient and has production flexibility (Ref. 11). There is less waste in additive manufacturing because parts are made layer by layer and require less machining. In addition, leftover material can often be reconditioned and reused. Since additive manufacturing equipment does not require additional resources regarding extra tooling or fixtures, manufacturers can build manufacturing locations close to customers, reducing the need for packaging and shipping.

Additive manufacturing is cost effective for low-volume, high-value products. The technology cannot fully compete with conventional manufacturing for high-volume production. There is variability from part to part and from machine to machine, and from process to process, which makes it difficult for high-volume AM production. In addition to variability, adoption of qualification and certification has been a challenge in AM (Ref. 2). Researchers such as S. Babu have focused efforts in qualification of AM through in-situ process control and ex-situ characterization and modeling (Ref. 15).

Applications of Metal Additive Manufacturing

Due to the design freedom additive manufacturing processes offer, there are a wide range of industries implementing these technologies such as the aerospace, medical and dental, and automotive industries, to name a few. Additive manufacturing is helpful in the aerospace industry because of the high-value, small-batch components found in satellites, helicopters, and engines, and the small-batch production (Ref. 16).

Additive manufacturing has helped improve the medical field by making accurate prototypes for surgery preparation and creating implants unique to individual patients. Prototypes can be printed in larger scales from CT scans, which further helps medical doctors to accurately and safely identify issues, before operating on a patient. Additive manufacturing has also been used to create custom implants to better fit patients. The design freedom of AM potentially allows for an implant to be denser in regions that require more strength and that are more porous to allow for bone adhesion. There is hope for AM to customize the composition for flexibility, creating regions near joints that are more wear resistant, like using a ceramic, and using more ductile material toward the core of the implant.

The automotive industry has also benefited from additive manufacturing, especially for production of low-volume luxury and racing vehicles. Some components made by AM are engine exhausts, drive shafts, gear box components, and braking systems (Ref. 16). Other applications for additive manufacturing are creating injection molds, negatives for investment casting, and for repair of components. The applications for additive manufacturing are likely going to expand as the technology becomes more accessible and enhanced.

Historical Background

Rapid prototyping was first introduced in the 1980s with the first commercialization of stereolithography (SLA) developed by 3D Systems in 1987 (Refs. 17–20). Stereolithography uses an ultraviolet laser to cure a liquid-based polymer resin. Laminated object manufacturing (LOM) was patented in 1988 (Ref. 11) and commercialized in 1991 by Helisys (Ref. 12). In LOM, an adhesive is added to sheet material that acts as a layer. The sheets are bonded by the adhesive and a laser is used to cut the shape of the layer. This process can be used with paper, plastic, and metals. In 1989, selective laser sintering (SLS) was patented and became commercially available from 3D Systems in 1992. The process uses a high-power energy source to melt small particles to build a layer. The materials used in SLS are polymers, metals, ceramics, and glass.

There was much development in additive manufacturing during the 1990s with improvements in the SLA material systems and also improvements in technologies to include other materials. In 1992, fused deposition modeling (FDM) was patented. This process extrudes material just above the melting point so the material solidifies almost immediately. Fused deposition modeling can be used for wax, thermoplastics, metals, and ceramics. Three-dimensional printing (3DP) was developed by MIT and patented in 1993. This process uses a liquid binder jetted onto a starch-based powder. The powder is essentially glued together by the binder. Many companies employ 3DP for metal structures and use liquid metal injection to fill up the porosity left behind by the binder. In 1997, Sandia National Laboratories with Pratt & Whitney developed laser engineered net shaping (LENS) and licensed this technology to Optomec. The LENS process was commercialized in 1998 and a patent was awarded in 2000. Constant improvements are made in additive technologies, improving efficiency, unit prices, and expanding material systems.

Metal Additive Manufacturing Technology

For metal additive manufacturing, there are three main types of process technologies: powder bed, powder feed, and wire feed. Each process has defining characteristics such as material, build procedure, build size, build tolerance, resolution of features, surface finish, etc. (Ref. 21). For example, powder processes provide higher resolution of features due to the smaller layer thickness; however, the surface finish is rougher than a wire process. A summary of the various metal additive manufacturing technologies is shown in Table 1. It is important to note the process nomenclature is not completely standardized. Often, these processes are named by the manufacturer. For example, LMD, LENS, and DMD are often used to describe a similar process if not the exact same process.

Powder bed additive manufacturing can employ either a laser or an electron beam as the energy source. In general, for powder bed systems, a

Table 1 — Summary of the Metal Additive Manufacturing Technologies*

Technology	Process	Energy Source	Manufacturer
Powder Bed	SLS	Laser	3 Geometry Matsuura 3D Systems
	SLM	Laser	EOS SLM Solutions Concept Laser 3D Systems Realizer Renishaw Farsoon Technologies
	EBM	Electron Beam	Arcam Sciaky
Powder Fed	LMD LENS DMD	Laser	Optomec DM3D Irepa Laser
	EBAM	Electron Beam	Sciaky
Wire Fed	WAAM	GTA GMA	Big Metal Additive Lincoln KUKA FANUC
	EBF^3	Electron Beam	Sciaky

* Modified content based on Ref. 16.

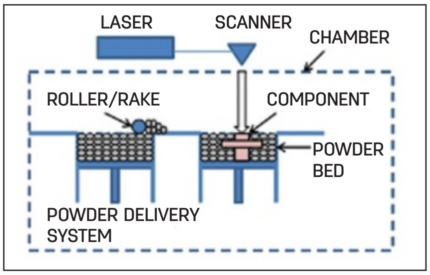

Fig. 2 — A schematic of a laser powder bed system (Ref. 2).

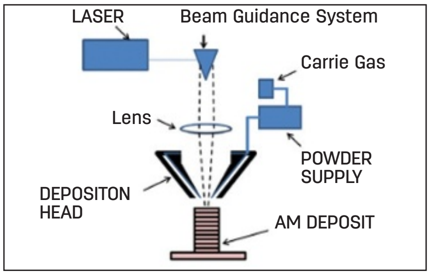

Fig. 3 — A schematic of the laser powder feed system (Ref. 2).

chamber is backfilled with a nonreactive gas such as argon or nitrogen. A rake rolls a small layer of powder across the powder bed. The energy source then scans a pattern over the freshly raked powder to either sinter or melt the new layer to the previous layer. The bed then drops, and a new layer of powder is raked over the bed and the process continues until the component is completed — Fig. 2.

The powder bed system is advantageous as it creates the highest resolution components and creates smaller microstructural features. The disadvantage to this process is it has strict size limitations and takes a longer time to build a component due to the finer layer size. There are three types of processes that use this technology: selective laser sintering (SLS), selective laser melting (SLM), and electron beam melting (EBM).

Selective laser sintering sinters the powder together without fully melting the two layers together. The binding mechanism involved in SLS can be viscous-flow binding, particle wetting, solid-state sintering, liquid-phase sintering, and true melting (Refs. 10, 22). To avoid use of a binder, a low-melting-point powder is mixed with a high-melting-point powder (Ref. 21).

Selective laser melting uses true melting to bond the layers together. This process improves the quality of a component such as improved surface roughness, reduced porosity, and fully dense components. There is some issue with heat input on dimensional tolerance and deposit cracking.

Electron beam melting uses an electron beam as the energy source and requires a vacuum. Hoppers dispense the powder onto a powder bed that is then raked over the bed and fully melted to create the layers of the component. Electron beam melting can produce larger components; however, the dimensional tolerance is lower than SLS or SLM.

Powder feed systems employ nozzles that direct powder into the energy source as shown in Fig. 3. The powder stream converges under the energy source on the AM component to melt the powder and form the next layer of the build (Refs. 23, 24). Just as with the powder bed system, the energy sources used for powder feed systems are laser and electron beam. This system can either have 1) a stationary workpiece and moving deposition head or 2) a workpiece that moves and a stationary deposition head. The processes that operate under powder feed technology are laser metal deposition (LMD), direct metal deposition (DMD), laser-engineered net shaping (LENS), and electron beam additive manufacturing (EBAM). In general, the powder feed processes deposit larger layer thicknesses and, therefore, result in larger microstructural features and lower resolution than the powder bed processes.

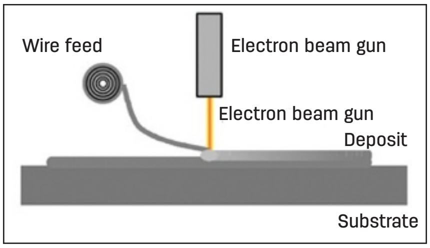

Fig. 4 — Schematic of the electron beam wire feed process (Ref. 27).

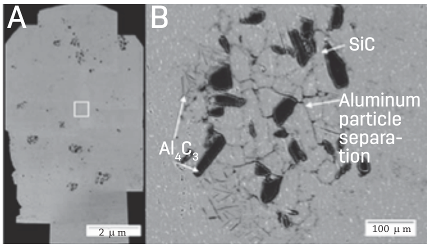

Fig. 5 — A — Macroscopic cross section of an Al MMC build that demonstrates clustering of the uncoated SiC particles; B — high magnification of the SiC cluster showing particle separation and Al carbide formation (Ref. 35).

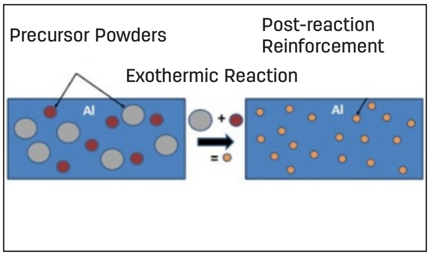

Fig. 6 — Schematic representation of the reaction synthesis process. Upon reaching the reaction temperature, the precursor components react and precipitate in situ a new ceramic or intermetallic phase.

Wire feed systems use wire as the material feedstock rather than powder. Wire is fed into the energy source and melted to create a layer. An example of a wire feed system is shown in Fig. 4. Different energy sources can be used such as arc, plasma, laser, or electron beam. Metal wire feed systems are not yet standardized and so it is common to turn a welding robot or electron beam system to operate under AM conditions. That being said, there are two types of processes that operate under the wire feed system, wire arc additive manufacturing (WAAM) and electron beam freeform fabrication (EBF^3); NASA-LaRC developed the latter process. The arc processes commonly used for WAAM are gas tungsten arc and gas metal arc. Wire feed systems can deposit material at a faster rate compared to both powder processes; however, because the deposition features are so large, there is a loss of resolution. Due to the deposition rate, larger structures can be made compared to the powder feed processes. In fact, researchers (S. Williams et al.) at Cranfield University's Additive Manufacturing program have successfully commissioned the world's largest metal 3D printer, capable of producing parts up to 10 m in length (Ref. 25). In 2015, those researchers produced one of the largest single AM builds, a 6-m-long double-sided spar, using WAAM (Ref. 26). Oak Ridge National Laboratory held the record for a trim and drill tool that was 17.5 ft.

Many industries and universities are involved in AM technologies with goals of improving the relatively young technology. These include Pennsylvania State University (PSU), The Ohio State University (OSU), University of Tennessee at Knoxville (UTK), and many others. Researchers from these institutions focus on improving AM technology for greater utilization in industry. Some of UTK's focus areas are optimization of scan strategies and microstructural control through tool path design (Ref. 28). OSU was awarded as one of the lead teams chosen by America Makes to develop qualification methods related to AM defect generation (Refs. 29, 30). National laboratories such as the National Institute of Standards and Technology and Oak Ridge National Laboratory have focused on AM qualification (Refs. 31, 32).

Developments in Additive Manufacturing at CSM

Additive manufacturing has expanded the design space and made significant improvements within many industries. Yet the technology still has inherent limitations regarding capabilities and applications. Research centers around the world are engaged in R&D activities to improve and overcome some of these issues. Colorado School of Mines is also engaged in a number of research initiatives that address the different aspects of additive manufacturing. The Alliance for the Development of Additive Processing Technologies (ADAPT) has focused its efforts on machine learning and processing parameters during the additive manufacturing process to improve part quality and characterization of internal defects in 3D builds. The Center for Welding, Joining, and Coatings Research (CWJCR) has focused its efforts on understanding metallurgical factors that affect the microstructure and quality of an AM component.

The CWJCR has focused its efforts on additive manufacturing consumables and microstructural development for the various AM technologies. In the presence of high-energy-density sources, alloying elements are known to vaporize during additive manufacturing (Refs. 33, 34). During EBF^3, solid or cored wires are typically used. However, Ti-alloy and Al-alloy builds are typically off the specified compositions due to vaporization. To mitigate alloy losses, the CWJCR group proposed to replace the solid (monolithic) wires with powder-cored wires. With the proper mix ratio, adding extra alloying additions to the powder can compensate for the alloying losses. To achieve a Ti-6Al-4V composition in the final build, the powder-cored wire should contain 19.5 wt-% Al and 12.5 wt-% V (Ref. 33). The CWJCR is also investigating development of consumables that could directly deposit metal matrix composite (MMC) builds. Coated and uncoated SiC particles were added to powder-cored wires so that upon deposition, the SiC particles would disperse into the Al matrix. Full dispersion of SiC particles proves to be a challenge. Figure 5 shows clustering of the ceramic particles in an aluminum matrix. However, coating the particles in nickel improved dispersion of the SiC particles (Ref. 35).

To improve MMC dispersion, Elementum 3D proposed use of a reactive additive manufacturing (RAM) powder instead of the SiC particles. RAM uses the concept of reaction synthesis, a process in which precursor components undergo an exothermic reaction and precipitate in situ new ceramic or intermetallic products (Fig. 6), generally on a much finer scale than the initial size of the precursor components (Refs. 36, 37). These new particulates then serve as both the reinforcement phase in the MMC and as inoculants during solidification, resulting in improved mechanical performance of the build while providing microstructural control and mitigation of solidification cracking. The exothermicity of the reaction synthesis process also increases wettability of the reinforcement by the molten metal,

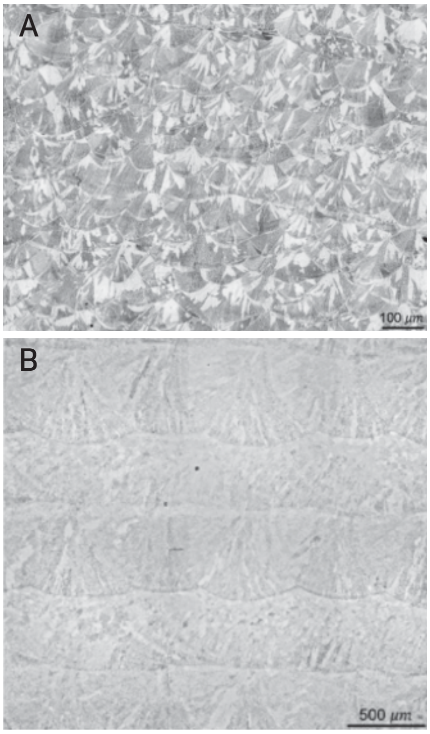

Fig. 7 — Representative micrographs of as-built 304L using the following: A — L-PBF; B — LP-DED (Ref. 39).

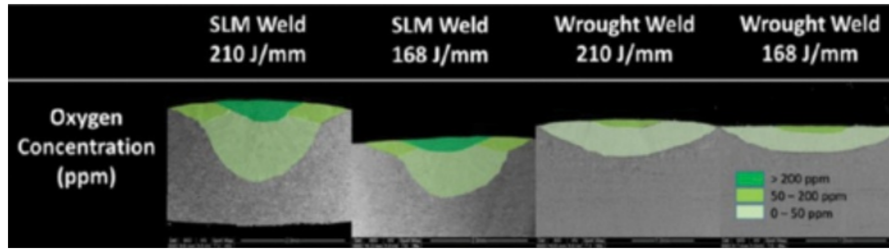

Fig. 8 — Measured oxygen concentration in gas tungsten arc welds made in L-PBF and wrought 304L stainless steels (Ref. 40).

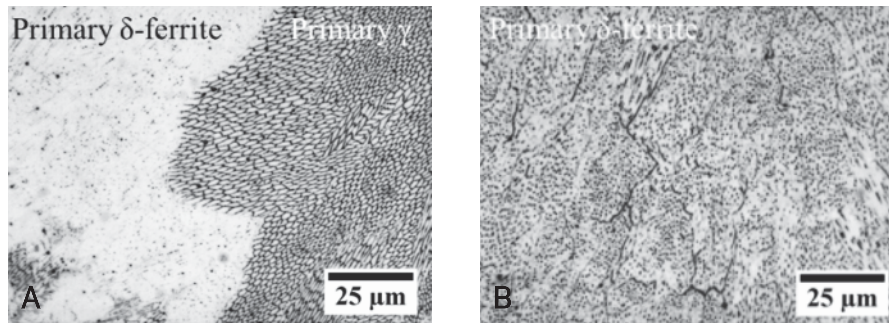

Fig 9 — A laser spot weld made in the following: A — L-PBF 304L demonstrating both primary ferrite and primary austenite solidification; B — wrought 304L demonstrating only primary ferrite solidification (Ref. 41).

which tends to improve dispersion of the reinforcement (Ref. 38).

The CWJCR has also focused on understanding the microstructural differences that result from various AM systems. Starting with similar SS304L substrates and powder feed, 3D printed materials from laser powder bed fusion (L-PBF) and laser powder directed energy deposition (LP-DED) were found to be different in terms of microstructure and mechanical properties (Ref. 39). Differences in deposit size and solidification rate of the two processes were partly responsible for the differences observed. The cooling rate for components produced through L-PBF was two to three orders of magnitude higher than those produced using LP-DED. The faster cooling rate affects the grain size and the solidification mode. Builds produced by L-PBF exhibited both primary austenite and primary ferrite solidification, while builds produced by LP-DED exhibited larger grains and only primary ferrite solidification as shown in Fig. 7. These microstructural differences led to differences in mechanical behavior such as yield strength and strain rate.

Even though AM provides much greater flexibility in engineering component manufacturing, welding is still expected in the life cycle of these components, either in the fabrication of larger components by joining together several AM components into a final assembly, or repair of AM components returned from service. There is little information available that demonstrates the welding behavior of various AM alloy systems.

The CWJCR is conducting research in the weldability of AM components with focus on the gas tungsten arc welding (GTAW) and laser welding behavior of L-PBF 304L stainless steel components. Due to the powder feedstock production, additive manufactured 304L components generally have a high concentration of oxygen. For GTAW, the high oxygen concentration affected the welding behavior by changing the surface tension fluid flow (Marangoni effect) resulting in deeper penetration for welds made in L-PBF 304L (Ref. 40). The difference in fluid flow behavior is demonstrated in Fig. 8, where welds made in AM 304L exhibited deeper penetration and higher concentrations of oxygen, while the welds made in wrought 304L exhibited shallow penetration and lower concentrations of oxygen. The higher oxygen and silicon concentrations also affected the ductility dip behavior of L-PBF samples. For laser welding of L-PBF 304L, the high oxygen concentration did not affect the Marangoni flow as it did for welds produced by GTAW. However, the solidification rate is slower for laser welds produced in L-PBF 304L, which has caused welds to solidify as both primary austenite and primary ferrite as shown in Fig. 9A (Ref. 41).

ADAPT at Mines has focused development in real-time sensing and feedback control for improved reliability on AM components, beginning with machine learning. The group has collected a large number of data to determine processing effects on defects such as porosity and incomplete fusion. They found that part orientation, part location, and the use of recycled powder have a considerable impact on defect formation (Ref. 42). This information can be applied to a machine learning model in hopes of reducing defect formation in the future and improving process parameters during the build process. In their work on microstructure and mechanical properties of L-PBF Inconel® 718, ADAPT has found that AM processing results in slightly different microstructures compared to wrought or cast products, which affects subsequent heat treatment (Ref. 43).

As-built Inconel 718 contains nano-sized oxide and carbide particles that mitigate grain growth, as well as containing a significant amount of dislocation cell structure that enhances the strength and elongation.

Future Vision of Additive Manufacturing

Additive manufacturing has made its mark in the manufacturing community, especially for high-value, low-volume components. The AM processes provide design freedoms that have helped to solve difficult problems and if the technology can be improved, it can be used to solve even greater design problems. New materials need to be applied in AM, expanding the range of AM usable alloys and with improved microstructural control (Ref. 44). For example, graded structures are being made through additive methods to create unique properties at location-specific regions (Refs. 4, 45). A patent was awarded to J. Dupont in 2009 for creation of an additive transition joint by dissimilar welding that produced a functional graded composition from 1080 to 316L (Ref. 46).

Other exciting challenges that limit the technology from reaching its full potential wait to be overcome. Product variability from build to build and from machine to machine need to be resolved. Researchers at Colorado School of Mines are aiming at addressing this issue so that AM technologies can produce higher quality components with less waste.

With the advancement of 3D manufacturing systems and the reducing cost of these systems worldwide, there has been a proliferation of small suppliers racing to build and supply industrial components. Not every company has the ability of consistent quality and product assurance. The performance of a similar component by different manufacturers cannot be easily assured. As the 3D deposition processes can affect quality and performance of the product, standardization (process, products, raw materials, and so forth) can prove to be challenging. Many professional societies and standards organizations are currently poring over known data and information to agree on which process parameters and product requirements to specify for control. Understanding and resolution of these issues will further the potential of AM technologies. Nevertheless, additive manufacturing has come a long way in the last five decades and is revolutionizing the modern manufacturing industry. WJ

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