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From Design for Manufacturing (DFM) to Manufacturing for Design (MFD) via Hybrid Manufacturing and Smart Factory: A Review and Perspective of Paradigm Shift

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Manufacturing paradigms have historically been shaped by social, economic, and technological aspect, including limitations and needs. Design for manufacturing (DFM) has been the main paradigm for last three decades since design is defined by the limitations of available manufacturing processes. Since reducing the time required for the development of new products has been one of the key issues for businesses, removing the gap between designers and manufacturers has been one of today's main goals. Many methods were developed to reduce this gap including information and communication technologies (ICT). However, current issues have been shifting towards design-related issues such that researchers have been trying to make products desired by the customers rather than that which is cheaper to manufacture. In this article, hybrid manufacturing (HM) and the concept of smart factory are introduced as key technologies for the future paradigm of manufacturing: Manufacturing for Design (MFD). Issues related to the development of HM process and examples of HM process are explained, and the importance of smart factories for the implementation of MFD is shown. Finally, future trends of HM and smart factory are predicted at the end of this article.

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1. Introduction

Manufacturing takes raw materials and transforms them into useful products through the use of diverse processes. Usually this process contains multiple steps including product design, selection of materials, material processing, manufacturing, packaging, etc. Throughout history, many different processes have been developed to fabricate useful products either through primary or secondary manufacturing processes, such as hot working and cold working processes and metal forming and metal removal processes. Also throughout history, changes in manufacturing paradigms have followed historical events, technology improvements or changes in consumers' demands. Fig. 1 shows the prevalent paradigm from the 1950s where manufacturing guides design. Labor, types of factories, strategies related to scale, time, manufacturing processes, and manufacturing technology are also factors that were considered based on the change in scope of manufacturing. In the 1970s, group technology, just in time (JIT), Taguchi and Design for X (DFX)[1,2] were the major focus in the industry. The concept of DFX states that the focus of the design process, as well as most of the factors and variables that are considered at the design stage, is related to the stipulations in order to add limits to the design that help in satisfying them. The reason for these limitation-based design processes is that limitations stemming from the manufacturing processes limit the freedom of design and thus drives cost up significantly when adding complexities to the product.

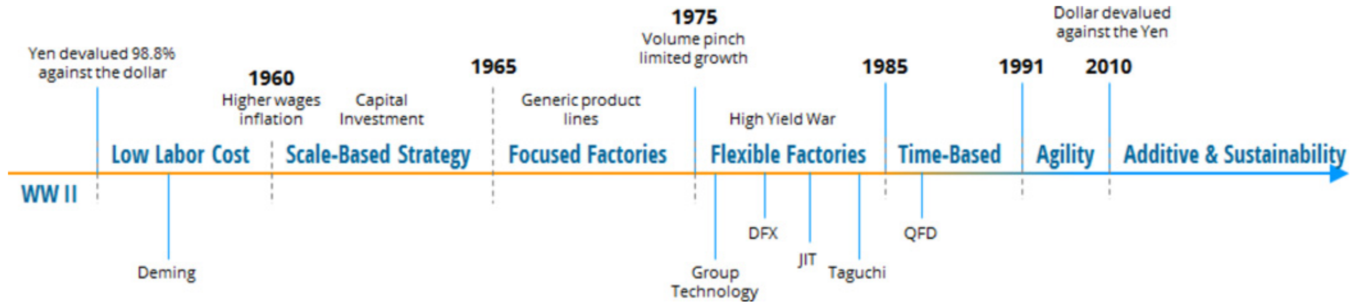


Fig. 1 Paradigm shift in manufacturing

Thus, in the late 1900s, increasing productivity via minimizing the cost of manufacturing was the main concern of designers, which led to standardized products being the norm. Consequently, the shape of the product was relegated to a secondary role and aesthetics was not highly considered during the design process. Subtractive processes such as machining represent the cornerstone of current manufacturing processes due to their high precision and ability to shape a wide range of materials, but these technologies have reached their limit in terms of producing complicated geometries and processing hard-to-cut materials.

The main theme of DFX is design for manufacturing (DFM) which was the dominant paradigm of the design and manufacturing industry of the 1990s. Since design decisions affect both the manufacturing costs and the productivity, designers played an important role not only in determining the shape and function of the product, but also its manufacturability, cost, and lifecycle. In the case of subtractive manufacturing processes, 80% of the cost of the manufacturing is determined during the design stage while the cost of designing itself is only 10% of the overall cost. The general rules of DFM consist of designing assembly with a minimum number of parts, standard parts, modular design, and multi-functional parts, making parts standard for multiple products, maximum surface roughness and tolerance, avoiding secondary processes, using materials that are easy to manufacture, minimizing the handling of parts, and setting the guidelines of design and shape. These general rules focus on the cost and manufacturability of the process, which lead to uniform/standardized products.

In recent years, additive manufacturing (AM) and sustainability have become widely discussed topics in the field of manufacturing. Additive manufacturing (three-dimensional (3D) printing) has opened doors to numerous new applications since there is no need to define a blank geometry or to consider jigs, fixtures, clamping, molds or dies, requires minimal set-up and avoids handling more material than is needed. Although additive manufacturing processes could find use in a wide range of areas due to their increased capability and simplicity, they have faced a lack of traction in industry. Material properties and precision of the part are still the main issues in additive manufacturing, but are not solely to blame for AM's lackluster adoption rate.

Customization and diversity have emerged as some of the main aspects desired by designers and customers alike, which is the opposite of the previous DFM paradigm which promotes standardization. In order to meet those needs, a new paradigm of manufacturing is required: Manufacturing for Design (MFD). This paper introduces Hybrid Manufacturing (HM), a tool of MFD, and discusses its key issues such as platform, modularization and integration. Examples of HM will be presented, and their importance in the successful implementation of MFD will be elaborated later in this article.

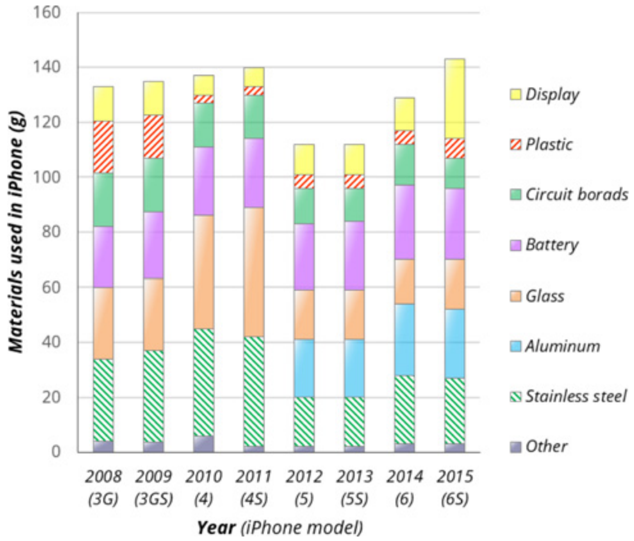


Fig. 2 Materials used in iPhones

2. Paradigm Shift from DFM to MFD

People have come to expect not only a specific functionality at a low price from products which they purchase, but also a product that fulfills other expectations: Aesthetics, multi-functionality, efficiency and eco-friendliness. Nowadays, a product that does not meet these needs is not likely to succeed despite being functionally sound. In parallel, regulations are forcing designers and manufacturers to consider end-of-life as a cost in addition to manufacturing costs. Thus, previous DFM guidelines do not meet the needs of today.

An example of this phenomenon is Apple's iPhone introduced in 2007, which was bundled with an array of functionalities in addition to being able to make phone calls and browse the internet, and has been successful largely due to its aesthetics. Fig. 2 shows the evaluation of the material distribution of each model from 2008 to 2015.[3] Since 2010, Apple has been using glass as a finishing material for the back panel instead of plastic, which increased manufacturing complexity, costs and weight of the phone. In 2012, the iPhone 5 increased its screen size from 3.5 inches to 4 inches while reducing its weight to 80% (112 g) of the previous model (140 g) by using aluminum for the structure, which was fabricated via precision machining. In 2014, the iPhone 6 introduced a filleted glass to the front of the phone, which required a manufacturing process more advanced than that of the previously used flat glass pane. The development of the manufacturing complexity of the iPhone was guided by the needs to make a product that customers wanted to purchase rather than one that met functional needs at a low price.

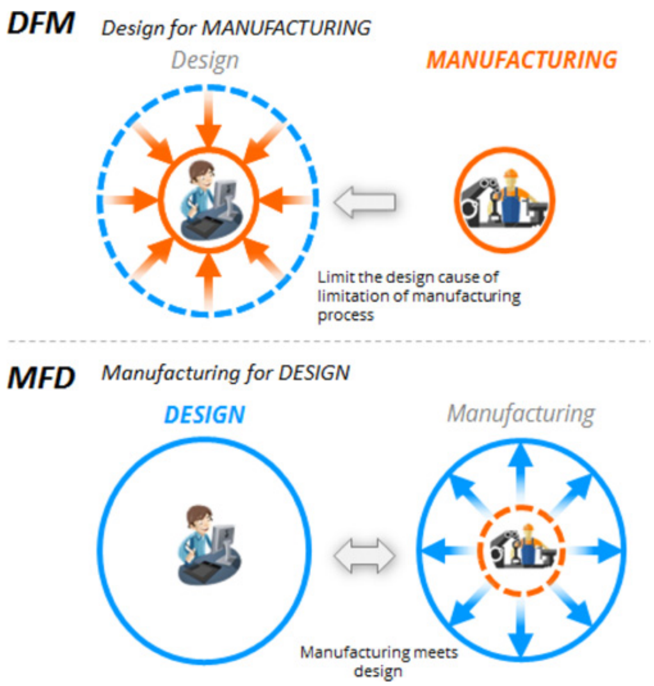


Fig. 3 Concept of DFM and MFD

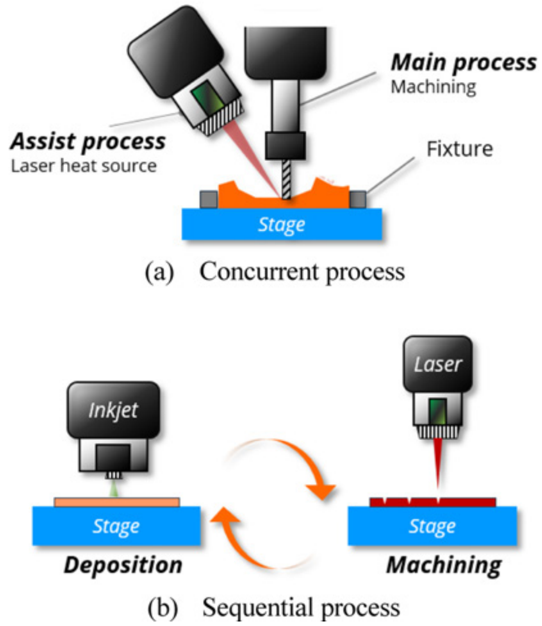


Fig. 4 Concepts of two types of HM processes

Table 1 A comparison between TM and HM process

Requirement	Limitation of TM process	Advantages of HM process
Development of a new process	Gradual	Innovation/Fusion (Physics + Chemistry + Energy)
Workpiece material	Single material	Multi-Material functionally graded material
Precision	Error from setup and transfer	Reduce reference error by sharing stage
Complexity of feature	Limited by single process	Full 3D feature by hybrid process*

* ex.: Machining + 3D Printing

Such is the main reason for the creation of a new paradigm called design realizing manufacturing (DRM) or MFD: manufacturing can be used as a tool to improve the design of the product and thus increase its viability in today's markets. This stands in stark contrast to previous practices where design was constrained by manufacturing limitations, as shown in Fig. 3. The importance of implementing Smart Factory concepts for MFD and meeting not only the customer needs, but also their desires, will be shown. Concepts, implementation considerations and examples will be discussed.

3. Hybrid Manufacturing

3.1 What is HM?

Although there are multiple definitions of HM, there is still an ongoing debate on which definition is the most appropriate.[4-21] In this article, HM, or hybrid process, is defined as a combination of processes that 1) have influence on the characteristics of the process or product, or 2) involve one or more processes having a significant effect on the results or characteristics of another. It can be perceived as a single process that simply combines two different processes on one platform, or a series of sequential processes taking place in separated environments, as shown in Fig. 4. Previously, hybrid approaches were implemented to improve the quality of the product or to enhance the productivity/efficiency of the process. Lately, however, the goal of HM has also expanded to enabling the manufacturing of products that cannot be manufactured or fabricated by traditional manufacturing (TM) processes.

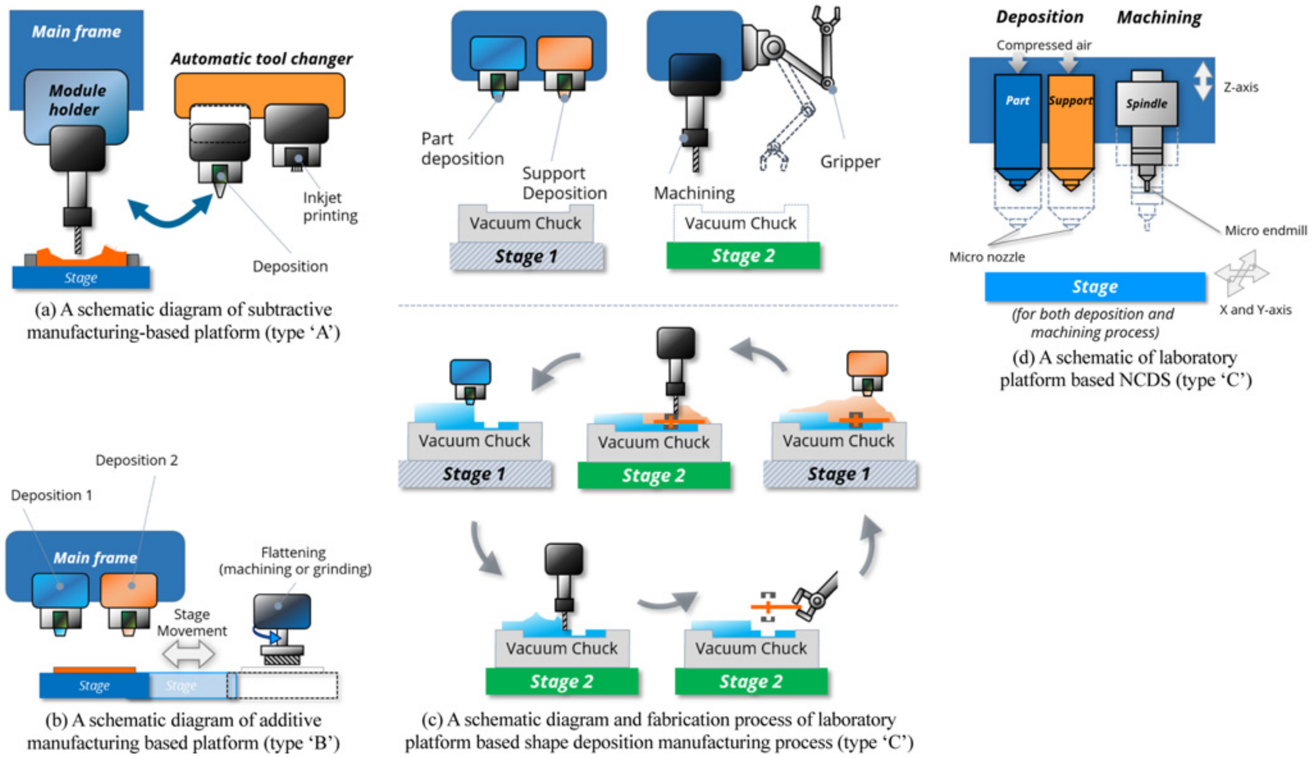
3.2 Why HM?

Some of the potential advantages of HM are: Efficiency, reduced energy consumption, ultra-precision, and ability to process hard-to-cut-material. A comparison of HM to TM, highlighting the advantages of each, is shown in Table 1. However, depending on the combination of processes the resultant hybrid hardware could give rise to inefficiencies, higher energy consumptions, referencing errors, and increased costs. Also, redundancies such as the non-operating time of each process, energy, total process cost, and others should be considered before implementing the HM process to avoid dealing with the aforementioned disadvantages.

3.3 Issues of HM

Three components should be considered for the implementation of HM: platform, process modules, and control (including S/W). The selection of an appropriate platform will affect the performance of the overall HM process since the precision, productivity, energy, and other such factors are dependent on the platforms. Three types of platforms are presented in this article, as shown in Fig. 5.

Type 'A' is a platform based on subtractive manufacturing (SM). SM is a TM method based on machine tools, which is one of the most common tools in industry. Similar to tool changers in machine tools, an automatic tool changer can be designed to enable modularized manufacturing processes and be attached to the machine tool such that processes like inkjet printing or deposition could be executed on a single platform. One of the main issues of Type 'A' is the consideration



(a) A schematic diagram of subtractive manufacturing-based platform (type 'A')

(b) A schematic diagram of additive manufacturing based platform (type 'B')

(c) A schematic diagram and fabrication process of laboratory platform based shape deposition manufacturing process (type 'C')

(d) A schematic of laboratory platform based NCDS (type 'C')

Fig. 5 Schematic diagrams of three different types of platform

of design of modules for additional processes.

Type 'B' is a platform based on additive manufacturing (AM), which is also well known as 3D printing. Some of the major issues with 3D printing technologies are the process time, finishing, material properties, post-processing, and precision. For these reasons, machining or other post-processes are often added to the process. However, since most of the 3D printing machines are designed for the deposition process, the platform has a low stiffness and is relatively weak compared to that of Type A. Therefore, additional processes are usually placed in different frames or locations and share the same stage. An alternative has been to place both processes in the same frame and to conduct limited work such as flattening through grinding or machining instead of freeform surface machining.

Type 'C' is a laboratory platform which is customized depending on the combination of processes. This type of platform might be constructed using components that are not available in the current market. Additional axes, modules, stages, can be easily adapted to the frame, and components like grippers or pins can be added. Similar to many custom-made platforms, this type of platform may have issues with rigidity. The advantages of this model are flexibility and expandability. Two examples of this type of platform are shown in Fig. 5 (c, shape deposition manufacturing (SDM) from Stanford University)[22-26] and (d, nano composite deposition system (NCDS)[27] from Seoul National University). SDM was developed in the late 1990s and uses a vacuum chuck to combine two different processes in different frames. As in Fig. 5(c), material is first deposited and the vacuum chuck is the used to transfer it to a different stage for the machining process. By repeating this process, 3D structures or parts can be fabricated with embedded component(s). The main issue of this process is the referencing between the two different platforms. NCDS, on the other hand, was developed to fabricate functional 3D structure in micro scale. The reference error, which usually occurs in sequential HM using different platforms, was solved by sharing the stage.

Table 2 Comparison of three different platforms of HM

	Type A	Type B	Type C
Process portion	SM > AM	SM < AM	SM AM
Frame stiffness	High	Low	Medium
Applicability of concurrent process	Medium	Low	High
Compactness of H/W	Low	High	High
Schematic diagram	Fig. 5(a)	Fig. 5(b)	Figs. 5(c) and 5(d)

* SM: Subtractive manufacturing, AM: Additive manufacturing

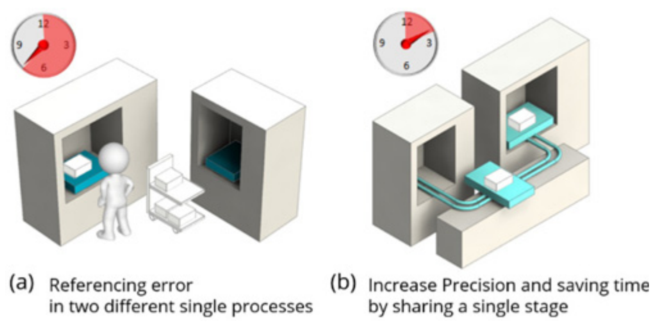


Fig. 6 Referencing issues in HM

Since HM has multiple processes, referencing between processes need to be considered. Also, the modularization of each process is required if each process has different environmental conditions. A strategy for sharing a single stage among multiple processes is important since changing stage affects the total process time and the quality of the part. If the processes are in the same axis or frame, the

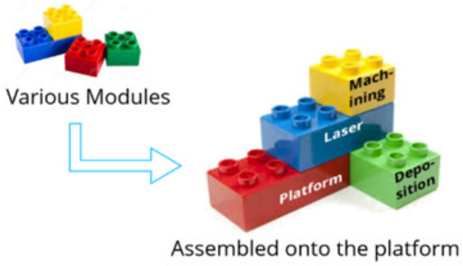


Fig. 7 An example of modularization in the HM

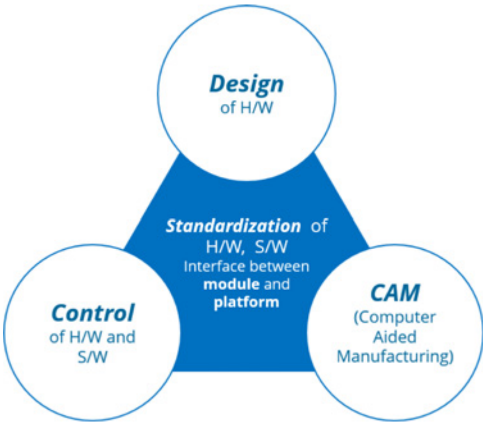


Fig. 8 Integration issues in HM

errors may be minimized, but the structure of the platform may need to be enhanced to support the increased weight from the additional processes. To enhance the precision and to avoid errors from using multiple stages as in Fig. 6(a), it is often suggested to use a single stage for the processes as in Fig. 6(b). Although additional control for the stage is required, the total process time will be decreased and the part quality will potentially be improved.

Previously, HM was conducted to enhance the productivity, improve surface quality, and increase the material removal rate.[21] Since relatively better results can be obtained compared to traditional single manufacturing processes, HM has also been applied to hard-to-cut materials or functional parts. Hybrid processes can also be used to expand the manufacturability and applicable areas. Modularization will be critical to expanding manufacturability and applicable areas using a single platform. As illustrated in Fig. 7, if various modules use a standard form, then it can be easily attached and assembled onto a single platform in order to conduct multiple hybrid processes.

Another issue that needs to be considered for the successful implementation of HM is integration of hardware (H/W) and software (S/W) and the use of integrated controls, as in Fig. 8. To connect different processes, the design of H/W, control of H/W and S/W, and CAM (Computer-Aided Manufacturing) for each process must be standardized for it to be used on a single platform.

The general process of developing an HM device has four steps. First, the requirements of the applications are determined in terms of materials, size, precision, porosity, or any other factors. Second, the selection of a combination of manufacturing processes capable of meeting these requirements is decided. Third, the modularization of manufacturing process and standardization of the hybrid platform is developed. Finally, the integration control of both H/W and S/W is implemented.

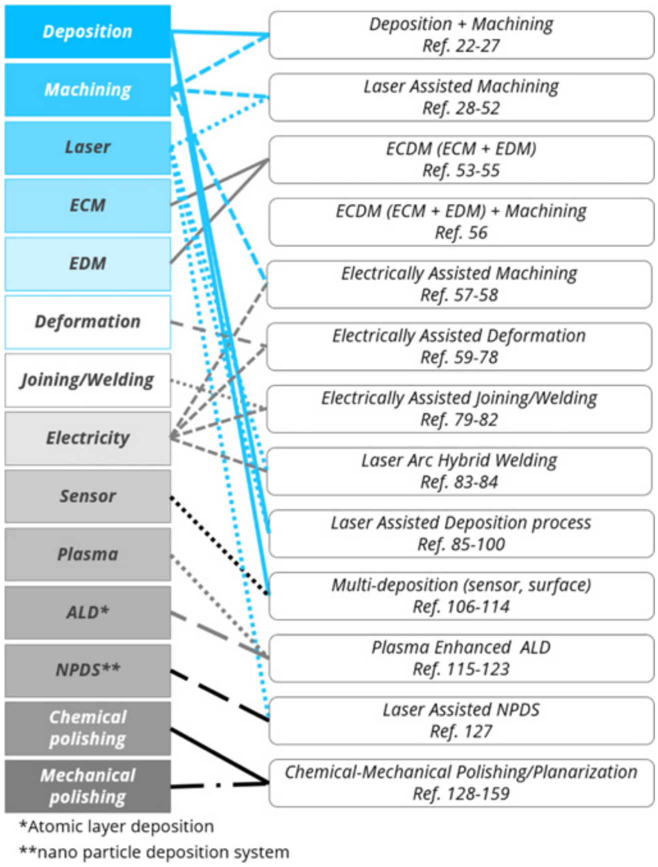


Fig. 9 A list of examples of HM process

3.4 Examples of HM Process

Numerous HM processes have been developed so far using diverse combinations of traditional and non-traditional processes. Currently available HM processes and the combination of manufacturing processes from which they were created are shown in Fig. 9.

Multiple examples of HM processes combining deposition and machining have been developed.[22-27] NCDS enables manufacturing at the micro-scale using multiple composite materials.[27] The system has a micro needle (140 micrometer in diameter) for the deposition process and a micro end mill (100 micrometer in diameter) for the machining process. The system has 3 axes for the movement of the stage, 3 axes for the tools, one for the machining process and two for the deposition nozzles of the deposition process. The hybrid process was compared with two other manufacturing processes, deposition-only and casting, and showed a lower error (0.17%) than both the deposition-only (23.32%) and casting (14.55%) processes.

LAMill uses a laser combined with a conventional machine tool to fabricate ceramic parts or parts from other hard-to-cut materials with three dimensional shapes. A schematic diagram of this process in shown in Fig. 10.[28-32] AISI 1045 steel and Inconel 718 were used to manufacture parts with a cylindrical shape using LAMill, and the required cutting force and part accuracy were compared with conventional machining. For the AISI 1045 steel part, the cutting force was decreased by 82% and the surface roughness was improved by

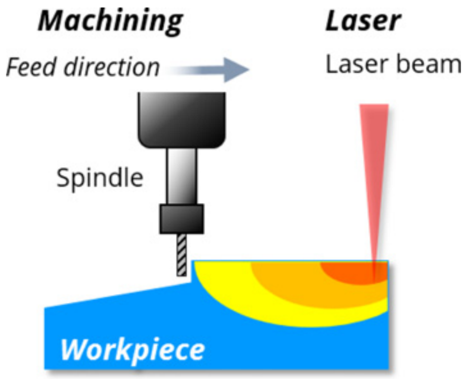


Fig. 10 A schematic LAMill system

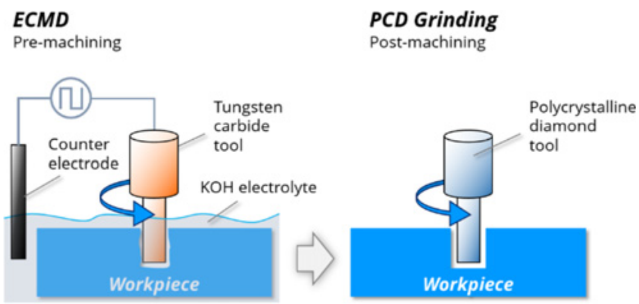


Fig. 11 A schematic diagram of hybrid micromachining using ECDM and micro grinding

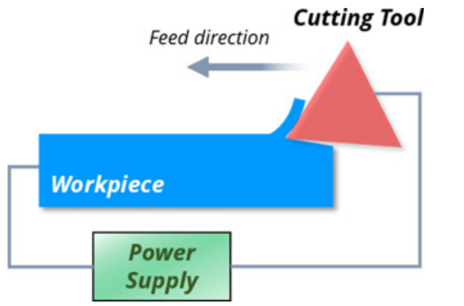


Fig. 12 A schematic diagram of electrically assisted machining

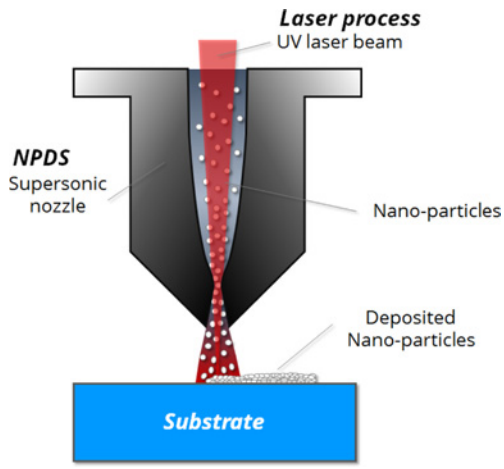


Fig. 13 A schematic diagram of laser assisted NPDS

53%. For the Inconel 718 part, the cutting force was decreased by 38% and the surface roughness was improved by 74%. Other laser assisted machining HM processes have also been explored, including turning, planning, face milling, end milling, ball end milling, etc.[33-52]

Electrochemical machining (ECM) and electrical discharge machining (EDM) were combined into an HM called electrochemical discharge machining (ECDM) in order to enhance the performance of key factors like the productivity and the surface roughness productivity and the surface roughness.[53-55] Micro ECDM and micro grinding were used to realize hybrid micromachining of glass (Fig. 11).[56] The total machining time of this hybrid process was 30% lower than conventional grinding processes while having better ground surface quality.

Electrically assisted manufacturing is an HM that uses the electro-plasticity of metals and metal alloys to facilitate manufacturing, obtain a low processing energy density, improve the quality of the product, etc.[57-82] A schematic of electrically assisted machining is shown in Fig. 12. A new HM welding process called laser arc hybrid welding was developed by combining an electric arc with a laser.[83,84]

Deposition processes can also be improved using additional processes such as the use of laser to fabricate sensors[85-100] with nanoscale structure, as well as to improve the surface properties.[101-105] Also, the process can be applied to flexible or stretchable sensors.[106-114]

To enhance the ability of atomic layer deposition (ALD), a plasma process was added to form a new HM.[115-123] This HM process is called PEALD (plasma enhanced ALD) and showed a reduced electrolyte thickness with higher surface grain boundary density.

Nano Particle Deposition Systems (NPDS) have been used to create nano/micro-sized coatings and structures.[124-126] NPDS was combined with a 355 nm pulsed laser to form an HM process called the Laser-assisted Nano Particle Deposition System (LaNPDS) to achieve decreased thermal damage and sintering effect (Fig. 13).[127] This HM process was used to fabricate flexible dye-sensitized solar cells (DSSCs) by depositing TiO_2 on glass and polymer substrates, and samples manufactured by LaNPDS showed better efficiency (1.00% for the glass substrate and 0.99% for the polymer substrate) than those manufactured using NPDS (0.45% and 0.42%, respectively).

Chemical and mechanical polishing (CMP) were combined to improve the quality of fabricated surface.[128-159] Many studies regarding the CMP were conducted, such as material removal rate (MRR), signal analysis, formation of material defects, slurry reduction, slurry components, process parameters, analysis of pressure distribution, mathematical model-based evaluation methodology, effects of a spray slurry nozzle, analysis of removal mechanism, macroscopic and microscopic investigation, abrasive size, effect of pad groove geometry, pad roughness variation, temperature distribution in polishing pad, contact angle between retaining ring and polishing pad, and their applications.

3.5 HM and MFD

It was shown that HM can be implemented in numerous methods using a wide variety of processes. The reason for developing new HM processes is that it brings to the table novel ways to produce parts with new types of features and capabilities, thereby allowing customization.

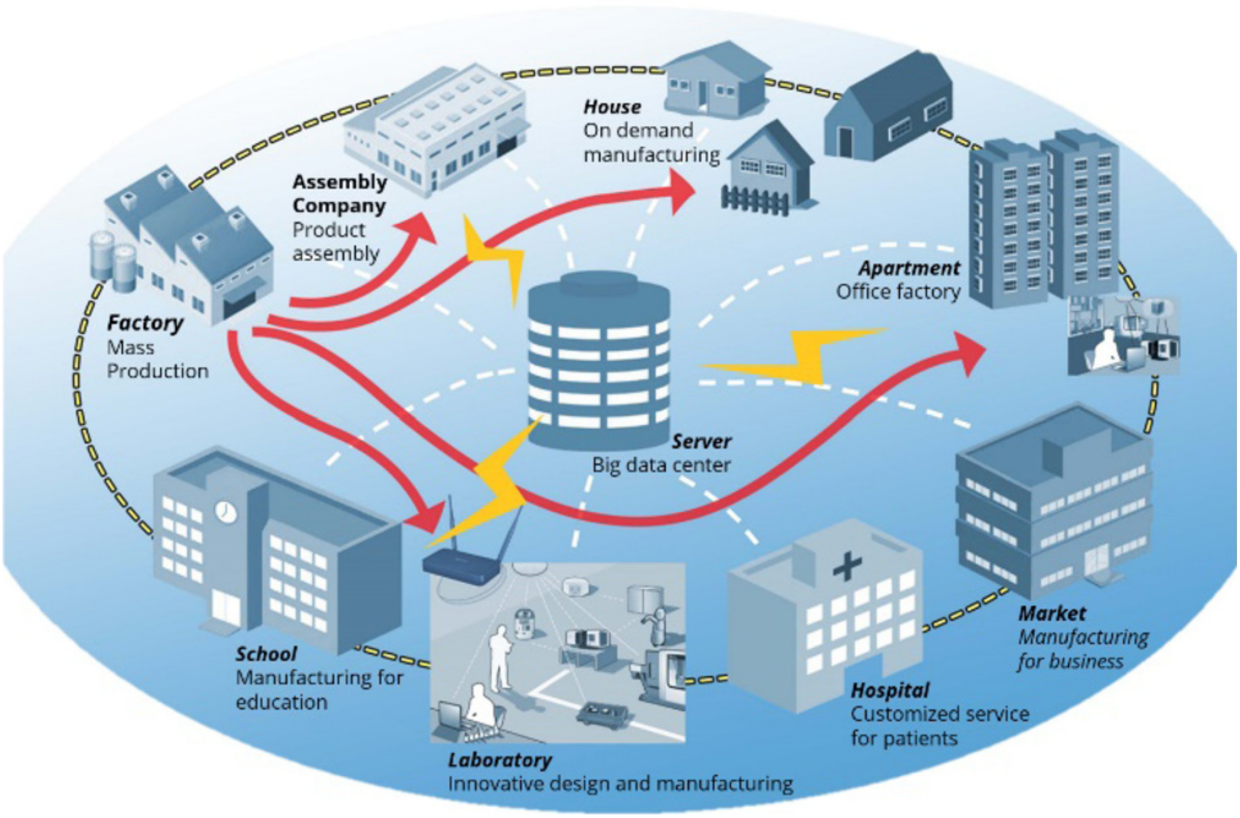


Fig. 14 Future smart factory based on distributed manufacturing and HM

It also increases efficiency and allows production in smaller batches. For these reasons, the use of HM will be one of the key enabling factors of MFD to efficiently manufacture products that reflect the designers' imagination and customers' wants by expanding the limitations of possible design, enabling even broader customization than what was considered possible.

4. Future Trends of HM and Smart Factory

MFD requires closer collaboration between designers and manufacturers while simultaneously providing access to a larger array of manufacturing processes for a more optimal function. However, MFD as a paradigm is not yet complete in today's industrial base, and will require modifications at all levels for it to reach its full potential. It was shown previously that a wide range of HM processes is available for designers to augment their designs in order to make a complete product. However, these new manufacturing processes are not likely to become as uniformly available to facilities as the current manufacturing processes. But rather, they can be easily adapted to a variety of designing requirements with flexibility. Therefore, the main issues of the HM involve accessing platforms, thus providing the designers with unrestricted access to these new manufacturing capabilities.

Cloud-Based services with monitoring and design have been gaining attraction and can be used as a platform on which the factories of the future - the Smart Factories - can be built. The goal of the Smart Factory concept is to enable any customer to access any manufacturing capability necessary to manufacture a desired product. The availability of cloud-based systems to design, improve and augment designs for anyone, and to connect these designers with the required manufacturing capability and processes, whether they are subtractive, additive or hybrid, in a timely and efficient manner will open a revolutionary door for the start of a virtual factory that connects customers and manufacturers who are working from distinct locations.together.

Fig. 14 shows the concept for a Smart Factory where all components ranging from customers to high-tech, low-volume laboratories are interconnected, functioning as a single unit through the use of cloud-based collaborative software. The factory might be a subtractive manufacturing center capable of processing high-volume parts, but without any HM capabilities. If the market demands a high-volume part made solely by subtractive manufacturing, along with lower volume parts made via the same process, followed by a hybrid process, the Smart Factory system would help connect the customer, the factory and the laboratory capable of the required HM process while functioning seamlessly as a single factory and without the implementation of a new supply chain.

5. Conclusions

As the prevalent paradigm of manufacturing shifts from DFM to MFD, the technology must also evolve to better meet the needs of designers and customers. In this article, HM was introduced as an ideal candidate for MFD due to its capability of increasing the speed and efficiency of manufacturing, and the design space it allows. However, HM faces many challenges in widespread adoption. The future research of HM should focus on platform development, modularization, and the integration of process planning and control.

Although HM can provide better MRR, productivity, energy consumption and/or precision than the current single processes, the advantages and limitations of the entire HM process must be considered, including any additional transport or delay in production introduced by the introduction of a more complex manufacturing system. For this reason, the concept of Smart Factory could assist in reducing or eliminating such drawbacks of HM by combining large-scale production by SM with remote small-scale HM capabilities, thus reducing delays and minimizing secondary costs.

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