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INTELLIGENT ENERGY FIELD MANUFACTURING (EFM)

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ABSTRACT

The nature of manufacturing is using information to control energy field in order to convert material into useful configurations, products, and systems. One way to view manufacturing differently is to explore it from the perspective of energy fields. In this paper, the origination and the evolution of Energy Field Manufacturing (EFM) and the concept of a dynamic M-PIE (Material-Process-Information-Energy) model of manufacturing are reviewed. The generality of energy fields and the importance of re-thinking of traditional and non-traditional manufacturing are discussed. Giving a general definition to intelligence, this paper further broadens the methodology of EFM to Intelligent EFM, which incorporates the ability to gather, interpret and use the information in energy fields, materials and systems in a systematic way. This paper further discusses the meaning and tasks of Intelligent EFM research. A systematic approach of energy field integration and optimization is proposed. Finally, representative processes are reviewed to highlight some principles of Intelligent EFM.

KEYWORDS

Innovation, Manufacturing Methodology, Energy Field Manufacturing (EFM), General Intelligence, Intelligent Energy Field Manufacturing, Logic Functional Material, Dynamic MPIE model, 3D Manufacturing, Process Optimization

BACKGROUND

In 1988, a USTC professor explained to the undergraduate class the over 20 processing steps to make a precision gage block. A discouraged student thought hard to simplify his future mechanical engineering career, and initiated the concept of "Virtual Mold 3D Manufacturing". The concept was developed into "Energy Field 3D Manufacturing" in 1995 [1, 2]. In competition with Rapid Prototype Manufacturing (RPM), a Chinese patent was filed to protect the core ideas of Energy Field 3D Manufacturing. These early studies focused on the methodology and hardware development to realize and simplify truly 3D manufacturing with low cost, high speed and high quality. A basic belief espoused in each of these studies is that 3D manufacturing requires newer and more complex methodologies than 2D and 2.5D manufacturing. A simple analogy between these methodologies can be understood by contrasting airplane transportation, which follows the contour of the earth, to automobile transportation, which follows the local contour of the land being covered.

Important concepts in Energy Field 3D Manufacturing include: *Energy Field Generator, Logic Functional Material and Dissociation Forming*. Energy Field Generators produce programmable energy fields in different directions and act on Logic Functional Material. At the cross location of energy fields, the material is physically or chemically modified, and dissociates from the bulk material, thus 3D geometry is continuously grown up or carved out. The use of programmable field aims to simplify the path planning work in traditional approaches and speed up the process through parallel processing.

Logic functional material was defined as a material with three states: normal state, excited state and qualitatively changed state. With suitable level of energy interaction, the material is excited close to the permanent modification state, but after the energy field is removed, it recovers to normal state. Elastic deformation would provide a relevant example. Material reaches an excited state when an additional energy field is applied or when a further increase in the intensity of energy field is used, preferably a selective energy field. In this case, the material changes permanently, and certain effects can be used to dissociate the affected zone from the bulk material. This bulk material can be gas, liquid or solid. When these concepts were initially proposed, they were regarded as too ideal to be practical. However, laser direct writing of micro-fluidic structures in photonic glasses, selective electric plating cell, and the selective chemical vapor deposition in micro engineering [3] all illustrate the value of the concept, although the field idea is not always implemented.

From 1999-2001, Columbia University and several other USA organizations participated in a NSF funded project—Combined Research and Curriculum Development on Non-traditional Manufacturing (NTM). Representative NTM (non-traditional manufacturing) processes, such as laser material processing, abrasive water-jet machining, and ECM/EDM, were studied, cross process innovations were discussed, and a web-based NTM curriculum was made available to the public [4-5]. This project reveals that:

1. NTM processes are normally regarded as the alternative to traditional manufacturing processes. They are employed when traditional methods couldn't meet the processing requirement. This way of thinking, in addition to the capital investment considerations required for NTM, hampers the wide spread use of NTM processes.
2. Current NTM teaching is process based, and it lacks a systematic way of introducing technology concepts. As a result, a change in NTM teaching is needed that will better prepare the next generation engineers for future challenges.
3. Process innovations clearly underscore the importance of breaking the barriers among various energy fields and processes. When trying to find the optimal solution to an engineering task, all energy forms should be considered. In reality, unfortunately, the old thinking of dividing people and resources into traditional and non-traditional disciplines seriously hampers successful innovation.

These deficiencies are understandable given that the majority of managers, engineers and workers are only trained in limited manufacturing processes, and trepidation toward the unknown world is human nature.

Innovation has been regarded as the single most important factor that decides the global technology leadership for a country or an organization in the global economy. Innovation is defined as the "first commercially feasible demonstration of the invention or the creative ideas." [6] Big-impact product innovations normally require some key process innovations; Thus, the success of a product innovation plan ties closely to the manufacturing processes or process innovations. Despite tools such as brain-storming, trade-off analysis, and benchmarking that help break the barriers of process innovation, it is observed that process innovation is still trial-and-error based, lacking a systematic approach. TRIZ, or Creative Problem Solving in Russian, gained certain success in USA, Japan and Europe. TRIZ proposed a systematic approach using patterns, principles and knowledge-bases to solve system contradictions using tool-object interaction analysis (or Sub-field Analysis) [7-8]. TRIZ is a good methodology for general problem solving; however, engineering innovations need not only the operable procedures to generate crude creative ideas, but also the clear skills and methodology to implement and optimize the creative solutions.

Over the years, it is felt that the methodology initially proposed for 3D manufacturing applies to general manufacturing processes. When combined with other engineering thoughts, a high-level methodology for engineering can be derived which facilitates systematic process innovation and efficient technical communication. This paper will focus on methodologies of manufacturing process innovation.

In this paper, we first discuss the barriers of innovation. Then we review the dynamic M-PIE (Material-Process-Information-Energy) model for manufacturing [9]. The generality of energy fields, intelligence, and logic functional materials are then introduced. Thus we extend the methodology of EFM to Intelligent EFM, which incorporates the tools and methodology to gather, interpret and use information in a systematic way. Finally, representative processes are reviewed to highlight some principles of Intelligent EFM.

CHALLENGES OF INNOVATION

Innovation, or the successful commercial implementation of creative ideas depends on many factors. Ref [6] mentioned that culture is insufficient in itself to explain the innovative capabilities of a society. The economic and political institutions which surround the cultural base of the society plays an important role as well. The same can be said to individual organizations.

With globalization, most organizations have been confronted with sharper competition, increased customer demands. As a result, they are forced into a cycle of continuous innovation of their products, services and production processes [10]. Innovations can be high risk. Innovation efforts meant to improve quality may show the opposite in reality. Innovation initiatives may fail, wasting time and resources. There are many barriers for efficient innovation, such as lack of clear strategic vision, resistance between different levels of the organization, unmatched innovation objectives and resources, defective decision making, unhealthy company culture, unsuccessful marketing and service execution etc. Integrated and controlled innovation trying to address these issues was discussed in detail in [10].

Innovations can be roughly divided into product or service innovation, process innovation, and organizational innovation. As shown in fig. 1, normally the strategy of an organization is decided based on market and technical pull, and then new product ideas are generated. Research and development efforts are heavily involved in new product idea generation and introduction. These new product ideas are then communicated to disseminate the ideas across the organization, and finally implemented and commercialized. This paper limits the discussion of innovation to the new product idea generation and production transition stage, with the understanding that the other phases are important as well.

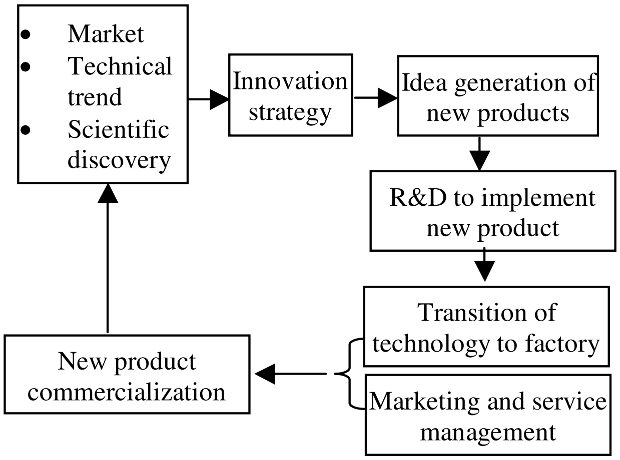

Fig. 1 Cycle of new product innovation

Successful innovation normally starts from scientific discovery. Next, the inventions or useful applications of scientific discoveries are realized, and finally, the invention is successfully commercialized through engineering implementation. It is not rare to see that many projects focusing on new product innovation run into trouble due to improper efforts and resource allocation during process innovations. As many leaders discovered, the challenge of innovation is not the lacking of ideas, it is the picking of the best ideas and how to effectively convert ideas into final products. Unfortunately, people good at scientific discovery may not be as good at process innovations, which are critical to bridge the creative ideas to final products.

In short, *process innovations are normally required in major product innovations, but their importance is normally underestimated.* A failed innovation project often heavily leaned on basic research, and only called upon the process engineers to help meet project deliverables in last minute, without realizing that manufacturing engineers should be involved in the very beginning of the innovation process, and process innovations require and deserve sufficient time and resource to succeed. An early thorough process innovation check will make the following innovation efforts much more efficient.

Besides these innovation management issues, there are innovation barriers within manufacturing engineers that are not widely discussed in literature. They are the historically biased view of manufacturing processes and the lacking of high level systematic ways to go about manufacturing process innovation.

As noted earlier, manufacturing processes are generally divided into traditional and non-traditional processes. Traditional manufacturing relies on direct mechanical contact between the tool and the workpiece, such as found in forging, turning, milling, etc. In contrast, non traditional manufacturing processes are (1) processes in which there are nontraditional mechanisms of interactions between the tool and the workpiece, and (2) processes in which nontraditional media are used to enable the transfer of energy from the tool to the workpiece [11]. These definitions of traditional and non-traditional manufacturing, however, change with the maturity of technology and are historically biased towards mechanical methods and tend to be empirically based. For example, casting processes have been utilized for thousands of years. They are generally regarded as conventional manufacturing although casting primarily involves thermally controlled phase transformations. On the other hand, diamond precision machining holds the highest machining quality, yet it is unconvincing to claim it as a traditional process.

Strict distinction between traditional and non-traditional manufacturing doesn't have much engineering value, but it is important to notice that improper education and research philosophy based on the historically biased vision of manufacturing may implicitly hamper technology innovation and integration. To better equip researchers and engineers with a systematic methodology for technology follow-up, improvement and innovation, and to better meet the challenges of modern technology development, the methodology and philosophy of manufacturing should be continuously studied. A general philosophy of manufacturing will lower the difficulties of process innovation by providing a framework for systematic and guided thinking, lowering the shock of technology progress, and providing a common vernacular for communicating engineering ideas, thus bringing engineering closer to the public.

This paper tries to outline the methodology for the analysis and innovation of manufacturing processes. The methodology is based on the dynamic M-PIE model and the generality of energy field, logic functional material and intelligence.

ENERGY FIELD MANUFACTURING (EFM)

Before the discussion of Intelligent EFM, the key points of EFM discussed in [9] are summarized in the following for completeness.

The Generality of Energy Fields

Energy is the ability to do work. Energy field is the spatial and temporal distribution of energy. People may assume that sometimes we are using "point energy", but this is only a relative and simplified concept—"point" is merely a localized energy field. Energy field is a more general concept and a more strict description of the real world. A focused laser beam might be regarded as a point energy source, however, in micromachining for example, we must consider its spatial and temporal distributions. Traditional machining commonly relates to stress fields and thermal fields. Gravitational fields and environmental pressure fields are always present.

In addition to mechanical forces, sound, light, electromagnetic fields, thermal fields, particle flows (such as electron beams, ion flows) and fluid flows (water-jet etc.), it is convenient to identify the medium or environment under which interactions take place as a special kind of energy field—a *Medium Field or Medium Environment*. Electroplating, Electro Chemical Machining (ECM) and Electro Discharge Machining (EDM) need a special medium environment to do their work. Reactive Laser Cutting uses oxygen to assist machining. A premature thought is that different medium distributions may be defined to be of different energy states, i.e., medium energy potentials. This not only helps explain physical phenomena, but also can help quantify the effects of medium environment. Medium fields, which are relatively easy to change and utilize compared with gravitational and pressure fields, play important roles in many processes, but not enough attention had been paid to optimize them.

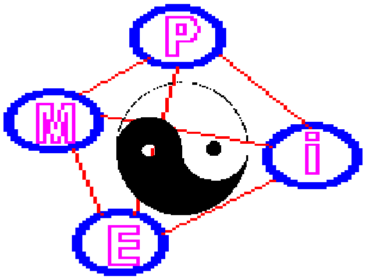

Fig. 2 The Dynamic M-PIE Model. Flows in Energy Field Manufacturing: Project/Process/Production (P), Information/Intelligence (I), Energy (E) & Materials (M).

One common feature of various manufacturing processes is the extensive use of various energy forms and energy fields. In fact, the whole engineering is the art of energy field utilization and manipulation. Rather than relying on personal inspiration, methodologies can be developed to systematically improve our skills of energy field manipulation and integration. We term engineering solutions featuring meaningful energy field manipulation and integration *Energy Field Methods*.

The Dynamic M-PIE Model

The essence of manufacturing engineering is that one must utilize information to control energy and mass to achieve desired objectives. Energy fields carry information and convert materials into final products. Thus energy field manipulation is central in all manufacturing processes. Fig. 2 illustrates three flows existing in any manufacturing processes (P) and systems: information flow (I), energy flow (E) and mass/material flow (M). Rather than dividing manufacturing processes into traditional or nontraditional, we should treat them equally as kinds of *Energy Field Manufacturing*, which features the optimal integration of energy field methods and high level integration of the M-PIE flows. Thus Energy Field Manufacturing is not a category of new processes, it is the methodology to solve engineering challenges and contradictions, and it is the software and hardware for manufacturing process analysis and optimization.

The Tai-Chi symbol in Fig. 2 highlights the pervasive existence of contradictions, the relative and the dynamic nature of these contradictions, and the interaction and mutual conversion of different flows. Additionally, many things are relative in nature and have their positive and negative sides. The key of EFM is to find a systematic way of addressing the contradictions and reaching a higher level of optimization. Understanding the generality and relativity of energy fields is the first step.

The Generality of Logic Functional Material

The concept of logic functional material was initially introduced to realize truly 3D manufacturing by energy field induced dissociation forming. There are many materials that do demonstrate some unique properties, such as shape memory alloys which can recover to original geometry when the temperature condition is recovered, and ER/MR materials, which changes from fluid to solid when electric and/or magnetic field are applied. Many "smart materials" are discussed in [12].

It is realized that all materials have certain logic functionality in interaction with energy fields. We call this the generality of logic functional material. Finding out the unique functionality of a material in reaction to the certain energy fields can usually lead to creative processes.

For example, many materials have three states, gas, liquid and solid depending on the temperature. We can heat the bulk material to a critical condition, then use a focused energy to selectively remove the material. In this way, requirements on the expensive energy device can be lowered or the controllability of the other energy form can be increased. For example, ceramics is normally regarded as brittle and difficult to machine directly by mechanical tools. Using a laser or plasma to preheat it to the softened temperature increases the ductility and reduces the cutting force [13]. IR imaging is another example. Objects are difficult to see visually in darkness, but objects with different thermal radiation can easily be differentiated using IR cameras. Thermal expansion of materials can also be used in a controlled way. For example, bolts in tight connection can be pulled out by spraying liquid nitrogen, and can then be easily inserted into the matching structure. The bolts then expand to tight tolerance at room temperature. This can be a useful methodology for many structures.

One barrier of innovation is that we are too used to common sense that the functional response of the material to energy field is not well explored. To address this issue, knowledgebase of materials' response to various energy fields should be referred. Many contradictions can be solved if the proper functionality of the material is utilized. This is related to the following discussion of intelligence of manufacturing processes.

The Information Flow in EFM

The information flow in EFM includes information about the material, energy field, the interaction between energy field and material, and the involvement of human beings. The functions of the information flow in manufacturing processes are: 1) Prepare and plan the process; 2) Design and develop energy field generators; 3) Monitor and control energy field—material interaction to achieve the desired function and configuration; 4) Feedback to improve and optimize the product and the process.

The progress in information and sensor technology had deeply influenced the evolution of manufacturing processes. CNC systems, CAD/CAM driven processes, digital manufacturing, closed loop manufacturing, model based manufacturing, distributed manufacturing, global sourcing and fabrication, etc., are some of the examples of how information and sensor technology have been employed.

When we take a higher system point of view towards manufacturing activities, we can say that quality control and project management procedures, such as Design For Six Sigma (DFSS), Lean Manufacturing, Lean Six Sigma [14], etc., are all about how to optimize the information flow in engineering.

So what difference does EFM bring about compared with the existing manufacturing methodologies and management procedures?

In EFM, we believe that the higher level the integration of information, material and energy flows, the more advanced the manufacturing processes; and the goal of process innovation and optimization is to achieve the most advanced process defined above given the new standard, bearing in mind the practical constraints. Currently, the integration of the three flows in manufacturing is not emphasized, although more and more processes are pointing towards this direction.

Here are several examples. The integration of information with material results in intelligent or smart materials, and many processes are based on self-assembly of materials under proper energy conditions. Rapid prototyping manufacturing solved the difficulties of 3D structure fabrication through layered forming. These systems show high-level artificial integration of the M-PIE flows. Nano-wires show many unique properties and can be used in next generation display or high efficiency X-ray generation. Fig.3 shows the picture of tungsten nano-wires [15]. Such features are difficult to make by current machining or forming tools, but human beings used the natural integration of material properties with the information and energy field to grow them.

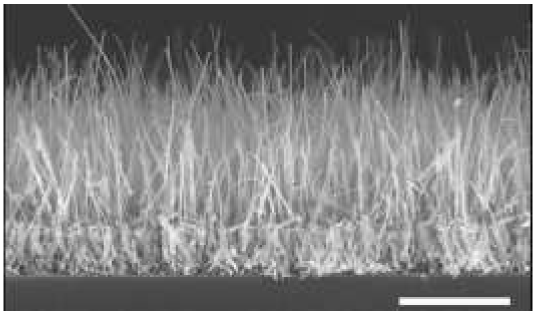

Fig. 3 SEM image of quasialigned WO_3 nano-tip arrays. Scale bar is 5μm [15].

Instead of studying individual processes and various engineering thoughts, which are being invented throughout our history, we should seek the main theme of technology innovation and try to find the methodology for innovation and optimization, thus better equip engineers to meet future challenges.

To achieve this goal, besides understanding the central role of energy field and the dynamic M-PIE flows, we need to introduce the concept of general intelligence and discuss the new standard of process optimization.

The Concept of General Intelligence

In certain sense, human beings' engineering activity is a process of injecting intelligence into the interactions between energy fields and materials. Intelligence can be defined as the ability to gather information, interpret the information, and take actions to profit from the information**.** Human beings may be too proud to claim themselves as the only intelligent existence. It is reasonable to say that animals and plants have different levels of intelligence. How about materials in general? Do materials have intelligence?

Our macro-scale observation concludes that "non-life" can't move and react with intention, and thus don't have intelligence. When one looks into the microscale and atomic scale, one must admit that based on the concept of intelligence outlined above, that atoms and molecules can sense and gather information about their environment. As a result, they will response to the surrounding fields (information) according to known or unknown natural laws. For a crystal, its growth, phase transition, chemical stability, and many other aspects, show similar adaptability to the environment.

*Thus, we define the **General Intelligence** as the capability of patterned response to surrounding energy fields. Patterned response means repeatable response given the same energy fields. Such patterned response can be beneficial or harmful depends on how we use it.* The matter or system is itself a sensor, receiver and activator of information imparted to it. To execute the message, it responds to or utilizes the surrounding energy fields.

Energy fields contains energy and information, so do materials. How energy, mass and information mutually convert is beyond the scope of this paper. It is beneficial to point out that: Anything, either a microscale particle or a macro system, has a certain level of general intelligence. Manufacturing engineers' task is to explore the general intelligence to realize higher level of advanced manufacturing processes.

INTELLIGENT EFM

All manufacturing processes are essentially energy field manufacturing processes. EFM featuring effective and systematic exploitation of general intelligence is defined Intelligent Energy Field Manufacturing. We need to differentiate Intelligent EFM in this paper from the Intelligent Manufacturing (IM) discussed in the 1990s [16]. Intelligent Manufacturing focused on the introduction of human-like decision-making capabilities into the manufacturing system to make it intelligent. Intelligent Manufacturing features knowledge based manufacturing utilizing intelligent techniques such as sensing and feedback control, expert systems, fuzzy logic, neural networks and genetic algorithms [17].

Intelligent EFM goes some steps further from the Intelligent Manufacturing: (1) In addition to using intelligent techniques in manufacturing, it features the methodology of EFM; (2) it emphasizes the utilization of general energy fields, the general logic functionality of materials and the general intelligence of materials and systems; (3) it is the combination of methodology, intelligent techniques, and the hardware innovation to implement Intelligent EFM.

The reason to propose Intelligent EFM is that a new methodology to meet future engineering challenges is needed. These challenges include:

3D and Intelligent Structure Manufacturing: Manufacturing is evolving from 2D manufacturing to 3D. Solving 3D issues using 2D technology is complex, is not cost effective, or is simply impossible. Beyond 3D manufacturing are intelligent structure manufacturing, which has both 3D geometry and self-sensing/self-repair functions. For example, structures with embedded sensors are being studied and used in airplane, spacecraft, buildings etc. to increase system safety.

Micro/Nano Fabrication: Manufacturing needs to solve issues at both macro and micro/nano scale. Conventional methods may be good for macro scale applications (dimensions > 100 microns). Shrinkage to dimensions below 100 microns requires the optimal use of various energy field methods and the general intelligence of materials and systems.

New Standard of Process Optimization: Quality, cost, cycle time, and responsiveness are the basic requirements for a process or a product. Conventional process and production considerations mainly consider manufacturer's interest. In Intelligent EFM, one must also consider the level of M-PIE flow integration and the impact of resource consumption. While M-PIE flow integration had been explained earlier, the impact of resource consumption emphasizes the consideration of environmental impact of human activity. Reducing pollution, considering the long term benefits to the society and the earth, and being wise stewards of our natural resources also need to be emphasized.

Winning in Global Competition through Innovation: Globalization is inevitable in information age. Any nation or organization that wants to take lead in the competition must have constant innovation in technology and management with minimal resource waste. Intelligent EFM addresses this challenge by reducing the innovation barriers and by developing a systematic way of technology innovation and optimization.

Adapt to and exploit the explosive increase of knowledge base: Human being's knowledge base is in explosive expansion and is becoming more accessible to a much wider population due to internet and globalization. Effective use of information will be critical for success. Innovation is constrained by the limited knowledge of the state of the art, and often, many resources are wasted in reinventing the wheels—solving the solved engineering challenges. Intelligent EFM aims to build up a system that naturally adapts to and helps engineers better exploit the explosive increase of knowledge base. Artificial intelligence and general intelligence are made part of Intelligent EFM.

By listing the issues and objectives involved in EFM, it is hoped that others will be attracted into the study of this direction. Next, we give a primitive framework to implement Intelligent EFM. The objective is to have a framework that is a self-sustaining open system.

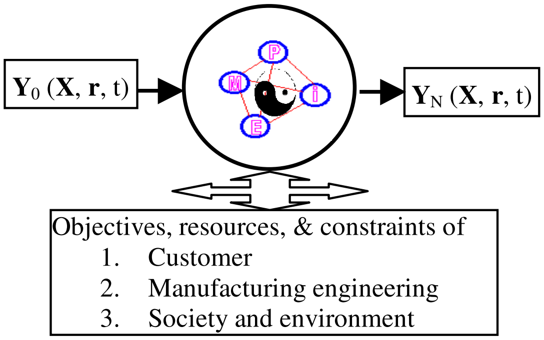

Fig. 4 The black ball links current status $\mathbf{Y}_0(\mathbf{X}, \mathbf{r}, t)$ to future status $\mathbf{Y}_N(\mathbf{X}, \mathbf{r}, t)$.

A FRAMEWORK OF INTELLIGENT EFM IMPLEMENTATION

The Black Ball Question

Fig 4 illustrates the task to be solved in manufacturing. Y_0 and Y_N are the current and final status of products/processes respectively, which are functions of time t, space $\boldsymbol{r}$, and other factors, $\boldsymbol{X}$. The black ball is the route we need to develop to link Y_0 and Y_N in the ($\mathbf{X}$, $\mathbf{r}$, t) space. The task of intelligent EFM is to optimize and execute the engineering route linking Y_0 and Y_N based on the objectives, resources and constraints from customer, manufacturing engineering, society and environment. This optimization is realized through EFM methods. Note that ($\mathbf{X}$, $\mathbf{r}$, t) is the optimization space. The more freedom of optimization we have, i.e., the wider range we take into account in $\boldsymbol{X}$, the higher chance of finding the best route.

The framework of Intelligent EFM mplementation trying to solve the Black Ball question is summarized in Fig. 5.

Step 1: From strategy to sub-task

When an organization decides its strategy of development, the desired future status of product or process is only vaguely known. Engineering team should study the technical trends and competitive landscape to understand and define the optimization space ($\mathbf{X}$, $\mathbf{r}$, t) based on the objectives, resources and constraints from customer, manufacturing engineering, society and environment, and then give a clear definition of Y_0 and Y_N. In General Electric, definition of Y_N is called CTQs (Critical To Quality). A practical management plan is worked out by dividing a big task into reasonable sub-tasks or milestones Y_0, Y_1, …Y_i…Y_N.

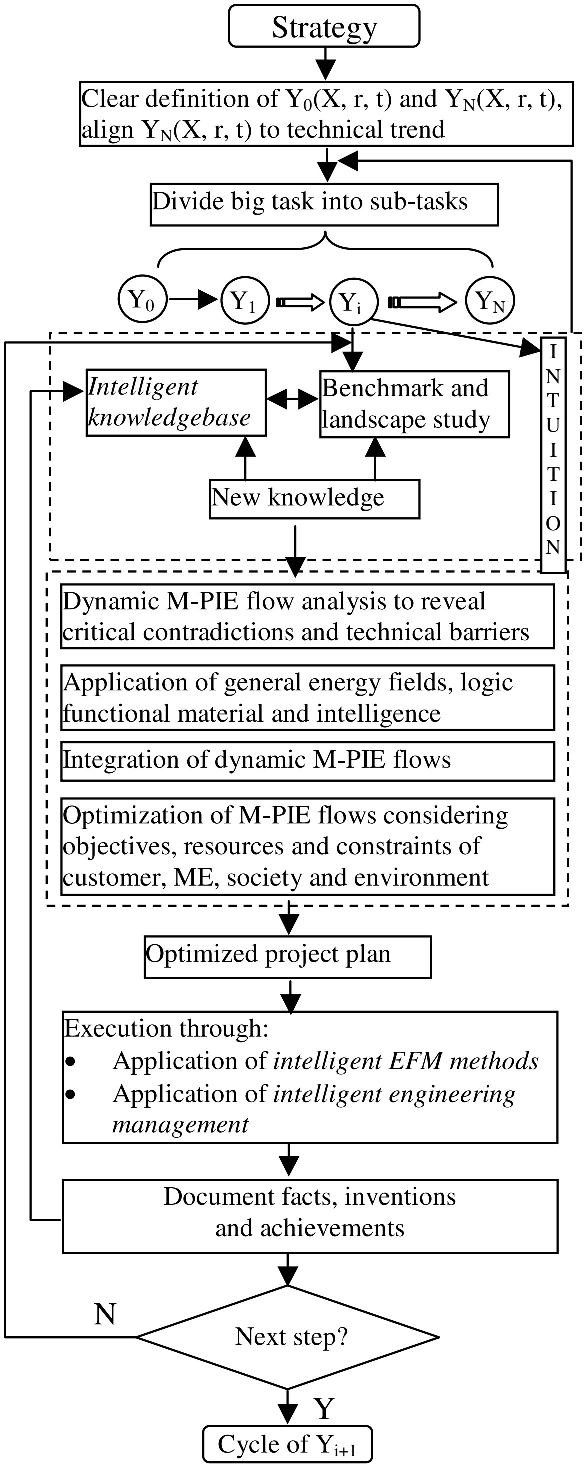

Fig. 5 A framework of Intelligent EFM implementation

Step 2: Making use of both heritage and intuition

It's not rare to see frequent reinvention of the wheels in R&D. Normally R&D is carried out by sub-set knowledge based intuition, such as the trade off of the brainstorming results from a group of experts. A historically solved problem may come up again. Due to dynamics within organizations, mismatched talents, improper documentation, and historical precedence, waste of resources during problem solving is pervasive.

The first thing differentiate Intelligent EFM from other methodology is that Intelligent EFM focuses on the intelligent and self-growing application of knowledgebase. An intelligent knowledgebase is set up and updated. It allows efficient and thorough study of benchmarking and landscape. Thus, when an engineering question is asked, historical and state of the art knowledge is checked systematically and thoroughly. Such knowledgebase ideally covers physical and chemical effects, publications, patents, document of tests, world wide web, internal web, and the current mindset. Software tools should be developed to facilitate this process.

Unlike TRIZ [7-8], which emphasizes a systematic approach of creative problem solving, Intelligent EFM references the complete set of human being's intelligence heritage, and emphasizes the equal importance of individual inspiration and intuition.

This step may require modifications to subtask planning. This step outputs the improved definition of the optimization space (**X**, **r**, t) and a better understanding of the competition landscape. Note that the Intelligent Knowledgebase is updated to include the new knowledge from both internal and external sources.

Step 3: Dynamic M-PIE flow optimization

Knowing the landscape and the optimization space, the current product or process goes through the dynamic M-PIE flow analysis to reveal critical contradictions and technical barriers. Solutions are found through the applications of general energy field, general logic functional material and general intelligence. The M-PIE flows are then integrated and optimized based on the objectives, resources and constraints of customer, manufacturing engineering, society and environment.

Integration of energy fields offers more freedom in solving the problem and brings a higher chance for finding the best solution. Close loop control is an integration effort trying to integrate information with the process. In intelligent EFM, we push such tacit trend to a higher level. Step 3 outputs the optimized engineering plan.

Step 4: Execution

The optimized plan is then executed through the implementation of these intelligent EFM methods and through the advanced management. Energy field generators, database, and software tools are produced. Successful execution requires a new category of leadership and management, referred to as intelligent engineering management. The concepts of M-PIE flow integration and optimization are relatively new. Actually current and earlier generations of engineers and accordingly engineering leaders are trained to be used to the conventional ways of R&D, project leaders and management layer should get trained to facilitate rather than impede the execution of Intelligent EFM.

Step 5: Evaluation, improve and move forward

The execution status is regularly evaluated and documented, and these documents become the internal part of the intelligent knowledgebase. The documentation covers successes such as patents and technical achievements, as well as failures and other facts of the project.

Good documentation and knowledgebase update will lower the impact of talent dynamics. This will also increase the efficiency of resource usage. For example, the database contains information of various energy field generating and measurement devices. In any large research organization, it is common to find many pieces of equipment idling after projects were finished. The Intelligent knowledgebase naturally provides information for sharing the equipment, material, and many other things. This principle may reduce waste and increase revenue immediately. Based on the evaluation results, the team decides to go to the next step or go back and improve the current step.

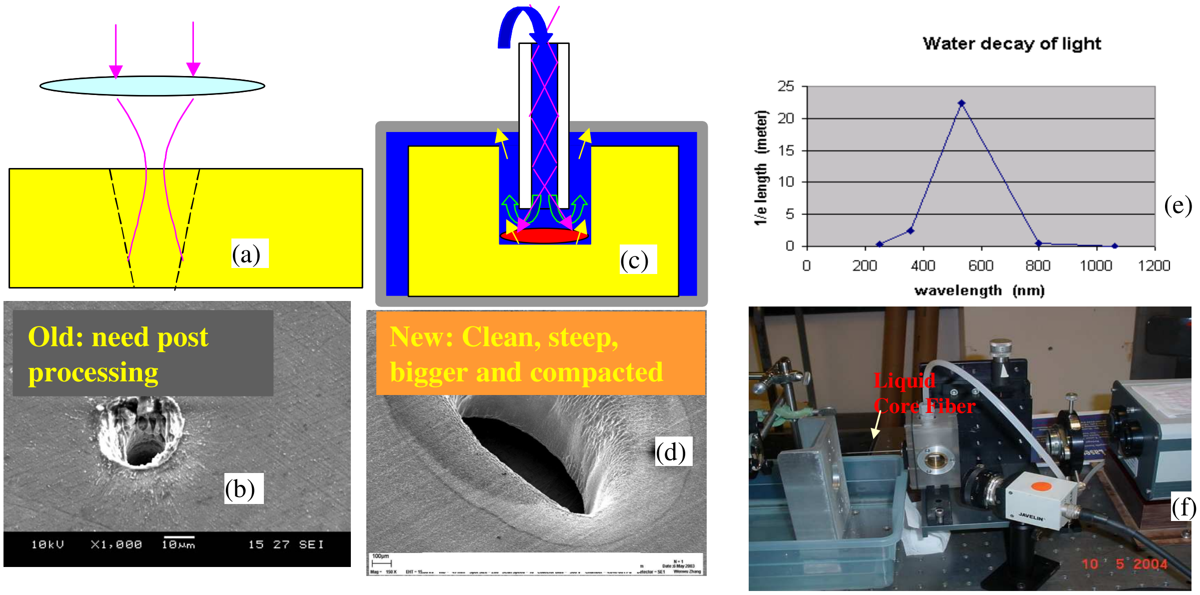

Fig. 6 Development of Liquid Core Fiber laser material processing technology

SOME PRINCIPLES OF INTELLIGENT EFM

In this section, typical examples to illustrate some of the important principles of intelligent EFM will be provided.

P1: Making use of the generality of energy fields, intelligence, and logic functional materials

As shown in Fig. 6(a), conventional laser machining focuses the laser energy onto the workpiece to remove materials in a gas environment. For nanosecond laser machining of metals, post-processing is normally needed to remove the redeposition shown in Fig. 6(b). There are many other issues in conventional laser machining, such as lens or cover glass damage due to the strong spattering in machining. To solve these issues, the author developed the Liquid Core Fiber laser material processing technology.

As shown in Fig. 6(c), by passing pulsed laser energy through a flowing water tube and satisfying the conditions of total internal reflection, laser energy as well as strong water flow can be delivered to the workpiece simultaneously. The laser locally ablates the substrate, and water flow flushes away the ablated materials. In addition, due to water confinement, strong shock waves can impart compressive residual stresses in the machined feature [18]. Due to the water flow, the workpiece is always cool, and there is no need to protect the lens. Fig. 6(d) shows the high quality hole drilled with this technology on Ti64 using a 25ns 532nm laser.

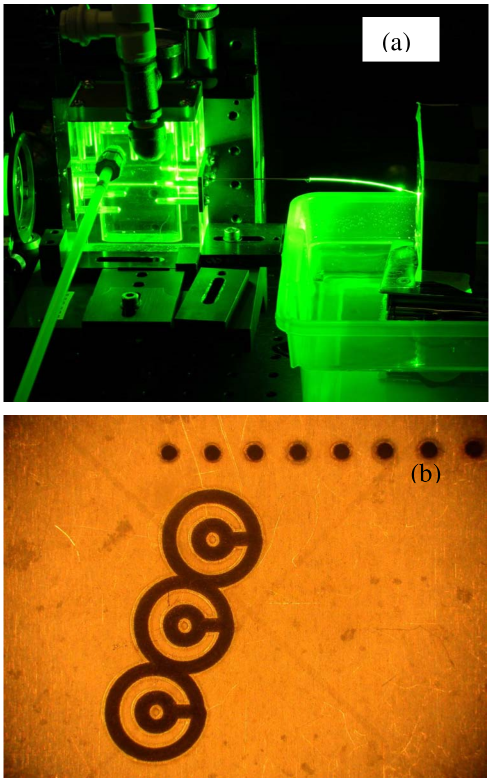

Fig. 7 (a) Liquid Core Fiber can bend and machine efficiently; (b) Features machined on SS304.

Fig. 6(f) shows the experiment setup. Noting that the liquid core fiber is like a long needle, it can reach very narrow locations that are impossible to access by conventional lasers. The design of the system is guided by the laser energy decay distance in water as shown in fig. 6(e). Green laser can have 95% of energy remaining after 1 meter of transmission in water and the water breakdown threshold at this wavelength is more than 4 GW/cm^2. When all these inherent benefits are combined, a record high intensity of pulsed laser energy transmission, >1GW/cm^2 at 100ns 532nm and >40GW/cm^2 at 110fs 810nm were achieved. Fig. 7(a) shows that the fiber can bend and can still drill efficiently. The machined features in SS304 are clean and burr free (Fig. 7(b)).

This invention illustrates the power of making use of the generality of energy fields, intelligence and logic functional materials. Energy fields used include laser, water flow, water-cooling, shock wave, and gas pressure. For general intelligence, we used the water transmission property of photon energy, the total internal reflection conditions, and the material-laser interactions were employed. For general logic functionality of materials, one can find the condition under which metal nanosecond laser machining can be ablation dominated. In fact, this technology can deliver laser energy from 0-4 GW/cm^2, making it useful for a very wide ranges of applications in laser material processing.

One thing we emphasized a lot in this paper is the general intelligence of materials, systems and configurations. This is an influential concept when it is fully appreciated. What is the intelligence of a circular structure? Wheels and ball screw can reduce friction, holes can be a nozzle to make an increased pressure jet, a matrix of holes with blowing air can be the floating bed to move heavy load very smoothly, and the technology of microblowing can reduce turbulent frictional drag by 90% relative to the flat surfaces [19].

The intelligence behind the low drag of shark skins, the super-hydrophobicity of lotus leaves, and the micro-lens structure of insects etc. leads people to the study of biomimetic engineering [20]. Non-linear crystals are used to convert the IR 1064nm laser beams into green, UV and DUV wavelengths. Self-assembling of particles is the basis of many surface engineering technologies, such as PVD/CVD, electroplating, and growth of crystals. Mechanical field has at least one advantageous property or intelligence relative to non-contact fields: it has the inherent feedback mechanism—the reacting force for position control, and it has near field effects. Structures and configurations have intelligence we can use. Composites, dome, grain orientation, etc., are such examples.

Along this thought, general methodology can be derived to use the generality of intelligence, energy fields and logic functional materials in engineering. As the first principle of Intelligent EFM, one must emphasize the systematic study of the generality of energy fields, intelligence and logic functionality of materials. A knowledgebase of this generality should be built up.

P2: Dynamic MPIE Flow Integration

Laser scanning can thermally deform the metal piece, as discovered in laser welding. Using this phenomenon in a controlled way gave birth to the process of laser forming. Some complex structures such as the blades in an engine, may have small geometry deviations from the standard geometry. Laser forming was studied to tune these blades as shown in Fig. 8. Unlike simple 2D bending, 3D structure tuning requires the high level integration of the dynamic MPIE flows. The original geometry of the blade is detected and compared with standard geometry, and the error map is derived. Simulation and DOE provide transfer functions to control the process, and in combination with the error map analysis, the lasing path is applied. The lasing process is monitored to avoid material damage, and the geometry is updated until reaching the target tolerance [21].

Rapid prototype manufacturing (RPM) based on layer-by-layer forming strategy makes it possible to make very complex 3D structures. Shown in Fig. 9 is the laser net shape deposition process in GE GRC. Laser energy is directed toward the workpiece, and the powder is injected simultaneously into melting pool. As a result, powders are melted and deposited on the substrate. Layer by layer, the 3D structures are grown up. A hollow thin wall In718 blade is shown on the right. With this process, a new design can be realized in several days instead of several months, because this process is CAD driven and no dies are needed.

In both examples, computer is used to measure, monitor and control the energy and material flows. Closed loop control helps improve the quality and the process robustness. A CAD driven process along with the integrated MPIE flows makes them very flexible manufacturing systems.

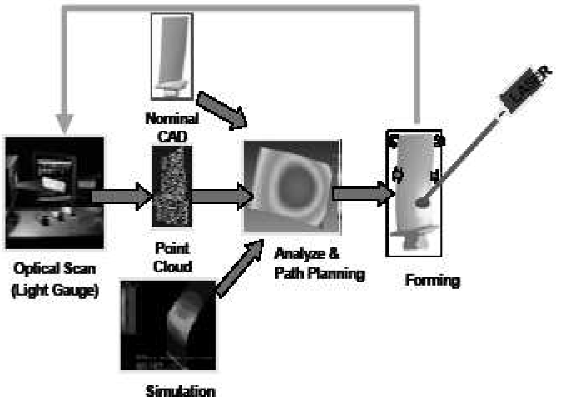

Fig. 8. Strategy for complex 3D structure tuning by thermal forming [21]

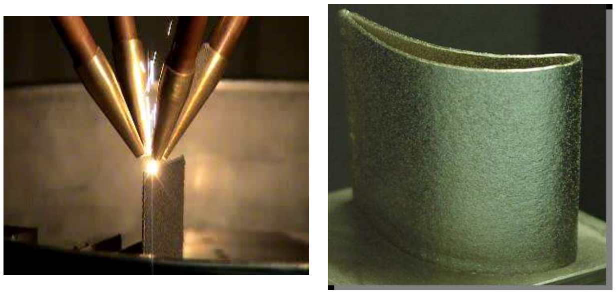

Fig. 9 Laser net-shape metal deposition (GE GRC)

Product innovation demonstrates similar trend of MPIE flow integration. Laptop computers and other portable electronic devices with wireless communication, standalone power supply, and comparable performance with non-portable counterparts take big market shares in the computer and communication business. Robotic technology integrates sensing, control, complex motion and communication capabilities in one system. Larger, advanced systems normally have intelligent decision systems to sense and control their performance. Take rocket for example. It has self-guidance system, a control unit, and a power unit etc. to fulfill desired flight tracks.

Manufacturing and engineering in general are marching towards the increased level of integration of the dynamic MPIE flows. As the second principle of Intelligent EFM, we emphasize the systematic use of the high level dynamic MPIE flow integration, the shortened cycle of feedback control, and the new standard of optimization considering this integration.

P3: Four Attributes Modulation of Energy Fields

Time, space, magnitude and frequency are the four basic attributes of energy field. Through the analysis of those four attributes, one can gain good insights about the energy fields and possible see ways of innovate the processes using these energy fields [9].

Laser material processing is complex due to the variety of laser pulse durations, wavelengths, energy levels, and energy distributions. Effects of time scale in laser material removal were reviewed in [22]. When the laser pulse duration is less than one picosecond, thermal equilibrium is not reached in laser-material interaction, thus thermal damage can be greatly reduced. That's the reason why fs lasers are increasingly popular in micromachining. On the other hand, the longer pulse durations and continuous wave can precisely impart thermal energy into the substrate, enabling the welding, deposition and surface treatment processes. Laser energy at high intensity can be used in material removal, while at low intensity it can be used for measurement and data reading. Different materials react differently to different laser wavelengths or frequencies. Thus, CO_2 laser is good for ceramics and organic material processing, while Nd:YAG laser is better suited for metal processing.

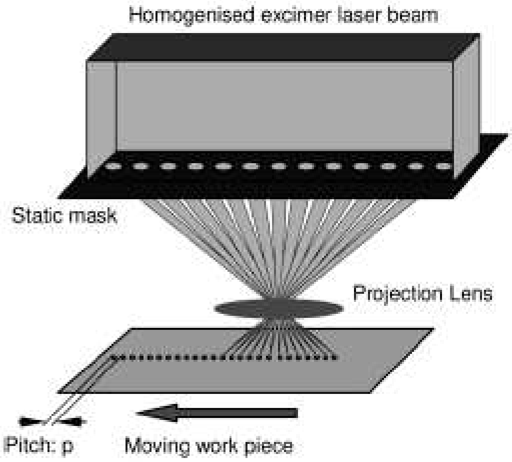

Fig. 10 Schematic of synchronized image scanning laser drilling [23]

As for the spatial modulation, lens-arrays and masks can be used to do laser material processing in parallel. Fig. 10 illustrates the Synchronized Image Scanning (SIS) laser drilling process [23]. It is a mask projection technique in which the substrate moves continuously. The mask contains a series of "building blocks" for the required feature and all image "blocks" are projected onto the substrate in a linear array at the same time. This results in the high-speed, high-accuracy production of micro-structures for long arrays and large area substrates with exceptional reproducibility.

As the third principle of Intelligent EFM, we emphasize the systematic 4-attributes modulation of the energy fields to optimize the processes. This principle summarizes the key point in many innovative solutions. For example, microwave used the resonant absorption of EM energy; High strain rate forming, such as explosive forming, impact forming, electro-discharge hydraulic forming, EM dynamic pressure forming etc., uses strain rate and speed much higher than normal forming to go beyond the normal forming limit of materials; Micro EDM/ECM uses nanosecond pulses to achieve the microscale machining resolutions. In summary, we should study the relativity of the MPIE flows, and modulate their attributes to find the optimal solutions.

P4: Integration and Segmentation to Increase the Degree Of Freedom of Optimization

The optimal solution is relative rather than absolute, because practical optimization is always under certain constraints and within certain domain. Integration of other facilitating factors (energy fields, medium, space, time, control etc.) can change the domain and the constraints of optimization.

For example, when high pressure water jet machining was first invented in late 1960s, it could cut relatively soft materials but the cutting speed was not very fast. To increase the cutting speed, the jet pressure could be further increased. But this would result in increased capital cost. When abrasive particles were mixed in the water flow, with moderate water pressure it achieved higher traverse speeds, thicker cutting depth and better edge quality. The integration of abrasives, water flow, cooling and flushing makes it a very widely used machining process [24].

The so-called Hybrid Processes are basically the integration of multiple mutually beneficial energy fields and mediums. The integration increased the degree of freedom for process optimization, and this usually results in a more ideal solution to a challenging task. Other interesting examples include laser and plasma assisted ceramic turning, mechanical-chemical ultra-precision machining, abrasive ECM/EDM, etc. Readers can browse the webpage in [25] for a more detailed discussion of these processes.

Another general rule of process innovation is integrated segmentation. The operations of binary 0 and 1 codes are simple, yet they have formed the basis of the digital technology. Instead of using a big bundle of energy, pulsating energy is widely used, as exemplified in pulsed laser material processing, ultrasonic machining, and abrasive waterjet machining. Using the integrated segmentation strategy, hardware and software are developed in Reconfigurable Manufacturing Systems to quickly adjust their production capacity and functionality within a part family in response to the sudden market changes or intrinsic system changes [26-27]. Continuous precision diamond cutting of hardened die steel has the issue of quick tool wear. This issue was solved by applying the elliptical vibration as described in [28].

In summary, the fourth principle of Intelligent EFM emphasizes the extension of the DOF of optimization through integration and integrated segmentation.

CONCLUDING REMARKS

It should be understood that Intelligent EFM is an open system. Many modern R&D methods, such as TRIZ, DFSS, Lean SixSigma, DOE, and neural network, etc., can be melted into it. Due to limited paper length, many aspects of Intelligent EFM are only briefly reviewed or outlined. The open structure of this engineering philosophy pointed out a lot of meaningful works ahead, far beyond the scope of an individual or a single organization. Thus, nation wide and hopefully international wide cooperation are used to accelerate its development.

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