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Editorial

Overview of extreme manufacturing

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1. Introduction

Today we live in a new era of economic globalization and rapid technological growth. The advancement of both our society and standard of living require us to delve into this new world and unleash the possibilities our future. We need to broaden the horizons of our universe to discover a new realm where the future of humanity can flourish. We need to be unafraid to unveil the mysteries hidden within the depths of our oceans to unearth treasures that will benefit not only us, but the generations to come.

To fulfill this vision, we must manufacture extremely large and extraordinarily fast equipment that will function seamlessly under the duress of extreme environments. On the other hand, matter is infinitely divisible. Thus, we also need to enter the microcosm of matter, where we must once again rely on manufacturing to fabricate specialized equipment and scientific instruments essential to operating in the extreme environment of infinite divisibility and observation of matter at microscopic scales. Therefore, to push past the limitations of existing technologies and embark on our journey to make cutting-edge discoveries that will advance mankind and transform our modern society, extreme manufacturing is paramount [1].

2. Basic concepts

Extreme manufacturing refers to utilizing advanced manufacturing technologies and high-end equipment to enable the fabrication of extreme-scale (extraordinarily large or small), high-precision, and high-performance structures, devices, or systems, as well as scientific lab equipment that can simulate extreme physical environments or conditions [2].

The intrinsic characteristics of extreme manufacturing are the effects of extreme scale or environment. In extreme scales and environments, the physical properties of materials and their component parts start producing atypical characteristics, which may even contradict the existing physics, materials science and manufacturing principles. Therefore, we must examine and understand the new principles, methods and technologies underlying these new phenomena. The fundamental scientific problems that extreme manufacturing aims to solve are understanding how matter, through complex and precise interactions with energy, can evolve to become compatible with the scientific laws guiding the behaviors of the products of extreme scales or environments.

The theories, methods, and technologies pertaining to the extreme manufacturing systems and processes mentioned above compose the science of extreme manufacturing technology.

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3. Significance

Extreme manufacturing aims to create cutting-edge innovations fueled by fundamental research to push past the existing limits in manufacturing in order to achieve higher standards of manufacturing. Moreover, extreme manufacturing is the most direct and impactful driving force behind the advancement of manufacturing equipment, processes and related industries; it is the pathway towards the future of manufacturing.

Extreme manufacturing technology has become the cornerstone of progress in high-tech fields. On the surface, extreme manufacturing pertains to products of extreme scales or extreme environments. Delving deeper, extreme manufacturing explores combinations of cutting-edge technologies from multi-disciplinary fields, which has the potential to create paradigm shifts in existing fields. The construction of high-performance integrated-circuits, spacecraft, large-scale rockets, aircraft carriers, high-energy density physics experiments, mega-scale scientific instruments, and other similar extensive systems can not only perfect our capabilities of extreme manufacturing and complex large-scale integrated manufacturing, but also spur technological advancements in aerospace, power electronics, materials, machinery, and even the fuel industry.

Any breakthroughs in manufacturing technology stem from fundamental research. Similarly, breakthroughs in extreme manufacturing's key technologies also begin with fundamental research in extreme manufacturing science.

4. Domestic and international research status and trends in extreme manufacturing

Developed countries have always placed great importance on cutting-edge manufacturing technologies that could determine the course of their future. Since 1959, the US Department of Defense has continuously implemented defense manufacturing technologies to maintain its world leadership. In 2008, the 'Development Forecast of Mechanical Engineering in the Next 20 Years' of the American Society of Mechanical Engineers proposed that in the next 20 years, the United States will confront issues associated with manufacturing extremely large or small-scale systems [3]. In 2011, development began for a new generation of heavy-lift launch vehicle (HLV) and space launch system, which studied manufacturing technologies under ultra-high temperature conditions. The United States has continuously been the world leader in extreme manufacturing systems and equipment, such as spacecrafts, large-scale rockets, aircraft carriers, large-scale aircraft, and integrated circuits.

In 2002, Germany launched the 'Optical Technology—Made in Germany' program. Subsequently in 2011, Germany launched the 'High-Tech Strategy 2020' plan [4], which named extreme manufacturing as one of the three development goals for sustainable development of the manufacturing industry. The European Union's (EU) production of the Airbus A380, Rolls-Royce aircraft engine, and ASML lithography systems displayed their global prowess in extreme manufacturing equipment and technologies.

In 2013, Russia issued the 'Russian 2030 National Policy in the Aerospace Sector' presidential order, which deemed the research and development of 'Waterfall' rockets with a carrying capacity of 130 tons as one of its key focus areas. Thus, the United States, Russia, the EU countries have always been at the forefront of extreme manufacturing.

Though a latecomer to research and development in the field of extreme manufacturing, China was the first to internationally introduce the concept. In 2004, during the International Conference on Frontiers of Design and

Manufacturing held by the National Science Foundation of China in Xi'an, Academician Jue Zhong was the first to propose the academic ideology, implication, significance, developmental status, and trend of 'extreme manufacturing' [5].

Over the years, China has continued to highlight the importance of extreme manufacturing to the future of technology. In China's 'National Medium- and Long-Term Plan for the Development of Science and Technology (2006–2020)', extreme manufacturing was highlighted as one of the key cutting-edge technologies [6]. In the 2012 'China Mechanical Engineering Technology Roadmap', extreme manufacturing was named as one of the four major trends in the development of mechanical engineering technology [7]. Moreover, 'Manufacturing Science in Extreme Environmental Conditions' has been listed as a priority funding area of the National Natural Science Foundation of China for the major strategic needs of the nation [8, 9].

Over the past few years, China has produced significant achievements in the field of extreme manufacturing. China has made a global impact with its strides in high-performance equipment and extreme manufacturing technology development. Examples include: Chang′e series lunar landing spacecraft, China Space Station, 3–5 m Long March rocket series [10], 001–003 large aircraft carrier, $420\,\mathrm{km\,h^{-1}}$ high-speed train [11], the world's largest 500 m diameter radio telescope (FAST) [12], 7000 m manned deep-sea research submersible (called Jiaolong) [13], 42 m high die forging press of 80 000 ton [14], 36 000 ton vertical metal extruder [15], 13 m diameter/90 m long large-scale shield machine [16], and 300 000 ton supertankers [17]. Recently, China has successfully developed a 5 nm plasma etcher and the world's first ultraviolet super-resolution lithography equipment with the highest known resolution [18]. Huawei Technologies Co. Ltd first introduced 7 nm chips to the global market, signifying the rapid assimilation of ultra-micro-scale manufacturing technology into international standards.

In China's 973 Program (National Basic Research Program), 46 major projects have been deployed in the manufacturing field. In the fields of large optical curved-surface mirrors, heavy-duty gas turbines, large-scale casting and forging, large semiconductor wafers, and next-generation chip packaging, major scientific problems have been resolved and key technological breakthroughs have been achieved. These breakthroughs include nano-precision polishing of hard and brittle materials, nano ultra-precision cutting of free-form surfaces, forming by ultra-high magnetic field, plasma/magnetorheological special processing mechanism, modeling and controlling the manufacturing process of large-scale components in extreme environments. These accomplishments have been successfully applied in major engineering and equipment manufacturing, playing a critical role in their successes. At the same time, during the implementation of the projects, multiple world-class national research groups with the best and brightest minds and platforms for innovation were established, laying a solid foundation for the further advancement of extreme manufacturing research.

The following trends are observed at the forefront of domestic and international research on extreme manufacturing technologies:

(1) The primary goal is to develop a new generation of state-of-the-art products with unparalleled performance; conduct research on new manufacturing principles and cutting-edge technologies;
(2) Manufacturing of products is heading in the direction of integrating materials, structures, and functionalities.
(3) The scale of component structures is either developing in the direction of having ultra-large dimensions or ultra-small dimensions with high precision.
(4) High-functionality operations advance toward ultrahigh and low-temperature resistance; high pressure and abrasion resistance; high speed, high density

and high fidelity information transmission; and the adaptability of both physical and mechanical properties under extremely high energy density.

5. Characteristics of the extreme manufacturing era

In the wake of rapid developments in both the manufacturing industry and modern science and technology, the implications of extreme manufacturing have noticeably shifted with time. That is to say, manufacturing accuracy, operating speed, environmental temperature/pressure, and other limit values have been changing with time. Only by becoming fully aware of how extreme manufacturing has shifted with time and being involved with its ever-advancing characteristics can we stay at the forefront of the international scientific community and remain competitive in modern industries.

5.1. Ultra-large-scale system manufacturing

The maximum rocket diameter is upwards of 10 m, where the formation of the head of the fuel tank needs to be both lightweight and seamless [19]. The largest aircraft carrier weighs over 100 000 tons [20]. The largest shield machine is over 18 m in diameter. The largest cargo ship weighs over 600 000 tons. Next generation long-lasting seamless stainless steel rings made for nuclear islands have diameters of over 15 m. The manufacturing of the above mentioned ultra-large equipment and components calls for extreme manufacturing technology.

5.2. Ultra-high-speed equipment manufacturing

The ultra-high-speed maglev machine tool spindle operates at up to 200 000 rpm, the maximum speed of vacuum tube maglev trains is expected to be 1000 km h^{-1}. Ultra-high altitude supersonic aircrafts can reach speeds of up to 8–10 Mach. The space probe can reach a maximum speed of 15 km s^{-1} (54 000 km h^{-1}). The transmission speed of micro-fluidic optical fiber transmission systems is about 10 times faster than that of current optical fiber systems. Next generation quantum computers can compute in 3 s what will take today's computers over ten billion years to compute.

5.3. Ultra-small micro-nano manufacturing

Ten years ago, the processing limit for chip linewidths was 28 nm. Recently, Taiwan Semiconductor Manufacturing Company successfully manufactured chips with linewidths within 7 nm, which is fast approaching the physical limit of chip linewidths. Tankettes are centimeter-scaled and capsule robots are millimeter-scaled. Chinese scientists have already successfully manufactured DNA nanorobots [21] and the creation of molecular atomic robots is expected in the near future.

5.4. High-precision manufacturing

Ten years ago, the highest level of precision possible for ultra-precision machining was on the nanoscale, which has since advanced to sub-nanometer and atomic scales [22, 23]. High-precision cutting tools that can attain the maximum precision have now achieved a surface roughness of 1 nm. Ultra-large scale integrated circuit lithography machine object lens has a surface accuracy of up to 2 nmPV [24]. The concept and research of quantum manufacturing have captured both domestic and international interest.

5.5. Manufacturing or operating in extreme environments (extreme high/low temperature, extreme high/low pressure)

Since the turbine inlet temperature of J-series gas turbines can reach up to 1600 °C, it is necessary to research and devise blade materials and processing that can withstand higher temperatures. Scientists have discovered that the elongation of aluminum alloys is markedly increased when formed in ultra-low temperature environments. Ultra-low temperature processing may be a new and improved approach to manufacturing extremely complex components. When operating deep-sea equipment at 10 000 m below sea level, water pressure reaches 100 MPa, thus requiring the equipment to have a high-pressure resistant structure and sealing.

5.6. Ultra-high-energy density manufacturing

The power density of super-intense and ultra-short focused lasers can reach up to 10^{26} w cm^{-2}, and the pulse width will be reduced to attoseconds (10^{-18} s). The water pressure of waterjet cutting can approach 600 MPa, with a jet velocity exceeding 4 Mach.

Exemplified by the cases mentioned above, the technological demands of extreme manufacturing are swiftly evolving with time. With growing international competition in manufacturing and rapid developments in advanced technologies, what may have once been seen as cutting-edge may quickly become obsolete. Inevitably, the life-cycle of current technologies is ever-shrinking. Only by ceaselessly continuing to explore and conduct in-depth research in the essential fields of extreme manufacturing can we keep pace with the world's scientific advancements contribute to technological prosperity. By doing so, we can alter the course of technological advancement and play a hand in transforming the world.

6. Exploration of new theories, processes, and technologies in extreme manufacturing

In existing material science theories, physics and forming principles can only be applied to specific conditions and environments. At extreme scales or in extreme environments, the physical properties of materials and components necessary for manufacturing desired systems or equipment will produce evident atypical characteristics, some of which may even contradict existing physics, materials science and forming principles.

For instance, Tian *et al* at Yanshan University, under a high-temperature and high-pressure environment, formed a superhard material with a hardness value that is double that of a diamond [25]; Shijian *et al* at the Harbin University of Technology conducted experiments which uncovered that when aluminum alloys are formed in environments below 180 °C, their elongation and hardness display significant changes [26]. Scientists have also discovered that after the diameter of microfluidic tubing is reduced to a certain degree, due to the considerably enhanced effects of surface tension, the Bernoulli equation becomes invalid. Scientists also predict that once chip linewidths reach their physical limit (<5 nm), Moore's law will become antiquated as well, thus requiring the conception of subversive laws and theories [27].

With rapidly increasing demand for ultra-large-scale integration (ULSI), modern deep-space and deep-sea exploration, HLV, long-range precision guidance, hypersonic aircrafts, and other similar systems and applications, researchers face a series of unprecedented scientific and technological challenges, including understanding and adapting to the effects of extreme environments or scale in materials, processes, design, technologies and equipment. Some principles, methods and technologies used in conventional manufacturing will no longer be applicable in extreme scales (extremely large or small) or extreme environments. Therefore, we must explore completely new theories, processes, and technologies that may subvert the scientific principles of today.

7. Key scientific issues in extreme manufacturing

The fundamental characteristics of the effects caused by extreme scales or environments in extreme manufacturing pose great challenges to manufacturing science and engineering. Thus, our research must dig deeper to refine and solve key scientific issues in extreme manufacturing engineering. In doing so, we can create breakthroughs and innovations that can arm the manufacturing industry with new theories, processes, and techniques to create extreme-scale high-performance equipment. The key scientific challenges facing us are described below:

Multi-scale effects are induced by ultra-strong energy fields, as well as energy transfer and conversion between ultra-strong processing energy fields and the systems being processed. For instance, manufacturing ultra-large components, as well as the energy transfer and conversion at high-density flip-chip interfaces. Another case is the coupled dynamic behavior of physical systems under extreme velocity, pressure and extreme temperature, compounded with the comprehensive effects of extreme environments.

Further challenges include: the dimension effects of micro-nanoscale manufacturing; ultra-high precision forming of micro-nanostructures along with the evolution of their properties, which include the energy and material transformation mechanisms of micro-nano growth, micro-nano formation, micro-nano removal at manufacturing interfaces, as well as the testing and evaluation of micro-nano manufacturing precision; the assembly and functionality formation of micro-nano systems, including quantum mechanics and molecular dynamics mechanisms during the process of micro-nano actuation, micro-nano manipulation, micro-nano joining, micro-nano assembly; the dynamic behavior and operating procedure of micro-nano systems, the unique physical characteristics of micro-nano components, and the micro-mechanics under loading.

Extreme manufacturing environmental effects, such as multi-field coupling as well as random disturbance and process stability experienced by extreme-scale processing in extreme manufacturing environments. Extreme environmental effects on material microstructure evolution and component structures/properties; the evolution of the performance and capabilities of extreme-scale systems during both their operating cycle and their entire lifecycle; the testing and evaluation of the physical quantity limits of manufacturing in extreme environments.

8. Main research areas and contents of extreme manufacturing

8.1. Ultra-large-scale manufacturing

The integrating of the large-scale equipment's main structure is a critical element in achieving high performance. However, existing manufacturing techniques lead to performance mismatch among components of large-scale equipment to 30%–50%. Hence, operations of the equipment face major safety risks.

Take HLV as an example. During the 13th five-year plan, the development of HLVs with a carrying capacity of 100 tons begun. Each HLV had an outer diameter of 10 m, a total length of 100 m, a diameter-to-thickness (D/t) ratio of 1000, and a cylinder D/t ratio of 10, forming a complex structure with high overall flexibility as well as high local rigidity. This creates uncertainty in the force transmission pathway and deformation during the manufacturing and servicing processes, in addition to randomness in structural evolution, performance, and residual stress. Furthermore, the HLVs need to perform in extremely low temperature environments (liquid hydrogen tank: $-252\,^{\circ}$C, liquid oxygen tank $-183\,^{\circ}$C). Manufacturing this type of high performance ultra-large scale components is extremely challenging; not only is it difficult to guarantee shape accuracy, it is also highly prone to partial performance weakening and partial shape variations that result in performance failure [28, 29].

In tackling precision manufacturing of ultra-large thin-walled structures, the traditional rheology of metals and composite materials in conventional manufacturing, phase transition uniformity theory, as well as accuracy and performance precision techniques are no longer valid. Rather, we need to enter the new frontier of extreme manufacturing, where we need to propose new theories and technologies to catalyze leading-edge breakthroughs and construct revolutionary innovations.

8.2. Ultra-small-scale manufacturing

Microelectronic and optoelectronic devices carry and transmit information streams from micro- and nano-scale structures. The precision of sub-nanomanufacturing greatly affects transmission quality. Improving the manufacturing quality of sub-nanoscale structures is the basis of our breakthrough in high-fidelity information transmission [30]. With the line width of ULSI chips fast approaching the manufacturing limit of 3–5 nm breakthroughs in atomic and quantum manufacturing technologies are imminent. Photonic integrated devices integrate lasers, modulators, gratings, etc on a single chip, which is the only way to tackle the high data transmission rates (>10 Gbps) and explosive growth in capacity expected in the future [31]. Therefore, extreme manufacturing must resolve key scientific issues, such as the loss of optical functions caused by lattice mismatch, the effects of lattice matching manufacturing on the fabricated device's structural function, and the relationship between the fabrication of nano-optical heterojunction interfaces and the refractive index of light.

8.3. Ultra-precision manufacturing

Ultra-precision optical components continuously push the limits in manufacturing accuracy. For instance, high-intensity optical elements are used in extremely high-powered (100 000 W) laser irradiation environments. These elements are crucial to high-intensity optical systems, such as laser weapons and inertial confinement fusion devices. The surface of high-intensity optical elements is a complex high-order curvatures, which requires nano-level surface accuracy, sub-nano-level roughness and a near-defectless surface [32, 33]. For example, in inertial confinement devices, the error of the lens wedge should be lower than $10''$, the surface accuracy should exceed 20 nm rms, and the surface roughness should be less than 0.5 nm Ra. For extreme manufacturing of such ultra-high precision complex surfaces, existing techniques for low stress manufacturing with nanoscale precision and low defect polishing mechanism may no longer be sufficient. Thus, we must explore new principles and technologies for manufacturing complex surfaces with ultra-high precision and near-zero defects.

8.4. Ultra-high performance manufacturing

In order to meet the extremely high standards for product performance, we need to draw from multi-disciplinary knowledge to create cutting-edge products with high functionality. Take for example the hypersonic aircrafts with speeds that go up to 8–10 Mach. Severe aerodynamic heating when flying at high speeds causes the temperature of the aircraft's surface to rapidly rise. Thus, the body of the aircraft must be constructed with heat resistant components that can withstand extremely high temperature (up to 2300 °C). New principles and technologies in thermoelectric conversion and microchannel heat transfer are important approaches in innovating brand-new high-functionality products like the above mentioned hypersonic aircrafts. Extreme manufacturing technologies such as high-performance thermoelectric conversion structures, fluid transmission in honeycomb structures and microchannel structures, thermal design, precise construction, and interfacing for systems under extremely high temperature and ultra-high speed operating environments have remained unexplored both at home and abroad.

8.5. Manufacturing of major equipment to generate extreme physical conditions

The future of science and technology will surely continue to uncover new revelations and innovations in various high-energy-density environments, nano/micro-scale materials, and complex giant systems. The manufacturing of equipment to generate extreme physical conditions is becoming the bottleneck in future science and technology development. For instance, the power of the next-generation light source for x-ray free-electron lasers will increase from the 100 MW produced by conventional light sources to 10 GW. Currently, the United States, Europe, and other developed nations are actively planning and constructing experimental devices of different performance levels. Photon energy has already reached or exceeded 25 KeV, with repetition frequencies surpassing MHz and approaching GHz, and is also fully coherent [34]. In the new generation of light sources, the design and manufacture of key components, such as large x-ray mirrors, high-energy load nanodiffraction elements, high-purity diamond single crystal refractive elements, and energy spectrum diagnostic components, along with technologies requiring ultra-high precision, high-photon-energy optical detection, and high-accuracy x-ray wavefront sensing, are all challenging problems in manufacturing science that have not yet attained substantial breakthroughs.

The common features of the above extreme manufacturing examples are:

(1) The demand for extreme manufacturing stems from the technical bottlenecks to national major strategic objectives;
(2) Compared to existing systems and technologies, they have features requiring extreme dimensions, extreme environments, extreme quality, or extreme performance;
(3) Existing manufacturing technologies do not satisfy the objectives of extreme manufacturing.

9. Conclusions

Extreme manufacturing addresses many of the ever-changing technological needs in our modern society. Hence, scientists and engineers have to continuously seek the answers to major scientific challenges, such as the effects of extreme dimensions and environments, in order to allow for future discoveries, innovations, and creations. Only by doing so can we promote technological advancements in this field and continuously improve our ability to observe, understand and triumph any of nature's bottlenecks.

Only when the government agencies formulate and prioritize the creation and deployment of critical technological plans, as well as support and encourage scientists to explore and innovate in the field of extreme manufacturing, can we keep pace with international trends in science and technology development, and contribute to the continued prosperity.

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