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REVIEW PAPER

Advancement of Mechanical Engineering in Extreme Environments

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Abstract

With the continuing increase in the use of technology in the modern world, the environmental demands placed on mechanical products have become increasingly harsh, especially in the fields of industrial equipment, vehicles, robotics, medical equipment, and weapons. For the development of mechanical engineering, it is essential to ensure reliable performance, high efficiency, and long durability in extreme environments (extremes of temperature, pressure, corrosion, vibration, etc.). The mechanical properties of the materials used to manufacture the components directly influence the component's characteristics in extreme environments. Mechanical design and manufacturing processes are also key factors that affect the reliability of mechanisms. With the development of composite materials, computer technology, and the 4th industrial revolution, extreme environment technology has also progressed rapidly. Engineering for extreme environments is considered as a very important field in the green and environmental-friendly technology. This is because the shortened working life of machinery under such extremely harsh environments leads to higher energy consumption and more non-recyclable wastes. This paper reviews the developments related to novel extreme environment technologies in terms of materials, design, and manufacturing that have come about in recent years. Moreover, an analysis of related articles, patents, and the economy of this field is carried out and a perspective on the developmental trend is put forward.

Keywords Extreme environment · Mechanical engineering · Extreme temperature · Extreme pressure · Mechanical design · Manufacturing processes

1 Introduction

The widespread use of technology has resulted in far-reaching industrialization, which can cause engineering products being subjected to extreme environments. The service life of mechanical products operating in extreme environments can be much less than that of products working under general working conditions. If such products are not properly designed and manufactured, their performance and life can be further reduced, which can lead to relatively high working energy consumption and failure rate. Such inefficiencies tend to increase the negative environmental impact of these engineering products. Therefore, in order to maintain a good cost to benefit ratio and to reduce the negative environmental impacts, engineering for extreme environments has become one of the important topics of Green Technology research in recent years. The development of engineering products for extreme environments has become a major direction of research in various industries ranging from materials to processing and applications [1–6]. Specifically in the mechanical engineering, many systems have been developed to replace

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humans working in harsh environments maintaining good working performance [7–11]. Such examples include turbine blades in jet engines operate close to their melting point in an oxidizing environment [12, 13], the structural and cladding materials of nuclear reactors need to work under high radiation and strongly corrosive conditions to ensure safety [14, 15], and the electrodes in the batteries of alternate energy vehicles must withstand large electrochemical forces and mechanical stresses [16]. Extreme environments can be referred to as environments with very high or low temperatures, immense pressures and vacuums, chemical hostility, extreme radiation, strong magnetic- and electric fields, and high wear and abrasion [17, 18]. There is no clear numerical representation for extreme environments, and we generally define an environment that exceeds the normal average operating condition as an extreme environment. Different industries and products have different extreme environmental conditions. For example, the general operating temperature range of a nitrile rubber sealing ring is – 25 to 10 °C, and if used outside this temperature range, it might face damage or failure. However, in some special applications such as turbines, extremely low temperature of – 40 °C may be required. Therefore, the study of matter in extreme environments helps develop solutions to deal with different unidentified working conditions.

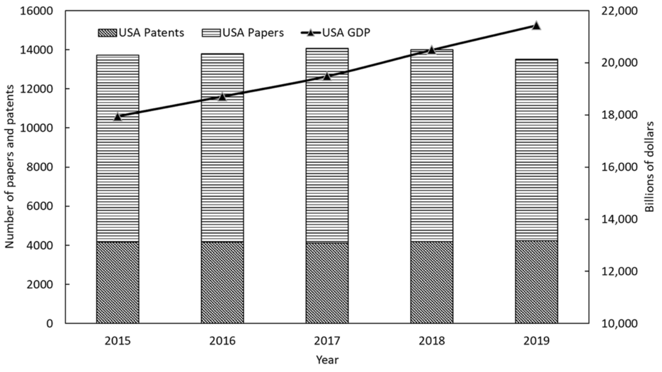
Mechanical engineering has widespread applications in industrial equipment, machinery, vehicles, robotics, medical equipment, and weapons [19–23].The lifespan and safety aspects of a machine have always been the pursuit of mechanical engineers working in different industries. Stricter requirements regarding working conditions, improved performance, better reliability, and robust design for extreme environment technology have gradually become a mainstream development direction for mechanical engineering [24]. Materials, design, and manufacturing processes are the key factors that affect the reliability of mechanical products in extreme environments. Advancements in high-strength, high-performance, high-temperature, and corrosion-resistant materials have paved ways for the development of mechanical products for extreme environments. The research direction of new materials in the twenty-first century is geared toward new fiber materials, functional polymer materials, new alloy materials, and fine ceramic materials. These new materials have great significance for the development of new generation high-performance mechanical products for extreme environments [25–28]. Mechanical design is an important part of mechanical engineering that includes studies, such as the operating principle, structure, force and power transmission of the machine, material selection of parts, shape, and size. With the development of electronic computer technology and network technology, mechanical design has also improved toward an intelligent and networked direction. New design theories and methods also affect the performance and lifespan of mechanical products in extreme environments [29–31]. Advanced manufacturing technology is an important medium for product innovation, production expansion, and improvement of a country's international economic competitiveness. Precision, surface finish, and machining size range and geometry that precision machining technology can achieve are important criteria for measuring the level of a country's manufacturing industry. Advanced precision machining technology allows materials to perform better in extreme environments [32–35].

In this article, we review the latest research related to mechanical engineering for extreme environments, including advanced materials technology, design methods, and product manufacturing processes technology. We provide a summary and perspectives on future developments in mechanical engineering in extreme environments.

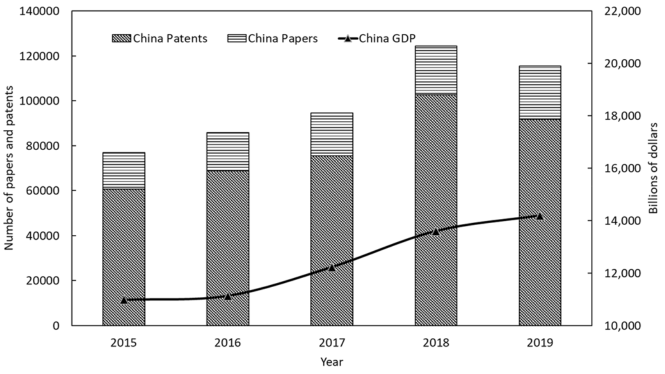
2 Statistical Survey of Extreme Environment Technology and Economy

Science and technology are regarded as the primary productive forces for economic development. To observe and discuss the development trend of academic research related to extreme environmental technologies and the economy, we present a series of statistical data and analyses. Gross domestic product (GDP) is often considered as the best indicator of a country's economy; patents and papers are the main forms that reflect the latest scientific and technological achievements. The research objects for the statistical analyses were selected based on the representativeness of a country; the three representative countries were: (1) the United States of America, which is a highly developed capitalist country; (2) China, a populous country with rapid economic development in recent years; and, (3) Germany, which is recognized as a mechanical power worldwide.

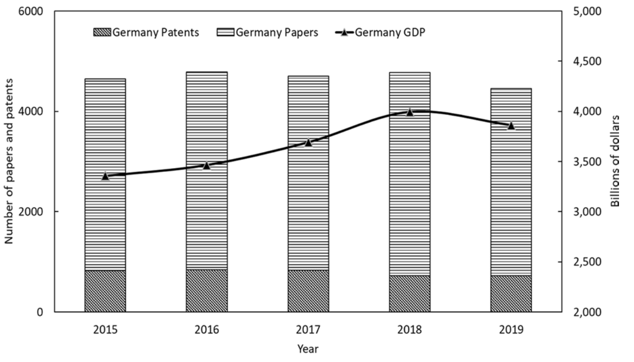
The information on patents related to extreme environment technology was obtained from the professional patent database WIPS ON. The main search string was set as "High temperature" OR "High pressure" OR "Low temperature" OR "extreme condition" OR "extreme environment". The number of relevant patents in the United States and China in the past 5 years was surveyed. SCOPUS is the largest peer-reviewed literature database that is used to search for the number of academic papers related to extreme environment technology. The same search string was used for the patent survey. The value of GDP was collected from major economic websites such as the International Monetary Fund. Figure 1a–c represent the academic research and GDP status of the USA, China, and Germany for the past 5 years, respectively. The diagonally shaded part of the bars indicates the number of patents, while the horizontally shaded part indicates the relevant number of papers. The bars correspond to the number represented by the vertical axis on the left. The curve in each figure represents the value of GDP and corresponds to the number on the right.



(a) United States of America



(b) China



(c) Germany

Fig. 1 Research and GDP statuses of three economic powers by year

Figure 1a shows that in the past five years, the number of patents on extreme environmental technologies in the USA has basically remained at 4000 per year, and the number of high-quality papers that has been inserted into the SCOPUS index has remained at 9000–10,000. In other words, in the past five years, the total number of academic research achievements (patents and papers) related to extreme environment technology has remained at a level of 13,000–14,000, showing a relatively stable trend. The GDP curve exhibits the annual stable linear growth of the GDP of the USA in the past five years. From this, we infer that the number of scholars in related fields in the USA has remained almost unchanged, and their academic achievements have promoted the stable development of the economy.

From the total number of academic research achievements related to extreme environment technology in China, as shown in Fig. 1b, from 2015 to 2017, the total amount has increased stepwise, with an increase of approximately 10%. Compared with previous years, a relatively high increase of approximately 30% can be observed in 2018. Following this, a shrinkage of about 7% was observed in 2019. As a developing country, China's academic research on extreme environment technology has showed an increasing trend, especially in terms of patents. The number of patents applied for (by Chinese developers) each year is several times that by the United States. Furthermore, the growth trend of the GDP also shows the same development trend as that of the increase in the number of related academic studies.

In Germany, which is a leading country in machinery manufacturing, the total number of academic studies on extreme environment technology from 2015 to 2018 remained stable at around 4700, while the GDP growth rate during this period also remained stable, as shown in Fig. 1c. However, the total number of patents and papers created on extreme environment technology in 2019 was considerably less than that in the previous years. Compared to 2018, the GDP also showed a sharp decline in 2019.

Although the analysis of these statistical data is not enough to prove a direct causal relationship between extreme environmental technology and GDP, it does show that the economic development of a country is inseparable from academic research on innovative technology. As more scholars have begun to invest in research on extreme environmental technology, the mastery of extreme environmental technology will surely become another important indicator of a country's economic and technological capabilities.

3 Extreme Environment Technologies in Various Fields of Mechanical Engineering

Compared to traditional mechanical engineering, extreme environment technology requires more attention to find ways to improve the working performance and durability of mechanical products in extreme environments [36–40]. In this chapter, we introduce new extreme environment technologies that are researched or applied in the fields of materials, mechanical design, and manufacturing.

3.1 Materials

New material technology is the basis for developing new mechanical products and improving product quality for use in extreme environments [41–43]. Since different materials have different mechanical properties, in the selection of mechanical materials, the aspects of functional requirements, economic adaptability, environmental protection, and energy saving should be considered. With an increase in the demand for extreme environments, studies on high-performance materials for extreme environments are also increasing [44–47]. Alloy materials, owing to their excellent mechanical properties, are still most widely used in mechanical engineering. In this section, we discuss extreme environmental technologies related to alloys that have been developed in recent years. Considering the main reasons for failure of mechanical products under extreme environments, this article mainly reviews the materials from the perspective of mechanical properties and corrosion resistance (chemical properties).

Guo et al. proposed a MoNbHfZrTi high-temperature alloy and reported its microstructure, phase stability, and mechanical properties. The structural stability of the MoNbHfZrTi alloy without any phase transition below 1743 K was confirmed by differential scanning calorimetry (DSC) analysis. It has a high compressive yield strength of 1719 MPa at room temperature and good yield strength characteristics at high temperatures (825 MPa at 1073 K, 728 MPa at 1173 K, 635 MPa at 1273 K, 397 MPa at 1373 K, and 187 MPa at 1473 K) [48].

To investigate the effect of titanium (Ti) on the mechanical properties of NbMoTaW and VNbMoTaW refractory high-entropy alloys, Han et al. [49] made experimental comparisons of their mechanical properties before and after the addition of Ti. The results are shown in Table 1, where $\sigma_{0.2}$, σ_p, and ε_p represent the yield strength, peak strength, and plastic strain, respectively. The addition of Ti makes both alloys highly resistant to compression, showing compression yield strengths of more than 600 Mpa, even at the high temperature of 1473 K. Furthermore, this indicates good thermal stability.

The mechanical properties of NbMoTaW and VNbMoTaW alloys were compared by Senkov et al. [50]. The VNbMoTaW alloy exhibited a high yield stress of 862 MPa at 873 K, which is 300 MPa higher than that of the NbMoTaW alloy. However, with an increase in temperature, the yield stress of the VNbMoTaW alloy decreases rapidly, resulting in two alloys having similar yield stresses at 1873 K.

Senkov et al. [51] fabricated NbTiVZr, NbTiV2Zr, CrNbTiZr, and CrNbTiVZr alloys through vacuum arc melting, hot isostatic pressing, and homogenization processes and compared their mechanical properties. Table 2 lists the results. Among them, $\sigma_{0.2}$, σ_{10}, σ_{20}, and ε_f, represent the compression yield stress, flow stress at $\varepsilon = 10\%$, flow stress at

Table 1 Comparison of mechanical properties at different temperatures of the TiNbMoTaW, NbMoTaW, TiVNbMoTaW and VNbMoTaW alloys

Temperature	Properties	TiNbMoTaW	NbMoTaW	TiVNbMoTaW	VNbMoYaW
298 K	$\sigma_{0.2}$ (MPa)	1343	1058	1515	1246
	σ_p (MPa)	2005	1211	2135	1270
	ε_p (%)	1401	2.6	10.6	1.7
873 K	$\sigma_{0.2}$ (MPa)	689	561	973	862
	σ_p (MPa)	1681	–	1590	1597
	ε_p (%)	35.4	> 20	18.8	13
1073 K	$\sigma_{0.2}$ (MPa)	674	552	791.3	846
	σ_p (MPa)	1618	–	1180	1536
	ε_p (%)	46.6	> 20	9.4	16
1273 K	$\sigma_{0.2}$ (MPa)	620	548	752.8	842
	σ_p (MPa)	1426	1008	1105	1452
	ε_p (%)	35.5	> 20	23.7	19
1473 K	$\sigma_{0.2}$ (MPa)	586	506	659	735
	σ_p (MPa)	814	803	696	943
	ε_p (%)	10.2	> 20	8.4	8

Table 2 Comparison of mechanical properties of NbTiVZr, NbTiV2Zr, CrNbTiZr and CrNbTiVZr alloys at different temperatures

Temperature	Properties	NbTiVZr	NbTiV2Zr	CrNbTiZr	CrNbTiVZr
298 K	$\sigma_{0.2}$ (MPa)	1105	918	1260	1298
	σ_{10} (MPa)	1430	1300	–	–
	σ_{20} (MPa)	1732	1635	–	–
	ε_f (%)	> 50	> 50	6	3
873 K	$\sigma_{0.2}$ (MPa)	834	571	1035	1230
	σ_{10} (MPa)	884	701	1130	1360
	σ_{20} (MPa)	767	716	1030	–
	ε_f (%)	> 50	> 50	> 50	> 10
1073 K	$\sigma_{0.2}$ (MPa)	187	240	300	615
	σ_{10} (MPa)	178	228	455	601
	σ_{20} (MPa)	174	185	435	512
	ε_f (%)	> 50	> 50	> 50	> 50
1273 K	$\sigma_{0.2}$ (MPa)	58	72	115	259
	σ_{10} (MPa)	68	60	138	205
	σ_{20} (MPa)	77	53	136	183
	ε_f (%)	> 50	> 50	> 50	> 50

$\varepsilon = 20\%$, and fracture strain, respectively. The CrNbTiVZr alloy shows the best mechanical properties compared with the other three alloys at normal and high temperatures.

Based on the abovementioned works, Roh et al. [52] proposed a high-temperature alloy material composed mainly of Nb, Mo, Ta, and W elements, which were made by mechanical alloying (MA) and spark plasma sintering (SPS) processes. Figure 2a shows the Vickers hardness values of the two samples at different temperatures. The two samples were sintered for 24 h and 72 h. The hardness of both samples gradually decreases with increasing temperature. The mechanical properties of high-temperature alloy materials commonly decrease rapidly when the temperature crosses 1000 K. However, owing to the characteristics of W, the NbMoTaW alloy can maintain a relatively satisfactory high hardness value even above 1073 K. Figure 2b shows the stress–strain curve of the 24-h sintered sample of NbMoTaW [49] at 1073 K. Compared with VNbMoTaW [50], NbTiVZr [51], and other alloys mentioned previously, the NbMoTaW alloy shows a higher compressive strength of 1630 MPa.

In recent years, alloy material composites have become a popular research topic. With significant optimization of the mechanical properties of alloys, such as improvement in strength under extreme pressures, alloy material composites have been applied in many machinery industries [53–57].

Shahrdami et al. [58] investigated the effects of carbon nanotube (CNT) and silicon carbide whisker (SiCw) reinforcements on the mechanical properties of aluminum matrix composites. When 0.5 wt% of CNTs was added, the maximum compressive strength of the Al–CNT composites increased to a maximum value of 290 MPa. On the other hand, for the Al-SiCw composites, when the amount of SiCw was 3 wt%, the A l–SiCw composites achieved the highest compressive strength (300 MPa). Before that, the compressive strength showed an upward trend with an increasing amount of SiCw. The results showed that CNT had a greater reinforcement effect than silicon carbide whiskers for aluminum.

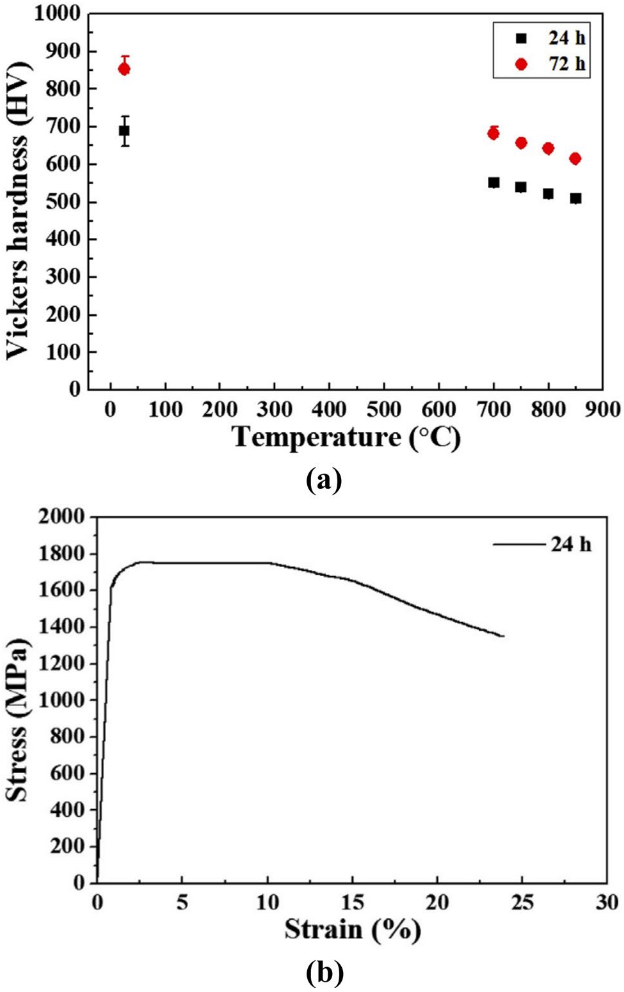


Fig. 2 Mechanical properties of NbMoTaW alloys

A novel Al-CMA nanocomposite was proposed by Ramezanizadeh [59]. The Al-10 wt% Al3Mg2 nanocomposite was produced by mechanical alloying/milling, cold pressing, sintering, and hot extrusion processes. A comparison of the mechanical properties of the nanocomposite and the alloy made of pure Al mix powders was carried out. It was found that the extruded Al-10 wt% Al3Mg2 nanocomposite showed significant improvement in mechanical properties while maintaining a good ductility up to 24%. The ultimate compressive strength increased up to 603%, yield strength increased up to 515%, Young' s modulus increased up to 181%, and hardness increased up to 406%.

To improve both wear and corrosion resistances of materials subjected to extreme corrosion environments, iron-based amorphous alloy technology has attracted the attention of many scholars in recent years and has been studied in depth [60–63].

Coimbrão et al. studied the corrosion resistance of amorphous and partially crystallized Fe68Cr8Mo4Nb4B16 alloys [64]. We found that a highly protective passivating film was formed on the surface of the fully amorphous Fe68Cr8Mo4Nb4B16 alloy in the presence of a chloride electrolyte, thereby showing excellent corrosion resistance characteristics where the suppression of crystallization is unavoidable.

3.2 Mechanical Design Field

Similar to the design of general mechanical products, the main goal of mechanical design used for extreme environments is to design the optimized mechanical product under the conditions of certain materials and processing. Inappropriate mechanism design, such as improper geometry, layout of components, and improper coordination between multiple physical phenomena, may cause problems. Such problems include overheating, high vibration and noise, and fracture and failure of mechanical products in extreme environments [65–70]. In this section, we discuss the design technology of mechanical products working in extreme environments developed in recent years.

With the ever-improving computer technology, simulation has become an indispensable method used in the mechanical design stage. Simulations can save a lot of costs and time compared to experiments.

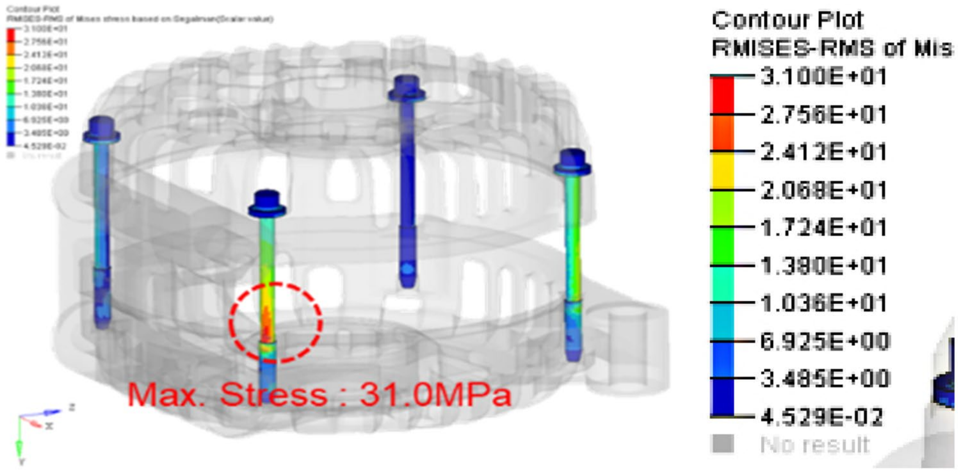
To study the soil-structure interaction and pile group effect on the dynamic response of an offshore jacket wind turbine with a jacket foundation, Shi et al. proposed a p-y model that considered the lateral soil resistance P-y curve with the pile group effect. The model predicted the modal and coupled dynamic response of the two models through a simulation method, laying the foundation for a more secure mechanical design of offshore machinery working in extreme corrosion environments [71].

For vehicles working in extreme environments, material brittleness and extreme vibration caused by changes in extreme temperature and high load engine operation, respectively, are common problems with mechanical products around engines. Qin et al. proposed a design method to reinforce the vibration resistance strength of the generator used in a sports utility vehicle working in extreme environments [72]. It is worth emphasizing that the radial dimension of the generator increases as the required output power increases; however, the space in the engine compartment is limited. Therefore, the space required to reinforce mechanical products needs to be considered. In the initial extreme vibration experiments, problems such as breakage of through bolts and cracks on the front bracket were observed. To reinforce that bracket so that it could resist extreme vibration, a new design using a separated mounting was proposed. Subsequently, the new design was analyzed for modal and random responses and compared with the original design. Figure 3 shows the simulation results of the two models using random response simulations. The red dotted circle indicates the location of the fracture that occurred due to extreme vibration during the initial experiment. The simulation results show that the maximum stress of the new design was reduced by 73.8% compared with the original design. The correctness of the simulation was verified using bench tests. The method of improving development efficiency by integrating geometric optimization and dynamic simulation is widely used in the design phase of extreme environmental products.

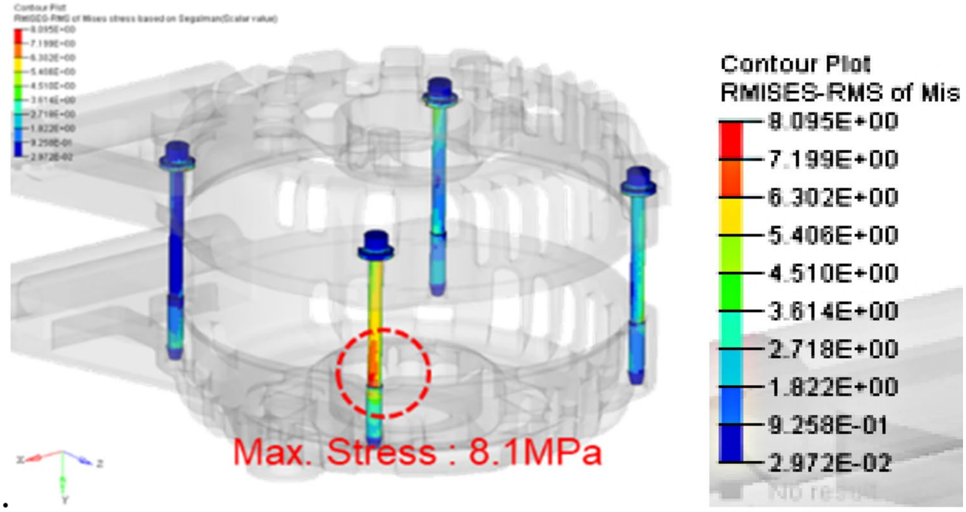
Similar to the method of strengthening mechanical equipment working in extreme environments through geometric optimization, Qin et al. presented research to reduce the extreme vibration and noise of a vehicle gearbox through geometrical modification [73]. Through repeated modifications of the lead crown and slope, involute barreling and slope, and linear tip relief on both sides of each gear, optimum modification was obtained. A contact finite element simulation was carried out based on the optimized model. The analysis results show that the optimal design makes the power transmission uniform, thereby improving the operating safety of the entire mechanical system working in extreme environments. Additionally, the transmission error between the optimized gears was reduced. Experimental measurements were conducted to prove these effects, where the noise value of the modified gearbox, at high RPM, was observed to have been significantly improved, as shown in Fig. 4. The method of optimizing the working performance of the machinery itself by changing the geometric shape is the main method of mechanical design in extreme environments. The combination of simulations and experiments can greatly reduce the cost and time in the production of prototypes and provide more opportunities for design optimization.

In extremely low temperature environments, the traditional double-layer butterfly valve composed of rubber and metal seals used on liquefied natural gas (LNG) marine engines is no longer adequate to meet the requirements of seal safety and durability. Kwak et al. presented a new design for a cryogenic triple-offset butterfly valve composed of compressible and elastic materials with strong sealing properties at extremely low temperatures [74]. Laminated multi-layer technology was applied to this design. The finite element method was used to simulate the actual state during the initial design stage, and hydraulic and cryogenic leakage

Fig. 3 Random response analysis results for through bolts



(a) Original design

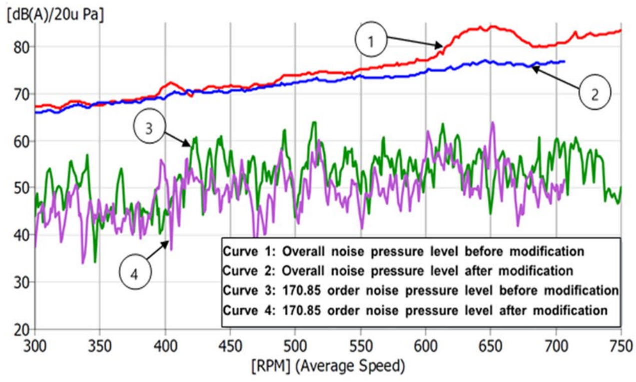


(b) New design

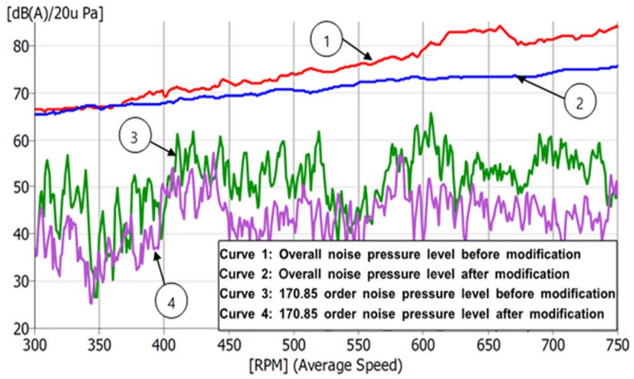
tests were conducted to prove its safety under extremely low temperatures.

To deal with the oil leakage caused by the failure of the bridge damper seal in extreme environments, Qin et al. proposed a novel design of a vibration energy absorbing mechanism (VEAM) based on multi-physics (magnetic spring, hydraulic system and structural dynamics). Figure 5 shows a schematic of the VEAM mechanism [75]. Through a passive vibration control mechanism, the large-amplitude vibrations, under extreme working conditions, and the most common small-amplitude vibrations are separately controlled in this system. Through a novel mechanism design, the goal of extending the service life of the equipment under extreme environments is achieved. Multi physical design(s) (methods), in recent years, have become an import aspect for extreme environment technology.

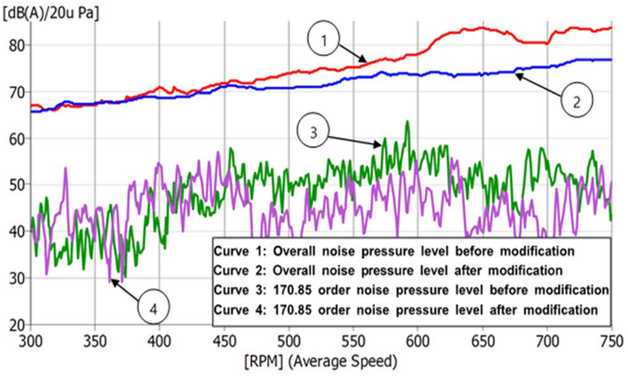
As an invisible physical field, the heat flow field is often faced in the design of extreme high- and low-temperature machinery. Park et al. developed different models for condensers in their initial mechanical design. The main difference between these models was the different arrangements for the condenser tubes. The commercial software FLUENT®, which has been widely used for fluid dynamics simulations, was used to perform the thermal flow simulations of the condenser models. The performance was reviewed based on the numerical results obtained. The pressure drop performance of the optimal model was found to increase by 40% compared with the original model [76]. For the obscured physical field, such as heat flow, the simulation based on the finite element or finite volume method can effectively restore the real



(a) 300Nm



(b) 430Nm



(c) 560Nm

Fig. 4 Comparison of noise measurements under different load conditions before and after gearbox optimization

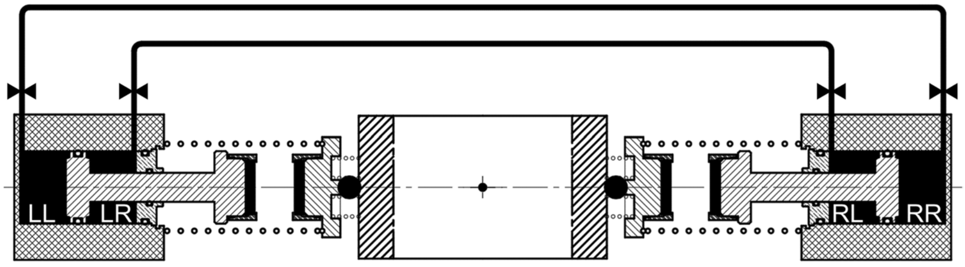


Fig. 5 Schematic diagram of the VEAM mechanism

application condition, which provides convenience for mechanical design for extreme environments.

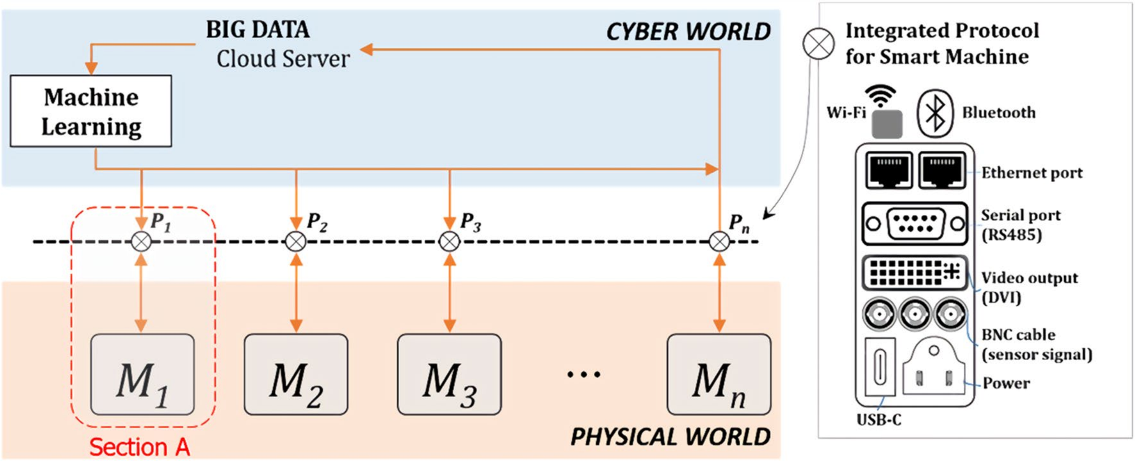
In response to different extreme environmental requirements, scholars have proposed various solutions. In summary, mechanical design technology can be divided into geometric optimization of parts, theoretical optimization of mechanisms, and performance optimization based on multiphysics. In these different facets of design, simulations based on different numerical analysis methods can increase the convenience of mechanical design.

3.3 Manufacturing Field

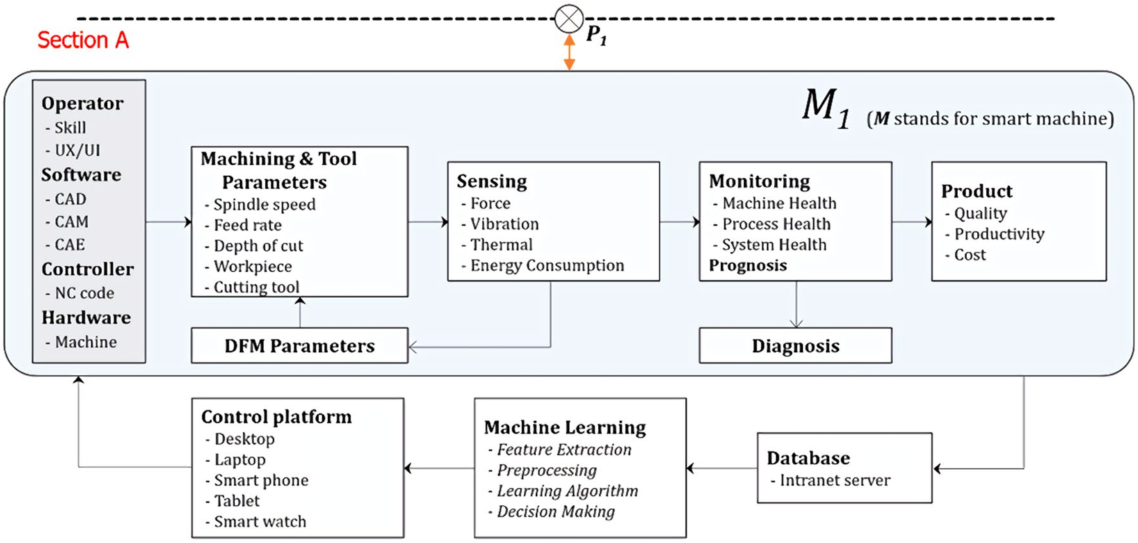
The manufacturing process of mechanical products is an important criterion for evaluating a country's scientific and technological strengths. Extreme environmental technology is mostly based on the quality of mechanical products. In recent years, with the continuous advancements of technologies related to manufacturing of machinery, extreme environmental technology has also achieved outstanding breakthroughs. In this section, we discuss some research related to advanced processing technologies.

The precision of processed products plays a decisive role in determining their service life and application possibilities (such as contact connection of components, coupling without sealing components, etc.) in extreme environments. To overcome the application problems of mechanical products under extreme environments, more precise processing technology is constantly being researched and developed. In this section, we summarize and discuss several representative examples of processing technology.

The fourth industrial revolution has catalyzed the development of various industries throughout the physical world. Smart manufacturing technology based on artificial intelligence (AI) has become an important developmental direction for the manufacturing industry [77–82]. Smart machining technology refers to a new processing paradigm that integrates machine learning into traditional machining processes to improve the quality of products and the efficiency of automated production. This provides more possibilities and solutions for the design of mechanical products intended for use in extreme environments. As shown in Fig. 6a, the integrated protocol for machine-to-machine and machine-to-server communication establishes the network between the cyber world and the physical world. This works to realize the self-optimizing process of interconnected machines



(a) Cyber and physical worlds



(b) Single machining process

Fig. 6 Schematic of smart machining

in the network. Figure 6b illustrates the machining process of a single unit in the network, which is mainly composed of machining, sensing, monitoring, and diagnosis modules. The data from each module are shared with the other connected machines through the integrated protocol and cloud technology [83].

As mentioned in Sect. 3.1, to meet the requirements of mechanical products under extreme environments, high-performance materials have been researched progressively. However, contrary to their desirable mechanical properties, they generally suffer from poor processability. Using traditional machining methods may have limitations regarding accuracy and processing effects and may cause an increase in manufacturing costs. Therefore, numerous studies have been dedicated to solving machining problems related to high-performance materials used in extreme environments [84–90].

Thermally assisted machining (TAM), which is a machining method with great potential for development, improves the machining speed by locally increasing the temperature of the material at the processing location. TAM is mainly implemented as laser assisted machining (LAM) [91–97], plasma enhanced machining [98, 99], or electric heating machining [100].

Woo et al. compared the characteristics of AISI 1045 and Inconel 718 materials subjected to conventional machining and LAM methods [101]. The finite element method was used to predict the milling depth. Consequently, the cutting force and surface roughness produced by LAM were significantly improved compared to the conventional machining methods. The effects of different cutting directions were compared. Taking the Inconel 718 material as an example, the machined surfaces after down-cut milling were superior to the surfaces after up-cut milling, as shown in Fig. 7. Compared with the results of conventional machining, the processing efficiency increased by up to 82%, and the surface accuracy was improved by up to 53% in the LAM of AISI 1045 steel. The processing efficiency increased by up to 38%, and the surface accuracy was improved by up to 74% in the LAM of Inconel 718. Subsequently, Hwang et al. proposed three LAM preheating methods: one-way, zig-zag, and back-and-forth. Simulations, comparative tests, and measurements were performed [102]. The results showed that the back-and-forth method had a more efficient preheating performance and the best surface roughness compared with the other methods.

Oh et al. [103] summarized the relationship between the acute angle of the machining route and the preheating distance during LAM. The effects of the acute corners and tool wear were proven through experiments.

Erdenechimeg et al. [104] applied LAM technology to the processing of carbon fiber reinforced silicon carbide (C/SiC) ceramic matrix composites. An in-depth exploration of its processing characteristics was conducted. Consequently, the optimal processing conditions were summarized as follow: spindle speed was 5000 rpm, feed rate was 200 mm/min, preheating temperature was 1100 °C) and DOC was 0.3 mm.

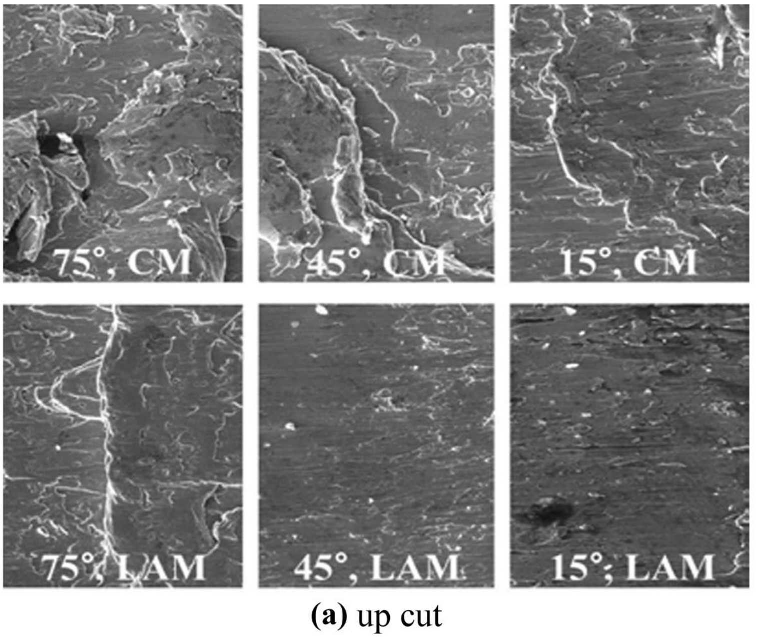
Moon et al. [105] studied the machining characteristics of Inconel 718 machined by plasma-enhanced machining. The main parameters were the plasma power and rotational speed. Consequently, the cutting force and surface roughness were reduced by plasma-enhanced machining. In addition, compared to LAM, it showed a similar cutting force and surface roughness value.

Lee et al. [106] investigated the optimal machining conditions and energy efficiency of Ti–6Al–4 V in plasma-enhanced machining. A table of orthogonal arrays was represented, and the Taguchi method was used as the design of the experiment (DoE). The optimal machining conditions were determined as follow: a feed rate of 50 mm/min, spindle speed of 12,000 rpm, and depth of cut of 0.2 mm. In addition, the energy efficiency (in terms of mechanical energy and specific cutting energy) of plasma-enhanced machining was improved by preheating compared to traditional machining.

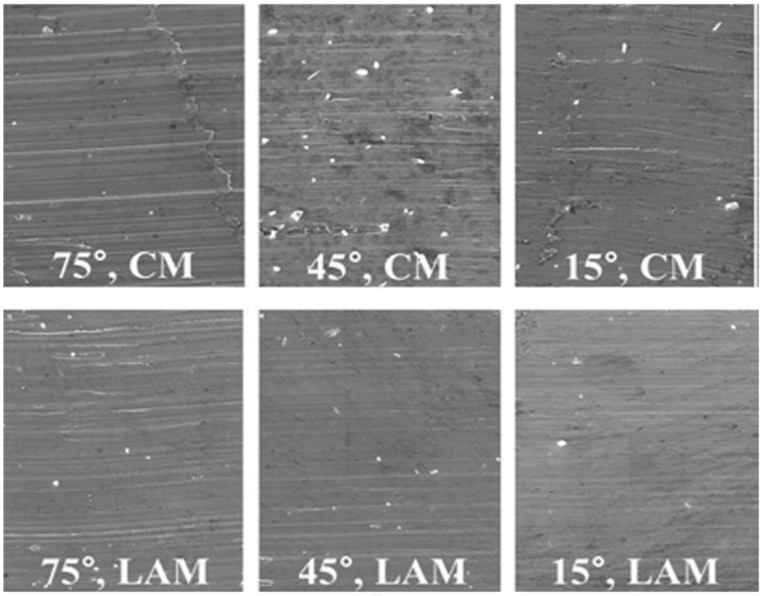
Additive manufacturing is a manufacturing method for creating 3D objects from a digital file. Complex 3D shapes that cannot be produced with traditional casting and subtractive manufacturing technologies can be manufactured using additive manufacturing technology. Metal additive manufacturing has recently been applied to the manufacturing and repair of extreme environment parts. Materials used for metal additive manufacturing include titanium alloys, cobalt chromium, stainless steel, nickel alloys, and aluminum alloys. The metal additive manufacturing method is largely divided into the directed energy deposition (DED) method and the powder bed fusion method. The DED method is mainly used for depositing and repairing large products in extreme environmental fields. In the DED method, powder and wire can be used as the build material, and laser or arc plasma is usually the heat source.

Kakinuma et al. [107] studied the influence of Inconel 625 powder characteristics on product quality. For the experimental conditions, the powder size and laser power were set as variables. The porosity according to the laser power was compared to calculate the efficiency of the laser power. In conclusion, conditions were proposed to suppress voids and cracks.

Dinovitzer et al. [108] investigated the effect of wire and arc additive manufacturing (WAAM) parameters on bead shape and microstructure. The wire was a HASTELLOY X alloy. The Taguchi experiment design was used to analyze the effects of the parameters. Furthermore, the experimental conditions included the travel speed, wire feed rate, current, and argon flow rate. Consequently, it



(a) up cut



(b) down cut

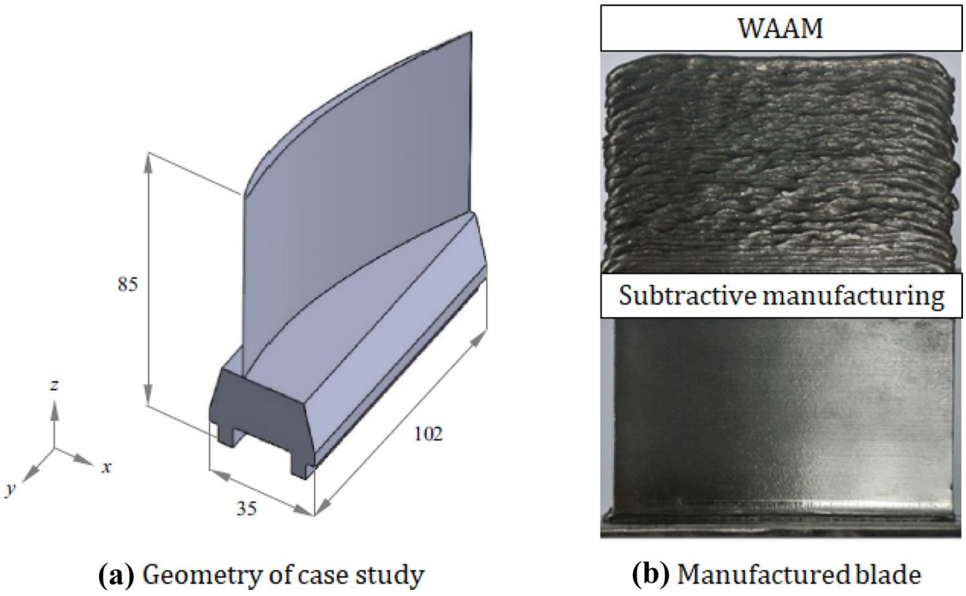
Fig. 7 Microphotograph of machined surfaces of Inconel 718

was suggested that argon gas had no significant effect compared to the other parameters.

Campatelli et al. [109] analyzed the energy efficiency of integrated WAAM-Subtractive and pure subtractive manufacturing. For the case study, blades (parts used in extreme environments) were manufactured with traditional machining after WAAM and traditional machining, as shown in Fig. 8. The results showed that integrated WAAM-subtractive manufacturing can significantly save material and energy.

4 Summary and Future Perspectives

This paper presents an overview of the development of extreme environment technology in mechanical engineering. Furthermore, an information analysis of the academic research results and GDP of three representative countries (the United States, China and Germany) is provided. We found that the total amount of research on extreme environmental technologies in both these countries is



(a) Geometry of case study **(b)** Manufactured blade

Fig. 8 Geometry and manufactured blade (modified from [108])

consistent with the trends of economic development in the last five years. The United States is a developed country with a stable economy. It began academic research on extreme environments a long time ago and has maintained steady research output. Germany is a leading country in machinery manufacturing, but its academic research on extreme environmental technology has not changed much in recent years, and there is even a decreasing trend in 2019. Conversely, China is a developing country with rapid economic growth in recent years. We found that the number of studies by Chinese scholars on extreme environment technologies is on the rise and is almost consistent with the development trend of the GDP. Although it is difficult to summarize the relationship between GDP and extreme environmental technology research with limited data, science and technology are the basic strengths that support a country's economy.

Subsequently, the development of extreme environment technology in the three most important areas of mechanical engineering (materials, mechanical design, and manufacturing) was summarized using examples. Alloys are still the main materials used in mechanical products. Therefore, an increasing number of scholars are working on improving the performance of conventional alloys in extreme environments by adding elements with unique properties and optimizing the manufacturing process. In addition, metal-based composite materials have also shown a rapid development trend. Owing to their excellent mechanical properties, traditional metals applied in mechanical products will be replaced by such composites in the future.

Reinforcing or modifying the geometric structure of mechanical products to obtain better performance in extreme environments is still one of the main methods used in mechanical design. With the development of computer technology, numerical simulation has become a more convenient, accurate, and time-saving method for simulating and predicting the performance of mechanical products in different environments. It provides a strong theoretical basis for mechanical design and saves time and cost to test new designs.

The integration of new technologies such as AI and big data has made the machining process more accurate and efficient. Processes such as thermal-assisted machining have improved the accuracy (up to 74%) and processing efficiency (up to 82%) of mechanical products. The performance of mechanical products in extreme environments will continue to be optimized along with the intelligent development driven by the fourth industrial revolution in mechanical manufacturing.

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Compliance with Ethical Standards

Conflict of interest The authors declared that they have no conflicts of interest to this work.

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