

Application and introduction of engineering plastics in humanoid robots

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Abstract: The development of the humanoid robot industry has entered a fast lane, and engineering plastics continue to benefit from their advantage of replacing traditional metal materials to achieve lightweight mass production. This article reviews the development history of humanoid robots and the application overview of engineering plastics in this field. It elaborates on the performance characteristics and application practices of several major engineering plastics in combination with specific application scenarios, verifying that engineering plastics possess multiple advantages in the application of humanoid robots and play a crucial role in promoting the development of humanoid robots. Furthermore, it provides an outlook on the application prospects of engineering plastics in the field of humanoid robots.

Key words: engineering plastics; humanoid robots; lightweight mass production; APP introduction

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Humanoid robots have shown remarkable potential and charm on the stage of the 2025 Spring Festival Gala, and are considered to be one of the largest industries in human history. Their product forms exhibit high adaptability and practicality, naturally adapting to daily living environments, with strong natural human-robot interaction. They will play a role in industries such as manufacturing, service, and household, and the market size is expected to grow rapidly in the coming years. To achieve human-like movement capabilities, humanoid robots need to minimize their own weight. Excessive weight will increase motor load, affecting movement flexibility, load capacity, and endurance performance. Humanoid robots commonly use lightweight materials such as aluminum alloy, magnesium alloy, and engineering plastics. Engineering plastics have excellent comprehensive properties, including high rigidity, low creep, high mechanical strength, good heat resistance, good electrical insulation, and good chemical resistance. They can replace metals as engineering materials. As a core category of high-performance polymer materials, especially specialty engineering plastics, with their high

temperature resistance, high strength, and chemical corrosion resistance, have become key basic materials supporting strategic industries such as humanoid robots.

1 Introduction and application of plastics in humanoid robots

1.1 Basic overview of humanoid robots

In 1969, the laboratory of Kazuhiro Kato at Waseda University in Japan developed the first robot that walked on two legs, marking the earliest prototype of a humanoid robot. In the 21st century, research on humanoid robots moved out of the laboratory, and the developed electrically driven ASIMO robot possesses functions such as intelligent interaction, flexible manipulation, and agile movement. Combined with multiple sensors such as vision and touch, it can recognize objects and perform appropriate fine manipulation, with strong

Biography: Tao Yongliang (1956-), male, is a professor-level senior engineer, mainly engaged in research on the application and molding process of polymer materials.

learning capabilities and autonomy. In 2023, Tesla developed the Optimus series of humanoid robots for rapid iteration. Based on AI technology and FDS (full self-driving) chips, it achieves task-level and action-level decision-making, as well as recognition of objects, faces, gestures, etc. in complex environments through an end-to-end neural network model. Its full-body pressure calculation and feedback mechanism enable the robot's limbs to move flexibly, smoothly, and naturally. Humanoid robots have gone through four stages: early exploration, integrated development, high-dynamic development, and now the intelligent development stage. As an integrated platform that integrates cutting-edge technologies from artificial intelligence, robotics, control engineering, and material science, humanoid robots are rapidly becoming an important research direction in the fields of intelligent manufacturing and human-robot collaboration.

1.2 Basic components of humanoid robots

Humanoid robots are complex systems that integrate multiple fields of technology, including mechanical design, sensing technology, and control algorithms. They can be divided into three core components: the body hardware, the control system, and the perception and interaction module. These components work together to achieve human-like movement and intelligent interaction capabilities.

Hardware serves as the carrier for robots to execute physical actions, encompassing mechanical structures, drive systems, and crucial components. It must adhere to the demands of high degrees of freedom, lightweight, and durability. The hardware is segmented into the head, torso, limbs (upper and lower limbs), and end effectors. Servo motors are employed as drivers, and in high-precision scenarios, harmonic reducers are integrated to ensure precision in joint movement and torque output. The control system is tasked with interpreting environmental information, planning motion paths, and driving the executing mechanisms, constituting the core of robot intelligence. The perception module achieves environmental cognition through multi-sensor fusion, while the interaction system facilitates human-robot collaboration and remote operation, serving as a pivotal component for robots to adapt to intricate scenarios.

1.3 Introduction to plastics used in humanoid robots

Humanoid robotics is a new industry, and the application of engineering plastics is comprehensively considered from usage perspectives. Combination of lightweight and high strength: It is necessary to ensure structural stability while reducing the robot's self-weight. The materials should meet the strength requirements of humanoid robots and also be lightweight. Wear resistance and corrosion resistance: Moving parts such as joints and gears should withstand long-term friction. The materials should have good wear resistance and corrosion resistance in high-temperature environments. Temperature resistance and insulation: Materials surrounding motors and electronic components should be resistant to high temperatures and provide insulation. Materials with high fluidity and dimensional stability are used for precision electrical components in high-temperature electrical insulation scenarios. Flexibility and bionic adaptation: Skin and flexible parts need to simulate human touch. Silicone and thermoplastic elastomers are used for soft touch parts and bionic skin. Common engineering plastics used in humanoid robots include polyetheretherketone (PEEK), polyimide (PI), nylon (PA), polyphenylene sulfide (PPS), PC/ABS alloy, liquid crystal polymer (LCP), ultra-high molecular weight polyethylene (UHMW-PE), etc. According to value ratio predictions, PEEK and composite materials account for 45%, electronic-grade specialty plastics PPS and LCP account for 30%, engineering plastics PA and PC/ABS account for 20%, and other materials such as PI and UHMW-PE account for 5%.

2 Application of engineering plastics in humanoid robots

2.1 PEEK

Polyetheretherketone (PEEK) is a polymer composed of repeating units containing two ether bonds and one ketone bond in its main chain structure. It is a material series of polyaryletherketones, featuring semi-crystalline characteristics and possessing properties such as high temperature resistance and chemical corrosion resistance. PEEK is an excellent special engineering plastic, with advantages such as high temperature resistance, excellent mechanical properties, good self-lubricity, chemical corrosion resistance, flame retardancy, peel resistance, radiation resistance, stable insulation, hydrolysis resistance, and easy processing. PEEK is widely

used in humanoid robots, where it is applied to parts such as knee joints, elbow joints, and wrist joints, as well as gears, racks, housings, and structural components, to withstand high loads and frequent impacts. By adding reinforcement materials such as carbon fibers, the strength can be further enhanced, effectively reducing friction and wear, and improving motion accuracy and lifespan. The lightweight of PEEK helps reduce the overall load on the robot and lower energy consumption. PEEK has good electrical insulation properties and chemical stability, providing a stable working environment for sensors and avoiding the impact of electromagnetic interference and chemical corrosion on sensor performance. PEEK is widely used in the packaging and fixation of components such as pressure sensors and tactile sensors.

2.2 PI

Polyimide (PI) is a high-molecular polymer with an imide structure in its main chain. Most high-performance PI main chains primarily consist of aromatic and heterocyclic structural units. PI boasts the highest flame retardant rating, excellent electrical insulation properties, mechanical properties, chemical stability, aging resistance, and radiation resistance. With a dielectric constant of 3.4 and a dielectric loss of only 10⁻³, it belongs to Class F to H insulation. Its use temperature range remains unchanged within -269 to 400 °C, earning it the reputation as "one of the most promising engineering plastics of the 21st century".

PI is widely used in humanoid robot applications. While ensuring strength, PI has a slightly higher density than PEEK but with 40% higher strength, making it suitable for lightweight structural components. This allows the mechanical arm wall thickness to be reduced to 0.8mm, resulting in an overall weight reduction of 25%. As a flexible substrate material, PI can be combined with carbon nanotubes, graphene, etc. for flexible sensors and electronic skin, which can integrate sensors for pressure, temperature, humidity, etc., enhancing the robot's ability to perceive subtle changes in the environment. PI can be used at a long-term operating temperature of 300°C and has a low friction coefficient of 0.17~0.25, meaning that under high-temperature loads, its wear is only one-third of that of traditional PEEK materials. It can be used for joints and gear components, extending the maintenance cycle of joints from 600 hours to 2,000 hours.

As the core material of flexible printed circuits (FPC), PI is used in control systems and flexible wiring. When applied to robot joints, PI enhances signal transmission efficiency and joint response speed, functioning like a robot's nervous system. PI can integrate various sensor circuits for environmental perception and multifunctional integration, detecting environmental characteristics such as contact force and vibration, and endowed with conductivity, self-healing, and other functions through nanocomposite technology.

2.3 PA

Nylon, scientifically known as polyamide (PA), is a general term for thermoplastic resins containing repeating amide groups in their molecular backbone. It includes aliphatic PA, aliphatic-aromatic PA, and aromatic PA. Among the five major engineering plastics, PA is the one with the largest production volume, the most varieties, and the widest range of applications. PA possesses characteristics such as high mechanical strength, good toughness, high tensile strength, low friction coefficient, good wear resistance, excellent self-lubricity, and good thermal properties. These properties meet the requirements for lightweight, mechanical performance, and wear resistance of humanoid robots. With its diverse properties, PA has potential applications in core components such as joints, structural parts, and casings.

2.3.1 PA66

PA66 (polyamide 66) has become one of the preferred materials for high-load components of humanoid robots due to its excellent mechanical properties and high temperature resistance. With a density of approximately 1.14g/cm³, it can reduce the overall weight to enhance movement flexibility and energy efficiency. Its tensile strength reaches 70~120MPa, ensuring structural stability. PA66 is used for joints and robotic arm skeletons that undergo frequent movement, and is reinforced with glass fibers to improve wear resistance and prolong service life. With a melting point of about 260 °C and a heat distortion temperature exceeding 262 °C, PA66 is suitable for high temperature environments and easy to process. It can be used with a woven nylon shell to achieve a combination of lightweight and impact resistance.

2.3.2 PA612

PA612 possesses characteristics such as flexibility, self-lubricity, and chemical resistance, and is primarily

used for dynamic components and protective structures. When utilized in joint connectors, it reduces energy loss during joint movement due to its low friction coefficient and wear resistance, ensuring smooth movement and extending component lifespan. It can be injection molded into complex-shaped protective shells, combining flexibility and impact resistance to protect internal electronic components during collisions.

2.3.3 PA12

PA12, characterized by excellent insulation, elasticity, and fatigue resistance, is used for internal cable sheaths, providing high insulation performance to prevent circuit short circuits and ensure stable operation of electronic systems. When used for seals, its elasticity and sealing properties prevent dust and moisture from entering the interior of machines. It is also used in joint bearings, motor interfaces, and other parts requiring protection.

PA covers the multi-dimensional needs of humanoid robots, ranging from structural load-bearing to precise protection. With the development of material modification technologies (glass fiber reinforcement, alloying), the role of PA in lightweighting and functional integration of robots will become further prominent.

2.4 PPS

Polyphenylene sulfide (PPS) is a kind of thermoplastic special engineering plastic with excellent comprehensive performance. In industrial production, PPS is synthesized through a condensation reaction using p-dichlorobenzene and anhydrous sodium sulfide in a polar solvent. The polar solvent is selected from N-methylpyrrolidone (NMP), hexamethylphosphoric triamide (HMPA), or N-methylcaprolactam. PPS is a sulfur-containing aromatic polymer. Linear PPS becomes thermosetting after crosslinking at temperatures above 350°C, while branched PPS remains a thermoplastic. PPS is a highly crystalline, hard, and brittle polymer. The relative density of pure PPS is 1.3. It exhibits excellent flame retardancy, with an oxygen index of over 44%, making PPS a high-flame-retardant material.

PPS is applied to structural components, transmission systems, and protective parts of humanoid robots. Joint links serve to connect joints and ensure smooth movement, while PPS, with its high strength and wear resistance, maintains

long-term stability. The mechanical arms and drive wheels of humanoid robots play a crucial role in load-bearing and high-precision transmission, and PPS, with its excellent dimensional stability, can maintain stable electrical properties in high-temperature and high-humidity environments.

The power center housing (battery box, motor housing) of humanoid robots needs to be heat-resistant, flame-retardant, and protect its internal components. PPS's heat resistance and flame retardancy can avoid high temperature risks. For the protective layer (shell, protective plate, etc.) of humanoid robots, PPS can reduce weight by up to 60% compared to traditional metals, with mechanical strength close to steel. It has strong resistance to corrosive substances such as acids and alkalis, and excellent electrical insulation properties, which can effectively protect internal components from external erosion. Through modification technologies such as carbon fiber reinforcement, PPS can be used for the body and limb skeletons, achieving a weight reduction of more than 40% and improving the flexibility of robots.

2.5 PC/ABS

PC/ABS alloy is an engineering plastic made by blending and modifying polycarbonate (PC) and acrylonitrile-butadiene-styrene copolymer (ABS) through graft copolymerization, combining the advantages of both materials to compensate for their respective deficiencies. It features high impact strength, excellent processing performance, weather resistance, and dimensional stability, and is applied in automotive, home appliance, and other fields. To enhance the interfacial compatibility between PC and ABS, compatibilizers such as maleic anhydride grafted POE and polystyrene maleic anhydride graft copolymer (SMA) are added to optimize the comprehensive performance of the alloy.

The impact strength of PC/ABS alloy at room temperature is 3 to 4 times that of pure PC, and it remains more than twice that of PC even after aging treatment at 120°C for 140 hours. After outdoor exposure for 2 years, its tensile strength and bending strength remain almost unchanged. Its melt viscosity is reduced by 1/3 compared to PC, with a lower molding temperature, small residual stress, and uniform product color. It is suitable for the production of thin-walled, long-process parts. Its weather resistance is better than that of pure PC, and its impact strength remains significantly higher

than that of pure PC even after outdoor exposure.

The SoftBank NAO robot utilizes PC/ABS for its shell and structural components. The heat resistance and processing fluidity of PC/ABS enable it to meet the molding requirements for complex-shaped parts of robots, while providing reliable structural support and impact resistance protection. Shenkai Hong and Leju Robotics have launched a teaching humanoid robot shell with a composite design of aluminum alloy and PC/ABS plastic materials. The PC/ABS part primarily meets the requirements for lightweight and flexible design of the shell, while the aluminum alloy enhances structural strength, achieving a lightweight body weighing 1.73kg. PC/ABS has high impact strength and rigidity, which can withstand dynamic loads during robot movement, and performs well in joint connectors and shell protection.

PC/ABS exhibits excellent melt flowability, making it suitable for injection molding of facial shells and sensor brackets. Its temperature resistance (heat distortion temperature of 110~135 °C) and UV resistance make it suitable for use in both indoor and outdoor scenarios. With surface treatment compatibility, it can be directly subjected to surface decoration processes such as spraying and electroplating, meeting the personalized appearance requirements of robots.

2.6 LCP

Liquid Crystal Polymer (LCP) is a kind of intermediate polymer between solid crystallization and liquid, with one-dimensional or two-dimensional order in its molecular arrangement. It exhibits liquid crystallinity in the molten state and is a new type of thermoplastic polymer material. The molecular structure of LCP contains rigid benzene rings, providing excellent heat resistance, chemical resistance, and mechanical strength. LCP has an irregularly regular fibrous structure, and its reinforcement with glass fiber, carbon fiber, etc. far exceeds that of other engineering plastics. With a dielectric constant (10 GHz) of 2.9, a dissipation factor (10 GHz) of 0.0025, a melting temperature (DSC) of 330 °C, and a water absorption rate (23 °C.24 h) of 0.04%, LCP has become a key material support for core components of humanoid robots due to its comprehensive properties such as high strength, heat resistance, low water absorption rate, and excellent electrical insulation.

LCP finds application in humanoid robots. Its high heat

resistance (continuous use temperature > 220°C) adapts to the high-temperature working environment of robot servo motors and other components, preventing thermal deformation that can lead to performance degradation. Its high heat resistance and dimensional stability make it the preferred material for robot servo motor connectors, ensuring stable operation of precision electronic components under complex working conditions. LCP's electrical insulation and low dielectric constant serve as a bridge for signal and electrical connections in high-speed connectors, playing a key role in data transmission within and outside robot systems, ensuring high-frequency signal transmission efficiency. LCP meets the lightweight and flexibility requirements of artificial muscles, simulating human muscle contraction and extension, helping robots achieve fine and natural movements. It is used to create electronic skin, enhancing robots' environmental perception capabilities. It is suitable for producing high-precision, high-reliability key sensing components such as pressure sensors and temperature sensors, supporting precise control and interaction of robots. LCP's low water absorption rate and dimensional stability ensure that component accuracy is not affected in humid environments or during long-term operation. Its weather resistance and radiation resistance make it suitable for use in open environments, enhancing the accuracy of robot motion control. LCP has a higher melting point and good fluidity, enabling injection molding, reducing the weight of the robot body compared to metal materials. If reinforced with glass fiber, carbon fiber, or other materials, its performance far exceeds that of other engineering plastics, enhancing endurance and meeting structural load requirements.

2.7 UHMW-PE

Ultra-high molecular weight polyethylene (UHMW-PE) is a kind of linear structure polyethylene material with a molecular weight exceeding 1 million. It possesses excellent properties such as ultra-high strength, wear resistance, and low temperature resistance, and is widely used in multiple fields. Its specific strength is 15 times that of high-quality steel, 2.6 times that of carbon fiber, and 1.7 times that of aramid fiber. Furthermore, its elongation at break is higher than that of carbon fiber and aramid, and it exhibits good flexibility and can maintain stable mechanical properties under high strain rates and low temperature environments. UHMW-PE also possesses

characteristics such as resistance to strong acid and alkali corrosion, UV resistance, low friction coefficient, hygiene, and non-toxicity. Its operating temperature can be as low as -70°C , and it is even suitable for liquid nitrogen environments. Due to its extremely high molecular weight, traditional processing of UHMW-PE is challenging. Through specialized injection molding machines and process optimization, efficient molding can be achieved, with production efficiency reaching 10 to 40 molds per hour, significantly improving compared to traditional pressing and sintering methods.

UHMW-PE, with its high strength, lightweight, wear resistance, and corrosion resistance, has become a key material for lightweighting and enhancing the motion performance of humanoid robots. Its unique properties are irreplaceable in the field of robotics. Its specific strength is 15 times that of high-quality steel wire and 1.8 times that of carbon fiber, while its density is only 0.97 times that of water, significantly reducing the robot's self-weight. Tesla Optimus Gen2 uses UHMW-PE lightweight material to achieve a weight reduction of 10 kg and a walking speed increase of 30%. With its low friction coefficient and self-lubricating properties, it is suitable for high-frequency motion transmission components (such as tendons and joints) and can withstand long-term high-load operation without easy wear. Its chemical corrosion resistance and bending performance make it suitable for protective shells and flexible transmission structures. It maintains toughness even in a liquid nitrogen environment at -200°C , avoiding the low-temperature brittleness problem of ordinary plastics.

The tendon transmission system plays a role in simulating human tendons in humanoid robots, driving joint movements by pulling or relaxing ropes. The tendon material is dexterous hand tendon, which pulls fingers to complete various actions and is an important material for enhancing the fine control ability and lightweight of dexterous hands. Tendon materials are mainly divided into polymer fiber and metal categories. UHMW-PE has replaced steel wire as the core material of tendons, with a weight only 1/7 to 1/8 of steel wire, requiring no rust prevention. The value of a single robot tendon is about 3,520 yuan. If the global shipment reaches 10 million units, the market size will exceed 35 billion yuan. UHMW-PE is used in joint components, integrated into the transmission and support structure of dexterous hands, simulating human tendons to

achieve high flexibility and low inertia, enhancing motion accuracy. When used in sliding components such as bearings and bushings, UHMW-PE requires no lubricating oil and has superior physical properties compared to metal materials. For sensors and body coverings: it combines protective performance and lightweight requirements, optimizing the human-robot interaction experience.

2.8 TPU

Thermoplastic Polyurethanes (TPU), a kind of linear block polymer composed of soft segments (long-chain oligomeric diols) and hard segments (diisocyanates and chain extenders), is a polymer material positioned between rubber and plastic. Its molecular structure is primarily linear, with strong polarity in the hard segments. The microphase regions of the hard segments form physical crosslinks through hydrogen bonding, distributed in the soft segment matrix to create a physical crosslink point, thus endowing the elastomer with the elastic recovery properties of vulcanized rubber. TPU forms physical crosslinks through hydrogen bonding, can be heated for plasticization, and is soluble in specific solvents. According to its composition, it can be divided into polyester and polyether types, featuring a wide range of hardness (60HA~85HD), wear resistance, oil resistance, transparency, good elasticity, and maintaining flexibility within the temperature range of $-40\sim 120^{\circ}\text{C}$ without the need for plasticizers.

The unique properties of TPU composite materials have demonstrated potential applications in humanoid robots, particularly in the areas of flexible components, structural materials, and electronic skin, which have garnered significant attention. By incorporating components such as glass fibers, carbon black, and silica, TPU composite materials enhance strength and heat resistance while maintaining lightweight characteristics, reducing robot energy consumption and enhancing motion flexibility. TPU materials combine the elasticity of rubber with the processability of plastics, offering excellent wear resistance and weather resistance, making them suitable for manufacturing components such as joint buffer layers and cable protective covers that require repeated deformation. They support 3D printing and complex structure molding, allowing for customization of properties such as hardness and elasticity through formulation adjustments,

meeting the functional requirements of different parts of the robot. With a flexibility close to human skin, TPU is used as the substrate for electronic skin to integrate flexible sensors for pressure, temperature, and other signal detection. 3D printed TPU has been utilized in the development of soft bionic skin. TPU is employed in robotic skeletons, shells, and other components, providing reliable support and reducing overall weight through honeycomb or porous structural designs. Its elastic properties are utilized to create buffer layers for knee and elbow joints, reducing motion impact and enhancing durability. Wear-resistant and anti-aging TPU coatings can extend the service life of internal cables and exposed components of the robot.

3 Conclusion

The mass production of humanoid robots is inseparable

from breakthroughs in new material technology. Engineering plastics, with their advantages of lightweight, high performance, and design flexibility, have become key materials for the skeletons, shells, and core components of humanoid robots. Engineering plastics are a key path for driving performance breakthroughs in humanoid robots, enabling them to achieve success in endurance, motion efficiency, precision manufacturing, cost optimization, and other aspects. Their technological progress and application expansion will directly determine the development speed of the robotics industry. With continuous breakthroughs in material performance and declining manufacturing costs, engineering plastics are expected to fully replace metals in the skeletons, joints, shells, and other parts of humanoid robots.