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Development and Application of Lightweight High-strength Metal Materials

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Abstract. This article reviews the performance, alloy composition and the development of advanced lightweight high-strength materials such as high-strength steels, high-strength aluminum alloys, high-strength magnesium alloys, and titanium alloys.

Introduction

Lightweight and high-strength is the eternal theme of material development. It is an important foundation for promoting social progress, economic development, national defense construction, scientific and technological progress, and strengthening national competitiveness [1]. Today, with the rapid development of science and technology, the application of lightweight high-strength materials is not limited to cutting-edge technology. Its application is widespread to all aspects. In particular, self-contained energy equipment consumes more energy and uses more lightweight materials.

1 high-strength steel

According to the definition of high-strength steel in the world, steels with a tensile strength between 270-700 MPa are collectively classified as high-strength steel HSS (Conventional HSS) , steels with a tensile strength greater than700MPa classified as advanced high-strength steels AHSS (Advanced HSS) [2, 3], the use of high-strength is an important way to achieve lightweight equipment.

In the coal mining industry, due to the small space in the underground industry and complex geology, fires, gas explosions, floods, and other extremely hazardous accidents[4] are very likely to occur. Therefore, equipment requirements are more stringent, and light metal materials are restricted to use because of their poor frictional spark safety. Underground equipment often uses steel or copper materials. In order to ensure adequate strength and lightweight equipment, high-strength steels are generally used in explosion-proof devices. The material of the explosion-proof system for down hole operation robots uses steel of a certain grade, and its thickness is generally 4-6mm[5].

In the automotive field, according to research, 60% of automotive fuel is consumed in the vehicle's own weight[6], reducing the vehicle's own weight can effectively save energy and reduce emissions. Every 10% reduction in the vehicle's quality, fuel consumption will decrease by 3%-7%[7], so it has been to ensure that the reliability and function of the car are not affected, the realization of lightweight car body is an important direction for the development of the automotive industry. In Europe, high-strength steels and ultra-high-strength steels have been widely used in automotive parts[8] that have already been introduced. Currently, high-strength and ultra-high-strength dual-phase steels (DP steels) with low yield ratios are commonly used in automotive parts. Combining high-strength and good plasticity of phase-change induced plasticity steel (TRIP steel), twin-induced plasticity steel (TWIP steel), martensitic steel (M steel), Q & P steel (quenching and partitio-ning), hot stamping Forming steel (HF steel, boron steel) and nanoparticle precipitation strengthening steel (NANO-HITEN steel)[9], and Fe-Mn which combines the advantages of high strength, high toughness, low density, impact resistance, candle resistance, etc. -Al steel, tensile strength of 700-1100MPa, elongation after breaking reaches 60%, higher Mn, A1, C and other light alloy content can guarantee its excellent formability and impact resistance, its density can be reduced to 6.5-7.0g/cm3, which is 11%-18%[10] lower than that of pure iron, is one of the important materials for realizing vehicle weight reduction[11]. Among them, Fe-Mn-Al light-duty high-strength steels are becoming the development direction of automotive steels in the future due to their high tensile strength, good plasticity, and low density[12].

In the field of construction, with the development of economy, China's building construction is developing rapidly. High-rise and super-high-rise buildings have been scattered all over the country. High-strength steel is a necessary material for high-rise and super-high-rise buildings. In addition, the use of high-strength steel instead of ordinary steel can effectively save energy. The amount of steel used in the 20-story building, tensile strength from 490MPa to 590MPa can save 20% of steel, so the tensile strength of 590MPa ~ 780MPa has become a new trend of high-strength construction steel[13].

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Domestic and foreign commonly used high-strength steels are Japan-produced BL385, SA440, and SA630, whose tensile strengths can reach 550 MPa, 590 MPa, and 780 MPa. Structural steels used in high-rise buildings in some European countries include Q235GJ, Q345GJ, Q390GJ, and Q420GJ. In recent years, the development of high-rise steel structure buildings and large-span space structures in China has imposed higher requirements on steel strength and other indicators. For example, the National Stadium uses the Q460E-Z35, the National Swimming Pool (Water Cube) uses the Q420C. The CCTV's new site uses the Q420D-Z25, Q460E-Z35 high-strength steel. High-strength steel achieves lightness by increasing its strength, but its quality is reduced to a lesser extent, and the production of high-strength steels or over-strength steels is also expensive, and its application in certain specific fields has certain limitations. The use of lighter alloy materials for the manufacture of transportation equipment components is another way to achieve lightweight equipment.

2 high-strength aluminum alloy

In modern materials science, aluminum alloy materials have become second only used less to steel, and high-strength aluminum alloys are based on Al-Cu-Mg and Al-Zn-Mg-Cu alloys. With high strength, good processing performance and excellent welding performance, it has been widely used in aviation industry and civil industry, etc. [14]. Especially in the aviation industry, it occupies a very important position and is one of the main structural materials for the aviation industry. Al-Zn-Mg-Cu series ultra-high-strength aluminum alloys have been used to manufacture aircraft hubs, spars and wing-assisted key bearing components[15], its yield strength exceeds 500MPa[16], compared with the same yield strength of steel materials, its weight is greatly reduced. Cui Caiwei et al.[17] used 7A04 ultra-high strength aluminum alloy (7A04 aluminum alloy belongs to Al-Zn-Mg-Cu alloy) to replace steel. The tensile strength of the base is more than 540MPa, the yield strength is greater than 460MPa, and the elongation is greater than 8% and its quality is reduced by 30% compared with steel.

In addition, there are some promising high-strength aluminum alloys: Al-Li alloy—Lithium is the lightest metal element. For every 1% increase of lithium element in aluminum alloy, the density can be reduced by 3%, and the modulus can be increased by 5 %. In addition to the advantages of light weight, high modulus and high strength, aluminum-lithium alloys also have excellent fatigue resistance and good low-temperature toughness. In recent years, aluminum-lithium alloys have developed toward super-toughness, ultra-low density, high-strength weldability, low anisotropy, and strong thermal stability. However, the cost of aluminum-lithium alloys is high, the storage of metallic lithium is small, extraction is difficult, the production process is more complicated, the production process needs to be protected by argon gas and the cold hardening speed is fast, and when the temperature is high at a short time, the toughness declines seriously[18]; Aluminum matrix composites, with its small density, high specific strength and specific stiffness, specific elastic modulus, good electrical and thermal conductivity, high temperature resistance, oxidation resistance, corrosion resistance, flexible manufacturing process and many other advantages caused people The general concern is that the aluminum matrix composites currently being developed mainly include SiC/Al, B/Al, BC/AI, Al_2O_3/Al, etc.; Rare-earth aluminum alloys add some trace rare-earth raw materials to high-quality primary aluminum to improve the strength of primary aluminum, such as tensile strength, electrical conductivity, ductility, corrosion resistance and so on. Such as silicon, niobium and other minor elements added to the aluminum such as A356 aluminum alloy in a specific ratio, dedicated to the automotive aluminum wheel casting[19].

3 High-strength magnesium alloys

Magnesium alloy is the lightest metal structural material[20], its density is 1.75g/cm3, about 2/3 of aluminum alloy, 1/4 of steel. Magnesium alloy has low strength and elastic modulus, but it has high specific strength and specific rigidity. In the same weight of components, the use of magnesium alloy can make the component get higher rigidity. Moreover, magnesium alloys also have high damping capacity and good shock absorption performance, and they can withstand large shock and vibration loads. In addition, magnesium alloys are rich in resources, casting properties, excellent cutting performance, easy recycling, and no pollution. Widely used in aviation, aerospace, defense, automotive, communications electronics, computers, home appliances and other industrial fields, known as "21st century green environmental protection engineering materials" [21].

However, the application of magnesium alloys is far less widespread than that of aluminum alloys. The main reasons for this are that magnesium alloys have low absolute strength, poor room-temperature deformation processing capabilities, and are prone to oxidative combustion and susceptibility to corrosion, which limits their development as structural materials[22], so the development of high-strength magnesium alloys is the key to solving this series of problems. The addition of alloying elements to strengthen magnesium alloys is a simple, effective and economical method to increase the strength of magnesium alloys. It is more effective to study the addition of rare earth elements on the surface. Rare earth elements can increase the electron concentration in the alloy and enhance the bonding strength between the magnesium alloy atoms. It can also purify the alloy melt, refine the grain, improve the alloy structure and casting performance, thereby improving the overall performance of magnesium alloys, especially high temperature mechanical properties[23], the world's total of rare earth cast magnesium alloy brands account for the total number of magnesium alloys More than 50% [24], the earliest preparation of high-temperature tensile Mg-Ce alloy, after the researchers found that the heat resistance of rare earth magnesium alloys in accordance with the

Table 1 Titanium grades comparison of different countries

Alloy type	China(GB)	Soviet Union (TOCT)	United States (ASTM)	United Kingdom (IMI)	Gemany(BWB)	France(NF)	Japan(JIS)
Pure titanium	TA0	-	-	-	-	-	-
	TA1	BT1-0	Ti-35A	IMI115	LW3.7024	T-35	KS50
	TA2	BT1-1	Ti-50A	IMI125	LW3.7034	T-40	KS60
	TA3	BT1-2	Ti-65A	IMI135	-	-	KS85
αtitanium alloy	TA4	48-T2	-	-	-	-	-
	TA5	48-OT3	-	-	-	-	-
	TA6	BT5	-	-	-	-	-
	TA7	BT5-1	Ti-5Al-2.5Sn	-	-	-	KS115
	TA8	BT10	Ti-5Al-2.5Sn	IMI317	TA5E	-	AS
βtitanium alloy	TB1	BT15	-	-	-	-	-
	TB2	-	-	-	-	-	-
	TB3	-	-	-	-	-	-
α+βtitanium alloy	TC1	OT4-1	-	-	-	-	ST-A90
	TC2	OT4	-	-	-	-	-
	TC3	BT6C	-	-	-	-	-
	TC4	BT6	-	-	LW3.7164	-	-
	TC5	BT3	Ti-6Al-4V	-	-	T-A6V	-
	TC6	BT3-1	-	-	-	-	-
	TC7	AT6	-	IMI315	-	-	-
	TC8	BT8	-	-	-	-	-
	TC9	-	-	IMI318	-	T-A6V6S2	-
	TC10	-	Ti-6Al-6V-2Sn	-	-	-	-

sequence of La, Ce, Nd increased, can make the microstructure of magnesium alloy refinement, improve plastic shape. Magnesium alloys commonly used include: Mg-Re-Zn-Zr alloys, Mg-Nd-Zn-Zr alloys, Mg-Y-Zn-Zr alloys, and Mg-Re-Al alloys. At present, the Mg-Zn-Y alloy developed in Japan has the highest strength, 2.5 times that of ordinary magnesium alloys.

The rare earth-free magnesium alloys include: Mg-Al alloys, Mg-Zn alloys, Mg-Sn alloys, etc. Among them, AZ91 alloys (belonging to Mg-Al-Zn alloys) have excellent casting process performance and good resistance. Erosion, the addition of Zn will enhance the strengthening effect, but will increase the thermal cracking sensitivity; Si addition can effectively improve the high temperature creep properties of magnesium alloys; adding Bi, Sn, Sb alloy structure can be significantly refined[25].

4 Titanium

Titanium alloy is a new type of structural material. It has characteristics such as low density, light weight, high fracture toughness, high heat resistance, high strength ratio, good fatigue strength and crack propagation resistance, and excellent toughness and corrosion resistance, which is widely used in aviation, aerospace, military, weapons, shipbuilding, vehicle engineering, biomedicine and other fields [26]. Titanium alloy tensile strength of up to 1500MPa, comparable to ultra-high strength steel, while the density of pure titanium is only 4.5kg/cm3, only 50% of steel, its specific strength is the highest in commonly used engineering materials.

In the 1970s, a high-strength titanium alloy developed by a U.S. company was mainly used for Ti6-23-20d alloys. It has high strength, excellent toughness, tensile resistance, and good creep resistance[27]. The Beta-C alloy developed by the same company is widely used in the fields of petrochemicals and natural gas. The new type of casting alloy BT36 developed in Russia can be used in places where the tensile strength is 1200 MPa, and its plasticity is better than that of the common Ti-16-2 alloy. It is commonly used as the aircraft body. At 50 ℃, the ultimate tensile strength of this alloy was 1200 MPa, 700 MPa at 300 ℃, and 350 MPa at 500 ℃[28].

China has also made some achievements in the research and development of titanium alloys. The earliest TB5 and TB6 titanium alloys were developed. After the reform and opening up, TB9 was an ultrahigh-strength titanium alloy. Shanghai Metal Research Institute successfully produced Ti-563 alloy, and its mechanical properties and the fracture toughness has been greatly improved compared with the former kinds; since the 21st century, the TD22 titanium alloy developed by the Northwest Institute of Metal Research in China has laid a good foundation for the production of titanium alloy castings.

Summary

For metal materials, the method of achieving equipments' weight reducted and securing strength requirements and improving applicability is mainly metal alloying, and metal alloying can substantially improve metal properties. At present, light-weight high-strength materials with promising development are mainly titanium alloy materials, but due to their high cost, their widespread application is affected.

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