Current Development of Weather-resistant High Strength Bolts for Steel Structures in China

中国钢结构用耐候高强度螺栓的发展现状

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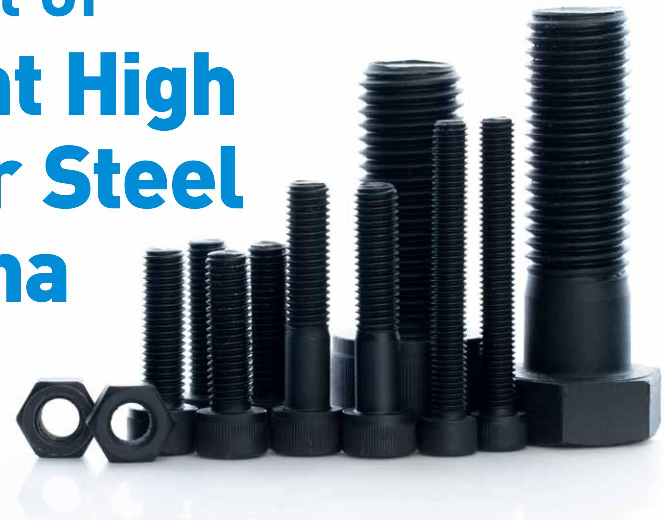


Introduction

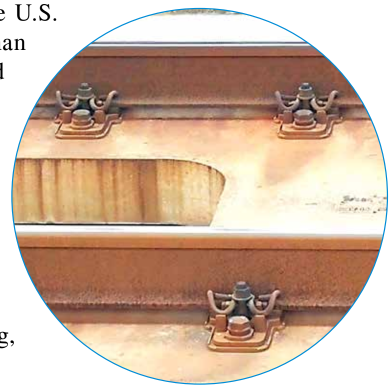
Bolt connection is still irreplaceable as an important connection method due to its technical characteristics such as simple construction process, easy installation and dismantling. It is widely used in plate girder bridges, diffracted girder bridges and box girder bridges. A single bridge uses hundreds of thousands to millions of such bolt sets. Not only to bridges, high-strength bolts for steel structures can be broadly applied to railways. By the end of 2021, China's high-speed trains totaled a mileage exceeding 42,000 km. If we count in ordinary railroads still under construction and those under planning, the total mileage reaches 150,000 km. the State Council of China printed and released the "Outline of National Land Planning (2016-2030)" on February 4, 2017 which proposes to build a well-developed and railroad network, accelerate the construction of high-speed railroads, inter-regional traffic lines, and national railways to develop citywide/suburban railroads and optimize the transportation network in dense urban areas; by 2030, the mileage of national trains will reach more than 200,000km. China currently uses 1,520-1,840 concrete railroad ties per kilometer of railroad, and 4 bolt sets per railroad tie. In minimal calculation, each kilometer of railroad uses 6,080 bolt sets, which translates to more than 600 million bolt sets used on the whole railway network. Adding bolts in bridges and tunnels, the total number goes up further.

China's steel structure bolts in use are mostly 8.8S and 10.9S grade high-strength bolts and usually in compliance to GB/T1231 standard, mostly made of ML20MnTiB, 35VB, 35CrMo, ML40Cr and other alloy steel for manufacturing bolts, but not resistant to atmospheric corrosion. Despite having the bolt's surface phosphated, hot dip galvanized or Dacromet treated, if the bolt is used for long in the countryside, the manufacturing sector, the ocean and other atmospheric environments, there are still more serious uniform corrosion, crevice corrosion and other rust phenomena.

After installation, stress corrosion and corrosion fatigue may also occur on ordinary high-strength bolts, and there is a risk of early failure with sudden brittle fracture and low-stress damage, which adds non-negligible safety hazards to steel structures such as bridges. Although stainless steel bolts can solve the corrosion problem of average bolts, stainless steel comes with the limitation of having lower strength, so it can not be used to manufacture high strength bolts for steel structures, and **the research on anti-corrosion for high strength bolts becomes more urgent and important.**

Advantages in Applying Weather Resistant Steel Bolts

Weather resistant steel is a low alloy steel with excellent atmospheric corrosion resistance by adding a certain amount of Cr, Ni, Cu, P, Re and other corrosion-resistant alloy elements to ordinary low alloy steel. When in use, the surface of the weather resistant steel will gradually form a layer of amorphous spinel oxide layer about 50pm-100pm thick which is dense and adheres well to the base metal. With dense and stable protection by the rust layer to prevent the infiltration of H+, O2-, Cl- and other ions formed by oxygen, water, salts and acids, stops the rust and significantly improves resistance against atmospheric corrosion. Weather-resistant steel can go without coating on condition of good ventilation and drainage, alternating dry and wet environment, low salinity, and minor acidity. Compared with the conventional "average steel structure + coating" solution, the "weather resistant steel structure + coating-free" solution has the advantages of lower comprehensive cost, shorter construction cycle, and effective environmental protection, with significant economic and social benefits. As a high-performance steel, weather resistant steel has been widely used in overseas countries. In 1964, the U.S. applied weather resistant steel to steel bridges for the first time. Now, the U.S. weather resistant steel bridges have accounted for more than 50% of all newly built steel bridges. Many countries around the world broadly use weather resistant steel on steel bridges. Japan's weather resistant steel bridges account for 20% of all steel bridges; Canada uses weather resistant steel on 90% of new steel bridges. The U.S. has more than 10,000 coating-free weather resistant bridges, and uses weather resistant steel on most of the 30 new steel bridges added every year. This has formed a system of weather resistant steel, welding materials and high-strength bolts, as well as their design, material selection, manufacturing, maintenance and other mature technologies and standards.



China in the 60s and 70s of the 20th century began in-depth research on weather resistant steel, and has developed a variety of weather resistant steel, mainly: 09CuPVRE, 09CuPTi, 09MnNb, 08CuPV and 10CrCuSiV and so on. In recent years, the development of weather resistant bridge steel is fast, including 15MnCrNiCu, 35MnCrNiCu and Q345qDNHY-Ⅰ, Q345qDNHY-Ⅱ; Q370qDNHY-Ⅰ, Q370qDNHY-Ⅱ; Q420qDNHY-Ⅰ, Q420qDNHY-Ⅱ, and so on; Since 1991 when weather-resistant bridge steel was first used on Beijing-Guangzhou Railway Bridge, the "weather-resistant steel + coating" solution was adopted due to the limitations in related technology and materials. The Shenyang Houtingxiang Bridge, the Weihe Grand Bridge in Xianyang, and the Mutuo Bridge in Tibet have been built. Yarlung Zangbo River Bridge is the first authentically coating-free weather resistant domestic steel bridge using high-strength bolts made of weather resistant steel. Coupled with Beijing Guantang Reservoir Grand Bridge, these two representative coating-free weather resistant steel bridges form the guidelines for the materials, technology and construction of such bridges, which marks China's deeper and full-fledged knowledge of such bridges and technology, and lays the foundation for multiplying such bridges.

Judging from the talks between National Fastener Standardization Technical Committee, the Bridge Steel Structure Branch of China Steel Structure Association, China Railway Bridge Design Institute, China Railway Second Institute, China Railway Third Institute, China Railway Construction Institute, Guangzhou Municipal Institute, and Shanghai Municipal Institute, the authorities, industry associations and design departments attach great importance to promoting the development of coating-free weather-resistant steel bridges in China. At present, although there is application to large bridges, the research and development of weather resistant bolts is relatively lagging behind, **China is faced with a large number of steel materials having corrosion failure when in use. Particularly, bolted joints on steel structures are much prone to corrosion in China leading to early failure of bridges and buildings in service, which is an urgent problem. Solving the problem of high-strength bolt corrosion from the material point of view is a critical path for the future development of Chinese weather resistant high-strength steel.**

R&D of Weather Resistant Steel Bolts in China

In 2017, Xingtai Iron and Steel Corp successfully trial-manufactured high-strength weather resistant steel XG835NH, with the following chemical composition: 0.32C, 0.25Si, 0.71Mn, 1.0Cr, 0.28Ni, 0.28Cu, etc. A thermal simulation test determined the critical point of the XG835NH steel as follows: Ac1 = 738℃, Ac3 = 782℃ Ac1=738℃, Ac3=782℃, Ms=348℃. **This steel is required to have atmospheric corrosion resistance, high strength, resistance to delayed fracture performance, and resistance to low-temperature impact in order to be used on high-strength weather resistant steel, and replace alloy bolting steel which is used as a new steel for bridge steel connection.** XG835NH weather-resistant steel alloy has a high variety and content of chemicals; the composition range is narrow, and at the same time there is the need for strict control of the level of mix-up, and surface quality control in casting billets is difficult. In a heat treatment technology test, when the cooling rate is less than 0.3℃ / s, we get a ferrite + pearlite structure; when the cooling rate is greater than 0.5℃ / s, bainite structure emerges; At the cooling rate of 10℃ / s, the structure is martensite. After heating, use quenching oil for rapid cooling, and use high-temperature tempering to obtain tempered sorbite plus tempered troostite. The 10.9S grade high-strength weather-resistant bolts made of XG835NH wire rods pass all performance tests and have been used on Larin Bridge in Tibet constructed in 2019 and Yan Chong Grand Bridge constructed for Winter Olympics 2020. The latter bridge uses weather resistant bolted joints and XG835NH weather resistant steel products. The minimal anti-slip coefficient of the bolted joint’s contact surface was set at a default of ≥ 0.55 upon shipping, and a minimal default at ≥ 0.45 upon installation. The combined use of sandblasting and wire brush meets the requirements for connecting coating-free weather-resistant steel bridges, but the post-sandblasting surface condition will change greatly the longer the bridge is exposed in the air. The anti-slip coefficient of is relatively stable for short-term samples; Longer outdoor exposure will decrease anti-slip coefficient significantly, so the validity of not requiring maintenance is being verified.

NL10.9 weather-resistant high strength bolt steel is a low-nickel weather-resistant steel developed by Ansteel Group and is used to manufacture high strength weather-resistant bolts for bridges and their nuts and washers with a nominal diameter below ϕ65mm.

Larin Bridge

NL10.9 steel's chemical composition is 0.28C, 0.15Si, 0.90Mn, 0.53Cr, 0.32Ni, 0.20Mo, 0.28Cu, etc.; heat treatment by aqueous quenching at 870 ± 10 ℃ PAG. With the increase in tempering temperature, the martensite lath form gradually disappears. Carbides are generated from the over-saturated α-phase, periodize on the martensitic border, and the size increases. The 480 ± 20 ℃ tempered structure gradually change to tempered troostite and tempered sorbite that is corrosion-free, coating-free, maintenance-free, labor-saving and energy-saving, reducing environmental pollution, with better resistance to hydrodynamic delayed fracture, meeting the technical requirements of 10.9S grade high-strength weather-resistant bolts. It has been successfully applied to a large number of national key projects, such as Larin Bridge, Hechuan River Weather-resistant Steel Bridge, China-Russia Heihe-Helongjiang Weather-resistant Steel Bridge, etc.

The use of high-strength bolts for connection of steel structures has the advantages of easy installation, removability, non-loosening, safety, etc. The connection of large buildings and other engineering structures requires higher performance strength of bolts. The current XG835NH, NL10.9 grade is a low-nickel steel, designed to withstand atmospheric corrosion for 20 to 30 years. In order to meet the requirements of 80 to 100 years of marine corrosion time, the development of high-nickel weather-resistant steel is inevitable at this stage, Ansteel Group, Pangang and Nanjing Iron and Steel Group are working with fastening enterprises to carry out this research.

Technical Points of Weather-Resistant Steel Bolts

For weather-resistant steel for fasteners, steel corrosion in the atmosphere is involved in a variety of chemical, electrochemical and physical processes occurring in the gas phase, liquid phase and solid-phase interfaces, mostly in the form of electrochemical corrosion. Unlike stainless steel, weather-resistant steel does not form a dense, extremely thin passivation layer, but rather, through constant interaction with the surrounding medium, a stable rust layer is formed on the steel surface over a period of time, which greatly delays further corrosion of the steel.

In the marine atmosphere, the air contains a large number of chlorine ions which deposit, resulting in steel being less resistant to corrosion than the ordinary field atmosphere. Many domestic and foreign scholars have studied the Ni and Cr alloy elements on the corrosion resistance of steel in a chloride ion environment and found that Cr is beneficial to the short-term corrosion resistance of steel, but after a prolonged period of time, Cr has reversed the phenomenon of corrosion resistance of steel. Therefore, in order to ensure that the steel can have better corrosion resistance in the marine atmosphere, it is feasible to add a certain amount of Ni instead of Cr. To investigate the amount of Ni added, the corrosion resistance pattern of steels with different Ni content was investigated in the laboratory. China is a typical oceanic atmosphere environment, and in response to China's demand for corrosion-resistant steels for the oceanic atmosphere, weather-resistant nickel steel (high nickel ≥ 3% Ni and low nickel ≤ 0.5% Ni) has been developed and applied to railroad bridges. Foreign and Japanese steel companies and some research institutions did exposure tests in different areas of different salinity for up to 11 years . It can be seen that the corrosion failure of high nickel steel is about 70% lower than low nickel weather-resistant steel.

Many domestic and foreign studies have shown that mix-up is the primary cause of pitting corrosion in low alloy steels. Sulfides are highly likely to induce pitting corrosion compared with others. In the process of pitting corrosion, mixed substances are the first to be dissolved and fall off the substrate to form pits. Due to the embrittlement effect of P on the material, precipitates will exist at grain boundaries, resulting in the weakening of the grain boundaries and a decrease in the impact force. For this reason, the P and S content of weather-resistant steel is lower than what is required in the national standard. The sum of the two should be ≤ 0.025%; P and S content is lower than what is required in GB/T1231. In addition, weather-resistant steel is smelted by converter or electric furnace, and should be refined outside the furnace. This is the only way to ensure the purity of steel and improve corrosion resistance.

For the use of weather-resistant bolts in different environments, coating-free weather-resistant bolts are recommended for dry areas under a wild climate. Coating-free weather-resistant steel bridges allow using blackened weather-resistant bolts; Surface-treated, Dacromet-coated, or polymer coated weather-resistant bolts are recommended for complex climatic conditions.

Weather-resistant bolts exposed to atmospheric conditions will initially form the same rust layer as plain carbon steel, but after 3 to 5a of environmental corrosion, the rust layer near the substrate will continue to dissolve and then precipitate to form a denser amorphous hydroxyl oxide. Finally, after many years, atmospheric corrosion resistant steel forms a stable rust layer, which plays a major role in protecting the internal rust layer. The layer is α-FeOOH enriched with Cr, Cu, Ni, P and other elements. Steel materials resistant to atmospheric corrosion is a very complex problem associated with the medium, temperature, time, space, geography and other factors. Some of the research is now more limited to the laboratory conclusions. There is still a lot of work to be done in terms of phenomena, rules and mechanisms.

Conclusion

The U.S. and Japan have formed a perfect standard system after years of exploration, summarization and accumulation in the construction of weather-resistant steel bridges. At present, China promotes the application of such bridges with reference to the American standards, such as design details, determination of corrosion resistance index, and so on. For weather-resistant bolted joints, relevant national research institutes should strengthen the basic research, determine suitable application guidelines for China's corrosion-resistant steel bridges and weather-resistant bolts according to the climate characteristics of different regions, and long-term atmospheric-exposure-to-corrosion test should be carried out to accumulate more fundamental information for the improvement of the standardized system, going from Made in China to Innovation by China.