Effects of Banded Structure on Fasteners (Part 2)

紧固件中的带状组织研究与控制（下）

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Difficulties in Reality

The steel standards GB/T3077-2015 "Alloy Structural Steel" and GB/T6478-2015 "Cold Forged and Extruded Steels" for bolts have strict control over the content of impurities P and S. The contents of P and S in all steel grades have been reduced (the former was reduced by 0.005% (≤0.030%) compared with the original standard, and the latter tempered steel being ≤0.025%). **As GB/T3077 and GB/T6478 standards do not have the requirements for banding structure testing, it is necessary to add amendments ASAP.**

The presence of phosphorus in steel will form a banded structure in the case of segregation. When the steel slowly cools down in the A3-A1 area, the temperature of the A3 high phosphorus area is high, forming ferrite. Carbon is concentrated to the low phosphorus area, resulting in low phosphorus and carbon-rich area. On subsequent cooling, eutectic transformation occurs, resulting in the formation of pearlite and layered arrangement.

Manganese is also an element that promotes banded segregation. In hot rolled steel, the Mn content is higher where pearlite is formed and lower where ferrite is precipitated. After the steel is hot rolled and slowly cooled, the proeutectoid ferrite will precipitate preferentially at low Mn area along the distribution of deformed fibers, and then the carbon will advance to the high Mn area to form pearlite, resulting in a banded distribution between pearlite and ferrite.

Professionals believe that although phosphorus segregation has an effect on the formation of banded structure, it should be the result of the combined effect of multiple alloys. Generally speaking, the diffusion coefficient of alloys in steel is smaller than that of carbon, which prevents the dendritic segregation formed during solidification from being completely eliminated by the heating before rolling, which is also an important reason for the formation of ferrite/pearlitic bands.

If there are non-metallic inclusions in the steel that are elongated into a band along the rolling direction, these inclusions may become the core of preferential precipitation of ferrite during the cooling process and form a ferrite band, which is generally difficult to be eliminated by normalizing. This band must be improved by uniform annealing followed by normalizing.

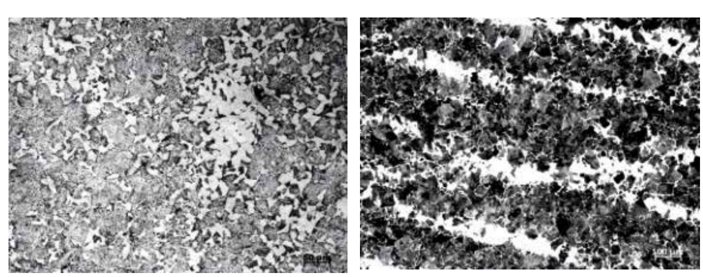

Fig. 1 Banded Structure of 42CrMo After Annealing（X100）

Fig. 1 shows that the structural composition is not uniform and the ferrite is aggregated into lumps. If the alloys in the austenite are not evenly distributed, it will result in a different tendency of grain growth, i.e., it is easy to leave undissolved carbide in the enriched area of carbide-forming elements, which reduces the diffusion rate of carbon atoms and inhibits grain growth; in the low area of carbide-forming elements the grain is easy to grow, so it is easy to appear mixed crystalline structure. When quenching, as the hardenability of the alloys in the impoverished area is low, it is easy to form a non-martensitic structure; and banded structure after the conventional heat treatment often features lower mechanical properties. In addition, due to the increase in the expansion coefficient and specific volume difference caused by compositional segregation, the bolt quenching deformation also increases.

The mechanical properties of banded structure are directional due to its microstructure layered arrangement (see ***Fig. 2***); that is, along the longitudinal banded structure the tensile strength is high, toughness is also good, but the transverse performance is poor (not only low strength, poor toughness, but also deteriorating the steel scrap performance, making the amount of deformation of the subsequent heat treatment and the unevenness of hardness increase. If there exists a banded structure before quenching, quenching and heating process is not possible to eliminate it. The residual banded structure after quenching will make the bolt to produce greater stress, or even cracking.

To see the mechanical performance testing result of the 42CrMo steel M45X280 bolt (quenched at 880±5℃ and tempered at (540±10℃), it indicates that the impact value is not qualified and the average value "21J" is 22% lower than the standard "27J". Ferrite aggregates and grows at the grain boundaries, which increases the grain size, reduces the resistance to crack propagation, and decreases the impact power.

Usually, the homogenization temperature of carbon in austenite is higher than 930°C, and that of alloys is higher than 1,050°C. The homogenization time is limited by the bandwidth of the band, the concentration difference between the bands and the degree of homogenization required. Therefore, it is difficult to homogenize the carbon (especially the alloys) in the banded structure, and it is difficult to eliminate the banded structure by conventional heat treatment (e.g. annealing, normalizing, quenching, etc.).

Inspection Standards

The severity of banded structure can be assessed according to GB/T 34474.1-2017 "Assessment Method of Banded Structure in Steel (Part 1): Standard Rating Chart Method" and GB/T 34474.2-2018 "Assessment Method of Banded Structure in Steel (Part 2): Quantitative Method". Under the observation of X100 visual field, those ≤2 levels are qualified.

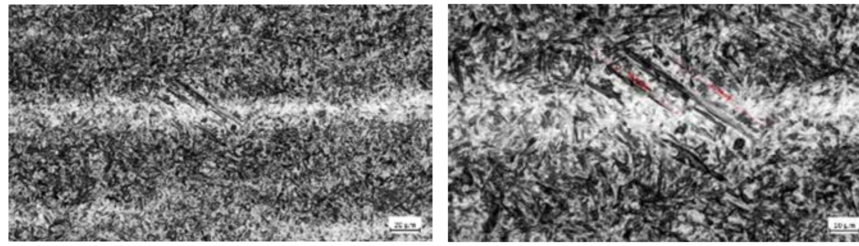

Fig. 2 Banded Structure of 42CrMo Steel After Quenching (Left: X500, Right: X1000)

Table 1. The Mechanical Performance Testing Result of the 42CrMo Steel M45X280 Bolt

	Tensile Strength/ MPa	Yield Strength/ MPa	Elongation After Fracture/%	Section Shrinkage %	HRC	Impact/J (-40℃)
Measured Value	1055	960	12.5	51.5	33.5/34.5/35	25/14/23
Technical Requirement	1040	940	9	48	33~39	27

Note: technical requirement referred from ISO/WD 898-11:2023

GB/T34474.1-2017 standard clearly specifies the sampling position and inspection status of test samples for banded structure assessment, and requires that the inspection surface of test samples should be parallel to the longitudinal axis of the steel. According to the standard, the carbon content of the steel will be divided into A to E series, and the banded structure of each series will be divided into 0 to 5 levels. Figure 2 shows that the banded structure of 42CrMo steel is relatively obvious, with ferrite and pearlite alternating in the form of bands, which is classified as Gr. 3 according to GB/T 34474.1.

GB/T34474.2-2018 can also be used to assess banded structure and is applicable to other banded structures except for ferrite, with a wider scope of use. However, it requires a lot of calculation and analyses, so adoption is low.

Conclusion

The mechanical properties of steel with banded structure are anisotropic, making it easy to break at the steel interface in the fastener process. When heat treatment is continued, the banded structure will lead to excessive deformation of steel or cracks which generally feature no oxidation and decarburization; the expansion direction of cracks during heat treatment is generally through and along the grain, and in severe cases they may appear as a single linear extension or even penetrate the entire bolt. Oxides may appear in cracks after quenching and tempering; the inclusions observed around cracks can be extremely detrimental to fastener quality. Since banded structure is not easily eliminated by normal heat treatment, the most cost-effective method is to solve the problem by redissolving the electroslag and increasing the crystallization rate. It's impossible to fully describe the effect of banded structure on fasteners in this article, but I tried to start a discussion on key issues. Hopefully, this will draw more attention from the industry.