3rd Automotive Steel International Conference
9–12 March 2025, Orlando, Fla., USA
10.33313/200/010

Developments and outlook of automotive sheet steels in China

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Keywords: China's automobile, electric vehicles, welding performance, hydrogen embrittlement, low carbon emission steel

INTRODUCTION

The output of China's automobile has been ranked first in the world for 15 years, Among them, new energy vehicles have developed rapidly, electrification is the most important technical route for reducing carbon emissions in the automobile industry. The changes in the structure of automobile have an impact on materials, advanced high strength steels for cold forming and boron steels for hot forming are still the main development directions of automotive sheet steels. In addition, low-carbon emission automotive steel has also been in urgent demand in recent years. The high strengthening and low carbon emission of steel sheets also bring technical challenges to production and application, such as manufacturability, surface quality, stability of mechanical properties, hydrogen embrittlement and welding performance. Some technological progress made by Baosteel in response to these technological challenges are introduced. Baosteel automotive steel sheets carbon neutrality routes and recent activities of developing low carbon emission automotive steel sheets by electric arc furnace process are shared in this paper.

AUTOMOTIVE INDUSTRY AND MATERIALS

Since 2009, China has become the largest automobile producer in the world with sales of more than 30 million units in 2023. However, the structure of automobile market has undergone significant changes due to new energy vehicles in particular. In 2023, the sales volume of new energy vehicles reached 9.5 million, with a penetration rate of 31.6% and a global market share of 64%. The development of domestic brands of new energy vehicles such as BYD is rapid, with an average increase of 11% in the past three years and reaching to more than 50% in 2023.

The significant change in the automotive market results in significant changes in materials, which has also brought opportunities and challenges to the use of steel for new energy vehicles. The use of long steel product and stainless steels has decreased, while the use of silicon steels for driving motors has increased significantly. Compared to fuel powered vehicles of the same class, electric vehicles have a weight increase of more than 20~30%, making lightweighting a pressing concern. As the main material for automotive lightweighting, ultra high strength steel sheets(UHSS) which TS is more than 780MPa for cold forming and boron steels for hot forming are still the development direction. Currently, more than 15 UHSS production lines and 300 hot stamping production lines have been built in China. In addition, low-carbon emission automotive steel has also been in urgent demand, and some OEM factories have proposed requirements for the proportion of recycled steels.

Comparison with conventional internal combustion engine vehicles, China's new energy vehicles are mainly driven by Tesla, BYD, and some new player such as ‘WEI XIAO LI’, these factories are more willing to adopt new technologies, especially aluminum alloy integrated die-casting technology (Giga Press), as they do not have the burden of traditional car factories, which poses a challenge to the use of steel sheets for vehicle bodies.

TECHNICAL PROGRESS IN UHSS SHEET PRODUCTS AND APPLICATIONS

Ultra high strength steel sheets

UHSS covers a wide range of steel grades such as DP, CP, DH, TRIP, QP, MS and PH, and according to customer requirements, specialized UHSS are also being developed that possess not only high tensile strength but also high elongation and superior burring and bendability. Table 1 summarized the portfolio of UHSS developed by BAOSTEEL.

Table 1. The portfolio of UHSS developed by BAOSTEEL

Variety		TS(MPa)						
		780	980	1180	1310	1500	1700	2000
DP	CR/EG	∉	∉	∉	∉	/	/	/
	GI	∉	∉	∉	⊄	⊗	/	/
	GA	∉	∉	∉	∉	∉	/	/
CP	CR/EG	∉	∉	∉	/	/	/	/
	GI	∉	⊗	⊗	/	/	/	/
	GA	⊗	⊄	⊄	/	/	/	/
DH	CR/EG	∉	∉	⊄	/	/	/	/
	GI	∉	∉	⊄	/	/	/	/
	GA	/	/	/	/	/	/	/
TRIP	CR/EG	∉	/	/	/	/	/	/
	GI	∉	/	/	/	/	/	/
	GA	/	/	/	/	/	/	/
QP	HR	/	∉	∉	/	/	/	/
	CR/EG	/	∉	∉	/	/	/	/
	GI	/	∉	∉	/	/	/	/
	GA	/	∉	⊗	/	/	/	/
PH	CR	/	∉	/	/	∉	∉	∉
	GI	/	/	/	/	⊗	/	/
	GA	/	/	/	/	⊗	/	/
	AlSi	/	∉	/	/	∉	∉	∉
MS	CR	/	∉	∉	∉	∉	∉	⊄
	EG	/	∉	∉	∉	⊄	⊄	/

●:Commercial, ⊗:Developed, O:Developing

Quenching and partitioning[1], as the third-generation advanced high-strength steel, has become a hot research topic in recent years. Since its first commercialization in 2010[2,3], based on this concept, three types of quenching and partitioning sheet steels for cold forming including hot rolled, cold rolled and zinc coated sheet steels with tensile strength more than 1GPa have been developed and applied successfully in automobile manufacturing. The developed hot rolled QP sheet steel has a high strength and a good wear resistance, the first hot rolled QP coil produced by Baosteel has been successfully applied in the field of concrete mixer truck to make the cylinders, and the cylinders weight reduced about 30%. Most of B pillars are made by hot stamping steel, the emergence of QP sheet steels give another solution for those automotive structural and safety parts with complex shapes and high strength requirements such as B pillar by cold forming.

Manufacturability of UHSS

Cold rolling of UHSS

Compared with ordinary high-strength steel, ultra-high strength steel is more difficult to cold roll, often experiencing problems such as high rolling force, strip breakage, and poor strip shape. The main reason is that the alloying elements such as Mn, Cr and Mo in ultra high strength steel are more than 2 times, which will reduce the critical cooling rate. If the temperature of hot-rolled coil after coiling is not controlled, it is easy to form high strength microstructures such as martensite at the head, tail, and edges of the hot-rolled coil, resulting in high and uneven strength of the hot-rolled steel coil. In order to improve the manufacturability of ultra high strength steel cold rolling, it is necessary to control the strength and uniformity of hot-rolled steel coils. The commonly used method is to conduct batch annealing treatment on hot-rolled steel coils, which has the disadvantages of long production cycle and high cost. In order to solve this problem, an online temperature control technology for hot-rolled steel coils has been developed in Baosteel. By controlling the cooling rate and temperature uniformity of hot-rolled steel coils after coiling, stable cold rolling has been achieved. For example, using this technology for a QP1200 grade steel can reduce the tensile strength of hot-rolled coils from 1000MPa to 800MPa, and the difference in tensile strength between the edges and middle of the steel coil from 400MPa to 200MPa, which helps to soften and improve the mechanical properties uniformity of hot-rolled steel coil performance, and easy to cold roll stably.

Internal oxidation in hot-rolled steel sheet

The selective oxidation of alloy elements in UHSS in the continuous annealing process has been widely studied in the last two decades. While the internal oxidation forms in the subsurface layer of hot-rolled high strength steel just received attentions in recent years[4,5]. Though the formation of internal oxidation in hot-rolled steel has a positive effect to reduce external oxidation and improve galvanizability of the cold rolled steel sheet, it significantly deteriorates the surface quality of the subsequent pickled, cold rolled, galvanized and even galvannealed steel sheet. In some cases, an unexpected continuous layer of pure iron covering the scale surface substantially delays the pickling rate in the initial stage of pickling, and usually results in under-pickling defects. In addition, the preferential grain boundaries oxidation is easy to be selective dissolved in the pickling process, but the internal oxidation zone is difficult to be completely removed by pickling, leading to a poor surface quality of the cold rolled and galvanized steel in the end. Due to the nonuniformity of internal oxidation on the entire coil of hot-rolled steel, surface defects such as colour difference of galvanized coating and dark streaky mark defect of galvannealed ultra-high strength steel may occur. Therefore, it is necessary to control the internal oxidation in hot-rolled steel. The most effective way which has been recognized is to reduce the coiling temperature and increase the cooling rate after being coiled.

A detailed mechanism of internal oxidation of hot rolled steel substrate as well as the microstructure evolution of oxide scale after coiling was proposed. The formation of pure iron layer at the surface of oxide scale, which was a unique phenomenon for AHSS, was clearly explained as a result of decreasing oxygen partial pressure of the atmosphere in the coil with the internal oxidation process of steel substrate. The kinetics of internal oxidation of hot rolled steel substrate under oxide scale for different coiling temperatures was experimentally determined. Besides that, effect of steel composition, especially the Al content, on internal oxidation rate after coiling was discovered.

Application challenges of UHSS

The hydrogern and delayed cracking of galvanized ultra-high strength steel sheets

Galvanized ultra-high strength steel sheets are widely used in auto industry for its better corrosion resistance. In recent years, with the development of automotive lightweight technology, the amount of galvanized automotive steel sheet with tensile strength above 1000MPa integrated into modern car bodies has increased. For uncoated bare steel, the hydrogen introduced to the steel during annealing and other production processes can be quickly released during subsequent production process, transportation and storage. However, for galvanized ultra-high strength steel sheets, because of the strong barrier effect of the zinc layer on hydrogen diffusion, the hydrogen is sealed inside the steel sheet, making it difficult to escape from the sheet at room temperature, and thus hydrogen induced delayed cracking may occur in condition of hydrogen and stress. Therefore, compared to bare steel sheet with the same strength, galvanized ultra-high strength steel sheets are more sensitive to delayed fracture.

Regarding the hydrogen induced delayed cracking of galvanized ultra-high strength steel sheet, the critical hydrogen concentrations for some galvanized ultra-high strength steel have been studied. For example, for galvanized 1200MPa DP and 1500MPa MS automotive sheet steels, the critical hydrogen concentration levels are 0.3 and 0.2 ppm, respectively[6]. However, we found that there is big difference in the hydrogen content depending on the galvanizing processes even if the same steel substrate is used, which results in significantly different hydrogen induced delayed cracking performance.

For example, DP1180GI and DP1180GA steel sheets are produced with the same steel substrate of 1180 grade, but there is a significant difference in the diffusible hydrogen content between the two products. Generally, the diffusible hydrogen content of GI plates is 0.1-0.2 ppm, while the hydrogen content of GA steel sheet is significantly higher than that of GI steel sheet, reaching 0.3-0.6 ppm or more. The U-bend test method recommended by the SEP-1970 standard was employed to evaluate the delayed cracking performance of GI and GA coated DP1180 steel sheets. The results showed that, the DP1180GI samples with hydrogen content of 0.3 ppm fractured within 96 hrs, while the DP1180 GA samples with the hydrogen content of 0.55 ppm did not fracture in 720 hrs, exhibiting better resistance to hydrogen induced delayed cracking. To understand the difference, the diffusible hydrogen content of DP1180GA sheet was measured after the Zinc layer was removed in HCl solution. The results showed that the diffusible hydrogen content decreased from 0.55 ppm to 0.2 ppm, indicating that more than half of diffusible hydrogen exists in the zinc coating or at the coating/ matrix interface, while the hydrogen in the steel substrate was only 0.2 ppm, which was not enough to induce delayed cracking.

The LME of QP steel sheets

Liquid metal embrittlement (LME) issue frequently occurs in resistance spot welding (RSW) of galvanized QP steel sheets, which limits the further application of QP steels in automotive industry. Coating types[7] affect the occurrence of spot welding LME, hence the LME phenomenon during RSW was investigated on QP980 steel sheets with three different types of metallic coating, namely GI, GA and EG, produced by commercial lines. The chemical composition of the QP980 is 0.2C-2.0Mn-1.5Si (wt%).

As reported in other literatures[8] , with the increase of weld current, the number and length of LME cracks for QP980-GI, QP980-GA, QP980-EG follows an increasing trend, due to the higher heat input. Meanwhile, expulsion has a fatal effect on LME cracks for these three kinds of material during RSW. When expulsion occurs, the length and number of LME cracks will increase significantly. In general, expulsion is caused by excessive heat input. On the other hand, liquid zinc, tensile stress, susceptible microstructure are the three key factors to cause LME cracks[9]. When expulsion occurs, molten metal will be ejected from the weld pool and the RSW joint will get deeper electrode indentation, which result in a sharp increase of stresses and higher pressure is likely to be applied in the nugget. Such severe stresses and excessive heat input during expulsion may increase the risk of generating LME cracks. Therefore, in order to prevent LME cracks during RSW, expulsion should be avoided as much as possible.

For QP980GI, despite the expulsion, LME cracks could be detected in each weld current which includes the suitable weld lobe. For QP980GA and QP980EG, in cases of no expulsion, no LME cracks were detected; if expulsion occurred, LME cracks can hardly be avoided. That is to say, QP980GI has more LME susceptibility than QP980GA and QP980EG during RSW in this study. Literature1 has shown that resistance spot welds were more prone to LME cracks with GI coating as compared to EG coating, due to aluminum in GI coating. During spot welding of GI coated materials, aluminum oxide layers with higher electrical resistance was found on the electrode surface which increased the surface temperature of the spot weld and thereby increasing the occurrence probability of LME cracks. Besides, liquid Zn is another important factor in causing LME. Compared to QP980GI, coating of QP980GA contains about 10% Fe, resulting in a higher melting point and less liquid Zn is formed during spot welding. The melting point of GI (Zn) coating is lower than GA (Fe-Zn) coating, which means that more liquid Zn is available for embrittlement at the same temperature during welding. Thus, GA coating has lower LME sensitivity than GI coating during RSW.

Welding of AlSi-PHS

Hot stamping parts have high strength and good dimensional accuracy with complex shape, and can effectively improve vehicle body collision safety performance. Some big parts such as B pillars and door rings must be welded before hot stamping. However, When laser welding aluminum silicon coated press hardening steel sheets (AlSi-PHS), the Al element in the AlSi coating combines with the Fe element in the base metal to form a brittle Al-Fe intermetallic compound, which will significantly deteriorates the mechanical properties of the welded joint[10] . The commonly used methods internationally are mechanical removal or laser ablation to remove the AlSi coating on the surface of steel sheets. The disadvantage of these methods involves complex and time-consuming processes, seriously reducing production efficiency. In order to solve this problem, Baosteel has developed a new technology for laser wire filling welding of AlSi coated steel sheets, which can effectively suppress the generation of brittle Al Fe intermetallic compounds, and can be successfully applied to the automotive industry.

LOW CARBON EMISSION STEEL SHEETS

As one of the largest carbon emitting industries, steel making industry has been under extreme pressure to reduce carbon emissions. In 2021 Baosteel has released a roadmap of 'carbon peaking and carbon neutrality’ , with the goal of carbon peaking by 2023, mastering the technology of 30% carbon reduction by 2025, fully achieving 30% carbon reduction by 2035 and realizing carbon neutrality by 2050.

The conventional automotive steel sheet production is a long process, composing of iron making with ore by a blast furnace, steel making with pig iron by a converter, casting with molten steel by a continuous casting mill, rolling and heat-treatment. In this process, the iron and steel making process takes the largest proportion of carbon emissions up to 70% or more. Therefore, a significant carbon reduction still requires a substantial change in the metallurgical process, i.e. raw material replacement. In terms of low-carbon metallurgical technology, Baosteel has been focusing on four main technological solutions, namely scrap-electric furnace technology, high scrap ratio converter technology, hydrogen reduction-electric furnace technology, and hydrogen-rich carbon cycle blast furnace technology.

Electric arc furnace (EAF) technology is to use scrap steel as the main raw material and electricity as the main energy source to produce steel products, which can significantly reduce CO2 emissions during steel production. With the Zhanjiang electric furnace production line put into operation in 2025, Baowu will have a million tons of manufacturing capacity. Blast furnace or basic oxygen furnace (BF/BOF) + scrap is to achieve partial replacement of ore with scrap or directly reduced iron (>40%) to reduce carbon emission, by minor technical upgrading and process development. This technology is especially benefit for those steel makers equipped with BF/BOF mills, and is highly potential to be one of the most important carbon reduction technologies in the next 10 years. Hydrogen-based shaft furnace (HySF) uses a hydrogen-based gas replacing the carbon reducing agent to reduce iron ore to iron. By using clean energy to produce green hydrogen, HySF + EAF may achieve near-zero carbon emissions from steel production. Baowu's HySF will be commissioned in 2023 in Zhanjiang mill with a million ton capacity. Combined with the commissioning of EAF production line, a zero carbon specialized production line will be accomplished. Hydrogen-rich carbon recycling blast furnace (HYCROF) is a modified BF, with the addition of top-of-furnace CO2 separation and recycling of CO, plus the use of hydrogen-rich reducers to achieve carbon reduction.

The promotion of low carbon emission products faces a number of challenges. The first challenge encountered in the development of low carbon metallurgical technology is the excessive contents of residual elements such as N, S, Sn, and Cu introduced by the addition of large amounts of reused materials, which exert various effects on product characteristics and manufacturability. Since residual elements have the greatest impact on automotive steels, it would be the top priority to investigate high cleanness steel making technology and products design technology for automotive steels with high residual elements. Another challenge would be the cost. It is noticeable that any low carbon technology inevitably causes an increase in cost more or less. Therefore, the development of low carbon steel production technology with high efficiency, high quality and low cost is a key basis for the steel industry.

Baosteel developed an full-scrap, full-green electricity 420LA, 980DP and 980QP product with EAF + scrap technology. An uncoated product and a hot-dip galvanized product have be produced. A complete characterization of the properties and a third-party evaluation of carbon footprint showed that the properties of the products well meet the specifications and a carbon reduction of over 60% has been achieved, respectively. With the collaboration with our major customers, many typical parts for car body and seat have been successfully manufactured.

CONCLUSION

In order to meet the demand of sheet steel products from China automotive industries in recent years, the sheet products with ultra-high strength steel have been boosted at an extremely fast pace during the last few years. Notable breakthroughs have been realized in research areas of selective oxidation, the hydrogen induced delayed cracking of galvanized ultra-high strength steel sheets, liquid metal embrittlement issue in resistance spot welding and laser wire filling welding technique for Al-Si coated steels. Low carbon emission ultra-high strength steel sheets will become the next key development direction.

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