Development of High-Grade Cold Rolled Steel with Ultra-High Strength

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In recent years, traditional automotive manufacturers have been transforming in response to meet global government targets for net-zero carbon emissions and international trends. They have been actively announcing plans to phase out the sale of fossil fuel-powered vehicles and introduce a range of new energy vehicles. With the gradual popularization of electric vehicles, the demand for ultra-high-strength steel is expected to increase, as it enables the creation of high-quality, lightweight, and rigid vehicle structures.

To meet the domestic manufacturers' demand for adapting ultra-high-strength steel for bumper reinforcement components, CSC has successfully developed CSC CR1300T, a cold-rolled ultra-high-strength steel with dimensions ranging from thickness 1.0 to 1.4mm and width 914 to 1,170mm. This steel has a tensile strength of over 1,300MPa and exhibits excellent hole expansion ratio and bending performance. Customers have provided positive feedback when using CSC CR1300T steel during the roll-forming process.

The innovative furnace cooling techniques, including GJ high-temperature air cooling, RGJ rapid gas quenching, RQ enhanced roller cooling, OA low-temperature self-tempering, and TPM high-stress strain, have replaced the original automatic temperature control mode in the continuous annealing line. These techniques have achieved a high proportion of martensite structure, addressing the issues of excessive ferrite and insufficient strength.

Subsequent improvement measures include refining the cooling modules, implementing production line speed limitations, and optimizing the temperature in the over-aging furnace. Furthermore, the best operating parameters are customized based on the incoming strip size conditions, ensuring excellent material structure, precipitation size, and work hardening capability while reducing the machine property variations associated with thickness changes.

As a result, the mechanical properties of CSC CR1300T steel with thicknesses ranging from 1.0 to 1.8mm are within the following range: YS of 1,034 to 1,107MPa, TS of 1,304 to 1,364MPa, and EL of 7.0 to 8.0%, meeting the specified standards.

Keywords: Net-Zero Carbon Emissions, Ultra-High-Strength Steel, Roll-Forming, High Proportion of Martensite Structure

1. INTRODUCTION

With the rolling out of new energy vehicles from major global car manufacturers and governments around the world proposing plans to ban the sale of fuel-powered cars, the electrification of transportation is becoming a top priority. How to increase the vehicle's range within a limited battery capacity is a crucial challenge. Besides continuously researching breakthroughs in battery energy density and motor efficiency, a key design focus is on high-quality lightweight, and rigid vehicle body materials. Currently, the use of ultra-high-strength steel is prevalent in the construction of passenger cabins and body structures to ensure high safety protection coefficients in the event of high-speed impacts.

Recently, the major aftermarket component manufacturers in Taiwan have also expressed a demand for domestically produced ultra-high-strength steel. This steel is mostly used in applications such as bumper reinforcements and support brackets(1). Currently, the material is mainly imported from China with thicknesses ranging from 1.2 to 1.4mm and a focus on tensile strengths above 1,300MPa, including grades such as MS1300 and MS1400. The combined annual demand is approximately 4,500 tons.

Scanning through CSC's cold-rolled product portfolio, there are currently no fully martensitic steel grades with tensile strengths exceeding 1,300MPa. As a result, CSC has planned the development of cold-rolled ultra-high-strength steel in its 2021-2025 new advanced steel product development blueprint. Starting in 2020, substantial research and development resources have been invested, combining innovative metallurgical design and process technology. The customized CSC CR1300T ultra-high-strength steel has been developed, allowing the material to consistently achieve a tensile strength above 1,300MPa.

2. THE DESIGNATION OF THE PRODUCTION PROCESS

The development of CSC CR1300T cold-rolled ultra-high-strength steel is based on the research foundation for dual-phase steel. Initially, we plan to use the same steel grade to facilitate the efficiency of steelmaking in the converter furnace, avoiding the creation of isolated steel grades and achieving cost-reducing goals with a single steel grade for multiple specifications.

The design primarily focuses on adding alloying elements such as Mn, Si, Mo, and Cr to enhance the solid solution strengthening effect and suppress the transformation of ferrite, pearlite, and bainite during the cooling stage, resulting in increased material hardening ability. Simultaneously expands the dual-phase region to stabilize the uniformity of the structure, as shown in Figure 1[2].

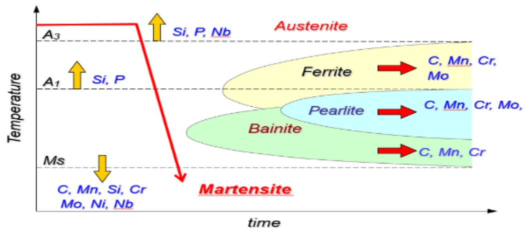


Fig.1. The relationship between alloy composition and phase transformation[2].

Based on the measurements from the quenching dilatometer, the continuous cooling transformation (CCT) diagram for this steel grade was obtained, as shown in Figure 2[3]. The critical cooling rate and transformation temperature for ferrite are -5ºC /s and 600ºC, respectively. For bainite, the critical cooling rate is -30 ºC/s. These critical phase transformation temperatures were then applied to simulate laboratory parameters and to design and develop the annealing, cooling, and overaging furnace conditions.

Considering the higher alloy proportions in the slab and the larger deformation resistance of the material, as well as the faster cooling rate at the outer edge of the coil after hot rolling, therefor will generate hard and brittle structures. If a continuous tandem mill directly rolling hot coil, the residual brittle structures from the hot rolling cooling stage, as shown in Figure 3, can pose challenges in terms of motor load and shape control at each rolling stand. And then leads to severe shape wave issues, as shown in Figure 4, and in extreme cases, even strip breakage risks. A batch annealing process can be applied to eliminate the brittle structures formed during the hot rolling cooling process, as shown in Figure 5. Then the following cold-rolling process can result in cold-rolled semi-finished products with high thickness accuracy, reduced edge drop, and excellent flatness.

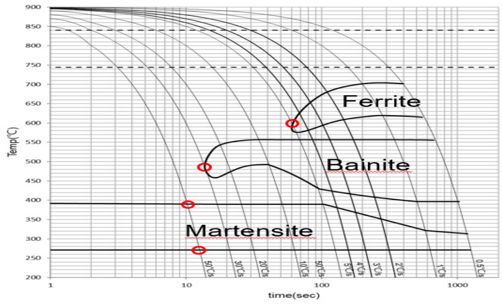


Fig.2. Continuous Cooling Phase Transformation Diagram[3].

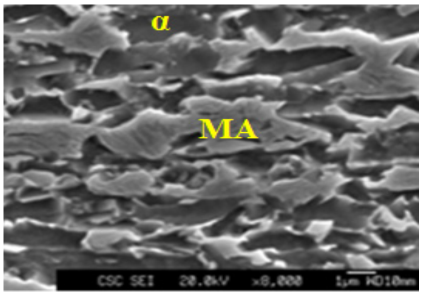


Fig.3. Unannealed hard and brittle microstructure.

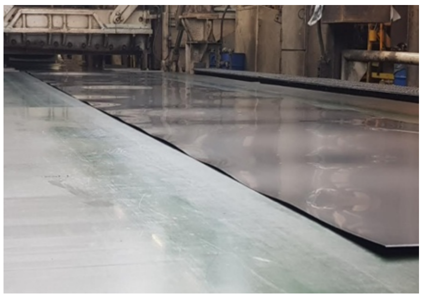


Fig.4. Severe wavy defect after cold rolling without pre-annealing

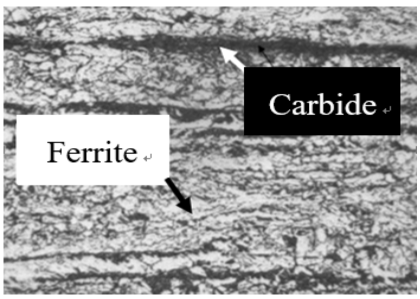


Fig.5. Softened microstructure after pre-annealing.

To get to the goal of achieving a tensile strength of at least 1,300MPa in a product, it is desirable to minimize the formation of ferrite and design for a full martensite microstructure. Referring to the CCT diagram, the material needs to be heated to a temperature above the austenite transformation temperature and held at that temperature for a few seconds to achieve a single-phase microstructure. Subsequently, the strong and rapid high concentration of nitrogen and hydrogen gas is used to cool down the material below the martensite start temperature to achieve a high proportion of martensite microstructure.

3. CONTROL METHOD FOR MICROSTRUCTURE

The over-aging (OA) zone and temper rolling mill (TPM) station located after the CAL cooling zone are critical control points for regulating the mechanical properties and the shape of the strip of CSC CR1300T. After the strip undergoes rapid high-pressure hydrogen gas cooling and water-cooled roller heat extraction, low-temperature tempering in the over-aging furnace can be applied to generate tempered martensite with fine carbide precipitation, known as the self-tempering effect[(4)]. The strip is held at temperatures of 180-250ºC in the aging zone to facilitate the formation of tempered martensite from the initial flash martensite and gradually precipitated carbide.

By applying the self-tempering metallurgical control technique, the fine carbide precipitation resulting from heat diffusion within the material leads to a slight sacrifice in tensile strength. However, it can help in relieving residual stresses, thereby improving yield strength[(5)]. Additionally, the precipitation of transitional carbides can enhance the pinning effect on dislocation movement, further enhancing YS performance.

Nevertheless, it is necessary to avoid excessive tempering temperatures and an overabundance of the self-tempering effect, which can cause the coarsening of carbides and deteriorate the material's strength, as shown in Figure 6. Therefore, considering the combined effects of YS and TS, it is crucial to optimize the strip temperature in the RQ and OA zones to achieve the optimal size of precipitated carbides during self-tempering. This allows for fully harnessing the strengthening effect of nanoscale fine carbide precipitation, as shown in Figure 7.

After the annealing and cooling cycle, the material goes through a phase transformation to form a martensite structure. Then in the OA zone, the material undergoes low-temperature diffusion, resulting in the dispersion of nanoscale carbides. This process combines phase transformation and precipitation-strengthening effects. Subsequently, the four-high wet temper rolling machine, located behind the CAL storage tower, was used to introduce dislocations and achieve work-hardening effects while maintaining high yield strength and tensile strength levels. To increase the degree of strip flexural deformation, the temper rolling machine's work rolls are replaced with smaller diameters. However, it should be noted that the operation space is narrower and more difficult to control with the smaller rolls.

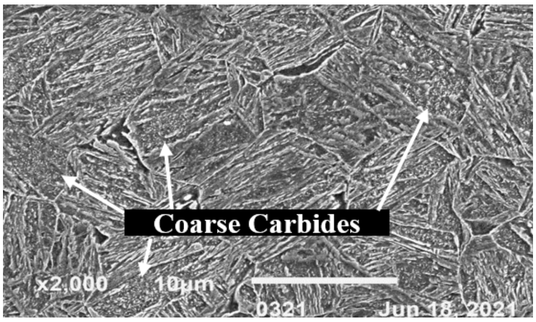


Fig.6 . Coarse self-tempering carbides in high exit temperature of RQ and OA zone.

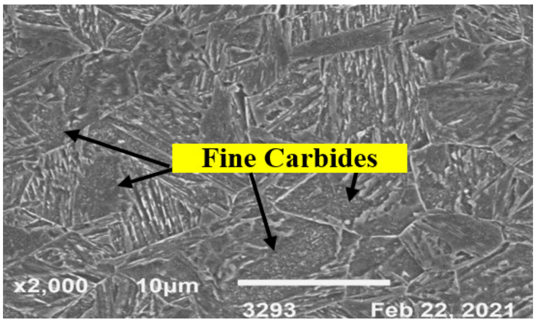


Fig.7. Fine self-tempering carbides in low exit temperature of RQ and OA zone.

To prevent poor edge flatness caused by high stress after tempering and reduce the problem of upward bending after shear cutting of ultra-high-strength steel thick plates: In addition to adjusting the heights of the front and rear wrinkle rolls in the optimizing temper rolling process, the temper rolling mode is also modified. Instead of the traditional fixed temper elongation rate mode, a fixed temper rolling force value is set. This is done to prevent excessive fluctuations in rolling force amplitude caused by producing the ultra-hard plate, which can lead to variations in strip shape and yield strength.

4. RESULTS AND DISCUSSION

Adopting the innovative operational techniques described above, results in a material with high yield strength and high tensile strength characteristics. During the annealing process, the strip hits the target temperatures at the exits of each furnace section, including heating, cooling, and over-aging. The exit of the RGJ and RQ section does not experience meandering or strip deviation issues that would affect operational stability. After the temper rolling mill, the flatness of the strip is maintained at a good level, and there is no upward bending during the shearing and stacking process, enabling the tension reel machine successful coil winding operations.

Considering the limited length of the CAL cooling section, which includes various functional cooling systems such as Gas Jet, Rapid Gas Jet, and Roll Quench, the configuration of each cooling zone is arranged in sequence. It is susceptible to a chain reaction due to the influence of the incoming/outgoing plate temperature, so it's necessary to stabilize the exit plate temperature of each cooling zone. Moreover, to achieve the expected work hardening effect, there is a need to introduce a quantified dislocation through high rolling force in the temper rolling mill; otherwise, it will be difficult to achieve the desired outcome. Therefore, by integrating the production experience of different thicknesses and widths, customized manual operating mode parameters for the GJ, RGJ, RQ zones, and TPM machine are formulated according to the order specifications of plate thickness and width. This improvement shortens the adjustment time for an operator when dealing with size conversions and ensures strip flatness, shape, material strength, and final structure.

After customizing the annealing parameters based on size specifications, the variation in mechanical properties within the thickness range of 1.0mm to 1.4mm of the CR1300T is reduced, and meets the CSC specification standards, with YS ranging from 1,034 to 1,107MPa, TS ranging from 1,304 to 1,364MPa, and EL ranging from 7.0 to 8.0%.

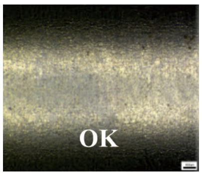
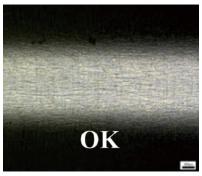
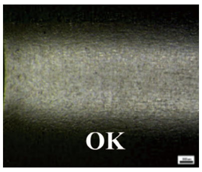
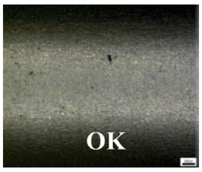
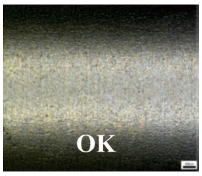
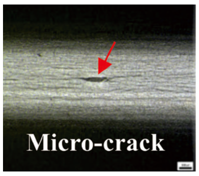
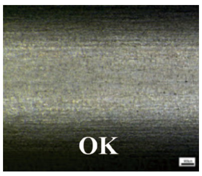
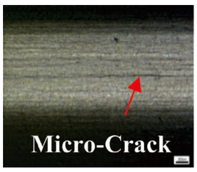
Additionally, tests were conducted on thicknesses of 1.2mm and 1.4mm coils to assess their bending performance with different bend radii. The results indicate that both longitudinal and transverse specimens can meet the requirement of 90-degree bending at a bend radius of 3.5t. The bending-related data and cross-sectional quality are shown in Table 1. Furthermore, the material exhibits excellent hole expansion properties, with an average Hole Expansion Ratio (HER) ranging from 69 to 81. The hole expansion characteristics are mainly attributed to the uniform martensite microstructure throughout the material, avoiding any issues with inconsistent hardness at the dual-phase interface. This results in a good hole expansion ratio and bending performance for the material.

5. FUTURE OUTLOOK

CSC has successfully developed customized CSC CR1300T cold-rolled ultra-high-strength martensitic steel with dimensions ranging from a thickness of 1.0mm to 1.4mm and a width of 914mm to 1,170mm, achieving a tensile strength of over 1,300MPa. After customer trial roll-forming, the material has been successfully used in the production of various automotive bumper reinforcements. Feedback regarding surface quality, dimensional accuracy, component strength, weldability, and formability has been excellent. The bumper reinforcements have also passed CAPA crash testing, demonstrating their high compressive strength and ability to maintain the integrity of the vehicle structure during severe crush, thereby ensuring passenger safety.

To continuously satisfy the increasing demand for

Table 1 Cross-sectional quality of CSC CR1300T with thicknesses of 1.2mm and 1.4mm in longitudinal and transverse at different bend radii of 90 degrees.

Direction	Thick.	R Degree		Thick.	R Degree	
		3.3t (4R)	1.6t (2R)		3.5t (5R)	2.1t (3R)
Longitudinal	1.2mm			1.4mm		
Transverse						

higher strength specifications of aftermarket bumper reinforcements in Taiwan's roll-forming automotive parts industry, such as tensile strength greater than or equal to 1,400~1,500MPa. Moreover, the materials usage ratio is gradually approaching 70%, indicating a growing demand. However, CSC currently does not have a production track record for this type of product. There is a need to actively invest in research and development resources and organize in-house trials to gradually expand the market share of cold-rolled martensitic ultra-high-strength steel. And to assist customers in moving towards local procurement and supply, aiming to reduce sourcing risks and promote domestic production of critical materials

6. CONCLUSION

In response to the ultra-high-strength material demands from Taiwanese automotive manufacturers for aftermarket components, such as bumper reinforcements or support brackets, CSC has independently developed an ultra-high-strength steel material known as CSC CR1300T martensite steel. This material boasts a tensile strength of over 1,300MPa. The aim is to gradually replace the imported cold-rolled steel coils from mainland steel and establish a localized supply chain system, promoting the domestic production of crucial materials.

The CSC CR1300T shares the same steel grade and rolling process as the existing ultra-high-strength steel used within the factory. By independently adjusting the heating and cooling parameters during the final annealing stage, it can meet various specifications for mechanical properties and formability. This not only improves the efficiency of steel refining and continuous casting but also provides flexibility in production scheduling.

The main alloying elements added in the compositional design are Mn, Si, Mo, and Cr, which enhance the solid solution strengthening effect and increase material hardenability. Considering the relatively high alloy proportions, the material has high deformation resistance and is prone to forming a hard and brittle microstructure after hot rolling, which is not suitable for subsequent cold rolling at room temperature. Therefore, a pre-annealing softening process is introduced before cold rolling to eliminate the hard and brittle microstructure formed during the hot rolling cooling period. This improves the stability of plate shape during high-speed cold rolling, ensures smooth production, and results in cold-rolled semi-finished products with high thickness accuracy, reduced edge drop, and excellent flatness.

During the initial development stage, the continuous annealing line continued to use the common operational mode for the cooling process, which resulted in the presence of an amount of soft ferrite phase within the base. However, through continuous evolution and improvement, innovative furnace operation techniques were introduced to modify the cooling process. These new furnace operation techniques included GJ high-temperature air cooling, RGJ high-speed forced hydrogen gas cooling, RQ high-pressure roller cooling, OA low-temperature self-tempering, and TPM high-stress reduction. These novel approaches replaced the original automatic temperature control mode, presenting a higher proportion of martensite structure within the base.

By reducing the excessive soft ferrite phase, the overall strength issue was rectified. The products now exhibit a stable tensile strength of over 1,300MPa, with excellent hole expansion rate and bending performance. Subsequently, continuous efforts have been made to modify the annealing operation parameters, such as optimizing the cooling module, controlling the production line speed for thin plates, and fine-tuning the temperature during the over-aging process, among other optimization measures. Additionally, the best operating parameters for GJ, RGJ, RQ, and TPM have been customized based on the specific dimensions of the incoming materials. These optimized processes strike a balance between superior material structure, precipitation size, and work-hardening characteristics. As a result, the variation in mechanical properties of thin and thick plates has been reduced. The material with a thickness of 1.0 to 1.4mm meets the CSC CR1300T specification standards, with the following mechanical properties: Yield Strength ranging from 1,034 to 1,107 MPa, Tensile Strength ranging from 1,304 to 1,364 MPa, and Elongation ranging from 7.0 to 8.0%.

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