Advancing weathering steel through thermomechanical processing and simulation techniques

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Abstract. Thermomechanical processing (TMP) techniques are pivotal in fabricating and advancing weathering steel, a high-strength, low-alloy steel admired for its exceptional corrosion resistance and aesthetic appeal. Combined with numerical and physical simulation methods, these techniques optimize mechanical properties, microstructure, and overall weathering steel performance. Selecting an appropriate steel composition is crucial before applying TMP techniques. Alloying elements like copper, chromium, nickel, and phosphorus are carefully incorporated to enhance corrosion resistance. Once the steel composition is determined, numerical simulations are employed to model and predict the behavior of weathering steel during processing. Hot rolling is the first stage of thermomechanical processing in which weathering steel is heated and deformed in rolling mills. Additionally, numerical simulations can be employed to study other heat treatment steps, normalization and stress relieving, to optimize their parameters and impact on weathering steel's microstructure and mechanical properties. In conjunction with thermomechanical processing techniques, physical simulations, accelerated corrosion testing, and environmental exposure, help assess weathering steel's long-term performance and durability. These techniques provide valuable data on the formation and behaviour of protective patina, contributing to the steel's corrosion resistance. In summary, combining thermomechanical processing techniques and numerical and physical simulations enables the precise control and optimization of weathering steel's mechanical properties, microstructure, and corrosion resistance. These advancements contribute to the development and application of weathering steel in various industries, where its unique combination of mechanical performance, aesthetic appeal, and long-term durability is highly valued.

Introduction

Weathering steel is a class of low-carbon steel alloys that may create stable protective rust coatings when exposed to outdoor elements such as rain, wind, ice, fog, and so on for several years. Rust layers form in the outer layer of the steel as a protective shield that prevents future corrosion. This beneficial corrosion process gives the material a generally appealing appearance, with a range of colours ranging from lighter browns to darker browns with probable purple tints, and helps to reduce maintenance requirements [1]. The main applications for weathering steels include civil structures such as bridges and other load-bearing structures, road installations, electricity poles, transmission towers, guide rails, ornamental sculptures, facades, and roofing [1][2][3].

Weathering steel alloys have a carbon concentration of less than 0.2% wt, with other alloying elements such as copper (Cu), chromium (Cr), nickel (Ni), phosphorus (P), silicon (Si), and manganese (Mn) accounting for a small percentage of total weathering steel alloys [1][4]. Patina refers to the protective rust layer produced on the outer surface of weathering steel [5]. The patina forming process is aided by frequent wetting and drying cycles on the surface of the weathering steel. It typically takes two to six years for the patina to fully develop. The rate of patina production and the ultimate hue of weathering can be affected by climatic conditions and surrounding air quality, such as moisture and pollution levels [1].

Recently, improving the properties of weathering steel and other grades is important in order to participate in achieving the sustainability requirements and solving environmental problems. Improving the mechanical properties of weathering steel, such as strength and stiffness, allows for the design of lighter and more efficient structures. This can lead to reduced material consumption, and increased energy efficiency during construction. By enhancing the mechanical properties of weathering steel, structures can be designed to withstand higher loads and stresses. This means that less steel is needed to achieve the required strength and performance, resulting in reduced resource consumption and lower environmental impact. Additionally, Stronger steel with enhanced mechanical properties improves the safety and resilience of structures, especially in critical applications such as bridges, high-rise buildings, and infrastructure exposed to extreme conditions. This ensures that structures can withstand natural disasters, reducing the need for reconstruction and the associated environmental impacts.

Simulation and Thermomechanical controlled processing of weathering steel

Thermomechanical properties play a crucial role in enhancing the properties of weathering steel. Thermomechanical Controlled Processing (TMCP) refers to the physical and thermal treatments applied to steel during manufacture. It precisely controls the temperature, strain, and strain rate during hot rolling of steel. Following controlled rolling, the steel is fully chilled using air cooling or accelerated cooling methods. The cooling pace and temperature profile have a considerable impact on the steel's ultimate microstructure and properties [6]. By subjecting steel to controlled heating and cooling processes, its microstructure and mechanical properties can be modified, resulting in improved performance [7][8]. Thermomechanical processing techniques, such as hot rolling, controlled cooling, and quenching and tempering, can increase the strength and toughness of steel. These processes refine the microstructure, promote the formation of fine and homogeneous grains, and induce the precipitation of strengthening phases, which leading to improved mechanical properties [9][10]. Proper thermomechanical processing can enhance the ductility and formability of steel. Techniques like annealing, hot working, and controlled rolling can refine the grain structure, reduce residual stresses, and improve the steel's ability to deform without fracture [11]. The manipulation of thermomechanical properties allows for the customization and optimization of steel's mechanical behavior, resulting in improved strength, toughness, formability, weldability, and resistance to fatigue and creep. These enhanced properties contribute to the development of more efficient and sustainable steel products for various applications across industries [3][12]. For industrial sectors, Sheet and plate manufacture uses TMCP with micro alloys to balance strength, toughness, and weldability through grain refinement. [12].

Any adjustment in process parameters or chemistry for improving weathering steel properties necessitates a detailed understanding of material behaviour. Furthermore, if done on a large scale, it is a time-consuming and expensive process. Sometimes it is not even feasible or economical. Furthermore, reduced study flexibility leads to fewer trials being conducted. This causes slow or constrained development, resulting in a lengthy product development cycle that is unprofitable or technologically infeasible. Hence, Numerical and physical simulation of thermomechanical processing plays a crucial role in the steel industry by providing valuable insights and benefits [6]. Numerical simulation software for thermomechanical processing offers significant advantages, including process optimization, predictive capabilities, resource and time savings, troubleshooting, material design, environmental impact assessment, and educational benefits. By leveraging these tools, the steel industry can enhance its efficiency, productivity, and sustainability while accelerating innovation and product development. Numerical Simulation software's allow to optimize thermomechanical processes by analyzing various parameters, such as temperature, strain rate, cooling rate, and deformation. It enables the exploration of different process conditions and helps identify the optimal combination of parameters to achieve desired material properties and performance. This optimization can lead to improved efficiency, reduced costs, and enhanced product quality. Moreover, they help in understanding the effects of thermal and mechanical treatments on the microstructure, phase transformations, and mechanical properties of steel. They provide predictive capabilities, allowing the assessment of the material's behavior under different processing conditions. This predictive capability aids in making informed decisions regarding process design and material selection. By using simulation software, the need for physical experimentation and trial-and-error approaches are reduced. Instead, they can virtually test different process scenarios and evaluate their outcomes, saving resources and time. This accelerates the development and optimization of thermomechanical processes, enabling faster time-to-market for new products. Additionally, by using numerical and physical simulations of TMCP in weathering production, Manufacturers can optimize the manufacturing processes and attain the required control to achieve weathering steel with predictable and dependable performance. This is a significant benefit that encourages the broad usage and application of weathering steel in a variety of industries.

The finite element technique (FEM) was used to simulate stress-strain curves of a duplex weathering steel. This article discussed effective aspects in duplex weathering steel, including the volume fraction of martensite and the yield stress ratio of martensite to ferrite. The simulated and measured findings are nearly identical, indicating the accuracy of the FEM developed in this study. The volume proportion of martensite clearly affected the plastic part of the stress-strain curve, rather than the elastic part. As the volume fraction of martensite decreases, the strain increases significantly. Furthermore, the yield stress ratio of duplex weathering steel clearly affected the stress-strain curve, rather than just the elastic component. The volume fraction of martensite has a greater impact on the stress-strain curve of duplex weathering steel than the volume fraction of martensite itself [13].

Physical simulation of TMCP reduces the cost and duration of studies by simulating real-world processes in the lab. It can also provide useful data for the creation of new goods, the optimization of process parameters, and so on [6]. The Gleeble machine is an outstanding integrated digital closed-loop control system that is used for physical simulation of TMCP. It can heat specimens at up to 10,000 C/s, maintain steady-state equilibrium temperatures, and cool at high rates (10,000 C/s). The Gleeble machine uses an infrared pyrometer to provide accurate feedback on specimen temperatures. Gleeble systems can perform thermal testing 3-10 times faster than traditional furnace-equipped devices. Simulation of the Gleeble machine results in complex microstructural changes caused by thermal, mechanical, and metallurgical impacts. The Gleeble machine provides researchers with insights into many stages of deformation, including dynamic recovery, dynamic recrystallization, and static recrystallization, by measuring mean flow stress versus deformation temperature [6][8].

Recently, 420 MPa grade weathering bridge steels were developed from Si Bearing steel alloys at various percentages (0.15-0.77 wt.%)[14] by applying TMCP which was simulated using a thermo-mechanical simulator. The TMCP included two stages of controlled rolling and an accelerated cooling process, for four experimental steels with varied Si concentrations (see Fig. 1). The study found that increasing the Si concentration in TMCP steel improved both yield and tensile strength.

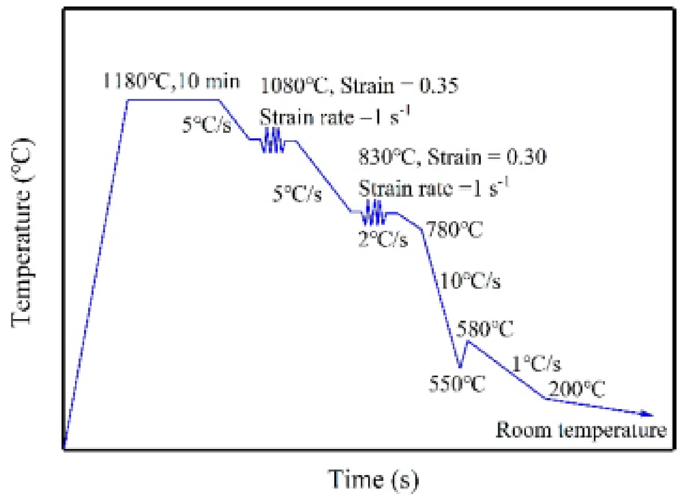

Fig.1. TMCP cycle of studied Si bearing weathering steel [14].

A novel Cu-P-Cr-Ni-Mo weathering steel was compressed using Gleeble 3500 to determine the mechanism of ferrite grain refining in the deformation temperature range from 750°C to 925°C [15]. The microstructure of the studied specimens revealed that the ferrite grain size decreased while the ferrite volume fraction rose with increasing compression temperature. Electron backscatter diffraction patterns indicated that some low-angle boundaries shifted to the high-angle boundary, resulting in fine ferrite grains surrounded by high-angle boundaries. At 750°C, several low-angle boundaries were found inside ferrite grains, indicating the presence of pre-eutectoid ferrite. Fine equiaxed ferrite grains with size ranging from 1.77 µm to 2.69 µm were produced in the (α + γ) dual phase region. As shown in Fig. 2**,** at temperatures ranging from 750°C to 775°C, ferrite grain refining may be caused by dynamic recrystallization, while at 800°C and 850°C, deformation-induced ferrite transformation is the primary mechanism. The flow curves produced at 875°C, 900°C, and 925°C demonstrated work hardening. Flow stress increased constantly as strain increased, and work hardening had a larger apparent peak stress than dynamic softening. Work hardening ability also decreased as the deformation temperature increased. This phenomenon could be related to the following factors: high distorted internal energy and less stable austenite, as well as the numerous nucleation sites offered by defects.

The Gleeble 3500 thermo-mechanical simulator was used for studying hot ductility behavior of 800 MPa weathering steel through tensile testing at different high temperatures. The reduction in area (RA) and tensile strength (TS) were acquired to draw hot ductility curve and hot strength curve. The results show that the third brittle zone of test steel is between 700ºC and 800ºC and which is mainly related to the formation of film-like ferrite along the prior austenite grain boundary and the precipitation of second phase. Moreover, the drop of hot ductility at 900ºC is rooted in the reduction of grain boundary strength owing to the precipitation of sulfides. Therefore, the findings concluded that the straightening temperature of test steel should be kept over 900ºC [16].

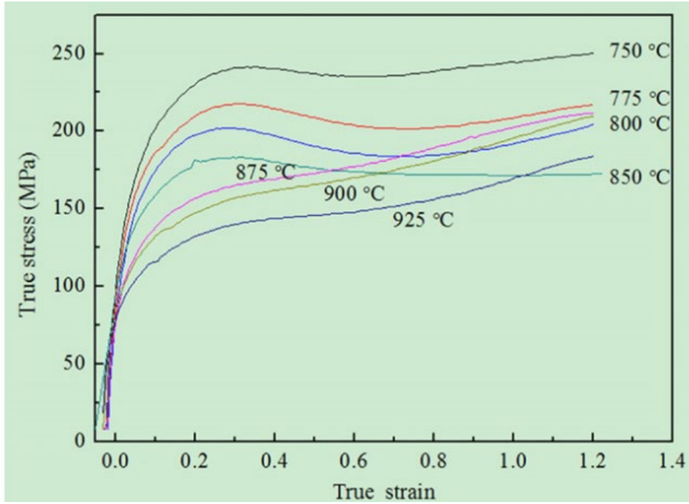

Fig. 2. Flow stress strain curves for different temperatures at strain rate of 0.1 s^{-1} [15].

Another research explored the microstructure evolution of Cu-P-Cr-Ni-Mo weathering steel after many passes of deformation (see Fig. 3) via hot compression simulation. At multi-pass deformation conditions, ultrafine ferrite grains of 1.8 µm were seen in the ($\alpha + \gamma$) area. The second phase of bainite and martensite was dispersed as a band on the ferrite matrix, becoming thinner with further passes. Microstructural analysis revealed that strain-enhanced ferrite transformation is the primary mechanism for structure refinement during initial pass deformation, while continuously dynamic recrystallization is the primary mechanism for ferrite grain refinement during later passes [17].

Evolution of weathering steel microstructure and characteristics

Because of their chemical composition, weathering steels are considered a popular alternative for applications requiring excellent atmospheric corrosion resistance. However, the decreased formability of weathering steels remains an issue that needs to be studied. Thus, Dual Phase (DP) weathering steel has been proposed as a steel grade that combines the better formability of DP steels and the strong atmospheric corrosion resistance of weathering steels [18]. The inter-critical annealed DP weathering steel has not only excellent corrosion resistance, but also a low yielding stress, a high elongation value, and a smooth flow-stress curve with a high strain-hardening coefficient. However, the intercritical annealing method has certain drawbacks, including a significant investment in equipment, high energy consumption, and low manufacturing efficiency and quality. Based on these parameters, development of directly hot-rolled DP weathering steel is required [19].

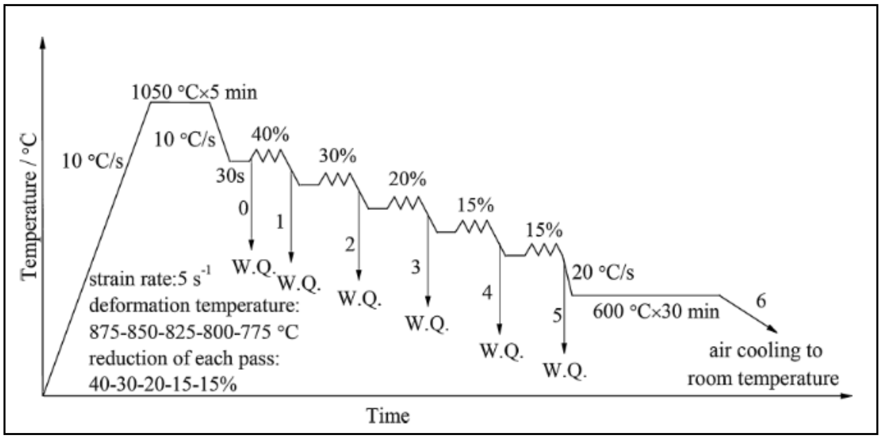

Fig. 3. Multi-pass deformation of the investigated weathering steel [17].

A prior study looked into developing novel Cu-P-Cr-Ni-Mo hot-rolled dual-phase weathering steels with a microstructure composed of ferrite-martensite phases. The Gleeble-3500 hot simulator was used to recreate the hot rolling process which shown in Fig. 4. The created hot-rolled dual-phase weathering steel containing 0.41% Mo with ferrite and martensite in its microstructure demonstrated superior comprehensive mechanical characteristics and formability compared to commercial weathering steel 09CuPCrNi[20].

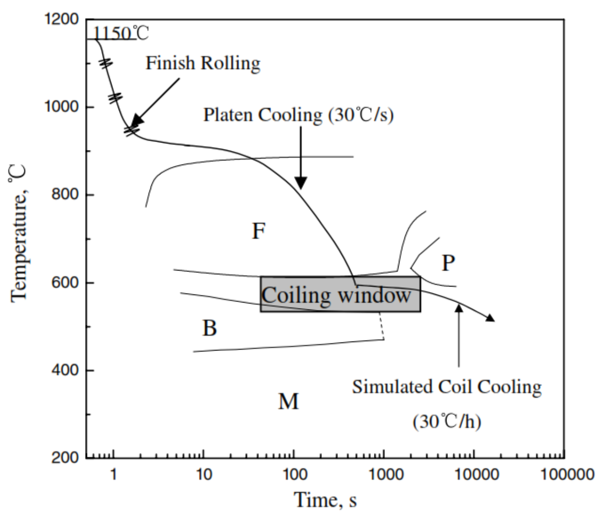

Fig. 4. Simulation of hot rolling processing cycles for the studied DP weathering steel.

Furthermore, electrochemical potentiodynamic experiments and simulated salt spray tests were used to investigate how dual-phase treatment affects corrosion resistance of the previously investigated 09CuPCrNi steels. The corrosion behaviour of DP780 and the as-received weathering steel is similar in 5% sodium hydroxide, 3.5% sodium chloride, 5% sulphuric acid, and different concentrations of hydrochloric acid solutions. However, dual-phase steels exhibit lower corrosion currents than the as-received steel. The rust layers of as-received steel and DP780 are similar, consisting primarily of three iron oxides (goethite, akaganeite, and lepidocrocite) and magnetite. The number and form of phase constituents impact the corrosion behaviour of DP steels [21].

The impact of microstructure evolution on the mechanical properties of a 500 MPa-grade weathering steel produced by an identical thermo-mechanical control process and different tempering treatments at 450-650 C was thoroughly investigated (See Fig.5)[22]. It is noticed from the results that the as-rolled steel has granular bainitic ferrite (GBF) and martensite/austenite (M/A) components, resulting in unsatisfactory mechanical characteristics. As tempering temperature increased from 450°C to 650°C, the massive twin-type M/A constituents dissolved preferentially into carbides, with stabilization of only a minor amount of fine lath-type M/A constituents. Merging the bainitic ferrite laths resulted in improved matrix recovery, reduced dislocation density, and enhanced high-angle grain boundary (HAGB) proportion. The simultaneous precipitation of nanoscale particles (Ti, Nb) C and ε-Cu resulted in increased yield strength. M/A ingredient breakdown reduces strain hardening capacity and tensile strength. Tempering at 450-600°C reduced twin-type M/A components and increased HAGBs, whereas tempering at 650°C caused necklace-like M23C6 carbides to precipitate at grain boundaries, reducing impact toughness. Additionally, tempering at 550-600°C resulted in an optimal mechanical property combination [22].

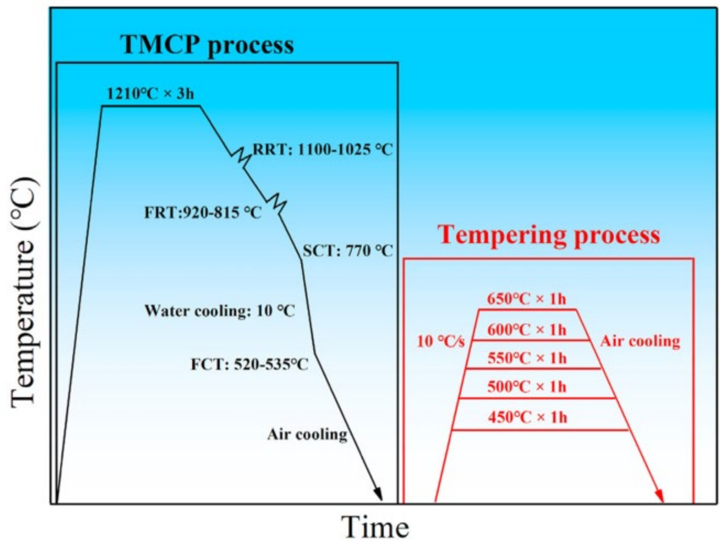

Fig. 5. The simulated TMCP of martensite/austenite 500 MPa weathering steel. RRT: rough rolling temperature, FRT: finish rolling temperature, SCT: start cooling temperature and FCT: finish cooling temperature [22].

Conclusion

- Weathering steel is a low alloy steel that combines simple carbon steel with minor amounts of Cu, Ni, Cr, and other alloy metals. This material offers superior toughness, ductility, and corrosion resistance compared to standard carbon steel. Weathering steel is commonly utilized in structures such as rails, automobiles, bridges, and towers that require long-term exposure.
- Thermomechanical processing are critical for improving the properties of weathering steel. Steel's microstructure and mechanical properties can be adjusted through controlled heating and cooling procedures, leading to increased performance. [6][7]. Hot rolling, controlled cooling, and quenching and tempering are examples of thermomechanical processing processes that can increase steel's strength and toughness. These processes enhance the microstructure, stimulate the development of fine and uniform grains, and induce the precipitation of strengthening phases, resulting in increased mechanical characteristics.
- Numerical simulation software for thermomechanical processing of weathering steel provides numerous benefits which promote optimization and analyzing processing parameters like temperature, strain rate, cooling rate, and deformation. It allows to find the best combination of parameters to obtain the desired material qualities and performance.
- Physical simulation of TMCP minimizes study expense and duration by imitating real-world processes in the lab. It can also provide useful data for new product development, process

parameter optimization, and other purposes. Different investigations utilized the thermo-mechanical simulator such as Gleeble machine to different grades of weathering steel via simulating thermomechanical process. Through these studies, they were able to develop different grades of steel with a maximum tensile strength value exceeded 500 MPa as well as determining effect of different TMCP on the microstructure and mechanical properties of weathering steel at low cost and time.

- However, the good corrosion resistance and tensile properties of weathering steels with Ferrite-Pearlite in its microstructure, they are characterized by lack of formability. Consequently, different researches focused on evolving dual phase Ferrite- Martensite weathering steel and via simulation of TMCP. They managed to enhance the tensile properties and formability of weathering steel without affecting its corrosion resistance.

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