Microstructure and mechanical properties of dual-phase weathering steel 09CuPTiRe

ZHANG CHUNLING*, CAI DAYONG, LIAO BO
Key Laboratory of Metastable Materials Science & Technology, Yanshan University, Qinhuangdao 066004, People's Republic of China
E-mail: zhangchunling92@sina.com.cn

ZHAO TIANCHEN, FAN YUNCHANG
Department of Materials Science & Engineering, Shijiazhuang Rail Institute, Shijiazhuang 050043, People's Republic of China

Weathering steel is one of the common candidates for steel constructions in the field of transportation. Normally, the chemical composition of weathering steel includes a small amount (in general less than 1%) of Cu, Cr, Ni, and P which are able to promote, after exposure to the atmosphere, the formation of a stable protective oxide layer, reducing the corrosion rate remarkably [1–3]. Nowadays weathering steel 09CuPTiRe is widely adopted for manufacturing rolling stock in China. To increase the velocity of the train, new weathering steel, which has not only high perfomance in corrosion resistance under conditions of sunshine, rain and snow, and temperature fluctuations, but also higher strength to reduce the weight of the train itself, must be developed.

Dual-phase steels belong to a new class of high-strength low-alloy steels characterized by microstructures mainly consisting of a dispersion of hard martensite particles in a soft ferrite matrix [4–6]. These steels have a combination of strength, ductility, and formability that makes them attractive for weight-saving applications in the automobile industry [7, 8]. Dual-phase steels were originally produced by an intercritical heat treatment. In the same way, a weathering steel may also be treated into a dual-phase steel, which may have both the excellent atmospheric corrosion resistance of the weathering steel and the favorable mechanical behavior and properties of the dual-phase steel.

The main objective of this study is to prepare the dual-phase weathering steel by intercritical heat treatment, to examine the resultant microstructures, to test the corresponding mechanical behavior and properties, corrosion resistance, and to determine the relationship between the intercritical treating processes and the microstructures and the subsequent properties.

The chemical composition of the supplied weathering steel 09CuPTiRe was Fe-0.06C-0.28Si-0.04Mn-0.073P-0.012S-0.01Ni-0.01Cr-0.28Cu-0.01Ti-0.13Re (wt%). It was received as hot rolled plates with a ferrite-pearlite structure (see Fig. 1), and its mechanical properties are $\sigma_{0.2}$-363.4 MPa, σ_b-462.0 MPa, δ-30.7%, n-0.12, and $\sigma_{0.2}/\sigma_b$-0.787.

Tensile specimens with a gage of 100 mm were cut from the as-received hot-rolled plate. The tensile specimens were heat treated for 10 min in the intercritical range (760–820 °C) and quenched in a 5 wt% NaCl aqueous solution (brine). These treatments were all carried out in a salt bath furnace. Tensile tests were conducted on an INSTRON machine with a cross-head speed of 0.5 mm/min. Volume fraction of martensite (MVF) was measured by quantitative metallography in each condition. Microstructure observations were performed by using a Neophot-21 Optical Microscope (OM) and H-800 Transmission Electron Microscope (TEM). Corrosion specimens were cut from the grip end of the broken tensile specimens and corrosion tests were performed using an artificial atmosphere-salt spray testing unit. The chemical composition of the corroded layer was analyzed using X-ray diffraction.

The microstructures of the steel, after intercritical quenching from various temperatures are shown in Fig. 2. Martensite islands are randomly distributed, but have appreciably larger dimensions in directions along prior austenite grain boundaries. The volume fraction of martensite increases with the increase of quenching temperature, as shown in Fig. 3. Such microstructures are typically found in dual-phase steels and may be called island-type dual-phase structure.

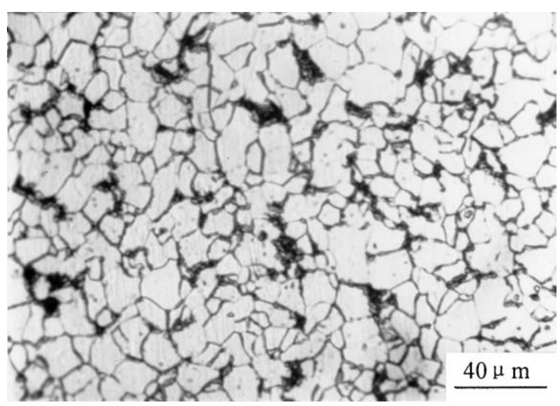

Figure 1 Microstructure of weathering steel 09CuPTiRe in hot-rolled state.

* Author to whom all correspondence should be addressed.

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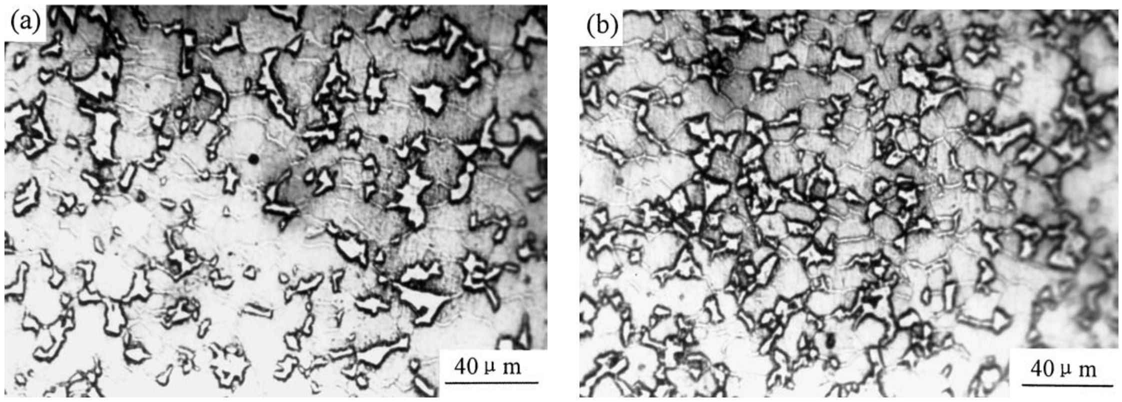

Figure 2 Microstructures of steel 09CuPTiRe after intercritical quenching at (a) 780 °C and (b) 800 °C.

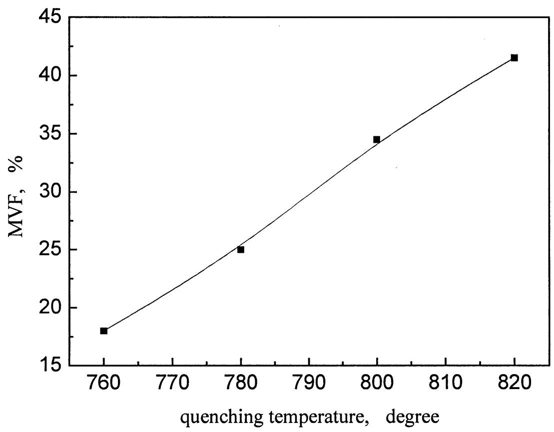

Figure 3 Relationship between MVFs (martensite volume fractions) of 09CuPTiRe dual-phase steel and intercritical quenching temperatures.

Transmission electron bright-field micrographs of steel 09CuPTiRe after intercritical quenching at 780 °C are shown in Fig. 4. Similar to previous results published for intercritically quenched steels [9], it is frequently observed that the dislocation density in the interior regions of ferrite grains is lower than that in the ferrite regions directly adjacent to the martensite phase (Fig. 4a). The higher dislocation density around martensite phase may be caused by the volume expansion accompanying the phase transformation occurring from austenite to martensite. The martensite phase is essentially lath type (Fig. 4b), although some microtwins can be also observed (Fig. 4c).

Stress–strain curves for the samples quenched at 780 °C and in the as-received condition are shown in Fig. 5. A yield point is found in the curve for samples in the as-received condition, in contrast, samples quenched at 780 °C exhibited a smooth parabolic-type stress–strain curve. The work hardening exponent ($n \approx 0.17$) for samples quenched at 780 °C increases by about 42%, compared to that of samples in the as-received condition. It should be noted that the dual-phase treatment gives the steel appreciable increase in strength but without any obvious sacrifice in ductility.

The mechanical properties are shown as a function of intercritical quenching temperature in Fig. 6. It can be clearly seen that the yield strength and the tensile strength increase in a nearly linear manner with quenching temperature in the range 760 to 820 °C. In contrast, total-elongation decreases nearly linearly from 23.1% to 20.7% when intercritical quenching temperature increases from 760 to 820 °C (Fig. 6a). The

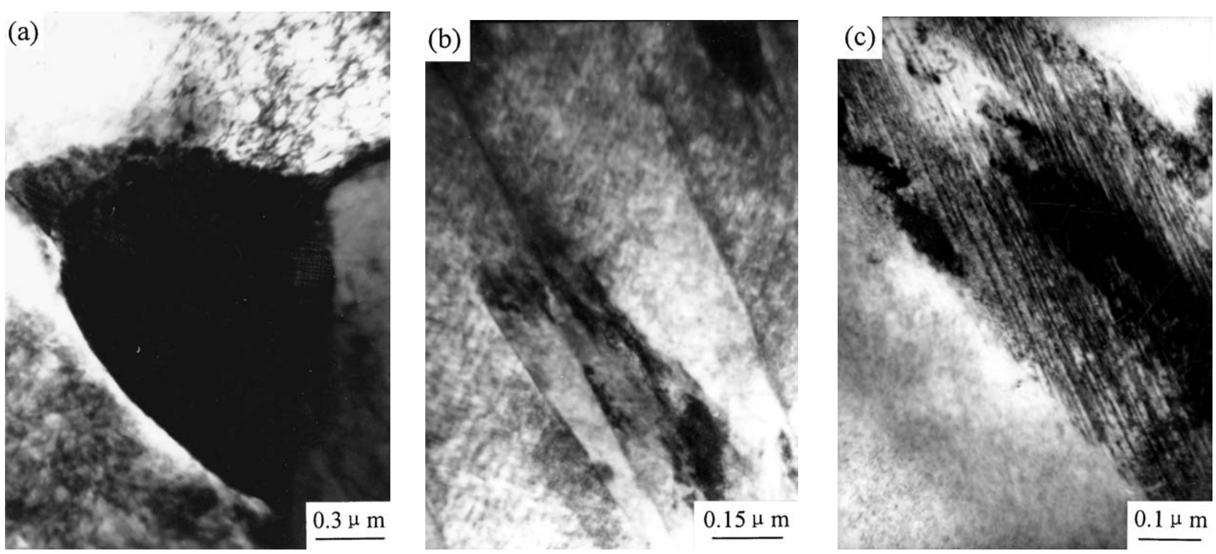

Figure 4 Transmission electron bright-field micrographs of steel 09CuPTiRe after intercritical quenching at 780 °C: (a) Martensite island surrounded by dislocations, (b) Lath martensite with dislocations, and (c) Martensite with microtwins.

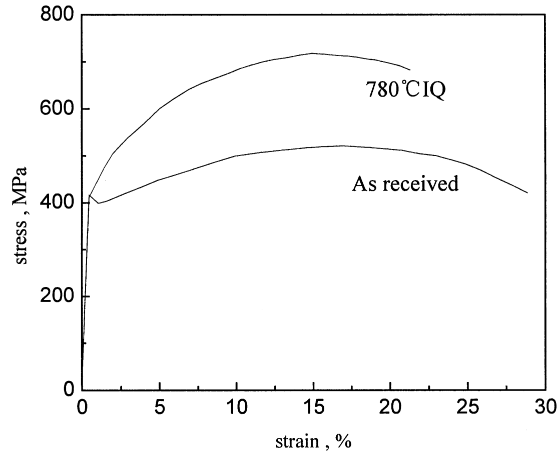

Figure 5 Stress–strain curves of the sample quenched at 780 °C, compared to the as received condition (IQ indicates intercritical quenching).

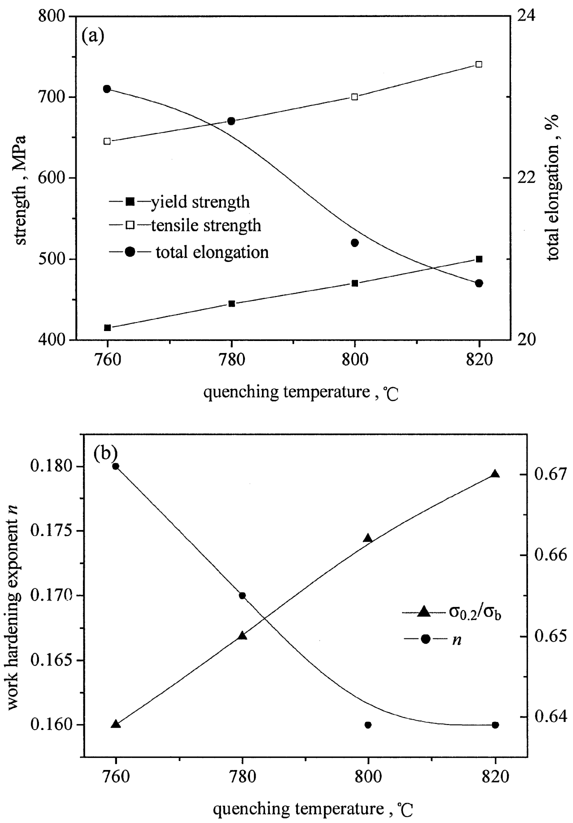

Figure 6 Mechanical properties as a function of intercritical quenching temperature.

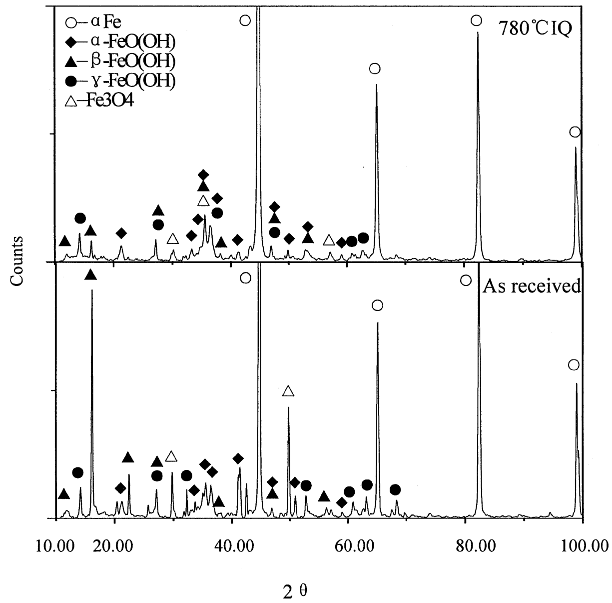

Figure 7 XRD patterns for rust layers on the samples of as-received steel 09CuPTiRe and the sample of the same steel intercritically quenched at 780 °C.

yield-to-tensile strength ratio increases while the work hardening exponent decreases with increasing intercritical quenching temperature, as shown in Fig. 6b. Formability of steels can be evaluated by their total-elongation (δ), yield-to-tensile strength ratio ($\sigma_{0.2}/\sigma_b$), and work hardening exponent (n). When the intercritical quenching temperature increases from 760 to 820 °C, the yield-to-tensile ratio increases from 0.639 to 0.670, while the work hardening exponent decreases from 0.18 to 0.16 (Fig. 6b). Compared with the as-received steel, the dual-phase 09CuPTiRe steel should have much better formability.

All the results presented above indicate that a successful dual-phase 09CuPTiRe steel with excellent mechanical properties and formability can be obtained through intercritical quenching at 780 °C.

A thin layer of unstable orange rust is found on the surface of the dual-phase steel 09CuPTiRe after 2 h of continuous spraying, and a stable rust layer forms about 10 h later. The thickness of the rust layer increases with the spraying time, but the rusting rate gets slower with increasing time. XRD patterns for both rust layers on the samples of the as-received steel and on the samples of the same steel quenched at 780 °C are shown in Fig. 7. The compound components of the rust layers on the two different samples are similar, mainly consisting of α-FeO(OH), β-FeO(OH), γ-FeO(OH), and Fe_3O_4. The corrosion rates (mm/a) in salt spray for the samples of the as-received steel and the samples of the same steel quenched at various intercritical temperatures are given in Table I. It can be clearly seen from the data in the table that the corrosion resistance of the dual-phase-treated weathering steel is better than that of the as-received original. Thus, dual-phase weathering steel 09CuPTiRe can be confidently used for the manufacture of rolling stock.

In summary, the microstructure of the intercritically quenched weathering steel 09CuPTiRe is composed of randomly distributed island-shaped martensite particles in a matrix of equiaxed ferrite grains. The morphology of the martensite phase is essentially of the lath type, with small areas of micro-twins appearing. The volume fraction of martensite phase increases with increasing intercritical quenching temperature.

TABLE I Corrosion Rate (mm/a) in salt spray for samples of as-received steel and samples quenched at various intercritical temperatures

Salt spraying time (h)	As-received	760 °CIQ	780 °CIQ	800 °CIQ	820 °CIQ
48	1.6650	1.5585	1.4131	1.4592	1.2339
120	1.3427	1.2817	1.1301	1.3368	1.2274

The tensile strength and yield strength of the treated steel increase when the volume fraction of martensite increases, while a decrease in the total elongation accompanies this trend. Excellent mechanical properties, such as yielding phenomenon disappearing, high-strain hardening exponent (n) values, a lower ratio of yield to tensile strength, and higher strengths, are obtained in dual-phase weathering steel 09CuPTiRe through intercritical quenching at 780 °C. The corrosion resistance of the dual-phase weathering steel 09CuPTiRe developed by intercritical quenching at various temperatures is better than that of the as-received hot-rolled steel.

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Received 11 August
and accepted 30 December 2003