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Using direct hot-rolling approach to obtain dual-phase weathering steel Cu–P–Cr–Ni–Mo

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Abstract A weathering steel Cu–P–Cr–Ni–Mo has been developed which exhibits special continuous cooling transformation characteristics which permit the desired dual-phase (DP) microstructure to be obtained by direct hot-rolling. Hot-rolling procedures to obtain DP microstructures have been designed based on the continuous cooling transformation diagram of weathering steel Cu–P–Cr–Ni–Mo. The results show that the microstructures of DP weathering steels Cu–P–Cr–Ni–Mo are characterized by an irregular distribution of island-shaped martensite–austenite in the matrix of polygonal ferrite grains. DP weathering steel Cu–P–Cr–Ni–Mo with favorable corrosion resistant property, weldability and mechanical properties, such as, high strain hardening exponent values, a lower ratio of yield to tensile strength, and higher strengths; and is obtained successfully by direct hot-rolling.

Introduction

Dual-phase (DP) steels belong to a new class of high-strength low-alloy steels characterized by the microstructures mainly consisting of a dispersion of hard martensite particles in a soft ferrite matrix [1, 2]. These steels have a combination of strength, ductility, and formability that makes them attractive for weight-saving applications in the automobile industry [3, 4], many large-scale research programs on these steels having been conducted in industrial laboratories and universities.

DP weathering steel produced by intercritical annealing has not only high performance in corrosion resistance, but a low yielding stress, a high elongation value, and a smooth flow-stress curve with a high strain-hardening coefficient [5–7]. However, the intercritical annealing method has some disadvantages: large investment of equipment, high energy consumption, and low production efficiency and quality. Based on these conditions, developing directly hot-rolled DP weathering steel is necessary.

For high strength low alloy steel, it is possible to obtain DP microstructure directly by hot-rolling and appropriate cooling, if its continuous cooling transformation (CCT) diagram exhibits a gap between the pearlite and bainite regions where the austenite is stabilized [8, 9].

The main objective of this study is to develop a weathering steel on the base of weathering steel 09CuPCrNi (which is a typical weathering steel used in China), which is suit for directly hot-rolling to obtain DP microstructure.

Materials and experimental procedures

Weathering steel Cu–P–Cr–Ni–Mo used in this research was vacuum-melted in a high frequency furnace; the chemical composition of the steel (in wt%) is 0.10C, 0.45Si, 0.42Mn, 0.008S, 0.075P, 0.65Cr, 0.22Ni, 0.28Cu, and 0.43Mo. The ingot was forged to 10 mm diameter bars and 40 mm thick slabs, normalized for 30 min at 970 °C.

Cylindrical dilatometer specimens with $\varphi = 3$ mm and length $= 10$ mm were machined from the diameter bars. The CCT diagrams were conducted on Formastor-Digital

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diatometer, and the corresponding specimens were firstly austenitized for 5 min at 1050 °C, then cooled at different linear cooling rates.

The CCT diagram of deformed austenite was conducted on Gleeble-3500 hot simulator, and the corresponding specimens with $\varphi = 8$ mm and length = 12 mm were firstly austenized for 5 min at 1050 °C, and then were given five passes compression deformation with 50% total reduction, and finally cooled at the linear cooling rates of 60, 30, 20, 10, 5, 2, 1, 0.5, 0.2, 0.1, and 0.05 °C/s, respectively. The specific compression deforming temperature, reduction, and strain rate of five passes compression deformation are 1050 °C–15%–5 s^{-1}, 1010 °C–15%–5 s^{-1}, 970 °C–15%–10 s^{-1}, 930 °C–10%–10 s^{-1}, and 910 °C–10%–15 s^{-1}, respectively.

Slabs were hot-rolled to strip on a testing roller 1700 according to the following processing conditions: initial thickness: 40 mm, final thickness: 4 mm, finish-rolling temperature: 850 and 890 °C, cooling mode between finish-rolling and coiling temperatures: water spraying, coiling temperature: 560 and 600 °C. The strips were named DP1, DP2, DP3, and DP4 with finish rolling temperature 890, 890, 850, and 850 °C and coiling temperature 560, 600, 560, and 600°C, respectively.

Tensile specimens with a gage of 100 mm (rolling direction) were cut from the hot-rolled strip. Tensile tests were conducted in an INSTRON machine. Martensite–austenite (M–A) volume fractions were measured by quantitative metallography. Microstructure observations were performed by using both optical and transmission electron microscopy. Metallographic samples were cut from the tensile sample grip ends and etched by 3% Nital. CO_2-shielded arc welding was used to study the weldability of the steel, and the chemical compositions, mechanical properties of the filler wire with diameter = 1.2 mm and detailed processes are shown in Tables 1, 2, and 3. Corrosion tests with length = 20 mm, width = 10 mm, and height = 4 mm specimens were performed using an artificial atmosphere-salt spray testing unit according to Chinese National Standards GB10125-88 (Corrosion Test in the Artificial Atmosphere-Salt Spray Test. Chinese National Standards GB10125-88).

Table 1 Chemical compositions of the filler wire

C	Mn	Si	Mo	Ni	S	P
0.09	1.2	0.3	0.45	0.65	0.017	0.017

Table 2 Mechanical properties of the filler wire

σ_b (MPa)	σ_s (MPa)	δ_5 (%)	Ak (J)
710	620	21	85

Results and discussions

CCT diagram of weathering steel Cu–P–Cr–Ni–Mo

The hot-rolled DP steel concept is based on a low carbon, low alloy steel which exhibits special CCT characteristics which permit the steel to be processed on a conventional, high production hot-strip mill to produce the desired ferrite–martensite microstructure in the hot-rolled coiled sheet. Special characteristics [9] that are needed in the CCT diagram include: (1) an elongated ferrite C-curve, i.e., the ability to form very large amounts of polygonal ferrite over a reasonably wide range of cooling rates on the runout table, (2) a suppressed (delayed) pearlite nose to ensure avoidance of pearlite formation during cooling to the coiling temperature, (3) a high pearlite finish temperature to avoid pearlite formation after coiling temperatures up to 620 °C, and (4) a gap between the polygonal ferrite and the bainitic ferrite regions to provide a temperature range of at least 75 °C within which no further transformation occurs, permitting the steel to be coiled with little or no sensitivity to the normal variations in coiling temperature that occur in commercial production.

Figure 1 shows the CCT diagrams of weathering steel Cu–P–Cr–Ni–Mo and 09CuPCrNi. From the CCT diagrams of the steels, it can be found that Mo has strong effects on the shape of the CCT diagram, namely retarding both the bainite-start and bainite-finish, retarding the pearlite-start, and heightening the pearlite-finish temperature. For weathering steel Cu–P–Cr–Ni–Mo, the ferrite–pearlite transformation region and the bainite transformation region are separated completely, and a metastable austenite gap appears between the two regions, which can provide “coiling window” after

Table 3 Technical processes of welding and mechanical properties of welding samples

Sample	Welding property		Welding parameter			
	σ_b (MPa)	δ_{50} (%)	Current (*A*)	Voltage (V)	CO_2 flux (L/min)	Welding rate (mm/min)
DP2	650.85	17.2	160	24	20	400
DP3	646.03	10.8	120	21		450
DP4	636.01	16.13	200	27		500

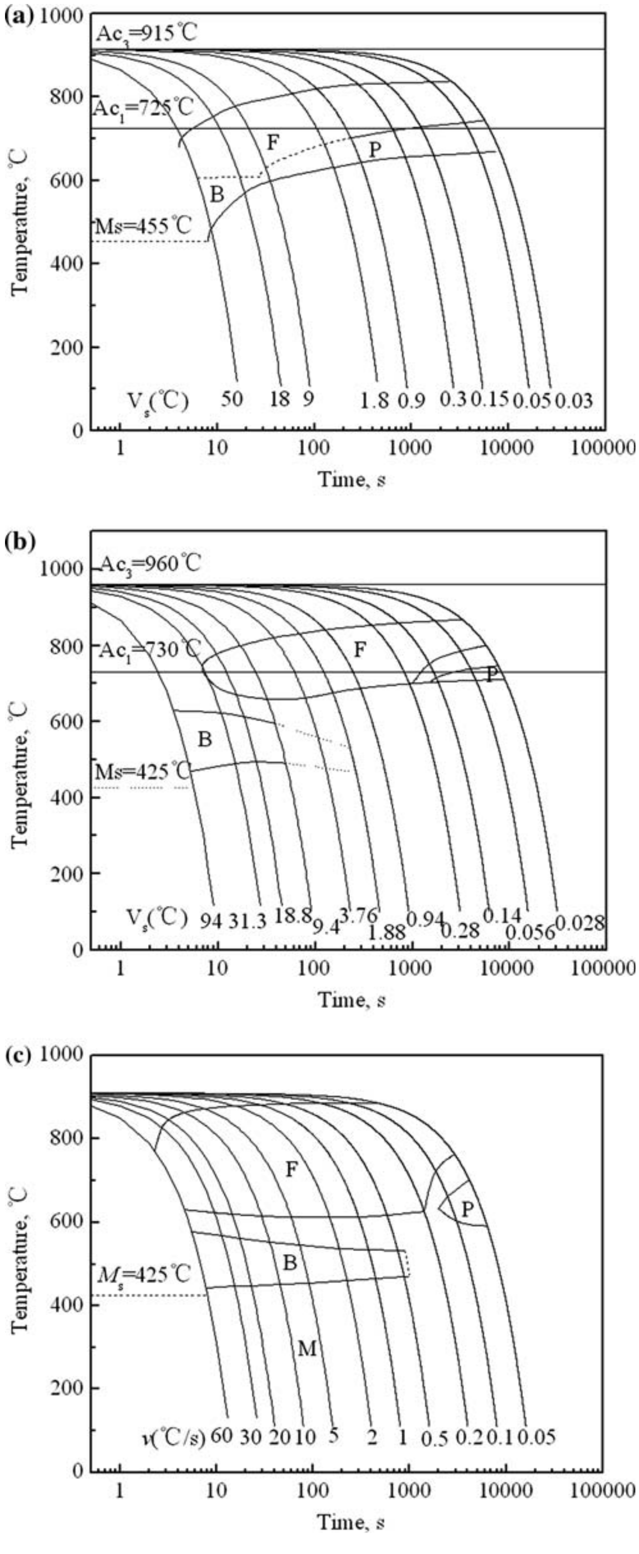

Fig. 1 CCT diagrams of weathering steels. **a** 09CuPCrNi, **b** Cu–P–Cr–Ni–Mo, and **c** Cu–P–Cr–Ni–Mo with deformed austenite

rolling, that is to say, when weathering steel Cu–P–Cr–Ni–Mo cools from the austenitization temperature at some cooling rate, austenite can transform to neither bainite nor pearlite, thus it can first transform to ferrite partly, then the left austenite transforms to martensite, which is called DP microstructure.

With deforming effects on the shape of CCT diagram, in order to constitute correct hot-rolling procedures, the CCT diagrams of weathering steel Cu–P–Cr–Ni–Mo with deformation must be constructed.

The dynamic CCT diagrams of weathering steel Cu–P–Cr–Ni–Mo are shown in Fig. 1c. Compared with the static CCT diagram, the nucleation period of ferrite transformation is shortened and the ferrite-start temperature is raised, so the ferrite transformation region is extended strongly. In addition, the nucleation period of pearlite transformation is lengthened and the pearlite transformation temperature is lowered.

The hot-rolling process such as the experimental rolling temperature range, coiling temperature, and cooling rates after rolling is deduced from the CCT diagram of weathering steel Cu–P–Cr–Ni–Mo with deformed austenite.

Microstructure of hot-rolled DP weathering steel Cu–P–Cr–Ni–Mo

Figures 2 and 3 show optical micrographs and transmission electron bright-field micrographs of DP steels Cu–P–Cr–Ni–Mo. The microstructures comprise polygonal ferrite, small patches of either martensite (M) or austenite (A) “second phase”, and trace of pearlite or bainite. Because of the subtle etching differences between the martensite and retained austenite particles together with their small sizes, optical identification and analysis is difficult and the amount of bainite or pearlite is small. Therefore, martensite, bainite, pearlite, and retained austenite are regarded as the second phase during optical quantitative metallography. The coiling temperature is among the metastable austenite range, in theory, austenite will not transform to pearlite or bainite during coiling process. In fact, when the coiling temperature is higher, the bainite transformation is avoided, but a small amount of pearlite may appear. On the contrary, when the coiling temperature is lower, pearlite transformation is avoided because of the cooling rate after finish rolling is rapid, but some bainite will be formed during the long time holding at coiling temperature. Therefore, the microstructure of DP2 and DP3 steel consists of a small amount of pearlite resulting in the higher coiling temperature. And there is a small amount of bainite in DP1 and DP4 steel for the lower coiling temperature.

Similar to previous results published for intercritically quenched steels [5], it is frequently observed that martensite phase distributes at the ferrite grain boundaries with island shaped (Fig. 3a). The martensite phase is essentially

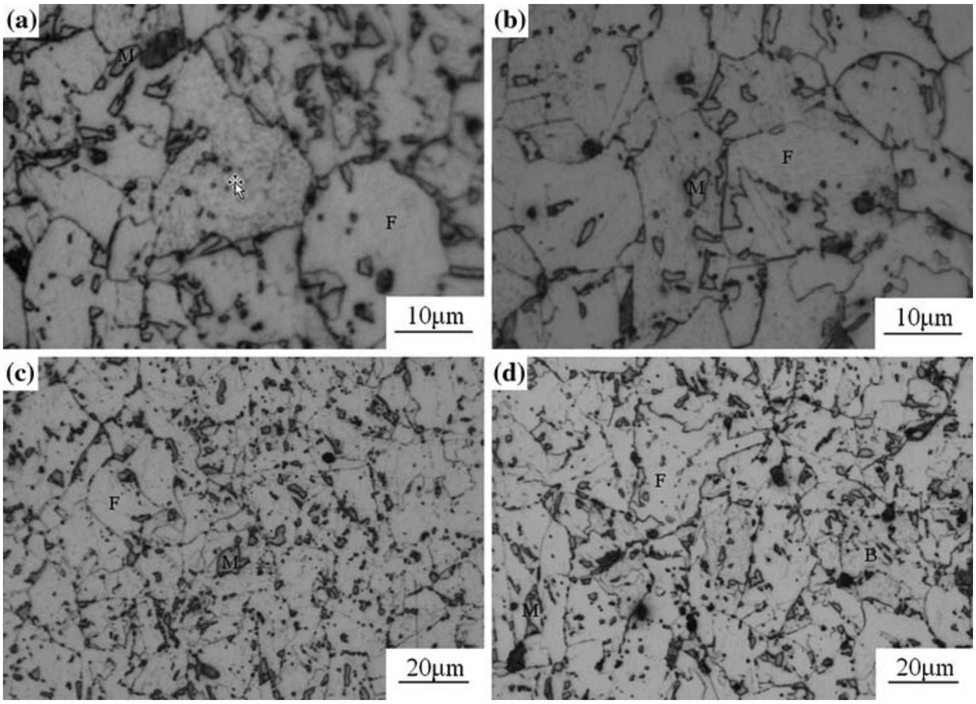

Fig. 2 Microstructures of hot-rolled DP steels Cu–P–Cr–Ni–Mo. **a** DP1, **b** DP2, **c** DP3, and **d** DP4

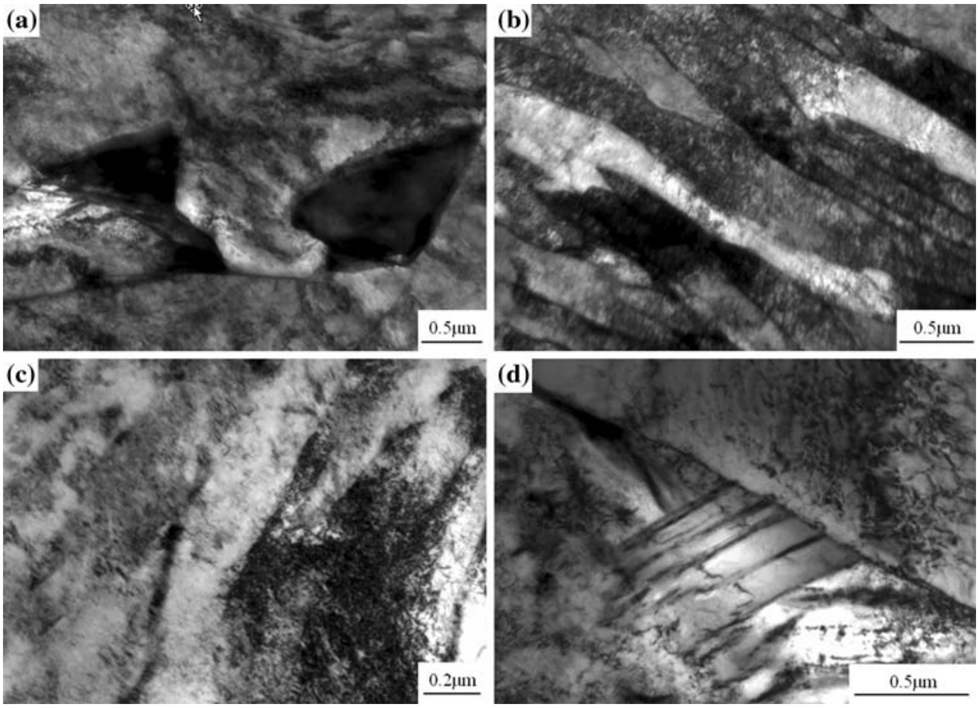

Fig. 3 Transmission electron bright-field micrographs of DP steels Cu–P–Cr–Ni–Mo. **a** Martensite island surrounded by ferrite, **b** lath martensite with dislocations. **c** Bainite caused by lower coiling temperature, and **d** pearlite caused by higher coiling temperature

lath type (Fig. 3b). Small amount of bainite (Fig. 3c) and pearlite (Fig. 3d) are also observed caused by lower coiling temperature and higher coiling temperature, respectively.

So coiling temperature has an important influence on the microstructures involved, i.e., the pearlite formed at high coiling temperature (600 °C) is replaced by bainite as the coiling temperature is lowered to 560 °C.

The data in Table 4 demonstrates that finish rolling temperature has an effect on the volume of M–A. It can be clearly seen that when the finish rolling temperature is increased from 850 to 890 °C, the volume of M–A is increased about 18%. The higher rolling temperature resulting in the volume of ferrite transformed from austenite is less, so the volume of metastable austenite is more

Table 4 Mechanical properties of DP weathering steels Cu–P–Cr–Ni–Mo

Sample	Hot-rolling procedures		MVF (%)	Mechanical properties				
	T_f (°C)	T_c (°C)		$\sigma_{0.2}$ (MPa)	σ_b (MPa)	δ (%)	n	$\sigma_{0.2}/\sigma_b$
DP1	890	560	16.1	423	742	21.1	0.25	0.57
DP2	890	600	15.9	454	770	19.3	0.23	0.59
DP3	850	600	13.4	432	698	21.2	0.25	0.62
DP4	850	560	13.7	439	720	19.4	0.24	0.61
Cu–P–Cr–Ni–Mo	–	–	–	399	561	36.4	0.14	0.71
09CuPCrNi	–	–	–	397	518	36.3	0.14	0.77

T_f finish-rolling temperature; T_c coiling temperature; *MVF* second phase volume fraction

when the strip cools to the coiling temperature, and the volume of the second phase is more.

Mechanical properties of hot-rolled DP weathering steel Cu–P–Cr–Ni–Mo

Table 4 presents the mechanical properties of the four DP steels Cu–P–Cr–Ni–Mo as well as weathering steel Cu–P–Cr–Ni–Mo and 09CuPCrNi with ferrite–pearlite. Weathering steel Cu–P–Cr–Ni–Mo and 09CuPCrNi with ferrite–pearlite are similar in mechanical property, except that the tensile strength of Cu–P–Cr–Ni–Mo is higher. Comparison of the mechanical properties of the weathering steel Cu–P–Cr–Ni–Mo with any of the four DP steels shows definite changes in strength, elongations, work hardening exponent, and ratio of yield strength to tensile strength. The tensile strength of DP steels is increased 24.4–37.2% by hot-rolling DP treatment but remains essentially 700 MPa with a tendency to increase at the higher finish rolling temperature. The yield strength of the four DP steels changes in a narrow range from 423 to 454 MPa. The tensile strength increased more and the yield strength increased relatively less resulting in the ratio of yield strength to tensile strength decrease obviously. Compared with weathering steel Cu–P–Cr–Ni–Mo, the total elongation is decreased about 44% but remains essentially constant with a value of 20%. For the tensile strength of 700 MPa, the elongation value is superior. From the data in Table 4, it can be seen that the work hardening exponent value is increased substantially.

The mechanical properties of DP weathering steels Cu–P–Cr–Ni–Mo shows that it has typical mechanical properties of DP steels as low $\sigma_{0.2}/\sigma_b$ ratios ($\leq$0.62), high initial work hardening rate, the superior elongation for a given tensile strength.

Corrosion resistant property of hot-rolled DP weathering steel Cu–P–Cr–Ni–Mo

The corrosion rates (mm/a) in salt spray for the samples of weathering steel 09CuPCrNi and Cu–P–Cr–Ni–Mo and the samples of DP steels Cu–P–Cr–Ni–Mo were given in Table 5. It is found that weathering steel Cu–P–Cr–Ni–Mo exhibited a superior corrosion resistance over weathering steel 09CuPCrNi, as indicated by a considerable decrease in corrosion rate (mm/a). For the cycle of 48 and 120 h, the corrosion rates of DP weathering steel Cu–P–Cr–Ni–Mo decreased 18.3–22.2% and 6.67–12.7%, respectively. Weathering steel Cu–P–Cr–Ni–Mo is developed by adding about 0.41 wt% molybdenum to weathering steel 09CuPCrNi. It has been widely reported in studies on atmospheric corrosion that the addition of Mo increased the surface activity and promoted the generation of positive defects, but suppressed the formation of negative effects at the interfaces. As a result, the addition of Mo could speed up the formation of the passive film of Cr-oxides, and stabilize simultaneously the oxides film. So the corrosion resistance of Mo-bearing weathering steel Cu–P–Cr–Ni–Mo is better than that of weathering steel 09CuPCrNi. For DP steels Cu–P–Cr–Ni–Mo, their corrosion resistance is equivalent

Table 5 Corrosion rates in salt spray tests for weathering steels

Materials	09CuPCrNi	Cu–P–Cr–Ni–Mo	DP2	DP3	DP4
Corrosion rate (mm/a)					
Testing Cycle, 48 h	1.6386	1.3264	1.3382	1.2748	1.3035
Testing Cycle, 120 h	1.3932	1.3205	1.3004	1.2465	1.2106

mm/a The average erosion depth (mm) in unit time of 1 year (a) to that of weathering steel Cu–P–Cr–Ni–Mo, but is superior to that of weathering steel 09CuPCrNi too. So the corrosion resistance of weathering steel is mainly dependent on its chemical composition rather than its microstructure.

Weldability of hot-rolled DP weathering steel Cu–P–Cr–Ni–Mo

In order to apply DP steel Cu–P–Cr–Ni–Mo in manufacturing rolling stocks, its weldability must be determined. The broken welded tensile specimens show that the fracture occurs at the heat-affected zone near the weld fusion line. The welding parameters and mechanical properties of weld samples are shown in Table 3. The tensile strengths of the welded specimens of DP2, DP3, and DP4 decrease about 15.5, 7.4, and 11.7% compared with their corresponding base metals, respectively, but they are still about 15.9, 13.4, and 15.2% higher than that of weathering steel Cu–P–Cr–Ni–Mo (561 MPa)(see Table 4). The results indicate that the hot-rolled DP weathering steel Cu–P–Cr–Ni–Mo has superior weldability.

All the results above presented indicate that DP weathering steel Cu–P–Cr–Ni–Mo with excellent comprehensive mechanical properties, formability, corrosion resistance, and weldability can be obtained through directly hot-rolling.

Conclusions

(1) A weathering steel Cu–P–Cr–Ni–Mo has been developed which exhibits a bay between the pearlite and bainite region where the austenite is stabilized which permit the desired DP microstructure to be obtained by directly hot-rolling.

(2) The microstructure of DP weathering steels is composed of randomly distributed island-shaped martensite–austenite particles and the matrix of polygonal ferrite grains.

(3) Hot-rolled DP weathering steels Cu–P–Cr–Ni–Mo exhibits tensile strengths in the range of 698–770 MPa, yield strengths in the range of 423–454 MPa, total elongation in the range of 19.3–21.2%, and ratio of yield to tensile strength between 0.57 and 0.62.

(4) Hot rolled DP weathering steels Cu–P–Cr–Ni–Mo exhibits a superior corrosion resistance over weathering steel 09CuPCrNi.

(5) The weldability of hot-rolled DP weathering steel is excellent. The tensile strengths of the welded specimens of DP weathering steels are about 15.9, 13.4, and 15.2% higher than that of weathering steel Cu–P–Cr–Ni–Mo.

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