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Review

Atmospheric corrosion data of weathering steels. A review

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ABSTRACT

Extensive information on the atmospheric corrosion of weathering steel has been published in the scientific literature. The contribution of the present work is to provide a bibliographic review of the reported information, which mostly concerns the weathering steel ASTM A-242. This review addresses issues such as rust layer stabilisation times, steady-state steel corrosion rates, and situations where the use of unpainted weathering steel is feasible. It also analyses the effect of exposure conditions. Finally it approaches the important matter of predicting the long-term behaviour of weathering steel reviewing the different prediction models published in the literature.

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1. Introduction

Weathering steels (WS), also known as low-alloy steels, are steels with a carbon content of less than 0.2 wt.% to which mainly Cu, Cr, Ni, P, Si and Mn are added as alloying elements to a total of no more than 3–5 wt.% [1]. The enhanced corrosion resistance of WS in relation to mild steel or plain carbon steel (CS) is due to the formation in low aggressive atmospheres of a compact and well-adhering corrosion product layer known as patina.

This definition, however, has not remained unchanged but has evolved as new WS compositions have been developed to achieve improved mechanical properties and/or withstand increasingly aggressive atmospheric conditions from the corrosion point of view, especially in marine environments. The American Society for Testing and Materials (ASTM) has standardised different alloy compositions for WS, from an initial 1.5% total weight of alloying elements added in the first standardised WS A-242 [2], to 5% in the last standardised WS A 709-HPS 100W [3], which is at the limit of the composition of intermediate alloy steels. Table 1 sets out the chemical composition of two commonly used WS [2,4].

The patina on WS not only offers greater corrosion resistance than on mild steel, but is also responsible for its attractive appearance and self-healing abilities. The main applications for WS include civil structures such as bridges and other load-bearing structures, road installations, electricity posts, utility towers, guide rails, ornamental sculptures, façades and roofing.

The literature contains a great deal of information on WS, and there are entire chapters in collective works dedicated to this issue, e.g. [1,5,6]. However, an in-depth bibliographic review on the atmospheric exposure data of WS and a rigorous analysis of the

published information are lacking. The review presented in this paper seeks to fill this gap.

2. Brief historical development

Albrecht and Hall [7] published a complete review on the historical development of WS.

The birth of WS can be traced back to the development of steels containing copper, known as copper steels [8]. In 1910 Buck observed that steel sheets with 0.07% Cu manufactured by US Steel and exposed in three environments of different corrosivities (rural, industrial and marine) showed a 1.5–2% greater atmospheric corrosion resistance than CS [9]. Hence, in 1911 US Steel started to market steel sheets with a certain copper content. Buck subsequently reported that the improvement achieved with Cu concentrations in excess of 0.25% was insignificant, noting that 0.15% Cu provided similar results to 0.25% Cu in most cases [10].

Once this capacity of copper steel became known, further research led to the development of WS and thus to High Strength Low Alloy (HSLA) steels [7]. In the 1920s US Steel produced a new family of HSLA steels intended primarily for the railway industry. Finally, in 1933 US Steel launched the first commercial WS under the brand name USS Cor-Ten steel (Early Cor-Ten steel or Cor-Ten B), a name which reflects the two properties that differentiate it from CS, i.e. its corrosion resistance (Cor); and from a copper steel, i.e. its superior mechanical properties (tensile strength, Ten). This product was claimed to provide a 30% improvement on the mechanical properties of conventional CS, thus reducing the necessary thickness and accordingly the weight of steel to be used for a given set of mechanical requirements [11]. Fig. 1 illustrates the corrosion of these three steels in the industrial atmosphere of Kearny and its evolution with time [12]. Attention is

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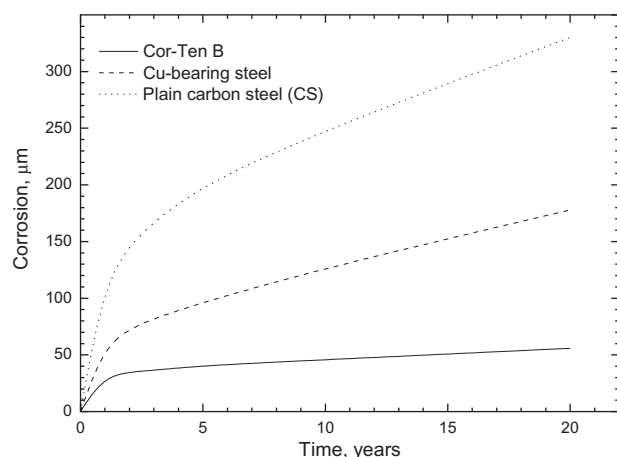


Fig. 1. Atmospheric corrosion of Cor-Ten B steel and its evolution with exposure time in the industrial atmosphere of Kearny [12]. Comparison with Cu-bearing steel and plain carbon steel (CS).

drawn to the lower corrosion experienced by the Early Cor-Ten steel.

Early versions of USS Cor-Ten steels were based on Fe–Cu–Cr–P systems, to which Ni was later added in order to improve corrosion resistance in marine environments. USS Cor-Ten steels presented two specifications, A and B, whose main difference lay in the amount of phosphorus present in their composition. USS Cor-Ten A can be said to be the WS with the highest phosphorus content (0.07–0.15% weight) and USS Cor-Ten B that with the lowest phosphorus content ($\leq 0.04\%$ weight) [13].

Greater knowledge of the role played by the different alloying elements (Cu, Cr, Ni, P, etc.) in the atmospheric behaviour of WS was achieved thanks to two ambitious studies carried out in the United States, one began in 1941 by ASTM Committee A-5 [14] and another began in 1942 by US Steel Co. [12]. In the first, 71 low-alloy steels were exposed to the industrial atmosphere at Bayonne, N.J. and to the marine atmospheres at Block Island, R.I. and at Kure Beach (250 m), N.C. In the second study, 270 different steels were exposed in the following atmospheres: South Bend, Pa (semi-rural), Kearny, N.J. (industrial) and Kure Beach (250 m), N.C. (marine).

The current composition of USS Cor-Ten steels has altered to a certain extent, especially in the case of specification B, with the addition of Ni ($\leq 0.40\%$ Ni), but they all continue to be marketed to the present day [15,16]. In 1941 the first WS was standardised by ASTM specification A-242; a steel that is roughly comparable to USS Cor-Ten A steel. Its main characteristic is its high resistance to atmospheric corrosion, which is approximately 4 times greater than that of CS due to the presence of copper, a high phosphorus content, and in general the presence of nickel (0.50–0.65%). However, it is now somewhat obsolete as a structural steel due to the fact that phosphorus can form iron phosphide (FeP_3) during the welding process, decreasing its weldability and causing the steel to become brittle.

In 1968 ASTM standard A-242 presented two specifications, one with a high phosphorus content ($< 0.15\%$ P) and the other with a

lower phosphorus content ($< 0.04\%$ P). The latter was ultimately replaced by ASTM standard A-588 WS [4] (see Table 1), which is roughly comparable to USS Cor-Ten B steel. This steel possesses less resistance to atmospheric corrosion due to its lower P content, but for this same reason it has better weldability.

Finally, in 1992 the US Federal Highway Administration (FHWA), the American Iron and Steel Institute (AISI) and the US Navy started to develop new improved WS for bridge building, known as High Performance Steels (HPS), and in 1997 the first bridge with HPS-70 W was built in Nebraska [17]. Three basic targets were set to improve the overall quality and manufacturability of the steels used hitherto for bridge construction in the United States [18]: (a) improve weldability, achieved by lowering the carbon, phosphorus and sulphur contents; (b) improve mechanical properties, such as fracture toughness and yield strength, achieved by raising the maximum manganese limit; and (c) maintain the formation of protective rust that characterises WS.

3. Requirements for the formation of protective rust layers on WS

As has been mentioned, the enhanced corrosion resistance of WS is due to the formation of a dense and well-adhering corrosion product layer.

Experiments carried out in 1969 by Schmitt and Gallagher with low alloy steel (Cor-Ten A) indicated that the texture of the oxide layer was dependent upon the washing action of rainwater and the drying action of the sun [19]. Surfaces sheltered from the sun and rain tended to form a loose and non-compact oxide while surfaces openly exposed to the sun and rain produced strongly adherent layers. On north-facing surfaces the protective layer developed somewhat more slowly as a result of receiving less sunlight. Matsushima et al. [20] subsequently studied the role of a large number of environmental and design variables in the behaviour of WS in architectural applications, verifying the decisive influence on the formation of the protective patina of whether or not the metallic surface was exposed to the rain, or whether or not areas where moisture was liable to accumulate were drained. These effects were more intense in atmospheres with higher pollution levels, in which case the protective patina may not fully form.

Extensive research work has thrown light on the requisites for the protective rust layer to form. It is now well accepted that wet/dry cycling is necessary to form a dense and adherent rust layer, with rainwater washing the steel surface well, accumulated moisture draining easily, and a fast drying action (absence of very long wetness times). Structures should be free of interstices, crevices, cavities and other places where water can collect, as corrosion would progress without the formation of a protective patina. It is also not advisable to use bare WS in continuously moist exposure conditions or in marine atmospheres where the protective patina does not form [5,6,21].

Therefore, the ability of weathering type steels to fully develop their anticorrosive action is dependent on the climate and exposure conditions of the metallic surface. It must also be taken into account that a truly protective oxide film may never develop on certain areas, or that their evolution will be excessively slow.

Table 1
Chemical compositions (wt.%) of commonly used WS.

| Weathering steel | C | Si | Mn | P | S | Cu | Cr | Ni | V |
|--------------------------------|-------------|-----------|-------------|-------------|----------|-------------|-----------|-------------|-----------|
| ASTM A-242 (CORTEN A) [2] | ≤ 0.15 | | ≤ 1.00 | ≤ 0.15 | < 0.05 | ≥ 0.20 | | | |
| Typical concentrations | | | | ≤ 0.15 | | 0.25–0.40 | 0.50–0.80 | 0.50–0.65 | |
| ASTM A-588 Gr.A (CORTEN B) [4] | ≤ 0.19 | 0.30–0.65 | 0.80–1.25 | ≤ 0.04 | < 0.05 | 0.25–0.40 | 0.40–0.65 | ≤ 0.40 | 0.02–0.10 |
| Typical concentrations | | | | ≤ 0.04 | | 0.30–0.40 | 0.60–1.00 | 0.02–0.30 | |

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