Alloy development of corrosion-resistant rail steel

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Development of novel rail steel with improved corrosion performance, compared to the standard rail steel used by the Indian Railways is reported. Specific problems related to corrosion of rails, especially under Indian conditions have been addressed. The significance of crevice corrosion at the rail foot locations under the liners of the rail fastening system has been particularly emphasized, with special reference to corrosion caused by discharge from the toilets. The possible methods to combat corrosion of in-service and new rails have been highlighted. Alloy development of corrosion-resistant rail has been elucidated by considering the effect of microalloying elements on the corrosion behaviour and mechanical properties of rail steel. The superior crevice corrosion resistance of the novel Cr–Cu–Ni rail compared to the standard C–Mn rail has been verified. The relevance of academia–industry–user collaborative research activities has been brought out in the present study.

Keywords: Alloy development, crevice corrosion, microalloying, rail steel.

LARGE funds are invested to upgrade and maintain the railway track system in India because of its importance in the transportation system of the country. One of the significant aspects of railway track maintenance is the detection of corrosion of rails and replacement of the corroded rails. Corrosion of rails causes huge economic loss because of frequent rail replacements. Further, rail failures due to corrosion affect the safety of the commuters and disturb normal traffic.

The economic cost due to corrosion of rails is significant. According to the Indian Permanent Way specification, the normal C–Mn rail is expected to have a life of 800 gross million tonnes (GMT), which works to approximately 12–13 years under normal traffic conditions in India[1]. It has been estimated that corrosion reduces the life of C–Mn steel-based rail to nearly half its expected life[2] (A. Jain and P. Funkwal, unpublished). An analysis of rail renewal in India for 2006–2007 (A. Jain and P. Funkwal, unpublished) indicates that only 32% of the replacement of rails took place after completion of normal expected life of the rails. Data show that 37% of the rails undergo replacement due to corrosion before their estimated service life, whereas only 16% of the rail replacement is due to wear and 15% due to rail-weld failure (A. Jain and P. Funkwal, unpublished).

Modern rails are normally eutectoid steels, i.e. high carbon steels containing about 0.70–0.80 wt% carbon. These steels possess a fully pearlitic microstructure, which provides a good combination of strength, hardness and ductility. However, the presence of a high amount of cementite in pearlite renders the structure susceptible to corrosion[3].

This article highlights the recent rail steel development activities focused on corrosion prevention of rails for the Indian railways, undertaken as a academia–industry–user (IIT Kanpur–Steel Authority of India (SAIL)–Indian Railways) collaborative research programme, to develop a novel rail steel of relatively improved corrosion performance than the standard rail steel currently in use. Under the aegis of the Technology Mission for Railway Safety (TMRS), initiated by the Ministry of Railways, the three institutions were brought together to find a solution to the acute corrosion problem faced by Indian Railways. The research team from IIT Kanpur was instrumental in planning the rail steel compositions and was responsible for carrying out experimental studies. The work was completed with additional efforts put together by the industrial partner, Bhilai Steel Plant (SAIL), which was responsible for manufacturing the rail steel plates on an experimental basis as well as manufacturing the actual novel corrosion-resistant rail.

In this context, the different forms of corrosion that are noted in rails and the rail fastening system, especially under Indian conditions, will be first considered in this article. Some relevant experimental details related to corrosion performance of actual rail samples will also be provided.

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Rail system in India

The Indian railway network spans over 65,000 km, one of the largest rail networks in the world. The composition of a typical rail is 0.71 C–1.04 Mn, usually called as C–Mn rail steel. It is essentially a wear-resisting grade rail, according to the Indian Railways specification[4]. From a strength perspective (ultimate tensile strength of 880 MPa or 90 kg/mm^2), the C–Mn rail is popularly known as 90 UTS rail or Grade 880 rail.

The second component of the rail track is the pre-reinforced concrete sleeper. The heavier weight of concrete sleepers provides more stability to the entire track structure[5]. A grooved rubber pad (made of natural rubber, styrene butadiene or poly butadiene rubber) is placed between the rail and the sleeper. This provides insulation, absorbs vibrations and impact, and also increases the coefficient of friction between the rail and the sleeper[6].

The third component is the rail-fastening system that is used to fasten the rails to the sleepers. Modern fasteners are elastic fastenings called elastic rail clips (ERCs) which allow for dampening of the vibrations. A spheroidal graphite (SG) cast iron insert is cast inside the sleeper. The leg of the ERC is then inserted in the SG cast iron insert. The ERC is made of silico-manganese spring steel[7]. A linear is placed between ERC and the rail. The liner prevents the rail foot from getting damaged due to impact from the ERC. The liners used by the Indian Railways are either made of mild steel or glass-filled nylon (GFN). GFN liner is increasingly being used in electrified rails to provide insulation due to its non-conducting nature[8]. The important location between the liner and rail foot is prone to a dangerous form of localized corrosion known as crevice corrosion. It is important to understand the forms of corrosion that reduce the life of rails and the related causes.

Form of corrosion in Indian rails

The most common form of corrosion of rails is atmospheric corrosion, resulting from the wetting and drying process. The atmospheric corrosion of rails results in uniform corrosion. Corrosion will be more severe for longer moisture residence time and frequent wetting and drying. Uniform corrosion will be aggravated in the presence of chloride ions, because they destabilize the protective rusts on the surface[9]. For this reason, rails laid near coastal regions are more prone to atmospheric corrosion, warranting more frequent replacement than rails in a dry climate.

Of far more importance, from both economic and safety perspectives, is the enhanced corrosion that takes place at certain localized locations. There are two origins for the occurrence of localized corrosion in Indian rails.

The first cause is due to leakage of current in electrified railway systems[10]. Intense corrosion attack takes place at the location where the electrons leave (or positive current enters) the track. This is known as stray current corrosion. This can be usually solved by proper design of the railway electrification system. Therefore, this problem is related more to design than material aspects.

The second problem is localized corrosion under the liners, leading to thinning of the rail foot under the liners. The end result is premature failure of the rails, which is a great safety concern. Intense corrosion takes place at these locations (i.e. under the liner) due to collection of moisture from the atmosphere and discharge from the open lavatories of the Indian coaches. The form of corrosion that is noted below the metal liner is commonly referred to as crevice corrosion. The region where oxygen is depleted (i.e. inside the crevice) becomes anodic with respect to the rest of the exposed material. This leads to an intense attack at the crevice location. The process is autocatalytic and more importantly, the attack is not easily visible to the naked eye. Crevice corrosion is accelerated in the presence of chloride ions, which are present in environments near the sea coast as well as in discharge from the toilets of passenger trains.

Combating corrosion

Corrosion of rails needs to be combated. Corrosion prevention methods are required for the two forms of corrosion (described above) that affect Indian rails.

Combating crevice corrosion at the liner location is difficult. The simple corrosion control philosophy, in this case, will be to apply a protective coating on the surface so that the environment will not flow into the crevice. With this aim, extensive field trials were conducted by the Indian Railways at a corrosion-prone location near Visakhapatnam to check the efficacy of different coatings. Polymeric coatings were not effective due to their degradation in the atmospheric environment[11].

The field trials further revealed that the best performance was noted in the case of rails that were coated with zinc. Protection is offered by the zinc coating which acts as a barrier and also as a sacrificial anode (cathodic protection). Cold-sprayed zinc coatings can be done quite easily in the field with minimum heavy-duty equipment. However, it may not be possible to actually implement the process in field due to practical problems. Moreover, the process is expensive.

A different way of approaching this problem is by developing corrosion-resistant rails of new chemistry that will resist corrosion better than the rail steel currently in use.

Development of novel rail compositions

The basic philosophy underlying alloying addition to the existing rail steel composition is that the element will induce passivity in iron. Further, it is obvious that one has to use a lower amount of alloying elements, as otherwise they will drastically alter the mechanical properties of the rail steel. Alloying elements like Cu, Si, Ni, Mo and Cr are normally added to rail steel to improve the mechanical properties of rails. Interestingly, these elements are also known to induce passivity in iron[12–15].

Low amounts of Cu, Cr, Mo, Si and Ni alloying additions are effective where the surface is dried easily by sunlight, after periodic wetting due to rain or dew[9,16]. The excellent resistance to atmospheric corrosion offered by phosphorus in iron, as exemplified by the 1600-year-old Delhi Iron Pillar[17], is a case in point. Therefore, the idea of microalloying was pursued in developing the corrosion-resistant rail.

Microalloying with Cu and Mo was already experimented by SAIL earlier[18,19]. A novel rail steel with these additions was developed by SAIL[18]. The philosophy of development of the Cu–Mo rail steel has been outlined elsewhere[18]. The typical composition of Cu–Mo steel is 0.69 C–0.24 Cu–0.18 Mo. This rail steel was subject to field trials near Visakhapatanam. Srikanth *et al.*[18] reported that visual examination of the Cu–Mo rails after 14 months of service at Visakhapatnam showed improved performance compared to C–Mn rail steel. The corrosion-resistant nature of rust was due to the formation of protective magnetite on Cu–Mo rails[19].

However, the high cost of Mo is an economic disadvantage for the large-scale production of Cu–Mo rails[20]. The main reason for the high cost of Mo is the meagre resources of its ore. There was, therefore, a need to seek out other alternatives, and the present study was undertaken with this aim in mind.

In a detailed study, different combinations of minor alloying elements were added to determine the synergistic effect of these elements on the corrosion behaviour of rail steel[21]. It was important to add the optimum amount of these microalloying elements, such that they remain in solid solution and provide corrosion-resistance. At the same time, the effect of these alloying additions on the mechanical properties and processing of rails had also to be considered in the design of compositions. The rationale of arriving at these chemical compositions is discussed elsewhere[21].

Corrosion studies of experimental rail steel: a research summary

The compositions of the experimental rail steel plates (Cu–Si, Cu–Ni, Cr–Cu–Ni and Cr–Cu–Ni–Si) and the compositions of C–Mn, Cu–Mo, Cr–Mn rail steels are given in Table 1. The rail steel plates were processed at the Research and Development Centre for Iron and Steel, Ranchi, using the same rolling parameters as used in the processing of rails at Bhilai Steel Plant.

A wide variety of tests were performed to assess the performance of the novel rail compositions, in particular the localized corrosion resistance. It was noted that all the novel compositions exhibited a pearlitic structure and that most of them possessed the required mechanical properties according to the IRS-T-12 specification[22]. The corrosion behaviour of the rail samples was evaluated using techniques like the immersion method, linear polarization method, Tafel extrapolation method and electrochemical impedance spectroscopy (EIS)[23,24]. The rates of corrosion of all the alloys were similar under complete immersion condition and therefore one could not judge the effectiveness of the alloying addition[23]. Under alternate wetting and drying condition, EIS studies and rust characterization revealed that the Cr–Cu–Ni (named as NCC) steel showed the best performance[24]. In addition, fretting wear studies also indicated the superior resistance of this composition compared to the other compositions[25]. In view of the improved corrosion performance, the Cr–Cu–Ni composition was recommended for trial rail manufacture.

Manufacture of corrosion-resistant rails

Based on the recommendation, 120 t of Cr–Cu–Ni rails were processed at Bhilai Steel Plant in June 2007 and 50 t were welded and laid over a 0.5 km track in the Vijayawada–Gudur section. Another 500 t of these rails has since been processed and will be laid in the East Coast Railways. Further, the Cr–Cu–Ni rail composition has been recently incorporated in the Indian rail standard IRS-T12 specification. The Indian Railways has also requested SAIL to process 10,000 t of Cr–Cu–Ni rail steel for use in corrosion-prone areas.

Crevice corrosion and general corrosion studies of corrosion-resistant rails

The Cr–Cu–Ni rails laid in the corrosion-prone areas are presently being evaluated under field conditions. At the same time, samples from actual Cr–Cu–Ni, C–Mn and Cu–Mo rails were evaluated specially for their crevice corrosion resistance using the standard ASTM G78 method. Flat, rectangular-shaped specimens of dimension $50 \times 50 \times 10$ mm with a 10 mm diameter hole at the centre were cut from the foot of each rail. The surfaces were mechanically polished progressively to 600-grit level. The immersion test was carried out using the crevice assembly, as shown in Figure 1. Two grooved washers were pressed onto the specimen using Ti nuts and bolts. In this manner; 20 small crevice sites were formed on each side of the specimen. The assembly was immersed in a solution of 3.5% NaCl + 3.5% $FeCl_3$ solution at ambient temperature (~ 30°C) for 30 days. After exposure of the materials, the surfaces were characterized for the extent of localized

Table 1. Chemical composition of C–Mn, Cu–Mo and the four new rail steels

Sample	C	Mn	Cu	Mo	Cr	Ni	Si	S	P
C–Mn	0.71	1.04	–	–	–	–	0.21	0.013	0.022
Cu–Mo	0.69	1.16	0.24	0.18	–	–	0.19	0.022	0.024
Cu–Si	0.60	1.20	0.35	–	–	–	0.66	0.024	0.027
Cu–Ni	0.63	1.02	0.41	–	–	0.20	0.31	0.020	0.028
Cr–Cu–Ni	0.71	1.15	0.40	–	0.59	0.20	0.35	0.026	0.027
Cr–Cu–Ni–Si	0.70	1.09	0.39	–	0.53	0.20	0.56	0.023	0.027

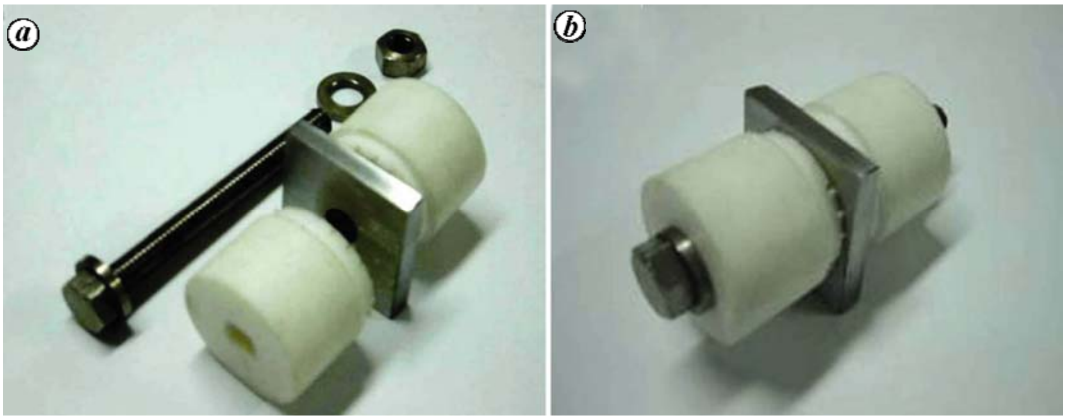

Figure 1. Arrangement for conducting crevice corrosion test according to ASTM G-78: ***a***, Unassembled components and ***b***, Assembled condition.

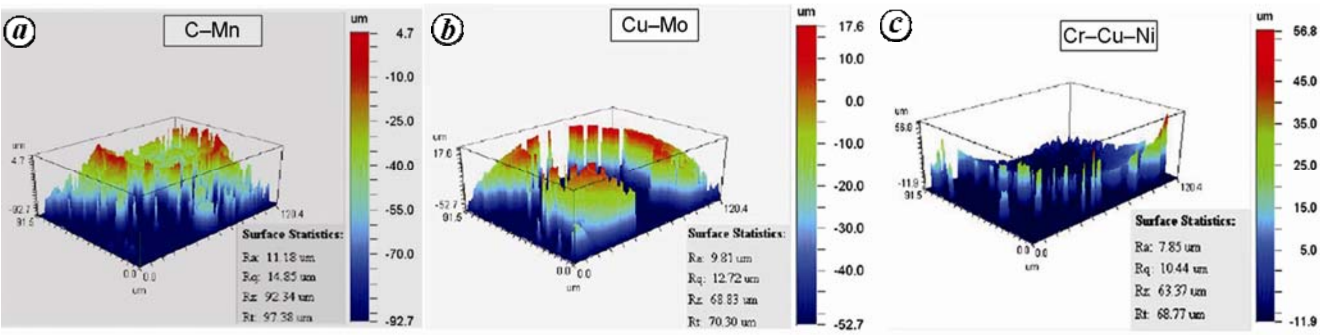

Figure 2. Typical results from profilometer analysis at the starting portion of the crevice (location 1). ***a***, C–Mn steel sample; ***b***, Cu–Mo and ***c***, Cr–Cu–Ni rail steel sample on immersion in 3.5% NaCl + 3.5% $FeCl_3$ solution after 30 days.

corrosion attack. Detailed observation by scanning electron microscopy (SEM) confirmed that the extent of crevice corrosion was the least in case of Cr–Cu–Ni.

The depth of corrosion attack at the crevices was evaluated using Optical Laser Surface Profilometer (VEECO NT 1100). Since localized corrosion at the location under the liner leads to removal of material, this will be indicated by the roughness of the surface at these locations. The higher degree of attack results in a rougher surface. In view of this, different roughness parameters were obtained at three locations in the crevice, namely at the beginning of the crevice mouth (location 1), between the mouth and centre (location 2) and at the centre of the crevice (location 3). Figure 2 shows the surface profilometer result for the rail steel samples from location 2. The average surface roughness values at the three locations are summarized in Table 2. It can be noted that the attack was more intense at the start of the crevice for each material (i.e. higher surface roughness). More important, the crevice corrosion attack in the case of Cr–Cu–Ni rail steel was lower compared to the other rail steels, thereby confirming its superior performance under crevice corrosion conditions. Therefore, evaluation of newly developed rail steel (Cr–Cu–Ni) indicates that it withstands localized corrosion to a better extent than the other rail steels.

The general corrosion behaviour of the rails were also studied and assessed. The C–Mn, Cu–Mo and Cr–Cu–Ni

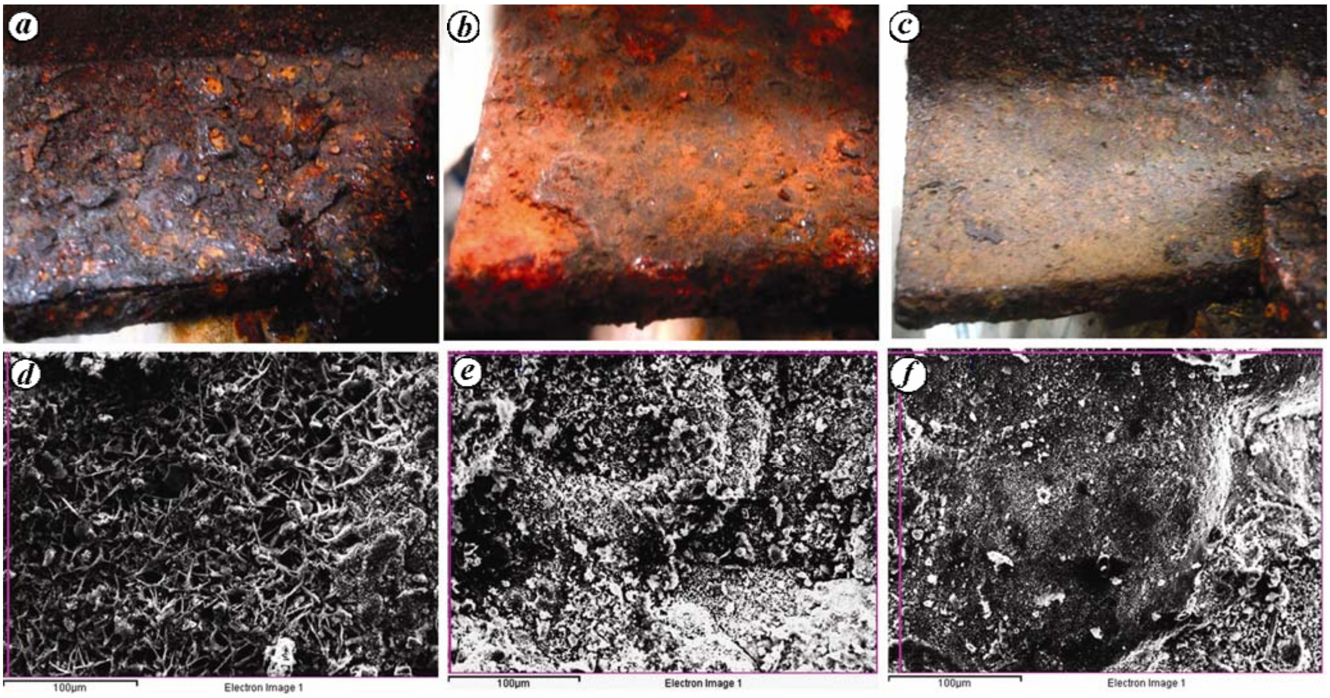

Figure 3. Macro images of foot portion of rail steel: ***a***, C–Mn; ***b***, Cu–Mo and ***c***, Cr–Cu–Ni and corresponding microscopic features (observed by SEM) of outer rust on the rail steels. ***d–f***, After six months of salt fog exposure showing the lower rusting and compact rust formation in the case of Cr–Cu–Ni rail steel.

Table 2. Average surface roughness (μm) at three locations on the crevice created in rail steels after immersion in 3.5% NaCl + 3.5% $FeCl_3$ solution after 30 days of immersion

	Location		
Metal	3	2	1
C–Mn	3.87	3.43	12.41
Cu–Mo	2.61	2.73	9.70
Cr–Cu–Ni	2.09	2.47	7.85

rails, with the entire assembly (clamped rail along with concrete base) were exposed to cyclic fog chamber (ATLAS CCX 2000, Germany) for six months and subjected to alternate salt fog exposure for the duration of 2 h and drying condition for the rest of the day (~ 22 h). A 3.5 wt% NaCl solution was used to create salt fog in the chamber. The outer loose rust and inner adherent rust were collected separately from the foot portion of the rail, where corrosion was more dominant and critical. The outer and inner rust were separately ground to fine powder and subjected to characterization techniques such as XRD, FTIR, Mössbauer spectroscopy and SEM analysis[26]. The enhanced corrosion protection of Cr–Cu–Ni rail compared to the C–Mn and Cu–Mo rail steel was correlated to the higher amount of $Fe_{3-x}O_4$ (magnetite) and presence of δ-FeOOH (goethite) in the rust. Photographs of the rails along with the SEM photomicrographs (Figure 3), clearly indicate that the rust formed on the Cr–Cu–Ni rail was more compact and therefore protective in nature.

In conclusion, the studies performed on the novel rail steel show that it has superior corrosion-resistant nature. The studies provide an insight into the enhanced life of the novel rail compared to the conventional rail, which will eventually result in significant economic savings.

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