Evolution of manganese crossings: an innovative Mn-Mo steel for crossings

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Summary

The trackside equipment constitutes at the same time keys for the robustness and performance, and also an important railway asset which should be maintained. These maintenance tasks (current maintenance and renewal) are necessary to satisfy the increasing demands on track safety and improved railway network performance, commensurate with the growing traffic density.

The lifespan of switch frog or diamonds is an important subject for the control of maintenance costs, in particular within the framework of switches installed on concrete supports. Seeking options for improving the durability conditions in parallel with reducing the maintenance costs, work has been carried out jointly with VOSSLOH COGIFER and TATA Steel to improve the performance of the frogs.

Austenitic manganese base material (AMS) has been successfully used for cast railway crossings for some considerable time. This success has been supported by significant improvements in the design, casting technology, mould design, and associated foundry and machining processes. Furthermore, the relatively recent use of explosive hardening has enabled higher levels of surface hardness to be achieved, resulting in enhanced resistance to wear and plastic deformation.

The challenges associated with flash butt welding of such crossings have also been overcome through the use of stainless steel inserts and precise control of the welding process. However, in view of the growing demands imposed by the complex rail wheel contact conditions under higher axle loads and vehicle speeds, further challenges remain to be overcome to ensure the continued widespread use of cast manganese crossings.

The development of a novel, wrought steel for railway crossing applications forms the second part of the present paper. The wrought steel developed by TATA STEEL and Vossloh COGIFER presents a reliable alternative to cast austenitic manganese, enabling the design of crossings with improved resistance to wear, plastic deformation and rolling contact fatigue, combined with enhanced weldability.
1. **Manganese frogs – Return of experience**

A common problem for all the infrastructure managers is the formalization of the economic link between the current maintenance costs and the renewal volumes. The maintenance optimization is today, more than ever, a major concern of the railways. The Infrastructure Management have sought a future maintenance need estimation method for current tracks and switches.

An extensive probabilistic approach study has been carried out on the French railway network to evaluate and describe the failure rate of manganese frogs in particular [1].

The study has demonstrated the technology to be a significant driver in terms of the frog performance: fish-plated and welded frogs show differences in their ability to adapt to the environment.

It has been shown, for instance, that the failure rate of welded manganese frogs used on UIC group 3 lines can be described by:

\[
\lambda(t) = \frac{\beta}{\eta} \left( \frac{t}{\eta} \right)^{\beta - 1}
\]

with \(\beta = 1.8\) and \(\eta = 19\), while \(\beta = 1.3\) and \(\eta = 18\) for fish-plated frogs.

Exploded manganese frogs are not used on the French network; such frogs are, however, currently utilised in heavy haul track for which the axle load is up to 40 t at 80 km/h, compared to typically 22.5 - 25 t on the French network where vehicular speeds can be as high as 220 km/h.

It is suspected that maintenance conditions and component life will be significantly affected by the axle load and traffic speed. Unfortunately, besides the French study, no data are available to express the failure rate in relation to load and speed. Nevertheless, a common value frequently reported for the life time of a manganese frog is generally 200 mgt, before repair or replacement is necessary.

The above figure is obviously not especially useful as it does not describe the relationship between traffic condition (load, speed, frequency) and track quality. It should also be borne in mind that the expected quality of the geometry of a passenger track operating at 220 km/h may be significantly different than a similar track operating at 80 km/h.

In this regard, the capability of the frog itself in maintaining the desired profile becomes a significant parameter in dictating the life of the component; manganese on the other hand, while crushing and wearing with accumulated tonnage, modifies the load transfer characteristics as a result of this deformation, thereby resulting in a deterioration in ride quality and, in turn, increasing the dynamic loads, thereby initiating the cycle of self-deterioration, unless remedial repair is carried out to restore the profile geometry.

For many years, maintenance teams have known very well that manganese will suffer from wear and crush; maintenance rules and regimes have adapted to this reality. The well-known property of manganese crossings to increase surface hardness under service loading conditions via the metallurgical process of work hardening, from typically 200 HB up to 500 HB after the accumulation of traffic tonnage, must be appreciated along with the change in geometry; thus while hardening, dynamic load increases.

The continued search for alternative materials showing enhanced wear and crushing performance is therefore a key issue in prolonging crossing life.

The Mn-Mo material has sought to address not only the above issues, but also two other major concerns of manganese crossings, i.e. their poor weldability and problems with inspection of internal soundness related to their coarse-grained cast microstructure.
2. The Mn-Mo concept

The principal objective in the search for an alternative crossing steel was one that addressed specifically the disadvantages associated with existing cast manganese (austenitic manganese steel, AMS) crossings, while still delivering the performance benefits expected of a crossing steel in the most arduous of track environments. In recent years, Tata Steel has considered a number of steel compositions which, although offering attractive property combinations, have always been found wanting in some respect, be it difficulties in their processing, some property deficiency or the ease of welding. Not least, they have proved undesirably, or in some cases prohibitively, expensive.

Existing cast AMS crossings rely on a fully austenitic microstructure for their recognised in-service performance attributes. The compositional design of the Mn-Mo steel has instead sought to achieve excellent resistance to rolling contact fatigue (RCF) and wear by way of a fine, mixed microstructure of retained austenite, epsilon-martensite and ‘conventional’ lath martensite. The presence of retained austenite ensures the necessary rapid work hardening of the Mn-Mo steel but crucially, the presence of low carbon martensite provides additional hardness in the as-manufactured condition (typically 350 HB) and a higher proof stress than in cast AMS. Furthermore, and probably more importantly, the low carbon content (~0.06%), together with the generally higher integrity of a rolled product, facilitates repair welding of the Mn-Mo steel.

2.1 - Laboratory developments

The initial phase of the development programme involved the manufacture of a series of 60 kg vacuum melted laboratory ingots that were subsequently rolled to 30 mm thick plate and thereafter naturally cooled in air to room temperature. Evaluation of the laboratory plates at Tata Steel’s main rail research laboratory in the UK involved tensile, Charpy and fracture toughness, rolling contact fatigue and wear testing, metallographic studies and cyclic fatigue assessments. The main compositional elements studied were carbon, manganese and molybdenum. Figure 1 below shows the binary Fe-C phase diagram at 13%Mn, superimposed on which is a blue line indicating the nominal composition of the Mn-Mo steels. The transformation temperatures for the favoured Mn-Mo composition are given in Table 1.

Nominal composition:
- 0.06C-0.25Si-12.5Mn-1.5Mo
- Water-quenched: γ + α’ + ε
- Slowly-cooled: γ +α’ + ε + (α + C)

<table>
<thead>
<tr>
<th>Ac1 (°C)</th>
<th>Ac3 (°C)</th>
<th>Cooling rate (°C/s)</th>
<th>Ms (°C)</th>
<th>Ms (°C)</th>
</tr>
</thead>
<tbody>
<tr>
<td>480</td>
<td>761</td>
<td>0.08</td>
<td>105</td>
<td>~100</td>
</tr>
</tbody>
</table>

Figure 1: Binary phase diagram at 13% Mn

Table 1: Transformation temperatures
2.2 - Composition optimisation for the manufacture of a rolled Mn-Mo railway crossing prototype

Mechanical properties for the laboratory Mn-Mo steels are given in Table 2 below.

<table>
<thead>
<tr>
<th>QA</th>
<th>Composition</th>
<th>Heat treatment</th>
<th>Elongation (%)</th>
<th>0.2%PS (MPa)</th>
<th>UTS (MPa)</th>
<th>Charpy toughness (J)</th>
<th>Hardness HV30</th>
<th>Wear (mg/m of slip)</th>
</tr>
</thead>
<tbody>
<tr>
<td>8JG24A</td>
<td>0.06C-12.01Mn-0.53Mo</td>
<td>As-rolled</td>
<td>4.3</td>
<td>289</td>
<td>1180</td>
<td>21</td>
<td>378</td>
<td>4.37</td>
</tr>
<tr>
<td>8JG25A</td>
<td>0.12C-12.61Mn-0.53Mo</td>
<td>As-rolled</td>
<td>3.5</td>
<td>203</td>
<td>924</td>
<td>37</td>
<td>379</td>
<td>2.81</td>
</tr>
<tr>
<td>10JF15*</td>
<td>0.055C-12.87Mn-2.06Mo</td>
<td>As-rolled</td>
<td>4.3</td>
<td>230</td>
<td>996</td>
<td>74</td>
<td>348</td>
<td>3.7</td>
</tr>
<tr>
<td>10JF16*</td>
<td>0.053C-12.82Mn-2.34Mo</td>
<td>As-rolled</td>
<td>5.0</td>
<td>356</td>
<td>1149</td>
<td>78</td>
<td>343</td>
<td>4.6</td>
</tr>
<tr>
<td>10JF17</td>
<td>0.08C-12.60Mn-1.53Mo</td>
<td>As-rolled</td>
<td>4.2</td>
<td>229</td>
<td>995</td>
<td>80</td>
<td>361</td>
<td>3.3</td>
</tr>
<tr>
<td>10JF18</td>
<td>0.047C-12.47Mn-2.51Mo</td>
<td>As-rolled</td>
<td>7.8</td>
<td>218</td>
<td>1309</td>
<td>92</td>
<td>384</td>
<td>4.2</td>
</tr>
</tbody>
</table>

Table 2: Key mechanical properties of laboratory Mn-Mo steels

Hardness levels achieved in the laboratory Mn-Mo steels in the range 335-385 HV were significantly higher than those of AMS of typically 210 HV. Attractive levels of 0.2%PS and UTS were also achieved. Variability in some of the 0.2%PS and UTS values and the relatively modest elongation levels in the range 3.5-7.8% were related to the relatively poor cleanliness in the laboratory steels. By virtue of its strong tendency for stabilising austenite, small variations in carbon were found to have an appreciable effect on the microstructure and properties with manganese less so. Furthermore, an increase in carbon content increases the risk of grain boundary embrittlement in Mn-Mo steels due to the formation of carbide networks, and for this reason, C levels were limited to 0.12% which in combination with Mn levels of ~12.5% gave appropriate amounts of retained austenite. Minimum Mo levels of 1.5% were required to facilitate the scavenging of phosphorus, thereby limiting the risk of embrittlement by P at the grain boundaries and ensuring attractive room temperature Charpy toughness levels of ~75 J. Water quenching trials involving reheating to 950 °C showed little improvement in impact toughness and elongation, indicating levels of carbide precipitation during slow cooling of the Mn-Mo steel to be minimal. The results of laboratory twin disc rolling contact wear tests showed the majority of the steels in Table 2 (and other laboratory compositions) to have exceptionally low wear rates. The significantly poorer wear resistance of compositions containing less than 11% Mn was attributable to their fully martensitic microstructures.

2.3 - Pilot-sized (5 t) ingot casts

In view of the attractive property combinations achieved in the 60 kg laboratory melts, three ~5 t ingots were manufactured at the TTC pilot plant in the UK and rolled to an appropriate rectangular section to facilitate machining to the finished crossing design at Vossloh Cogifer in France. Rolling of the ingots was carried out at the rolling facility at the Stocksbridge plant within Tata Steel in the UK and cooled naturally in air to room temperature. The 3rd ingot was not subjected to an ‘annealing’ (stress relieving) treatment following rolling in an effort to increase toughness. The composition, rolled profile and mechanical properties of the three casts are given in Table 3.
<table>
<thead>
<tr>
<th>Identity</th>
<th>Composition (wt%)</th>
<th>Dimensions (mm)</th>
<th>Reduction ratio</th>
<th>0.2%PS (MPa)</th>
<th>UTS (MPa)</th>
<th>El (%)</th>
<th>Charpy (J)</th>
<th>HV30</th>
</tr>
</thead>
<tbody>
<tr>
<td>1st ingot (10JF41)</td>
<td>C 0.06</td>
<td>Si 0.26</td>
<td>Mn 12.33</td>
<td>Mo 1.39</td>
<td>255 x 175</td>
<td>5.38</td>
<td>238</td>
<td>1227</td>
</tr>
<tr>
<td>2nd ingot (12JF17D)</td>
<td>C 0.11</td>
<td>Si 0.33</td>
<td>Mn 12.50</td>
<td>Mo 1.62</td>
<td>355 x 200</td>
<td>3.38</td>
<td>224</td>
<td>1058</td>
</tr>
<tr>
<td>3rd ingot* (13JF33)</td>
<td>C 0.05</td>
<td>Si 0.31</td>
<td>Mn 11.92</td>
<td>Mo 1.48</td>
<td>430 x 203</td>
<td>3.47</td>
<td>275</td>
<td>961</td>
</tr>
<tr>
<td>3rd ingot (13JF33)</td>
<td>C 0.05</td>
<td>Si 0.31</td>
<td>Mn 11.92</td>
<td>Mo 1.48</td>
<td>430 x 203</td>
<td>3.47</td>
<td>224</td>
<td>1185</td>
</tr>
</tbody>
</table>

All samples ‘annealed’ for 12 h @ 630°C except * and # samples annealed in the laboratory

Table 3 : Mechanical properties of the three pilot-sized 5 t casts

The results show the beneficial effect of an ‘annealing’ treatment owing to a refinement of the microstructure, an increase in the quantity of retained austenite and a reduction in the sensitivity of elongation to inclusions. However, it can lead to carbide formation and slightly lower toughness. The higher proportion of martensite in the as-rolled condition has resulted in very low elongation while relatively poor elongation in the sample from the second ingot was attributed to oxides in the steel (visible on the fracture faces). SEM micrographs showing essentially an intergranular fracture type corresponding to low elongations and a more desirable ductile fracture are shown in Figure 2 (a and b).

![SEM micrograph showing typical microstructures in Mn-Mo steels](image)

Figure 2 (a and b) : Fracture appearance of broken tensile test specimens

![SEM micrograph showing typical microstructures in Mn-Mo steels](image)

Figure 3 : SEM micrograph showing typical microstructures in Mn-Mo steels

Both optical and SEM micrographs, Figure 3, show the complexity of the Mn-Mo steel three-phase microstructure. X-ray diffraction (XRD) confirmed the expected increase in the volume fraction of retained austenite with increasing Mn and C contents, and decrease in hardness with increase in retained austenite.
Fig. 4 (a and b): Laboratory twin disc RCF and wear performance data for Mn-Mo and a variety of rail steels

Of importance is the exceptional resistance to RCF offered by the Mn-Mo steels, as exemplified by the test data in Figure 4 (a). However, also noticeable is the potentially high variability in the performance, for which differences in the proportion of the various microstructural constituents and steel cleanness play significant contributory roles. Also readily apparent is that the Mn-Mo steels confer excellent wear resistance, with only a small variation in performance over the range 320-500 HV, Figure 4 (b).

EBSD studies conducted on twin disc rolling contact fatigue (RCF) test specimens show the majority of the retained austenite and epsilon martensite to have transformed under load to lath martensite to a depth of ~100 μm. Fig. 5 below shows a ‘map’ of the three microstructural constituents beneath the specimen surface.

Surface

Figure 5: EBSD image of a twin disc RCF test specimen to a depth of 100 μm below the surface

2.4 - Advantages of Mn-Mo steel railway crossings

The intensive investigations carried out to date jointly by Tata Steel R&D and Vossloh Cogifer have highlighted a number of advantages offered by as-rolled Mn-Mo steels for railway crossing applications over conventional cast AMS crossings. These are given below:

- As-manufactured hardness and proof stress values are significantly higher than AMS owing to the presence of epsilon and lath martensite in addition to retained austenite. These attributes should result in a reduced need for re-profiling of the crossing nose prior to achieving operating hardness levels
- Mn-Mo crossings provide consistent hardness and properties through the full depth of the crossing compared to the limited hardened and porosity-free depth achieved in explosively hardened cast AMS crossings.

- They have an excellent capacity for rapid work hardening, by virtue of the significant proportion of retained austenite.

- There is no need for water quenching during manufacture owing to the significantly reduced tendency for carbide precipitation of the lower C-containing Mn-Mo composition.

- Mn-Mo steels can be flash butt welded directly to existing pearlitic rail grades (reduced carbide precipitation) without the need for stainless inserts, thus reducing by half the number of welds required and associated failure risk at welds.

- The rolled Mn-Mo material does not have porosity commonly associated with cast products which necessitates the use of careful weld restoration techniques to enhance crossing life. In combination with the improved integrity, the low C content also facilitates the use of in-situ welding techniques to rebuild the surface to further enhance the life of the crossing.

- Owing to it being a rolled product, Mo-Mo crossings permit the use of ultrasonic testing, either in the workshop or in track, to ensure greater control of integrity.

- The manufacturing process route for rolled Mn-Mo crossings allows for significantly enhanced design flexibility, thus eliminating the costs associated with individual patterns and castings.

2.5 - Field test

A field test has been conducted at the Transportation Technology Centre of Pueblo to evaluate the evolution of the wear rate.

The operating conditions were a 39 t axle load with vehicle speeds of typically 80 km/h.

The test was conducted for ~100 mgt comparing a standard explosively-hardened manganese AREMA frog (B) with a Mn-Mo frog (A) of the same design, as shown in figure 6.

Wear and metal flows were recorded by measuring the surface profiles at different locations both in front of and after the crossing toe using a MiniProf™.

Figure 6: Field test in Pueblo
The plot presented in figure 7 shows the wear on the riser, 8” after the point, after 105 mgt of traffic.

The two uppermost curves relate to the Mn-Mo test frog (A) while the lower two curves relate to the standard manganese frog (B).

It is readily apparent that the riser of the standard manganese frog B has suffered significantly more metal flow and exhibits a higher wear rate over the duration of the test compared to that of the Mn-Mo test frog A.

Figure 7: Plot of the riser profile, 8” beyond the point toe

The plots presented in figure 8 below show the area loss at different locations from the toe of the point: -26 and +8” from the frog point.

Figure 8: Loss of material, 26” ahead and 8” beyond the toe of the point

The test data in figures 7 and 8 confirm the wear resistance capability of the new Mn-Mo crossing steel. The data also demonstrates encouraging low crushing properties of the Mn-Mo steel in comparison with that of the exploded manganese crossing. At the same time, the enhanced welding and ultrasonic inspection capabilities of the Mn-Mo steel have been demonstrated.

Unfortunately, the test has been terminated for safety reasons owing to the appearance of cracks within an unloaded part of the test frog. The cause of these cracks remains uncertain but metallurgical investigations are in hand to establish the reasons for their occurrence.
2.6 - Further studies

Further development work within Tata Steel R&D is to proceed via a number of parallel work streams:

- Laboratory investigations will seek to clarify the structure / property / composition relationships
- Specific laboratory studies will aim to determine the mechanical and thermal stability of the retained austenite, optimise the ‘annealing’ treatment and further optimise the steel chemistry
- A 4\textsuperscript{th} ingot (annealed) of the existing Mn-Mo composition (1\textsuperscript{st} ingot) will be manufactured and evaluated in track focusing on precise compositional control and good steel cleanness
- Options will be considered for evaluating feedstock from the smaller 1\textsuperscript{st} ingot rolled blank via an alternative crossing design, e.g. a profiled Mn-Mo V-nose secured to a low C base plate
- A larger ingot will be considered to allow a larger reduction ratio and improved consolidation.

3. Conclusions

A novel Mn-Mo steel has demonstrated exceptional performance attributes that promise to make it an attractive alternative to existing cast manganese crossings for use in the most arduous of track environments. The bespoke alloy composition produces a unique microstructure comprised of typically 50% retained austenite and various proportions of epsilon-martensite and lath martensite in the as-rolled condition conferring exceptional resistance to rolling contact fatigue. This microstructural combination also provides Mn-Mo steel with an excellent capacity for accommodating the high stresses during service, with rapid work hardening under load ensuring excellent wear and batter resistance.

At the same time, the low carbon composition ensures good weldability, allowing it to be flash butt welded directly to existing pearlitic rail steels and facilitating in-situ weld restoration without the debilitating phenomenon of carbide precipitation. Furthermore, as a rolled product, consistent through-profile hardness and properties, ultrasonic testability, no requirement for water quenching during manufacture and crossing design flexibility overcome many of the drawbacks associated with its cast manganese counterpart.

Preliminary field tests have demonstrated attractive service behaviour of the Mn-Mo steel including enhanced wear performance.

In conclusion, the cost effective and weldable, high performance rolled Mn-Mo steel crossing promises to challenge existing cast manganese crossings and other high performance crossing products.
4. References


