Influence of rail material grade on wear and rolling contact fatigue behaviour

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The choice of rail steel used for a particular application has a significant impact on the overall performance and life-cycle cost of the rail. Input cast rail steels, for example those manufactured domestically before the introduction of continuous casting, were often prone to segregation issues developed during the manufacturing process. Consequently, these rails often developed internal defects that not only impacted the life of the rail but also presented a considerable risk to railway operations.

Over the years the rail steel manufacturing process and the quality of material produced has improved significantly, such that steel cleanliness issues are relatively rare in current-generation rails. Further improvements have also been made through alloy design and/or heat treatment (HT) procedures.

With increasing operational demand for higher vehicle loads and greater throughput, particularly in heavy haul and freight operations, there has been a need to develop stronger and more wear and defect resistant rails, in order to minimise rail maintenance costs and maximise asset life.

As a result there has been significant development in so-called “premium” grade rail steels, which generally offer increased strength and resistance to wear and rolling contact fatigue damage. These are all produced using improved hot-rolling and in-line heat treatment procedures, in combination with a range of alloy designs that include increasing carbon levels to as high as 1 per cent.

The resultant microstructures are fully pearlitic, often with subtle differences in carbide morphology (Figure 1) associated with the hot-rolling and in-line heat treatment procedures used by individual manufacturers.

The material properties of these improved hyper-eutectoid steels are compared with other more common rail grades in Table 1. Clearly, the improved strength and wear resistance properties of the hyper-eutectoid grades come at the expense of toughness and ductility (the latter as measured by reduction of area in a standard tensile test).

The results of in-track monitoring under heavy load conditions (1) has shown a significant reduction in wear can be achieved through use of premium grade rail steels. In fact, the average results shown in Figure 2 show rail life for hyper-eutectoid (HE) rail steels to be between 2-3 times that of standard head hardened rail, depending on carbon content.

The influence of material strength on damage at the wheel-rail interface can be examined using the shakedown diagram (Figure 3), which takes into consideration traction or creepage levels at the wheel-rail interface (x-axis), and the maximum contact stress divided by the yield strength of the rail material in shear (y-axis); the latter is designated the shakedown ratio.

Using an example of wheel-rail contact conditions developed within the high rail of a moderate curve under a 30 tonne axle load, Figure 4 shows the shakedown ratio for standard carbon rail is well above the kinematic hardening shakedown limit, hence repeated plastic deformation (ratchetting) is expected to occur, resulting in surface and sub-surface deformation and damage. By using head hardened rail, the shakedown ratio drops to within the elastic shakedown region, where after some initial yielding, the material stabilises and hence behaves more-or-less elastically under subsequent similar loading. Under these conditions, some initial mild deformation may occur. However, cumulative surface and sub-surface deformation is not expected.

If hyper-eutectoid rail was used, Figure 3 shows the shakedown ratio falls below the elastic limit for the material; hence the rail performs elastically and no deformation or damage is expected for subsequent similar loads.

High adhesion/creepage effects introduce severe shear stresses near the rail surface which result in the development of surface-initiated RCF and/or wear (i.e. towards the right-hand side of Figure 3). As the development of RCF surface cracking (which if not controlled through a preventative rail grinding strategy) can impair ultrasonic testing of the rail, the expected reduction in maintenance requirement may not be realised under these conditions.

Wheel-rail profile design and implementation becomes very critical when using harder rail steels. Care must therefore be taken when grinding harder rails to ensure profile and surface finish are completed to within specified tolerances, as the higher strength and reduced ductility of harder steels means the rails are less likely to deform under a lower stress condition (resulting in cracking), should profile or surface anomalies appear. When selecting rail steel grades for particular service conditions, therefore, consideration also needs to be given to the ability of the track maintainer to control surface condition and profile during rail grinding operations in order to obtain the desired benefits.

An additional consideration when selecting rail grades for more demanding service conditions are the rail welding requirements, particularly for flashbutt welding. The range of steel compositions in currently-available high strength and premium rail grades mean that welding conditions (in particular post-weld cooling conditions) can vary from normal air cooling, light or moderate air quenching only, to high-pressure air quenching such as that required for the plain C-Mn heat treated grades. With the increasing use of mobile flashbutt welding equipment for new track construction activities, achieving the required post-weld cooling conditions can sometimes be difficult, thereby increasing the risk of soft welds and increased post weld biter (Figure 4). For such applications, use of a low-alloy heat treated grade which does not require air-quenching of welds should be considered.

Aluminothermic welding procedures are generally more tolerant of differences in rail grades, as the weld position can be selected so as to produce weld hardness levels comparable with the parent rail.