Micromechanical characterisation of Indian rail steel

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Abstract. Railway transport dynamics cause rails in general to experience a time varying rolling contact load to add shear strain to that from traction and normal strain from the axle loads. These loading conditions together with the frictional heat at the contact interface alters the microstructure in the near-surface region of the rails and wheels. This paper presents the hardness and microstructural study of used Indian rail steel to expose the influence of load parameter active at the interface. Samples are prepared from the rail section taken from Dhanbad railway division. The hardness variation along the rail head cross-section and metallurgical variations of the test sample are presented. Microstructural examinations reveal existence of micro cracks near to the rail surface favouring formation of wear debris. Also, the presence of the pro-eutectoid ferrite and cementite phase at the grain boundaries of the pearlitic rail material is observed. The fatigue cracks are found to initiate across the grain boundaries containing the pro-eutectoid ferrite phase. This study will help to develop a better understanding of rolling contact fatigue (RCF) crack initiation and wear debris formation mechanisms on the rails. Thus, these results can be used to improve rail maintenance planning and risk assessments.

1. Introduction

Rails are subjected to severe contact stress, frictional heat and shear stress due to traction load [1]. In addition to this, it also bears dynamic forces transmitted by the wheels rolling on it. All these loading condition deteriorates material condition of the contacting zone and favours rail degradation in terms of wear and rolling contact fatigue [2]. Often rails become unsuitable for rail transport operation due to worn rail profiles, shelling and spalling defects. These defects are the major cause for vibration, noise and commuters discomfort, increased dynamic forces, increased maintenance costs, safety and reliability of railways.

In spite of the use of improved rail steel quality, the increasing demands of higher axle load, increased traffic volume and higher speed introduce increase in rolling contact fatigue defects and undesirable track quality. These irregularities further raise the dynamic forces at the contact zone and in severe condition it may lead to catastrophic rail fracture. Thus, an understanding of material condition at the wheel-rail contact zone are key to improve safety and efficiency of railway transport system.

Most of the rails are of medium-high carbon steels with a pearlitic microstructure. Pearlite steels consist of identically oriented cementite lamellae embedded in a softer ferrite matrix [3]. This type of microstructure induces high strength and improved fatigue and wear resistance suitable for railway applications. The rolling–sliding contact between the surfaces of rail and wheels give rise to severe
plastic deformation and microstructural changes in the vicinity of contact region. Literature [4] indicates the processes of wear and RCF development are associated with the formation of pro-eutectoid ferrite and pro eutectoid cementite at the grain boundaries of the pearlite colonies.

This paper presents the hardness and microstructural variations of used rail steel. The samples are prepared form commonly used 880 UTS rail grade steel of Indian Railway. Changes in the microstructure are observed optically for varying depths and profile locations. Hardness test are also done to expose its ranges across the rail head cross-section. The results are presented in the form of hardness mapping along with metallurgical investigations of the test samples.

2. Experimental Procedure

2.1. Material

The rail used in this work is collected from Dhanbad Railway Division. Material specifications of the considered rails are: 880-60-0 Sail I/2014 for the virgin material and 880-60-0 Sail X/1990 for the used one. The used rail was laid at: 384/14-12 HRE Stn Limit DN GC as a straight track in the year of 1991, under Dhanbad railway division. It carried 802.215 GMT during its service up to the year 2014. The removal of the rail was due to vertical wear of 3 mm and lateral wear of 1 mm was observed at the rail head surface. The chemical composition of this material is tested by EPMA (Electron probe micro analyzer) and the results are shown in Table 1.

Table 1. Chemical composition of used rail steel

|    | Fe  | Mn  | C   | Si  | Al  | Cu  | Cr  | Zn  | Mg  | S   | Ni  |
|----|-----|-----|-----|-----|-----|-----|-----|-----|-----|-----|-----|
|    | 97.7| 1.1 | 0.72| 0.19| 0.09| 0.03| 0.02| 0.02| 0.02| 0.02| 0.01|

2.2. Sample preparation

The samples for the materials’ hardness and microstructural characterization were prepared from both virgin and used rail sections. A cutting plane sample is shown in figure 1. Before microscopic analysis samples were ground, polished with varying diamond suspensions (6, 3, and 1 microns are used here) and etched with Nital solution (2% nitric acid with ethanol) for microstructural examination.

Figure 1 Rail head section sample cutting plane

2.3 Experiments conducted

Hardness profile of the materials were tested in a Tinius Oslen FH-006 Vickers hardness tester with 0.5 kg of load for 10 sec of dwell time. Test sites were predetermined at symmetrically spaced
coordinate locations of the mid plane of the rail head section taken in parallel lines over the face. Corresponding results are given in table 2. Polished and surface treated samples of rail steel were examined under Carl Zeiss Standard Metallurgical Microscope to get the presence of inclusion within the material. Corresponding results are shown in figures 5-9.

3. Result and Discussion

Hardness measure of material provides a qualitative assessment of the material to represent its strength according to bonding formation that directly exposes the possibilities of brittle or ductile crack formation accordingly the low or high wear ability. For the better understanding of variation of hardness of the material, it is measured along vertical as well as lateral directions at different points. Vickers hardness profile of full rail section is presented in figure 2.

![Figure 2. Hardness map of rail section](image)

The observed variation of the HV range from 309 to 287 are averaged over five different samples and its distribution pattern indicate material as a relatively ductile substrate just below the rail head and a harder substrate at the gauge corners of the rail head. Variation of average value of hardness with depth is presented in figure 3 while the variation of hardness in lateral direction (left to right) at each level of depth is presented in figure 4.

![Figure 3. Variation in hardness along the depth](image)

![Figure 4. Variation of hardness in lateral direction](image)
The variation of hardness with depth of the rail head cross-section is found to decrease non-linearly as the depth increases while its variation in lateral direction has a rather a wavy pattern for subsequent horizontal layers of the material from top to bottom and the HV magnitudes reduces from top to bottom nearly maintaining wavy patterns though they are not identical. This softer hardness value favours harder surface material to dissipate much of its stored energy to this softer region. This in turn reduces the propensity of crack initiation. Right most points of each level showing higher value of hardness because these points are nearer to gauge section. This part of the rail is in contact with the wheel flange causing slippage. Due to the slippage occurring at the gauge corner the material there work hardens causing higher hardness.

Microscopic examination of ground and polished specimen is conducted on metallurgical microscope. Different type of inclusion such as sulphide and oxide were found randomly distributed over the cross section. Distribution of inclusions are shown in figure 5. Inclusion density lies well within the acceptable range of 1% to 2%. These inclusions are more susceptible to develop internal cracks causing defects like Tache Ovale or ‘kidney’ rail failure shown in figure 6 [5].

Sample preparation, as stated earlier was polished by diamond paste and then etched with 2% Nital solution. The virgin rail material clearly shows lamellar pearlite structure of alternate plates of cementite in softer matrix of ferrite shown in figure 7. Surface pitting, may have formed by surface corrosion cracking penetrating the layers of material. These are observed in the used rail specimen shown in figure 8.
These pitting points are the most popular micro crack initiation sites. In presence of contact pressure and surface traction along with micro slippage can generate impulsive temperature rises to evolve thermal and mechanical load induced rolling contact fatigue. These promote easy crack initiation due to multiaxial fatigue state within the layers of materials. The consequent decarburisation by sudden temperature rise metallurgical transformation of pearlitic structure shifts towards ferrite formation. Such microstructures are ductile in nature surrounded by brittle strain hardened materials. These are observed as white patches near the grain boundaries and remarkably cracking can be observed from the cementite phase present there. These confirms that pro eutectoid steel generates larger ferrite density than hard cementite and crack initiates and propagates through these cementite phase as a consequence of rolling contact fatigue. The grains of proeutectoid ferrite are softer in nature causing the formation of soft spots that poses lower resistance to wear. This weaken the surface favouring initiation of fatigue cracks.

![Figure 9](image)

**Figure 9.** Rolling contact fatigue cracks initiation and branching leading to separation/wear of material.

Optical micrographs study of used worn rail has indicated that RCF cracks are mostly initiated at the rail surface around the gauge corner. Figure 9 (a) shows rolling contact fatigue cracks propagating along the pro-eutectoid ferrite layer situated along the pearlite grain boundaries and figure 9 (b) shows crack initiation sites. A continuous network of proeutectoid ferrite precipitating upon slow cooling from austenite and arranging on its grain boundaries can be observed in above (figure 9 (a) and (b)). Grain boundaries serve as preferred nucleation sites because the dissolved carbon segregates them and the nucleation of a new phase proceeds easier at the boundaries rather than inside the grains [6]. An increased amount of pro-eutectoid cementite and ferrite has an adverse effect on the fatigue life of the rail steel [7]. This is because of the increased preferential straining in the pro-eutectoid cementite leading to earlier fatigue crack initiation. Location I in figure 9 (a) specifies crack propagation towards the surface leading to material separation and the formation of wear debris. Branching of crack can be seen at location II that is propagating in the line of proeutectoid cementite across the strained grain boundary. One part of the crack branch is growing toward the surface while other is moving down the rail surface. The initiation of these cracks can be seen at the location III (figure 9 (b)). This is the outcome of plastic strain accumulation incrementally over thousands and millions of cycles by ratchetting. As the rail material accumulates strain with each wheel pass its ductility exhausts and the material fails producing rupture.
4. Conclusion

This study primarily focused on material responses of worn out rail steel in terms of its hardness profile and microstructure variations. The study clearly depicts the consequence of basic pearlitic steel of rail to generate hardness distribution indicating softer core confined in harder outer surfaces. The microstructure observation reveals the influence of rolling contact fatigue induced by thermo-mechanical loading develops wear by forming more and more of softer ferrite distribution with harder cementite layer moving near to the outer surface. The consequence of such cementite portion is found in helping crack initiation and propagation by branching out in the cementite region only. The contribution of RCF, thus obtain, can be utilised to design a better material also to formulate more appropriate safety strategy from the discussed result in the study.

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