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Experimental Investigation of Damage Morphology in High-Speed Railway Crossings with Different Structural Designs

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Abstract

This study compares damage mechanisms in fixed and swing-nose crossings made of Hadfield manganese steel used in high-speed rail, with particular focus on the influence of impact loading on deformation behavior and crack morphology. Although Hadfield steel exhibits high work-hardening capacity, repeated wheel loading leads to progressive surface hardening and eventual fatigue crack initiation. Specimens extracted from in-service crossings were experimentally analyzed.

In the swing-nose crossing, rolling contact-induced shear stress was dominant. Work hardening extended to a depth of approximately 3 mm, and surface-parallel cracks, similar to rail squats, were observed. In contrast, the fixed crossing experienced significant impact loading during wheel transfer, resulting in higher surface hardness (up to 650 HV) and a deeper work-hardened layer exceeding 5 mm. In addition to surface-parallel cracks, vertical and internal horizontal cracks were identified. Twinning deformation under impact loading was concentrated in a preferred direction, corresponding to crack propagation paths. X-ray diffraction revealed peak broadening near the surface in both crossings, with more pronounced broadening in the fixed crossing, indicating higher strain.

These results demonstrate that impact loading strongly affects strain distribution, work-hardening depth, and crack configuration.

Keywords: Hadfield manganese steel, swing-nose crossing, fixed crossing, work hardening, rolling contact fatigue, impact load, wheel-rail contact.

1 Introduction

Switches and crossings (S&C) are essential components of a railway network, providing operational flexibility by guiding trains from one track to another at junctions. At the same time, their geometric complexity and discontinuities make them more vulnerable than contiguous tracks, and are subject to high peak stress. When a train passes through a crossing, wheels transfer from wing rail to nose rail, -- or vice versa -- depending on the running direction. In addition to rolling contact stress, both nose and wing rails experience impact loading caused by their geometric discontinuity. This impact can reach up to four times that of a contiguous track and often leads to fatigue cracks and spalling [1]. Swing-nose crossings without gaps are used in high-speed railways to reduce impact loading; however there are still reports of rolling contact fatigue cracks [2].

Hadfield manganese steel, which has an austenitic face-centered cubic (fcc) structure, is widely used for railway crossings due to its high work-hardening capacity, high fracture toughness, strength, high ductility, and wear resistance. Under repeated impact and contact loading, the surface layer of a Hadfield manganese steel crossing hardens, and fatigue cracks may eventually develop both at and beneath the surface.

Previous studies on deformation microstructure and crack propagation at the nose of Hadfield manganese steel crossings have focused mainly on fixed crossings, and published data are limited [1,3–7]. These studies have indicated that deformation is non-uniform and involves a number of mechanisms. One observation reported discontinuous dynamic recrystallization layers at worn surfaces, while another one reported crack formation associated with vacancy cluster aggregation. Yet another reported high-density mechanical twins leading to microstructural refinement and brittle fracture, and one reported the presence of deformation-induced martensite at the extreme surface.

In contrast, except for the authors’ earlier work [2], swing-nose crossings have rarely been examined. Therefore, the purpose of this study was to compare the damage occurring at the nose sections of two types of crossings — fixed and swing-nose — under the same conditions in train load, and to clarify the unique effects of rolling as well what impact may have caused and exacerbated damage in the Hatfield manganese steel.

2 Methods

Material analyses were conducted on damage observed in one fixed crossing and one swing-nose crossing that had been installed on a Japanese high-speed railway line. High-manganese cast steel (SCMnH3) as used in Japan is of the chemical composition shown in Table 1. No explosive hardening treatment has been applied.

Element	C	Si	Mn	S	S
Wt.%	0.90-1.20	0.30-0.80	11.00-14.00	Max 0.050	Max 0.035

Table 1: Chemical composition of Hadfield manganese steel.

The fixed crossing was installed on a slab track with a JIS 60 kg rail, simple 1-in-14 turnout. The crossing experienced facing-direction traffic at a train speed of 80 km/h. Annual traffic tonnage was 48.5 million gross tons (MGT). Damage occurred after 13 months (cumulative 50 MGT), and the crossing was subsequently replaced. A photograph of the external condition is shown in Figure 1, showing surface spalling and cracking.

Figure 1: Defect appearing on fixed crossing.

The swing-nose crossing was laid in ballast track with a JIS 60 kg rail, simple 1-in-16 turnout with annual traffic tonnage of 10.6 MGT. It was used for 18 years (cumulative 145 MGT) before being replaced due to surface damage. External condition is shown in Figure 2. A squat-like crack pattern was identified similar to that observed in rails.

Figure 2: Defect on swing-nose crossing.

Specimens were cut from the damaged noses for metallurgical investigation as indicated in Figures 1 and 2. Vickers hardness measurements (0.49 N load) were performed to determine the hardness distribution in the direction of depth. Optical microscopy was used to observe the etched microstructure. XRD analysis was carried out using CuKα radiation in continuous scan mode over 2θ = 35–65° with a step size of 0.03° and a counting time of 2 seconds per step.

3 Results

3.1 Hardness Measurements

Hardness was measured from a depth of 25 μm to 4000 μm, with three measurements taken at each depth and the average value plotted. The results for the swing-nose crossing, the fixed crossing, and a rail with squat (for purposes of comparison) are shown in Figure 3. The position of cracks for each crossing in the direction of depth are also indicated in the figure.

It was the wheel-to-rail contact surface that experienced the greatest deformation in the swing-nose crossing. The surface layer was work-hardened, reaching a maximum hardness of 543 HV. Hardness decreased with increasing depth and returned to the base material hardness (220 HV) at around 3000 μm. A local increase in hardness at a depth of 650 μm was observed near the lower region of a crack, indicating a sharp hardness gradient in the crack's vicinity. This increase is attributed to localized loading associated with crack formation.

The extreme surface was also work-hardened in the fixed crossing, reaching 650 HV, which is significantly higher than that of the swing-nose crossing. The work-hardened region extended deeper, and hardness did not return to the base material value within the measured range of 5000 μm. A pronounced variation in hardness near cracks was also observed, similar to the swing-nose crossing. Impact loading in fixed crossings has been reported at as much as four times higher than that in normal tracks, whereas that with the swing-nose crossing showed little difference. The greater degree and depth of work hardening are therefore attributed to repetitive impact loading. Similar trends have been reported in explosively hardened high-manganese steel, where increased shock augmented the depth of hardening, likely a difference due to the frequency of shock received [8].

Work hardening in pearlitic steel reaches about 500 HV at its surface when compared with pearlitic rail steel (in which squat damage occurred on a Shinkansen line) and decreases to the base material hardness within 1 mm from the running surface [9]. These results indicate that high-manganese steel undergoes more severe and deeper work-hardening than pearlitic steel. Similar behavior has also been confirmed in twin-disc rolling tests [10].

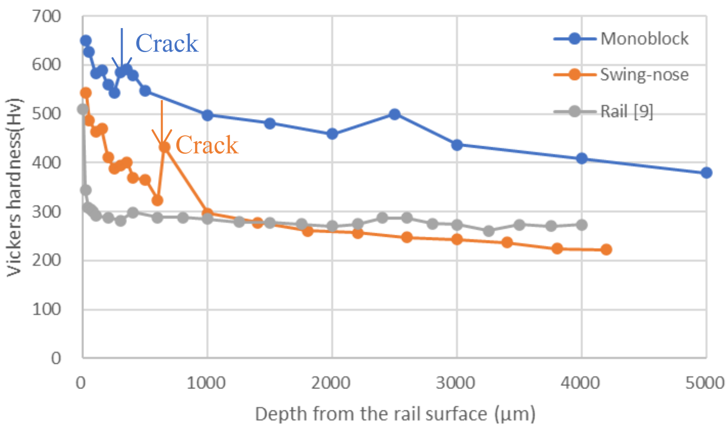

Figure 3: Micro-hardness profiles.

3.2 Optical Microscopy

First, to describe the damage observed in the swing-nose crossing, Figure 4 shows an optical microscopy of an etched cross-section taken in the rail's longitudinal direction. Cracks initiated at the surface and propagated both to the fore and the rear along the running direction, with horizontal crack length reaching 35 mm. Cracks grew mainly along the surface layer, with limited propagation in depth; a pattern similar to squat observed in rails. Figure 5 presents a more highly magnified image of the region shown in Figure 4. Numerous deformation bands were observed within grains beneath the contact surface. In conventional pearlitic steel, grains elongate in the shear direction during deformation. In contrast, grain elongation was not observed in the Hadfield manganese steel of the swing-nose crossing; rather deformation bands formed inside the grains, with density being highest near the surface and decreasing with depth. Near the contact surface, deformation bands intersected within grain, whereas at greater depths they appeared mostly in a single direction. The bands were unevenly distributed and their orientation varied from grain to grain. These bands are believed to consist of mechanical twins or dislocation boundaries, neither of which can be distinguished by optical microscopy.

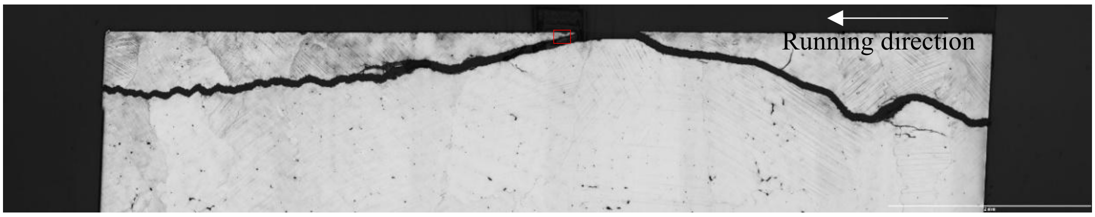

Figure 4: Crack propagation in swing-nose crossing using optical microscopy

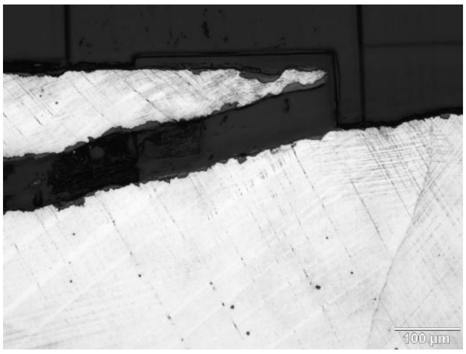

Figure 5: Results of optical microscope after etching.

Figure 6 shows the rail longitudinal cross-section of the fixed crossing. Cracks propagated mainly parallel to the surface, with local surface spalling also observed. Vertical cracks extending into the material and internal horizontal cracks were also identified. Figure 7 shows a magnified view of the region marked in Figure 6. Deformation bands were densely distributed near cracks. Near the surface, the bands did not intersect but appeared bent with similar one-directional deformation bands reported in explosively hardened high-manganese steel [8]. Vertical loading may promote directional deformation, since slip in high-manganese steel occurs preferentially along specific crystallographic directions. The bands observed are considered to be deformation twins and the apparent bending of the twins may be a result of material flow under high impact and shear during wheel transfer. Vertical crack propagation is attributed to impact stresses exceeding local fracture strength. Internal horizontal cracks may indicate that impact stress had been transmitted subsurfacely.

Although both crossings exhibited deformation bands and mechanical twins within grains, their morphology differed. In the fixed crossing, impact loading had a stronger effect than rolling-induced shear force.

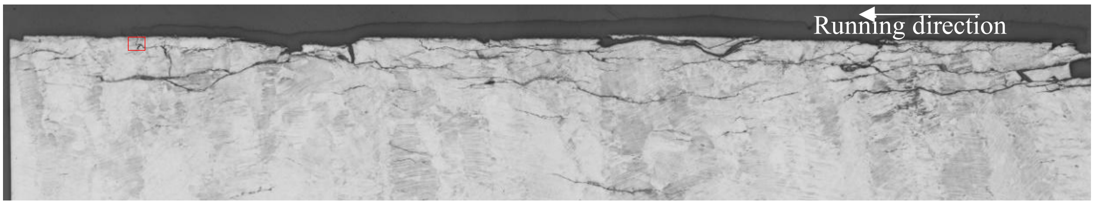

Figure 6: Crack propagation in fixed crossing using optical microscopy.

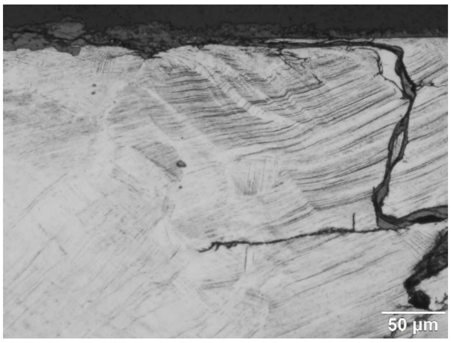

Figure 7: Observation results by optical microscope after etching.

3.3 XRD

X-ray diffraction (XRD) measurements were conducted at several depths from the surface of both specimens to examine phase transformation induced by deformation. The full width at half maximum (FWHM) of the diffraction peaks obtained by XRD is an indicator of crystal characteristics such as crystallite size and lattice strain. In particular, FWHM is closely related to lattice strain, and an increase in FWHM can be interpreted as reflecting an increase in strain within the crystal.

Figure 8 shows the FWHM results for the swing-nose and fixed crossings. In both cases, peak broadening was observed near the surface, with large FWHM values. The FWHM decreased was depth increased , indicating reduced influence in wheel–rail contact.

A comparison of the two crossings shows that at a depth of 50 μm from the surface, the fixed crossing exhibited a larger FWHM than the swing-nose crossing, indicating a higher level of strain. At depths greater than 100 μm, however, no significant difference was observed, and strain levels were similar. The greater strain at the extreme surface of the fixed crossing is consistent with the hardness results, which indicate more pronounced work hardening.

A difference in hardness remained below 100 μm, although the FWHM values were similar. This discrepancy may be related to the measurement scale: hardness was evaluated over a very localized region, whereas the XRD results represent an average over a width of 0.2 mm. No martensite was detected in either specimen.

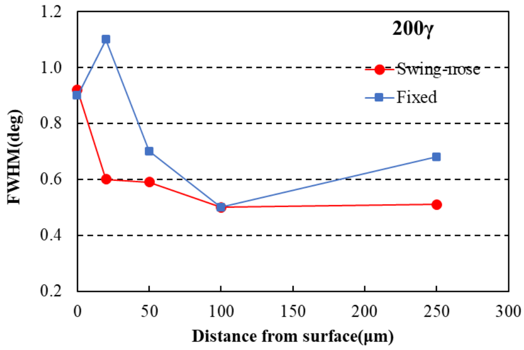

Figure 8: Full width at half maximum results.

4 Conclusions

This study examined deformation and damage at the nose region occuring from use of two types of crossings made of Hadfield manganese steel. In both crossings, high vertical and shear forces from passing wheels acted on the nose, producing work hardening, significant plastic strain, and subsequent crack initiation. However, differences in impact loading between the swing-nose and fixed crossings resulted in different crack morphologies.

In the swing-nose crossing, shear forces generated deformation bands and work hardening to a depth of approximately 3 mm. Cracks initiated from parts of the hardened surface layer and propagated along the surface in both the running and opposite directions. This crack pattern is similar to squat-type defects observed in rails.

In the fixed crossing, the running surface reached a hardness of approximately 650 HV, and the work-hardened region extended to depths greater than 5 mm. XRD measurements also showed higher lattice strain near the surface compared with the swing-nose crossing. These results indicate that stronger impact loading in the fixed crossing increased the degree and depth of work hardening. In addition, many cracks were observed to have propagated vertically into the material and horizontally within the interior. This suggests that impact loading promoted preferential twinning in specific crystallographic directions, along which cracks developed subsequently.

Although both crossings were subjected to the same conditions, differences in impact load altered the deformation band structure, strain distribution, and degree of work hardening. Consequently, crack morphology differed between the two crossings, reflecting the effects of shear-induced plastic flow combined with reduced ductility associated with impact-related work hardening.

References

[1] B. Lv, M. Zhang, F.C. Zhang, C.L. Zheng, X.Y. Feng, L.H. Qian, X.B. Qin, “Micro-mechanism of rolling contact fatigue in Hadfield steel crossing”, Int. J. Fatigue 44, 273–278, 2012.

[2] K. Adachi, F. Aoki, "Experimental investigation on rolling contact fatigue on hadfield steel swing nose crossing", WCRR2025.

[3] K. Ankit, R. Petrov, J. Sietsma, "Damage and Microstructure Evolution in Cast Hadfield Steels Used in Railway Crossings." Intelligent Quality Assessment of Railway Switches and Crossings. Cham: Springer International Publishing, 63-80, 2021.

[4] T. Gustavo, T. Tependio, M. Masoumi, J.I. Pereiral, "Microstructural Evolution and Strain-Hardening Behavior in Hadfield Steel Railway Crossings." Tribology in Industry 46.4 539-650, 2024.

[5] S. Dhara, H.K. Danielsena, S. Fæstera, C. Rasmussenb, Y. Zhangc, D. J Jensenc, “Crack formation within a Hadfield manganese steel crossing nose”, Wear, 438-439, 2019.

[6] O.A. Zambrano, G. Tressia, R.M. Souza, "Failure analysis of a crossing rail made of Hadfield steel after severe plastic deformation induced by wheel-rail interaction." Engineering Failure Analysis 115, 104621, 2020.

[7] Q. Luo, M. Kitchen, J. Li, Y. Li, "Experimental investigation on the spalling failure of a railway turnout made from Hadfield steel", Wear 523,204779, 2023.

[8] A. Oda, "Some characteristic of explosion hardened high manganese austentic cast steel", Journal of the Society of Materials Science, Japan Vol. 33(370), 36-41, 1983.

[9] Y. Satou, Y. Inoue, "Behavior analysis of rolling contact fatigue on the running surface of on rails used in Shinkansen traffic", RTRI report Vol. 6, No. 5, 1992

[10] F. Aoki, K. Adachi, Y. Michitsuji, J. Kobayashi, " Rolling contact fatigue properties of manganese steels used in crossings", CM2025, 2025.