利用課題名

Evaluation of residual stress relaxation in Shinkansen vehicle axles subjected to fatigue loads by neutron diffraction

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（概要）

Our previous studies have observed that the axial CRS in the shinkansen axle surface layer, exceeded −600 MPa, inconsistent with the permissible stress value before service [1]. In this case, a conventional safe-life-based assessment would undoubtedly indicate an infinite lifetime. Nevertheless, recent results have highlighted the RS release during fatigue loading of surface-strengthened large metal components. For instance, Su et al.[2] employed neutron Bragg-edge imaging (BEI) to investigate the release and redistribution of RS in induction-hardened gears during bending fatigue loading. It was clearly found that on the compression side of the gear tooth root, significant initial RS relaxation behavior was observed after fatigue loading. Similarly, Minamizawa et al.[3] attempted to elucidate the relaxation mechanism of RS in carburized steel under rotational bending fatigue loads. Liljedahl et al.[4] discovered the redistribution phenomenon of welding stress under fatigue loading through *in situ* neutron diffraction and finite element (FE) simulation, identifying its significant effect on crack propagation rates. These studies almost attribute CRS relaxation to plastic yielding during the compression loading stage. In our own previous studies, the RS measurements of railway S38C axles after 3 million kilometers of service indicated no significant release of initial stress [5], [6]. By contrast, once the axle initials fatigue crack, the residual stress inevitably release or redistribute, as evidenced by the previous BEI measurement [5].

（1 行あける）

1．目的

To investigate the evolution of residual stress during crack propagation, SENB fatigue samples with varying crack depths were prepared under identical loading conditions.

2．方法

The initial crack depth of the SENB sample was 0.5 mm. FCG experiments were conducted in terms of GB/T 6398-2017 standard using an Instron 8801 multi-function tester, with loading ratio of R = 0.1 and frequency of 30 Hz. The fatigue crack length was measured using a crack opening displacement extensometer. The crack depth was then determined using the flexibility method. In total, six SENB samples with crack depths of 1, 2, 3, 5, 6 and 8 mm were prepared. Quasi *in situ* neutron diffraction experiments were performed using the neutron diffractometer for Residual Stress Analysis (RESA) of engineering materials at the Japan Research Reactor No. 3 (JRR-3). A diffraction slit with dimensions of 2×2 mm^2 was selected to balance neutron flux with measurement accuracy. To precisely capture the stress gradient distribution and avoid contributions from empty volume, measurement points were located at the crack center, with the increasing depths of 1.5, 3, 5, 8, and 10 mm, respectively. In addition, an undamaged bar sample with the same dimensions as the SENB sample was carefully prepared to verify the stress release. The measurement points were concentrated in the hardened layer region at 1, 1.5, 2, 3, 5, and 7 mm.

３． 結果及び考察

As demonstrated in Fig. (c) and (d), the appearance of fatigue cracks on the axle surface results in the substantial release of CRS. Compared with the initial stress state, the absolute values of CRS in the hoop and axial directions decrease rapidly with increasing crack length, indicating significant stress relaxation. However, at a crack depth ≤ 2.0 mm, the RS distribution at different depths in the samples remains the same as that of the initial distribution when the fatigue crack depth exceeds 5 mm, the CRS introduced by induction hardening in the axle is completely released and gradually stabilizes.

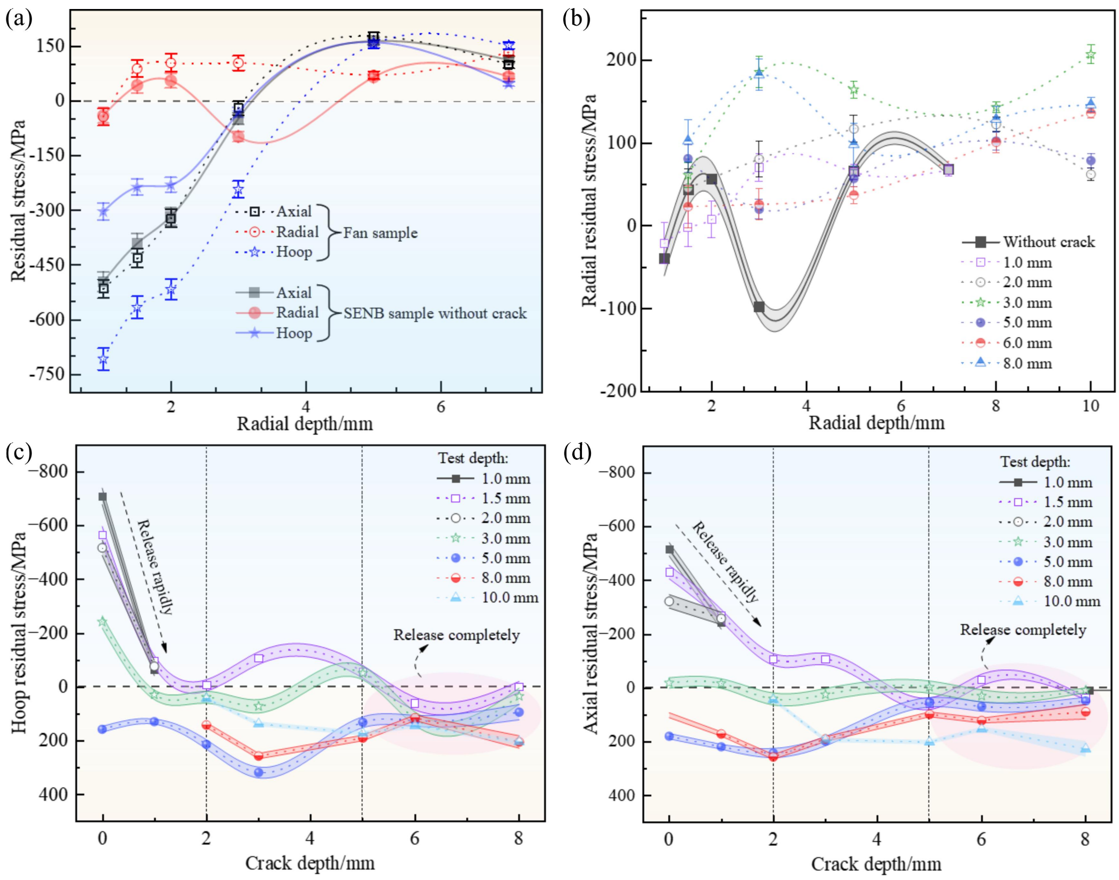

Fig. 1. RS measured by quasi *in situ* neutron diffraction: (a) Difference of RS between non-cracked SENB sample and fan-shaped sample; (b) Radial RS evolution containing cracks of different depths, (c) and (d) are the variation of hoop and axial RS with crack depth growth in different depth regions of the axle surface, respectively.

Currently, research has shown that RS release after fatigue crack initiation is a dynamic process dominated by local plastic deformation - crack closure confinement - macroscopic stress redistribution. Stress concentration at the crack tip induces local yielding, and dislocation slip in the plastic region leads to relaxation of lattice distortion, resulting in partial release of residual stresses. Su et al. demonstrated that the release of residual stresses in the plastically deformed region is accompanied by a significant decrease in dislocation density using neutron diffraction. At the same time, crack initiation disrupts the continuity of the material and breaks the stress equilibrium in the undamaged state (this is also the principle of preparing stress-free d_0 samples using wire cutting). The incomplete release in the short-crack stage at the crack tip originates from the double limitation of the crack closure effect and the size of the plastic zone, whereas the full release in the long-crack stage is related to the crack full opening and the plastic zone propagation. These findings underscore the necessity of incorporating it into the structural integrity assessment, as solely considering the initial stress state may yield dangerous conclusions.

４． 引用(参照)文献等

[1] Qin TY, Hu FF, Xu PG, Zhang H, Zhou L, Ao N, et al. Gradient residual stress and fatigue life prediction of induction hardened carbon steel S38C axles: Experiment and simulation. Int J Fatigue, 2024; 185: 108336.

[2] Su YH, Oikawa K, Shinohara T, Kai T, Horino T, Idohara O, et al. Neutron Bragg-edge transmission imaging for microstructure and residual strain in induction hardened gears. Sci Rep, 2021; 11(1): 4155.

[3] Minamizawa K, Arakawa J, Akebono H, Nambu K, Nakamura Y, Hayakawa M, et al. Fatigue limit estimation for carburized steels with surface compressive residual stress considering residual stress relaxation. Int J Fatigue, 2022; 160: 106846.

[4] Liljedahl CDM, Zanellato O, Fitzpatrick ME, Lin J, Edwards L. The effect of weld residual stresses and their re-distribution with crack growth during fatigue under constant amplitude loading. Int J Fatigue, 2010; 32(4): 735-743.

[5] Hu FF, Qin TY, Ao N, Zhou L, Xu PG, Parker JD, et al. Gradient residual strain determination of surface impacted railway S38C axles by neutron Bragg-edge transmission imaging. Eng Fract Mech, 2024; 306: 110267.

[6] Zhou L, Zhang H, Qin TY, Hu FF, Xu PG, Ao N, et al. Gradient residual strain measurement procedure in surface impacted railway steel axles by using neutron scattering. Metall and Mater Trans A, 2024; 55(7): 2175-2185.