様　式　Ｃ－１９、Ｆ－１９－１、Ｚ－１９　（共通）

科研費 KAKENHI

科学研究費助成事業　　研究成果報告書

令和　４ 年　 ６ 月　 １ 日現在

機関番号：８２１１０
研究種目：若手研究
研究期間：2020～2021
課題番号：２０Ｋ２０１０６

研究課題名（和文）Development of two-dimensional strain mapping technique around a fatigue crack using the pulsed neutron Bragg-edge transmission imaging and neutron diffraction

研究課題名（英文）Development of two-dimensional strain mapping technique around a fatigue crack using the pulsed neutron Bragg-edge transmission imaging and neutron diffraction

研究代表者
蘇　玉華（SU, Yuhua）

国立研究開発法人日本原子力研究開発機構・原子力科学研究部門　Ｊ－ＰＡＲＣセンター・技術副主幹

研究者番号：２０６４４２６４

交付決定額（研究期間全体）：（直接経費）　　2,000,000円

研究成果の概要（和文）：機械部品における破壊事故全体の約80%は、金属疲労が原因と言われている。き裂先端周辺の非線形ひずみ/応力分布が、疲労及びき裂成長挙動に大きな影響を与えている。この研究では、ブラッグエッジイメージング法と中性子回折法を組合せた組織評価法を用いて、疲労き裂の発生・進展の観察法の確立に取り組んだ。これにより、異なる疲労荷重条件下にあったコンパクト・引張サンプルの不均一な残留ひずみと、微細構造の2次元マップを評価することができる。また、中性子回折測定を実施し、ブラッグエッジイメージング結果の定量性を検証した。これらの結果により、合金の組成やミクロ組織による疲労き裂進展特性改善の可能性を検討する。

研究成果の学術的意義や社会的意義
これまでの研究では、実工業製品における高周波焼入歯車の結晶組織構造・残留ひずみが評価できた。その一方で、構造材料における事故の 8 割を占めているのが疲労破壊であり、材料の疲労き裂発生及び進展挙動の理解は実用上の最重要課題であった。疲労き裂の進展特性の定量評価技術を開発するために、中性子ブラッグエッジイメージング法及び中性子回折法を用いて、繰り返し負荷によるひずみの進展の計測が可能となった。中性回折法によって疲労き裂先端近傍の残留応力分布が測定できた。また、相応力解析において疲労き裂周辺の残留応力分布は、材料の相違によって異なることが確認された。

研究成果の概要（英文）：Fatigue damage is known as one of the major concerns in maintaining the integrity of large-scale engineering components. The nonlinear strain/stress distribution around a fatigue crack tip has a great impact to understand the fatigue and crack growth behavior of engineering component. This research is devoted to develop the fatigue evaluation technique by a combination of two neutron methods: Bragg-edge transmission imaging and diffraction.Two-dimensional maps of inhomogeneous residual strain and microstructure for the compact tension samples, which had been under different fatigue loading conditions, were determined by Bragg-edge spectral analysis. The obtained Bragg-edge imaging results were quantitatively compared with those determined by diffraction. The obtained original information of the strain and crystalline structure state inside the bulk gives a greater understanding on crack tip elastic and plastic strain evolution mechanisms in engineering materials.

研究分野：金属材料

キーワード：疲労　中性子ブラッグエッジイメージング　中性子回折　残留ひずみ　ステンレス鋼

１．研究開始当初の背景

Fatigue damage is known as one of the major concerns in maintaining the integrity of engineering components such as ships, bridges, pressure vessels and other large-scale structures. It is reported that 80% of accidents are due to metal fatigue. In structures undergoing fatigue loading, the nonlinear strain/stress distribution around a fatigue crack tip has a great impact to understand the fatigue and crack growth behavior of engineering component. Therefore, it is essential to understand the residual strain/stress distribution around a fatigue crack under different conditions, which is important for improving the fatigue lifetime and helpful for the design of engineering structures. The newly developed time-of-flight (TOF) Bragg-edge transmission imaging method, which follows similar principles to the neutron diffraction method, generates two-dimensional (2D) mapping of strain over the entire detector field of view in a single measurement and can quantitatively and non-destructively visualize the spatial distributions of the wider area of textures and the microstructures inside a relatively thicker material than the traditional electron, X-ray experiments.

２．研究の目的

We consider that it is possible to reveal local variations in strain and microstructure around a fatigue crack tip throughout the thickness of the material by using the non-destructive neutron Bragg-edge imaging and established neutron diffraction probes. The aim of this study is to develop 2D strain mapping technique using the pulsed neutron Bragg-imaging and neutron diffraction. The evolution of the internal stress fields around the crack tip during fatigue crack growth under applied loads will be investigated. The developed technique will be applicable for non-destructive fatigue strain inspection of different kinds of complicated engineering products, which will provide complementary information to the conventional methods.

３．研究の方法

To investigate the influence of austenitic (γ) and ferritic (α) phases on the changes in the strain and microstructure of steels during cyclic fatigue, we selected a typical single austenite stainless steel SUS304 (100% γ) and a duplex stainless steel SUS329J4L (approximately 50% γ, 50% α). The fatigue tests on the compact-tension samples were conducted with a servo-hydraulic fatigue testing machine. The 6 mm thick samples were subjected to constant amplitude loading until a crack of 25 mm was developed in SUS304 after 2.9×10^5 cycles or in SUS329J4L after 3.9×10^5 cycles. The pulsed Bragg-edge imaging experiment on the fatigued samples was performed at BL22 RADEN, the energy-resolved neutron imaging system at the Materials and Life Sciences Experimental Facility (MLF) of the Japan Proton Accelerator Research Complex (J-PARC). The time-of-flight neutron diffraction strain mapping was performed at BL19 TAKUMI, an engineering diffractometer in MLF/J-PARC. The Bragg-edge spectral were analysed by RITS (Rietveld Imaging of Transmission Spectra) code to obtain 2D maps of crystallographic information. Neutron diffraction data were analysed by the Z-Rietveld software to obtain the residual lattice strain, texture, and phase volume fractions. In addition, the digital image correlation measurement was performed complementarily during the fatigue tests to obtain the surface strain on the on the compact-tension samples.

４．研究成果

Fig. 1. shows the schematic illustration of the neutron diffraction measurement positions of a SUS304 sample, which was subjected to constant-amplitude cyclic loading mode until a crack of 25 mm was developed after 2.9×10^5 cycles, where TD, RD and ND data in the mid-thickness of the 6 mm samples were obtained with the gauge volume of $2\times2\times2$ mm^3

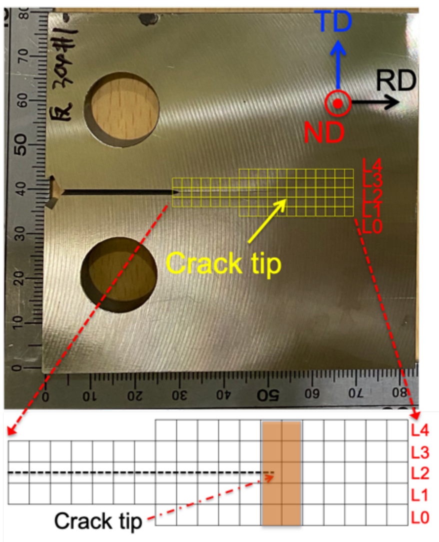

Fig. 1. Schematic illustration of the neutron diffraction measurement positions.

by using radial collimators and an incident beam slit. The residual strain was obtained by Rietveld refinement using the whole diffraction pattern. Fig.2 (a) shows the obtained residual strain distributions determined by diffraction in three directions at the middle thickness of a 6 mm thick SUS304 sample along the L2 line in Fig. 1. It reveals strong compressive residual strains at the crack tip and rising to near-zero with increase of distance from the crack tip in the TD and RD directions, while those in the ND direction show tension near the tip and decreased to near zero at about 7 mm from the crack tip. The residual stresses in all three were calculated using the generalized Hooke's law. Fig. 2(b) shows the calculated interphase residual stress of the SUS304 sample. In all TD and RD directions, the austenite phase shows compressive residual stress near the crack tip while the residual stress is almost 0 MPa in the ND direction. The residual stress in TD is from -150 MPa around crack tip to 120 MPa ~10 mm ahead of the crack tip.

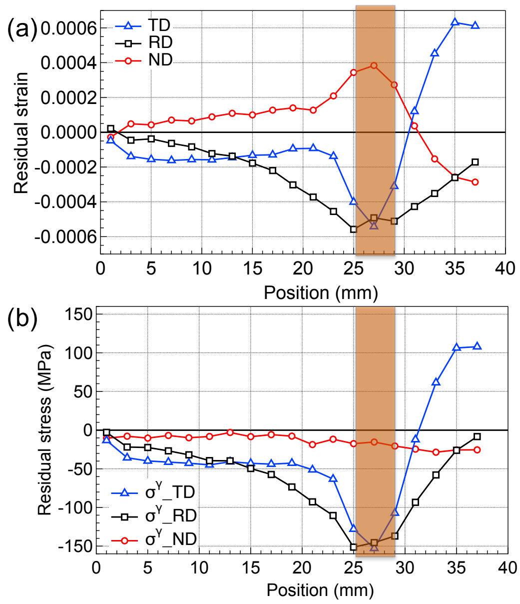

Fig. 2. Residual strain (a) and residual stress (b) of SUS304 samples along L2 in Fig.1.

The dashed box in black and the line box in red in Fig. 3 indicate the analyzed regions zooming in Fig. 4. Fig.4 shows the 2D maps of the obtained lattice constants obtained by neutron diffraction and Bragg-edge imaging, respectively. The distribution of the lattice constants obtained from the Bragg-edge imaging data was in agreement with the results obtained from the diffraction data.

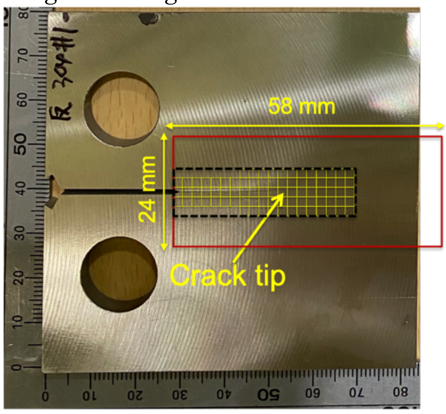

Fig. 3. Schematic illustration of the neutron diffraction and Bragg-edge imaging analysis positions.

2D maps of the nonlinear microstructure and strain/stress around a fatigue crack tip by further analysis can help characterize the fatigue damage behavior in engineering materials and may be helpful for the design of engineering components. We will compare the different fatigue behaviours between austenitic stainless steel and duplex stainless steel and analyse samples tested under different loading conditions. We will also compare the obtained Bragg-edge imaging and diffraction results with those by digital image correlation methods in our future analysis.

The technique may be applicable for non-destructive fatigue strain and microstructure inspection of different kinds of complicated products, such as welded large components.

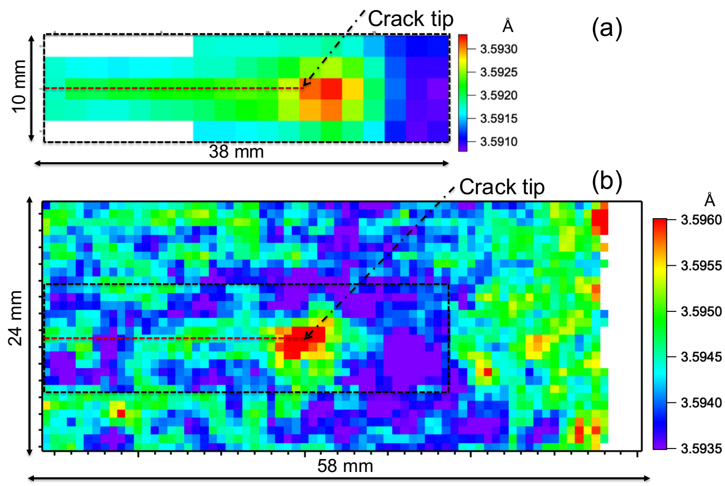

Fig. 4. 2D maps of lattice constants obtained by neutron diffraction (a) and Bragg-edge imaging for SUS304 sample.

５．主な発表論文等

〔雑誌論文〕　計1件（うち査読付論文　1件／うち国際共著　0件／うちオープンアクセス　1件）

１．著者名 Su Yuhua、Oikawa Kenichi、Shinohara Takenao、Kai Tetsuya、Horino Takashi、Idohara Osamu、Misaka Yoshitaka、Tomota Yo	４．巻 11
２．論文標題 Neutron Bragg-edge transmission imaging for microstructure and residual strain in induction hardened gears	５．発行年 2021年
３．雑誌名 Scientific Reports	６．最初と最後の頁 1 and 14
掲載論文のDOI（デジタルオブジェクト識別子） 10.1038/s41598-021-83555-9	査読の有無 有
オープンアクセス オープンアクセスとしている（また、その予定である）	国際共著 －

〔学会発表〕　計2件（うち招待講演　0件／うち国際学会　2件）

１．発表者名 Yuhua Su, Wu Gong, Stefanus Harjo, Takuro Kawasaki, Kazuya Aizawa
２．発表標題 Strain and Microstructure Distributions around a Fatigue Crack Tip Studied by Neutron Diffraction
３．学会等名 10th International Conference on Mechanical Stress Evaluation by Neutron and Synchrotron Radiation - MECASENS 2021（国際学会）
４．発表年 2021年

１．発表者名 Yuhua Su, Joseph Don Parker, Takenao Shinohara, Kenichi Oikawa, Tetsuya Kai, Wu Gong, Stefanus Harjo, Takuro Kawasaki, Kazuya Aizawa, Yoshiaki Kiyanagi
２．発表標題 Strain and Microstructure Distributions around a Fatigue Crack Tip by Neutron Bragg-edge Imaging and Diffraction
３．学会等名 the The 9th International Topical Meeting on Neutron Radiography (ITMNR-9)（国際学会）
４．発表年 2022年

〔図書〕　計0件

〔産業財産権〕

〔その他〕

－

６．研究組織

	氏名 （ローマ字氏名） （研究者番号）	所属研究機関・部局・職 （機関番号）	備考

７．科研費を使用して開催した国際研究集会

〔国際研究集会〕　計0件

８．本研究に関連して実施した国際共同研究の実施状況

共同研究相手国	相手方研究機関