

In-situ Deformation Testing System for Engineering Materials at Shanghai Synchrotron Radiation Facility Beamline BL12SW

Authors: Chang, Dr. Hai, Zichong Zhang, Zhang, Hongbo, Shi Zheng, Cheng, Miss Lili, Zhang, Zhe, Zhong, Mr. Cheng, Dr. Feifei Huang, Zhao, Dr. Zilong, Dr. Zhaohui Dong, Dr. Chunyin Zhou, Dr. Ke Yang, Zhang, Mr. Ding, Dr. Weimin Gan, Brokmeier, Prof. Heinz-Guenter, Prof. Jinkui Zhao, Sun, Prof. Dongbai, Jin, Prof. Ying, Jin, Prof. Ying

Date: 2025-12-15T18:38:34+00:00

Abstract

One in-situ deformation testing system funded by the project of High Energy Photon Source-Testing Facility has been installed at the ultrahard X-ray multifunctional application beamline BL12SW which belongs to the phase-II beamline project in Shanghai synchrotron radiation facility. Aiming to meet the requirements of high energy X-ray diffraction and imaging using the monochromatic light, the in-situ testing system was designed to apply multiple functions including tensile/compression and the simultaneously rotation along the tensile axis, as well as the electric heating of the metallic specimen. A digital video extensometer was utilized to measure the deformation strain avoiding any contact with the specimen. Various investigations such as lattice strain partitioning, texture evolution, contrast imaging under mechanical loading have been verified. Moreover, one electrochemistry hydrogen charging cell was developed to study the structural changes of the material during the in-situ hydrogen charging combined with mechanical loading. This system could be a function expansion of BL12SW and more different types of experiments could be conducted on engineering materials.

Full Text

Preamble

An in-situ deformation testing system for engineering materials has been installed at the ultrahard X-ray multifunctional application beamline BL12SW of

the Shanghai Synchrotron Radiation Facility (SSRF), funded by the High Energy Photon Source-Testing Facility project. Designed to meet the requirements for high-energy X-ray diffraction and imaging using monochromatic light, the system enables multiple functions including tensile/compression testing with simultaneous rotation about the tensile axis, as well as electric heating of metallic specimens. A digital video extensometer measures deformation strain without contacting the specimen. The system has been validated through various investigations including lattice strain partitioning, texture evolution, and contrast imaging under mechanical loading. Additionally, an electrochemical hydrogen charging cell was developed to study structural changes in materials during in-situ hydrogen charging combined with mechanical loading. This system represents a functional expansion of BL12SW capabilities, enabling a broader range of experiments on engineering materials.

Keywords: Shanghai synchrotron radiation facility, beamline BL12SW, in-situ deformation testing system, hard X-ray, X-ray diffraction (XRD), X-ray imaging

Introduction

Over the past decade, synchrotron radiation high-energy X-ray diffraction (HEXRD) and imaging have emerged as among the most effective methods for characterizing engineering materials [?]. High-energy light sources have been widely employed to study phase analysis [?], strain partitioning [?, ?], crystallographic anisotropy [?], residual stress [?], defect observation [?, ?], and other phenomena. When combined with various environmental devices, numerous multi-objective in-situ experiments can be conducted effectively at beamlines. The High Energy Photon Source (HEPS), officially approved in 2018 and scheduled for completion in 2025, will be China's first high-energy diffraction-limited storage ring light source [?]. As an R&D project for HEPS, the High Energy Photon Source-Testing Facility (HEPS-TF) project ran from 2016 to 2019, during which the techniques required for constructing a diffraction-limited storage ring—including accelerator, beamline, and end-station technologies—were thoroughly studied and demonstrated [?].

Based on the 4R concept (Real process for Real materials in Real conditions and Real time), several in-situ testing systems were developed to characterize the performance and structural evolution of engineering materials, aiming to meet scientific research requirements during melting, processing, and service in multi-field coupling environments. One such in-situ deformation testing system was designed to observe the structural evolution of metallic materials during deformation using high-energy X-ray techniques. Unfortunately, as no high-energy light source was available in China in 2019, this testing system remained unused at any beamline following the national acceptance of HEPS-TF.

The ultrahard X-ray multifunctional application beamline BL12SW is a phase-II beamline at the Shanghai Synchrotron Radiation Facility (SSRF) [?, ?] and represents China's first dedicated experimental station for engineering materi-

als. The primary X-ray techniques employed are high-energy X-ray diffraction and imaging using both white and monochromatic light. The Eng 2 hutch at BL12SW provides a large experimental space (11 m \times 7 m \times 5 m) and an extremely heavy-load sample stage with a maximum capacity of 2 tonnes for large equipment. Three detector types—a large field-of-view imaging camera, a flat detector for high-energy XRD, and a 23-element energy-dispersive detector—can be switched according to experimental requirements. Detailed beamline parameters have been reported in Yang's work [?]. The official opening of BL12SW in 2024 provided the opportunity to validate the designed functions of the in-situ deformation testing system.

This contribution reports in detail on the design and specifications of the in-situ deformation testing system. To ensure stable test positioning during in-situ research, symmetric loading was adopted. The ω -rotation of the specimen about the tensile axis, driven by two rotation servo motors, was optimized for structural analysis of metals. Using rotation motors prevents the loading frame columns from blocking the incident beam during ω -rotation. A video extensometer measures strain and monitors the deformation process, while a heating system combined with a protective gas chamber enables phase transformation analysis. This study presents preliminary results focusing on strain partitioning in a high-entropy alloy, texture evolution in TC4 titanium alloy, and imaging of the bonding interface in an explosively welded Ti/Fe cladding plate. Additionally, an electrochemical hydrogen charging cell was developed to study the effects of in-situ hydrogen charging on the deformation behavior of metallic materials, with particular discussion of mobile hydrogen's influence on the deformation mechanisms of X80 pipeline steel.

2.1. Design

The testing system was specially optimized for installation and integration at a synchrotron radiation beamline. The basic frame is a universal double-column testing rig with a vertical layout. The global view and main components are shown in Fig. 1 [Figure 1: see original paper]. The system dimensions are 800 mm (W) \times 350 mm (T) \times 1500 mm (H) and include the main frame with loading components, a heating system integrated with a non-contact video extensometer and high-speed pyrometer, a gas chamber, and a control system. A high-precision XYZ-translation stage enables accurate positioning and alignment relative to the incident beam. When mounted on the XYZ stage, the sample center height is 1325 mm from the ground, matching the beam height at SSRF.

Based on the penetration depth of a 100 keV X-ray beam, a 3 mm diameter steel bar was selected as the standard sample for system design. The maximum axial load in tension or compression is ± 15 kN. Two electrical actuators provide symmetrical axial loading, maintaining a constant exposed sample volume in the beam during loading. Additionally, two electrical torsional actuators enable symmetrical torque application up to ± 30 N \cdot m. Consequently, ω -rotation of

the specimen about the tensile axis within $\pm 110^\circ$ can be achieved without losing alignment while under axial load and torque. An alignment fixture between the crosshead and load cell maintains rotation axis alignment during loading, which is essential for rotation angle scanning in texture or imaging experiments. Compared to conventional designs placing the test rig on a rotational table, this approach prevents the loading frame columns from blocking the incident beam during ω -rotation.

Round bar samples are preferred for this system to ensure stable sample volume coverage by the beam during ω -rotation. A set of grips with clamping diameters ranging from 4-12 mm accommodates various standard round samples. Threaded fastening clamps the round bar samples for rotation or torsion tests, while two adapters enable plate sample testing. Fig. 2 [Figure 2: see original paper] shows typical samples used in this system.

A non-contact video extensometer records sample deformation strain. Mounted on one column of the testing rig, it uses two lenses for stereo-mode continuous measurement of axial deformation and rotation angle. Before measurement, black and white spray creates a dot pattern on the sample surface for image analysis. By tracking selected patterns in the region of interest (ROI), deformation strain and strain distribution are calculated and recorded. The extensometer's field of view is 200 mm wide with a resolution of approximately 0.5-1 μm . Supplementary Material S1 shows the symmetric tensile test history of Q235 steel recorded by the extensometer, demonstrating stable behavior in the middle area.

A high-speed electrical resistive heating system enables temperatures up to 1200 $^\circ\text{C}$ through direct sample heating via low-frequency electrical current under load. Heating components with integrated water cooling are fastened to the tensile rods. A high-speed pyrometer with 0.1 ms minimum response time, mounted on the other column, provides non-contact temperature measurement. The sample center temperature is measured as feedback, and the controller dynamically adjusts output power (current) via PID algorithm to maintain set temperature. The low-voltage power control mode offers superior precision. A water-cooled inert protective gas chamber prevents sample oxidation during heating, equipped with two Kapton windows for X-ray transmission and sapphire glasses for the video extensometer. Supplementary Material S2 demonstrates sample rotation combined with heating.

2.2. Control system

The testing system is controlled by the digital controller PCS8000 developed by Walter+Bai Corp. The PCS8000 supports up to twelve modules, providing a flexible, modular data acquisition and control system for mechanical testing machines. Multiple controllers can be networked for synchronized multi-channel control. In the in-situ testing system, five integrated controllers manage the upper/lower linear servo motors with force and torque sensors, upper/lower rotation servo motors, and heating system. Tensile/compression/torsion tests can

be conducted independently or synchronously. Besides automatic control, a handwheel and emergency stop are provided for sample installation and unexpected situations.

The software Dion 7 with four packages controls the testing system. The Free Programmable Interface (FPI) mode enables creation of customized programs for special loading processes required by X-ray measurements. Table 1 details the testing system parameters. For user convenience, Table 2 lists the main parameters of another fatigue testing machine at SSRF.

3. Experiment results in beamline BL12SW

Fig. 3 [Figure 3: see original paper] shows the testing system layout in the Eng 2 hutch of BL12SW at SSRF. The system is placed vertically on the heavy-load sample stage and operated remotely from outside the hutch. For diffraction measurements, the beam size was $0.5 \times 0.5 \text{ mm}^2$ with energy of 101.69 keV (wavelength 0.1219 Å). A flat 2-D detector with 3072×3072 pixels and 139 $\mu\text{m}/\text{pixel}$ resolution collected diffraction patterns at a sample-to-detector distance of approximately 1430 mm. CeO_2 powder was used for calibration.

3.1. Strain partitioning of high entropy alloy (HEA)

Eutectic high-entropy alloys (EHEAs) represent a promising class of multi-principal-element alloys that can form hierarchical microstructures of dual-phase lamellar colonies, offering excellent mechanical properties [?]. In this study, an $\text{AlCoCrFeNi}_{2.1}$ high-entropy alloy was selected for in-situ tensile measurement using high-energy diffraction. This alloy typically contains an FCC phase with L12-type ordering and a BCC phase with B2-ordered structure [?]. Al and Ni tend to form an Al-Ni-rich B2 structure due to their strong negative enthalpy of mixing, with Al and Ni preferentially occupying alternating lattice sites, while Cr is relatively depleted in the B2 phase. The L12 phase is enriched in Co, Cr, Fe, and Ni but depleted in Al. Formation and detailed atomic arrangements of the ordered L12 phase in $\text{AlCoCrFeNi}_{2.1}$ are rarely reported [?]. According to Zhang' s report [?], hypothetical L12 site occupancies involve C atoms randomly replacing A atoms at corner sites, and D/E atoms randomly replacing B atoms at face-centered sites. High-entropy alloys do not exhibit strict stoichiometry for each element but may be stoichiometric for the sum of certain atoms. The volume fractions of FCC and BCC phases were identified as 76% and 24%, respectively. This study investigated the effect of pre-fatigue treatment (5000 cycles at 600 MPa maximum stress, stress ratio 0.1) on lattice strain partitioning between FCC and BCC phases during tensile deformation.

Continuous symmetric tensile tests were conducted on dog-bone specimens at room temperature with a strain rate of $1 \times 10^{-3} \text{ s}^{-1}$ at a fixed ω -angle of 0° . Diffraction patterns were collected at 2 s intervals during tensile loading. Fit2D software analyzed the patterns, generating one-dimensional (1-D) diffraction profiles along the loading direction (LD) by integrating specific azimuth angles

within $\pm 10^\circ$. Lattice strain and phase stress partitioning calculation methods followed Ref. [?].

Fig. 4 [Figure 4: see original paper] shows lattice strain evolution of different planes in AlCoCrFeNi_{2.1} alloy along LD as a function of applied stress. The {111}, {200}, {311} planes of the FCC phase and {110}, {200}, {211} planes of the BCC phase were analyzed. For the cast alloy, all planes showed linear response below 400 MPa tensile stress. After pre-fatigue treatment at 600 MPa, yield stress increased to 600 MPa and the linear lattice strain region expanded accordingly. During plastic deformation, lattice strain deviated from linearity. The different slopes of various hkl reflections reveal different elastic responses in cubic structures, attributable to elastic anisotropy and consequent elastic load sharing among differently oriented polycrystalline grain families [?, ?]. The cubic elastic anisotropy factor $A = (h^2k^2 + k^2l^2 + l^2h^2)/(h^2 + k^2 + l^2)^2$ describes plane stiffness [?, ?]. The softest orientation is the {200} plane for both BCC and FCC phases, while the stiffest is the {311} plane of the FCC phase. The {110} and {211} planes of the BCC phase, having identical anisotropy factors, show similar stiffness.

Lattice strain evolution in Fig. 4 [Figure 4: see original paper] also reveals separation between FCC and BCC phases based on different lattice strains at the same stress level. Fig. 5 [Figure 5: see original paper] shows stress partitioning between BCC and FCC phases during in-situ tensile tests. The BCC phase endured greater deformation than the FCC phase in both cast and pre-fatigued alloys (Fig. 5(a) and (b)), consistent with previous reports on AlCoCrFeNi_{2.1} [?]. Interestingly, the stress partitioning ratio in the BCC phase was smaller for the pre-fatigued alloy than for the cast alloy. Since pre-fatigue was conducted at 600 MPa—apparently above the macroscopic yield stress of the cast alloy—stress redistribution between FCC and BCC phases likely resulted from FCC phase hardening due to high dislocation density introduced by the 5000-cycle pre-fatigue test. More detailed analysis and microstructural investigations will be presented in future work.

3.2. In-situ texture measurement

Crystallographic texture influences various material properties including deformation mechanisms, corrosion behavior, and stress corrosion cracking (SCC) [?]. This study verified the rotation function through texture measurements on an extruded TC4 round bar during tensile testing. Prior to measurement, the TC4 bar was electrochemically hydrogen-charged for 24 hours. Most synchrotron texture measurements use rotational tables on which the testing rig is placed, yielding only incomplete pole figures due to loading frame column obstruction. In this study, complete pole figures were obtained through specimen rotation driven by upper/lower torsional actuators.

As described in Section 2.2, the loading process was programmed via FPI, enabling synchronized control of four actuators. Fig. 6 [Figure 6: see original

paper] shows the typical loading history for texture measurement. The sample rotated from -90° to $+90^\circ$ in 5° steps at each deformation level, with diffraction patterns collected at each step for 500 ms. Upon reaching $+90^\circ$, the sample automatically loaded to the next deformation level, collecting 37 patterns per level. The Stress Texture Calculator software (Steca, <https://jugit.fz-juelich.de/mlz/steca>) calculated pole figures from these patterns [?, ?].

Fig. 7 [Figure 7: see original paper] shows pole figures of the hydrogen-charged TC4 round bar at tensile strains of 0%, 1.6%, and 6.6%. The 0% strain pole figures exhibit typical extrusion fiber texture with $\{10.0\}$ distributed along the extrusion direction. For comparison, Fig. 8 [Figure 8: see original paper] shows pole figures measured by Electron Backscatter Diffraction (EBSD), verifying the measurement procedure. Minor differences likely arise from EBSD' s local measurement area versus synchrotron radiation' s larger measurement volume. At 6.4% strain, the main texture type remained largely unchanged. The $\{10.0\}$ maximum intensity decreased slightly at 1.6% strain then increased again, while $\{00.2\}$ intensity decreased initially but remained constant from 1.6% to 6.4% strain. This slight decrease may result from $\{00.2\}$ rotation from the radial to tensile direction. Prism slip and a+c pyramidal slip in large alpha grains and cross-slip in the beta phase caused texture changes during tensile deformation [?]. TC4 texture evolution may relate to strain partitioning between alpha and beta phases, deformation mechanisms such as twinning, slip system operation, and dislocation accommodation. Further work including orientation distribution function (ODF) analysis is needed to interpret texture evolution comprehensively. The effect of hydrogen charging on texture evolution under loading also warrants follow-up investigation. Nevertheless, complete pole figures were successfully obtained, facilitating studies of crystallographic anisotropy in metals at beamline BL12SW.

3.3. In-situ imaging under loading condition

An explosively welded Ti/Fe cladding plate, containing materials with different X-ray absorption coefficients, was used to verify the imaging function. A round tensile specimen with 3 mm gauge diameter was machined along the bonding interface. Images were collected at 0% and 10% strain levels. Since microstructural features barely changed during holding, these quasi in-situ tests with interruptions are referred to as in-situ tests.

Projections were recorded using a 2560×2160 pixel PCO.EDGE 5.5 detector with a $2\times$ magnifying lens, yielding an effective pixel size of $3.0 \mu\text{m}$. The field of view was $3.2 \times 3.2 \text{ mm}^2$, with each tomographic dataset comprising 900 projections at 0.2° angular increments over 180° ($\pm 90^\circ$) using 400 ms exposure time. The entire imaging process ran automatically via FPI-programmed loading. An automatic triggering apparatus sent signals to the camera at each angle position. PITRE software reconstructed 900 projections into approximately 1600 slices, with CT images processed graphically and quantitatively using Avizo software.

Fig. 9 [Figure 9: see original paper] shows the 3D morphology of the as-welded Ti/Fe cladding plate. The typical wavy structure resulting from joint shock wave and collision is evident on both Fe and Ti sides. A micropore on the Fe side bonding interface (white arrow) corresponds to a Ti particle incorporated during explosive bonding due to surface friction. Interestingly, some Ti particles distributed along the waves are not in contact with the Ti interface. Fig. 10 [Figure 10: see original paper] shows the 3D morphology at 10% strain, revealing extra relief and wrinkles along both sides of the bonding interface. Some pores twisted and new small pores formed on the Fe side, while Ti particle morphology in the vortices also evolved.

In this study, the flyer TA1 plate was propelled by the detonation wave onto the Q235 steel base plate, forming wave morphology due to high pressure at the collision point. Typical vortices introduced by circular movement formed on the Fe side, with intense stirring causing strong Ti-Fe intermixing and local melting at wave crest fronts due to heat accumulation from severe deformation [?, ?]. Presumably, un-melted Ti incorporated into Fe waves was the main source of non-contact Ti particles along the wavy structure. The Ti/Fe cladding plate can be considered a heterostructured material composed of zones with dramatically different mechanical or physical properties [?]. Different relief and wrinkle degrees on the bonding interface imply different deformation capacities of Ti and Fe. Global strain partitioning between Ti and Fe can be analyzed to investigate deformation mechanisms in detail.

Fig. 11 [Figure 11: see original paper] shows micro-pore distribution at different strain levels. As mentioned, vortices introduced by circular movement likely trapped micro-pores along wave structures. At 10% strain, larger pores were observed and pore volume fraction appeared to increase due to deformation. Fig. 12 [Figure 12: see original paper] quantifies voxel volume and pore number statistics before and after straining, defining defects as pores >8 voxels (vx). At 10% strain, defect numbers increased noticeably across all volume ranges: from 25 to 31 in the 8-50 vx range, 27 to 36 in the 50-300 vx range, and 10 to 15 in the >300 vx range. This indicates that applied strain induces more small-volume defects, promotes medium-volume defect generation, and drives defect evolution toward larger volumes. Since micro-pores significantly affect mechanical properties, detailed shape and quantity analysis should be pursued.

In summary, for explosively welded Ti/Fe plates, the relationship between interface morphology and mechanical properties is crucial. Beyond defect analysis, deformation behavior of Fe/Ti bimetallic sheets can be investigated through strain partitioning analysis between Fe and Ti, considering wavy structure morphology. This study provides a valuable tool for investigating materials composed of different zones with varying X-ray absorption.

3.4. Electrochemical hydrogen charging cell

Hydrogen embrittlement (HE) is increasingly implicated in premature fracture of industrial components [?]. Hydrogen can degrade mechanical properties including fracture strain and fatigue life while altering fracture mode. HE mechanisms based on hydrogen-dislocation interaction, such as Hydrogen-Enhanced Localized Plasticity (HELP) and Adsorption-Induced Dislocation Emission (AIDE), explain plasticity localization and brittle fracture. Mobile dislocation density and effective activation volume relate to hydrogen presence [?]. Electrochemical permeation devices on tensile machines can control hydrogen flux to isolate effects of trapped versus mobile hydrogen on HE behavior [?]. Real-time microstructural evolution observation during deformation in hydrogen-containing environments is necessary to understand these mechanisms. Therefore, an electrochemical hydrogen charging cell was designed for this in-situ testing system.

Fig. 13 [Figure 13: see original paper] shows the hydrogen charging cell installed on the testing machine. A three-electrode system (counter, reference, and working electrodes connected to the sample) controls hydrogen flux via current density or potential from an electrochemical workstation. A thermocouple measures solution temperature when needed. Two Kapton windows enable X-ray transmission. Solution enters through a lower inlet and exits via an upper outlet. This system simultaneously obtains diffraction patterns, electrochemical information, and tensile properties to study material structure evolution under controlled hydrogen charging conditions.

X80 bainitic steel, commonly used in pipelines, verified the cell function. A 0.2 M NaOH solution with 10 g/L Na₂S was used, applying 10 mA · cm⁻² cathodic current to generate hydrogen atoms on the sample surface. Diffraction patterns were collected during tensile tests, and five reflections were used to calculate dislocation density via the modified Williamson-Hall relationship [?]. This in-situ hydrogen charging cell enables deep understanding of mobile hydrogen effects on X80 pipeline steel deformation mechanisms.

Fig. 14 [Figure 14: see original paper] compares tensile curves for in-situ hydrogen charging versus pre-charged samples. In-situ charging caused obvious elongation reduction and slight yield stress increase, whereas pre-charging did not significantly deteriorate tensile plasticity. Dislocation density evolution during tensile tests is also shown in Fig. 14 [Figure 14: see original paper]. In-situ hydrogen charging caused drastic dislocation density increase compared to pre-charging. Most hydrogen likely escaped the pre-charged sample due to low solubility in BCC steel, minimizing hydrogen effects. Generally, diffusible hydrogen dominates dislocation plasticity [?], while trapped hydrogen affects plasticity by enhancing void nucleation and growth around inclusions and precipitates, favoring ductile fracture [?]. Mobile hydrogen causes embrittlement or plasticity deterioration through mutual interaction with dislocation motion [?, ?]. Mobile dislocations drag hydrogen, while hydrogen facilitates dislocation nucleation and

movement by reducing activation volume and energy [?, ?]. Therefore, in-situ hydrogen charging resulted in higher dislocation density during tensile testing. Similar to Rao's work [?], the pronounced hydrogen-induced stress increase may be attributed to dislocation tangles from higher dislocation density. This study focused on device development; detailed hydrogen concentration, dislocation behavior, and their interactions require future investigation to fully interpret HE mechanisms.

To date, most designed functions are operational. Future work will optimize heating functions and experimental procedures for specific measurements, while ensuring stable operation and functional expansion to meet diverse user requirements.

4. Conclusions

A universal in-situ deformation testing system has been successfully installed at the ultrahard X-ray multifunctional application beamline BL12SW, a phase-II beamline project at the Shanghai Synchrotron Radiation Facility and currently China's first operational high-energy beamline. This system enables in-situ observation of metallic material structural evolution during deformation using high-energy X-ray diffraction and imaging. Designed functions include tensile/compression testing with simultaneous rotation about the tensile axis and electric heating of metallic specimens. Two electrical torsional actuators provide symmetrical torque, achieving ω -rotation without beam obstruction by loading frame columns. A digital video extensometer measures deformation strain without specimen contact. Successful experiments include lattice strain partitioning in eutectic high-entropy alloys, texture evolution in TC4 alloy during tensile deformation, and imaging of explosively welded Ti/Fe cladding plates under load. An electrochemical hydrogen charging cell was developed to study structural changes during in-situ hydrogen charging combined with mechanical loading. This customized testing system represents a functional expansion of BL12SW and is anticipated to significantly contribute to both universal and specific studies of engineering materials.

Authors Contribution: Hai Chang contributed to manuscript writing, conceptualization, methodology, commissioning, investigations, and data collection/analysis. Zichong Zhang contributed to manuscript writing, data analysis, and curation. Hongbo Zhang, Shi Zheng, Lili Cheng, Zhe Zhang, Cheng Zhong, and Feifei Huang contributed to sample preparation, investigations, and data collection/analysis. Zilong Zhao, Zhaohui Dong, Chunyin Zhou, and Ke Yang contributed to beam optimization and beamtime acquisition. Ding Zhang, Weimin Gan, and Heinz-Guenter Brokmeier contributed to programming, methodology, and data analysis. Jinkui Zhao, Dongbai Sun, and Ying Jin contributed to conceptualization, resources, and funding acquisition. Ying Jin provided supervision.

Acknowledgement: We thank the Shanghai Synchrotron Radiation Facility

BL12SW (<https://cstr.cn/31124.02.SSRF.BL12SWRL>) for beamtime and assistance with high-energy XRD measurements. We also thank Mr. Han Zhang for help during measurements at SSRF. This study was supported by SSRF proposals No. 2023-SSRF-HZ-505301, No. 2024-SSRF-PT-505456, and No. 2024-SSRF-PT-508527.

Funding: This work was supported by the National Key Research and Development Program of China (Grant No. 2022YFA1603803), National Natural Science Foundation of China (Grant No. U23B2078), Opening Project Fund of Materials Service Safety Assessment Facilities, and Fundamental Research Funds for the Central Universities (Grant No. FRF-BD-25-012).

Data availability: Data will be made available on request.

References

- [1] K. Yang, Z. Dong, C. Zhou, et al., Ultrahard X-ray multifunctional application beamline at the SSRF. *Nucl. Sci. Tech.*, 35: (2024). DOI: 10.1007/s41365-024-01468-4
- [2] X. H. Hu, X. Sun, L. G. Hector, et al., Individual phase constitutive properties of a TRIP-assisted QP980 steel from a combined synchrotron X-ray diffraction and crystal plasticity approach. *Acta Mater.*, 132: (2017). DOI: 10.1016/j.actamat.2017.04.028
- [3] S. Ackermann, S. Martin, M. R. Schwarz, et al., Investigation of Phase Transformations in High-Alloy Austenitic TRIP Steel Under High Pressure (up to 18 GPa) by In Situ Synchrotron X-ray Diffraction and Scanning Electron Microscopy. *Metall. Mater. Trans. A*, 47: (2015). DOI: 10.1007/s11661-015-3082-2
- [4] M. Zhang, L. Li, J. Ding, et al., Temperature-dependent micromechanical behavior of medium-Mn transformation-induced-plasticity steel studied by in situ synchrotron X-ray diffraction. *Acta Mater.*, (2017). DOI: 10.1016/j.actamat.2017.09.030
- [5] K. Yan, K. Liss, I. B. Timokhina, et al., In situ synchrotron X-ray diffraction studies of the effect of microstructure on tensile behavior and retained austenite stability of thermomechanically processed transformation induced plasticity steel. *Mater. Sci. Eng. A*, 662: (2016). DOI: 10.1016/j.msea.2016.03.048
- [6] A. Ghosh, R. Jain, H. Brokmeier, et al., Microstructure-texture-micro-strain evolution during tensile deformation of $\alpha+\beta$ titanium alloy using in-situ Synchrotron X-ray diffraction and CPFEM simulation. *J. Phys. Conf. Ser.*, 2380: (2022). DOI: 10.1088/1742-6596/2380/1/012137
- [7] A. Suárez, J. M. Amado, M. J. Tobar, et al., Study of residual stresses generated inside laser cladded plates using FEM and diffraction of synchrotron radiation. *Surf. Coat. Technol.*, 204: (2010). DOI: 10.1016/j.surfcoat.2009.11.037
- [8] G. Fan, L. Geng, H. Wu, et al., Improving the tensile ductility of metal matrix composites by laminated structure: A coupled X-ray tomography and digital image correlation study. *Scr. Mater.*, 135: (2017). DOI: 10.1016/j.scriptamat.2017.03.030
- [9] T. Ohgaki, H. Toda, M. Kobayashi, et al., In-situ High-resolution X-ray CT Observation of Compressive and Damage Behaviour of Aluminium Foams by Local Tomography Technique. *Adv. Eng. Mater.*, 8: (2006). DOI: 10.1002/adem.200600039
- [10] Y. Jiao, G. Xu, X. Cui, et al., The HEPS project. *J. Synchrotron Ra-*

diat., 25: (2018). DOI: 10.1107/S1600577518012110 [11] H. Wang, C. Li, H. Zhu, et al., Test of Magnet Girder Prototypes for HEPS-TF. *J. Phys. Conf. Ser.*, 1067: (2018). DOI: 10.1088/1742-6596/1067/8/082023 [12] X. Sun, F. Chen, X. Yang, et al., Superconducting multipole wiggler with large magnetic gap for HEPS-TF. *Nucl. Sci. Tech.*, 33: (2022). DOI: 10.1007/s41365-022-01001-5 [13] R. Tai, Z. Zhao, Overview of SSRF phase-II beamlines. *Nucl. Sci. Tech.*, 35: (2024). DOI: 10.1007/s41365-024-01487-1 [14] J. Ren, Y. Zhang, D. Zhao, et al., Strong yet ductile nanolamellar high-entropy alloys by additive manufacturing. *Nature*, 608: (2022). DOI: 10.1038/s41586-022-04914-8 [15] I. S. Wani, T. Bhattacharjee, S. Sheikh, P. P. Bhattacharjee, S. Guo, N. Tsuji, Tailoring nanostructures and mechanical properties of AlCoCrFeNi_{2.1} eutectic high entropy alloy using thermo-mechanical processing. *Mater. Sci. Eng. A* 675, 99-109 (2016). DOI: 10.1016/j.msea.2016.08.048 [16] Y. Dong, J. Yuan, Z. Zhong, S. Liu, J. Zhang, C. Li, Z. Zhang, Accelerated design eutectic-high-entropy-alloys using simple empirical rules. *Mater. Lett.* 309, 131340 (2022). DOI: 10.1016/j.matlet.2021.131340 [17] X. Gao, Y. Lu, B. Zhang, N. Liang, G. Wu, G. Sha, J. Liu, Y. Zhao, Microstructural origins of high strength and high ductility in an AlCoCrFeNi_{2.1} eutectic high-entropy alloy. *Acta Mater.* 141, 59-66 (2017). DOI: 10.1016/j.actamat.2017.07.041 [18] Q. Zhang, M. Song, G. Luo, T. Shen, H. Hu, D. Wang, Recent Advances of High-Entropy Intermetallics for Electrocatalysis. *Chem. Mater.* 36, 10967-10985 (2024). DOI: 10.1021/acs.chemmater.4c02151 [19] J. Shen, J. G. Lopes, Z. Zeng, et al., Deformation behavior and strengthening effects of an eutectic AlCoCrFeNi_{2.1} high entropy alloy probed by in-situ synchrotron X-ray diffraction and post-mortem EBSD. *Mater. Sci. Eng. A*, 872: (2023). DOI: 10.1016/j.msea.2023.144946 [20] Y. Tian, S. Lin, J. Y. P. Ko, et al., Micromechanics and microstructure evolution during in situ uniaxial tensile loading of TRIP-assisted duplex stainless steels. *Mater. Sci. Eng. A*, 734: (2018). DOI: 10.1016/j.msea.2018.07.040 [21] D. Guan, X. Liu, J. Gao, et al., Effect of deformation twinning on crystallographic texture evolution in a Mg-6.6Zn-0.2Ca (ZX70) alloy during recrystallisation. *J. Alloys Compd.*, 774: (2019). DOI: 10.1016/j.jallcom.2018.10.065 [22] B. Jiang, Q. Xiang, A. Atrens, et al., Influence of crystallographic texture and grain size on the corrosion behaviour of as-extruded Mg alloy AZ31 sheets. *Corros. Sci.*, 126: (2017). DOI: 10.1016/j.corsci.2017.08.004 [23] S. Cao, C. V. S. Lim, B. Hinton, et al., Effects of microtexture and Ti₃Al (α_2) precipitates on stress-corrosion cracking properties of a Ti-8Al-1Mo-1V alloy. *Corros. Sci.*, 116: (2017). DOI: 10.1016/j.corsci.2016.12.012 [24] C. Randau, U. Garbe, H. Brokmeier, StressTextureCalculator: A software tool to extract texture, strain and microstructure information from area-detector measurements. *J. Appl. Crystallogr.*, 44: (2011). DOI: 10.1107/S0021889811012064 [25] R. E. Brydon, J. Burle, J. Coenen, et al., "Stress and texture calculator Steca, version 2" . [26] Q. Chu, X. Tong, S. Xu, et al., Interfacial Investigation of Explosion-Welded Titanium/Steel Bimetallic Plates. *J. Mater. Eng. Perform.*, 29: (2020). DOI: 10.1007/s11665-019-04535-9 [27] Q. Chu, M. Zhang, J. Li, et al., Experimental and numerical investigation of microstructure and mechanical behavior of titanium/steel interfaces prepared by explosive weld-

ing. Mater. Sci. Eng. A, 689: (2017). DOI: 10.1016/j.msea.2017.02.075 [28] Y. Zhu, X. Wu, Heterostructured materials. Prog. Mater. Sci., 131: (2023). DOI: 10.1016/j.pmatsci.2022.101019 [29] D. Guedes, L. Cupertino Malheiros, A. Oudriss, et al., The role of plasticity and hydrogen flux in the fracture of a tempered martensitic steel: A new design of mechanical test until fracture to separate the influence of mobile from deeply trapped hydrogen. Acta Mater., 186: (2020). DOI: 10.1016/j.actamat.2019.12.045 [30] S. Wang, N. Hashimoto, Y. Wang, et al., Activation volume and density of mobile dislocations in hydrogen-charged iron. Acta Mater., 61: (2013). DOI: 10.1016/j.actamat.2013.05.007 [31] W. Zhao, T. Du, X. Li, et al., Effects of multiple welding thermal cycles on hydrogen permeation parameters of X80 steel. Corros. Sci., 192: (2021). DOI: 10.1016/j.corsci.2021.109797 [32] J. Rao, S. Lee, G. Dehm, et al., Hardening effect of diffusible hydrogen on BCC Fe-based model alloys by in situ backside hydrogen charging. Mater. Des., 232: (2023). DOI: 10.1016/j.matdes.2023.112143

Note: Figure translations are in progress. See original paper for figures.

Source: ChinaXiv – Machine translation. Verify with original.