Fast-current-heating devices to study *in situ* phase formation in metallic glasses by using high-energy synchrotron radiation

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ABSTRACT

Details of fast-resistive-heating setups, controlled heating ranging from $\sim 10^1$ K s⁻¹ to $\sim 10^3$ K s⁻¹, to study *in situ* phase transformations (on heating and on cooling) in metallic glasses by high-energy synchrotron x-ray diffraction are discussed. Both setups were designed and custom built at the Leibniz Institute for Solid State and Materials Research Dresden (IFW Dresden) and have been implemented at the P02.1 Powder Diffraction and Total Scattering Beamline and the P21.1 Swedish Materials Science Beamline at PETRA III storage ring, DESY, Hamburg. The devices are interchangeable at both beamlines. Joule heating is triggered automatically and is timed with the incident beam and detector. The crystallization process can be controlled via a feedback circuit by monitoring the change in the time-dependent resistivity and temperature of glasses. Different ambient atmospheres, such as vacuum and inert gases (He and Ar), can be used to control oxidation and cooling. The main focus of these devices is on understanding the crystallization mechanism and kinetics in metallic glasses, which are brittle and for which fast heating gives defined glass-crystal composites with enhanced plasticity. As an example, phase-transformation sequence(s) in a prototyped Cu-Zr-based metallic glass is described on heating, and a crystalline phase beneficial to the plasticity is identified.

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I. INTRODUCTION

Metallic glasses (MGs) have some interesting mechanical properties, for example, high toughness and hardness, large fracture strength, and low mechanical damping,¹ which make them stand out from other traditional metallic-based alloys. Nevertheless, MGs suffer from poor compressive plasticity and tensile ductility, which limit their application as structural materials. Among other methods to improve the mechanical properties of MGs,^{2–5} forming glass-crystal composites has given materials with significantly enhanced plasticity (up to $\sim 10\%$ plastic strain can be achieved⁶), ductility,^{7,8} and with higher toughness than the corresponding glass.^{9–11} In

order to control and tune the mechanical properties of the resulting MG-crystal composites, the crystallization mechanism and kinetics of phase formation have to be understood. The final composite microstructure, phase types, crystal size, and their distribution are better controlled on heating the glass, rather than on cooling the liquid, which allows for tuning the crystallization mechanism by changing the heating rate, Φ .

A Cu-Zr-based family of metallic glasses has often been studied in theoretical and experimental works because of its good glass-forming ability and interesting features of the crystalline phases formed upon annealing. The cubic B2-CuZr crystalline phase (space group $Pm\bar{3}m$ and a prototype CsCl structure) is known to be

beneficial to plasticity, but it is metastable at low temperatures; the stable temperature is ~ 900 K and above.¹² For a Cu–Zr–Al-based glassy family, heating rates of $\Phi \sim 10^2$ K s⁻¹ and higher are needed to suppress the unwanted formation of the brittle low-temperature phases, such as Cu₁₀Zr₇ (space group C2ca) and CuZr₂ (space group I4/mmm), and to directly go into the crystallization regime in which the ductile B2 phase is dominantly formed.¹³ Therefore, heating cells with heating rates varying from ~ 10 K min⁻¹ to $\sim 10^2$ K min⁻¹ are not sufficiently fast.^{14–16} To access higher heating rates, the so-called flash-annealing methods utilizing electric current passing through the sample, named resistive or Joule heating, and eddy currents induced by a high-frequency external magnetic field (induction heating) can be used.^{6,17–19}

Küchemann and Samwer²⁰ have presented a capacitance-discharge-heating device, designed after the work of Johnson *et al.*,²¹ which gave new insights into *in situ* structural evolution and crystallization of a Zr-based metallic-glass ribbon at the beamline P07 at PETRA III, DESY, in air. Given the capacitance of 1 mF and a built-in discharge circuit resistance, heating was intentionally limited to extremely high rates of $\sim 10^5$ K s⁻¹ to 10^6 K s⁻¹ only. Also, dominant formation of ZrO₂ was observed at highest heating rates because of the ambient atmosphere. The oxidation of Vit106a glass was later suppressed by doing the capacitance-discharge heating in an argon atmosphere, and structural changes on fast heating were studied at the beamline 11-ID-C at the Advanced Photon Source of the Argonne National Laboratory.²² A combination of conventional calorimetry, DC heating, and the above-noted capacitance-discharge heating was applied by Küchemann *et al.*²³ to study the kinetics of the glass-transition temperature, T_g , and the onset of crystallization, T_x , for Φ ranging from 10^{-1} K s⁻¹ to 10^6 K s⁻¹ in Zr₆₅Cu_{27.5}Al_{7.5} metallic glass. Note that there have been a variety of fast-resistive-heating devices constructed to study the influence of crystallization on magnetic properties of soft-magnetic Fe-based glasses.^{17,18,24–26}

Here, we describe and demonstrate the capabilities of two current-induced-heating devices, designed and constructed at the Leibniz Institute for Solid State and Materials Research Dresden (IFW Dresden), to study *in situ* phase formation at controlled conditions (heating/cooling rate, temperature, and atmosphere). One device is intended for controlled DC heating of ribbons and the other device is for pulsed heating of bulk-metallic glasses (BMGs). The devices have been implemented at the P02.1 Powder Diffraction and Total Scattering Beamline and at the P21.1 side branch of the Swedish Materials Science Beamline at PETRA III storage ring, DESY, Hamburg. Third-generation synchrotron radiation sources are particularly of interest for *in situ* studies of structural changes and associated physical responses in a variety of materials.²⁷ The beamline P02.1 is operated at a fixed photon energy of 60 keV and is suitable for high-resolution high-energy powder diffraction.²⁸ The recently built P21.1 beamline operates at 52 keV, 85 keV, and 100 keV and is dedicated to high-energy x-ray single-crystal diffraction and total scattering.²⁹

Although the main focus here is on demonstrating case studies of crystallization with the aim to form MG–crystal composites, the custom-built devices can also be used to study fundamental properties of glass-forming liquids, for example, continuous-heating- and continuous-cooling-transformation diagrams, *in situ* structural changes in glasses and supercooled liquids, nucleation and crystal-growth kinetics, and influence of thermal history on glasses' properties

by rejuvenating/relaxing glasses via glass–supercooled liquid–glass cycling—all of these are beyond the scope of this instrumental review paper.

II. DEVICES' DESIGN

Figure 1 shows schematics of the fast-heating setups custom built at IFW Dresden for probing crystallization in [(a) and (b)] metallic-glass ribbons and [(c) and (d)] bulk-metallic glasses at DESY. Photographs of the devices are presented in Fig. 2: Fig. 2(a) shows the device for ribbons and that in Fig. 2(b) is for BMGs.

A. Ribbons

Melt-spun ribbons (≈ 30 μ m thick, ~ 2 mm wide), cut into ≈ 5.4 cm long pieces, ≈ 3 cm of an active length, are resistively heated in a constant-current mode by using a Delta Elektronika SM 52-30 power supply. The sample surface temperature is monitored by using a LumaSense IGA 320/23-LO pyrometer with a temporal resolution of 2 ms in analog mode, which is calibrated on the known melting point of the glass—measured independently by high-temperature calorimetry. All monitor and signal data are analyzed and collected by a digital analog converted USB-6211 (National Instruments; a sampling rate of up to 250 kS s⁻¹) and processed in Labview based software on PC. In the case study presented in Sec. III, data were acquired at a rate of 48 kS s⁻¹ with subsequent averaging, reducing the sample rate down to 4 kS s⁻¹. Before sample resistance is directly measured by the acquisition card, the voltage drop along the sample is reduced by a voltage divider with a reduction ratio of $\frac{1}{4}$ to adjust it to the card input range at high heating currents.

B. Bulk-metallic glasses

Heating of a BMG sample, ≈ 10 mm long, ≈ 500 μ m thick, and ≈ 1.5 mm wide, is done via an electrical-current pulse generated by a power supply unit (Magna-Power SL 25-60 equipped with the Option + HS 1,5-15) connected to a signal wave generator (Rohde & Schwarz HMF2525). The surface temperature is monitored by a LumaSense IGA 12LO pyrometer (temporal resolution of 2 ms), which is calibrated using a type T thermocouple. The current is measured via a current probe (Chauvin Arnoux E3) with switching electronics that transform it into a voltage signal. A datalogger (FLUKE NetDAQ 2645A) with a sampling rate of 1 kS s⁻¹ is utilized to record temperature, electrical current, and voltage signals.

For both setups, a high-speed pyrometer is focused on the sample through a KBr window and coincides with the primary x-ray beam (Figs. 1 and 2), which passes through a polyimide-foil window (thickness of 250 μ m). The output windows are made of borosilicate glass (100 mm in a diameter and 5.5 mm thick), thermally strengthened similar to DIN 7080 from Herberts Industrieglas GmbH & Co, Wuppertal, Germany, for the ribbon setup, and of polyimide foil (23 mm in a diameter and 250 μ m thick) for the BMG setup; lids are not shown in the photographs (Fig. 2). Typically, a sample is kept in vacuum when heated, but the presence of a gas inlet allows for different atmospheres, commonly Ar and He, to be maintained in the closed chamber to prevent oxidation, typically dominated by the formation of ZrO₂ for Cu–Zr-based glasses,³⁰ and to control the cooling rate. A typical controlled heating rate ranges from

FIG. 1. Schematics of the fast-current-heating devices designed and custom built at IFW Dresden for *in situ* high-energy x-ray studies of phase transformations in metallic-glass (MG): [(a) and (b)] ribbons (≈ 3 cm of an active length) and [(c) and (d)] bulk samples (≈ 10 mm long, ≈ 500 μm thick, and ≈ 1.5 mm wide) in a transmission mode at DESY, Hamburg. For clarity, parts in (a) and (c) do not show the air-tight lid used during the experiments. Please refer to Fig. 2 for scaling.

~ 50 K s^{-1} to $\sim 10^3$ K s^{-1} for ribbons and between ~ 50 K s^{-1} and ~ 3000 K s^{-1} for BMGs. For ribbons, a heating up to 10^5 K s^{-1} can be achieved to study, for example, crystallization kinetics and structural changes, but the sample temperature is difficult to control, and such fast heating is impractical for composites formation. An initial cooling rate is about 200–300 K s^{-1} in a vacuum of 10^{-4} mbar for both

devices. Additionally, both devices can be equipped with an external high-speed video camera accessory, for example, a FASTCAM SA3 model 120K with a frame rate of up to 120 000 fps, to study *in situ* the propagation of a thermal front for heated samples. The camera can be triggered automatically from extern and synchronized with heating.

FIG. 2. Photographs of the fast-current-induced heating devices for (a) ribbons and (b) bulk-metallic glasses. The x-ray beam direction is highlighted by the yellow arrows. Please refer to Fig. 1 [panels (a) and (b)] for the description of the individual components.

III. CASE STUDY OF PHASE-TRANSFORMATIONS IN Cu–Zr-BASED GLASSES

A. Sample preparation

Pre-alloys of $\text{Cu}_{47.5}\text{Zr}_{47.5}\text{Al}_{4.0}\text{Co}_{0.5}$ (at. %) and $\text{Cu}_{44}\text{Zr}_{44}\text{Al}_8\text{Hf}_2\text{Co}_2$ (at. %) were prepared from high-purity elements ($\geq 99.99\%$) by arc-melting in a Ti-gettered Ar atmosphere. Each ingot was remelted three times to ensure chemical homogeneity. $\text{Cu}_{47.5}\text{Zr}_{47.5}\text{Al}_{4.0}\text{Co}_{0.5}$ alloy was melt-spun as a ribbon and $\text{Cu}_{44}\text{Zr}_{44}\text{Al}_8\text{Hf}_2\text{Co}_2$ alloy was cast into bulk-metallic-glass plates. The ribbon, $\approx 30\ \mu\text{m}$ thick and $\sim 2\ \text{mm}$ wide, was spun from a master-alloy melt ($T \sim 1320\ \text{K}$) on a Cu wheel rotating at $29\ \text{m s}^{-1}$. The plates (with a width of $\approx 10\ \text{mm}$, a thickness of $\approx 1.5\ \text{mm}$, and a length of $\approx 55\ \text{mm}$) of $\text{Cu}_{44}\text{Zr}_{44}\text{Al}_8\text{Hf}_2\text{Co}_2$ were prepared via suction casting in a water-cooled copper mold (Edmund Bühler) under a Ti-gettered Ar atmosphere. The as-cast plates were cut into $\approx 10\ \text{mm}$ long pieces.

B. Synchrotron experiments

In situ high-energy synchrotron x-ray diffraction (XRD) carried out in a transmission mode is shown here to demonstrate the devices performance and properties. In most experiments, heating is done in a vacuum of 10^{-4} mbar (if not specified otherwise).

For ribbons, high-energy x-ray diffraction was done at the P21.1 beamline at DESY (wavelength $0.1204\ \text{\AA}$ and a beam size of $\approx 900 \times 900\ \mu\text{m}^2$). Scattered intensities were captured by using a hybrid pixel Dectris PILATUS3 X CdTe 2M detector (pixel size $172 \times 172\ \mu\text{m}^2$) operated at 250 Hz. Diffractograms were derived from the recorded 2D patterns by azimuthal integration using the Fit2D v17.006 software.^{31–33}

For BMGs, prior to measurements, the as-cast glassy plates were grinded down to a uniform thickness of $\approx 500\ \mu\text{m}$; the final sample was then $\approx 10\ \text{mm}$ long and $\approx 1.5\ \text{mm}$ wide. High-energy x-ray diffraction was performed at the P02.1 beamline at DESY (wavelength of $0.2066\ \text{\AA}$ and a beam size of $\approx 500 \times 500\ \mu\text{m}^2$). Diffraction patterns were derived from the recorded 2D data of a Lambda 2M GaAs detector (X-Spectrum, pixel size $55 \times 55\ \mu\text{m}^2$). The 2D data were taken at a frame rate of 100 Hz. The collected 2D patterns were integrated using the DESY p02_processing_tool software (version 0.26m_beta11; May 11, 2018) package developed by one of the authors of this paper.³⁴ Both resistive-heating setups are interchangeable at both beamlines.

Heating of the glasses can readily be controlled by the applied power as consistent with Joule heating, $P = I^2 \times R$, where I is the applied current and R is the sample resistance. In a constant-current mode, the heating rate scales linearly with the applied power up to $10^3\ \text{K s}^{-1}$, as shown in Fig. 3 for ribbons. For heating at $\sim 1000\ \text{K s}^{-1}$ and slower, the rate is non-linear, and it is difficult to transpose T_g and T_x on the same heating curve. An effective heating rate is estimated by assuming linear heating between room temperature and T_x . This provides Φ values comparable with the literature^{6,13} and consistent with ultra-fast scanning calorimetry.^{35,36} For ribbons, a fast $\sim 250\ \text{ms}$ probing period is introduced to determine the sample's resistance before heating. The known resistance is then used as an input parameter to match heating rates, applied power, of different samples in a constant-current mode.

The glass-transition temperature, T_g , and the temperature corresponding to the onset of crystallization, T_x , can readily be

FIG. 3. Linear dependence of an effective heating rate, Φ , on the applied power, P , for the $\text{Cu}_{47.5}\text{Zr}_{47.5}\text{Al}_{4.0}\text{Co}_{0.5}$ glassy ribbon in the typical range of heating rates used for composites formation and in a vacuum of 10^{-4} mbar. The solid line shows a linear fit to the experimental data points ($R^2 = 0.9979$).

measured by monitoring the temporal evolution of resistance and sample temperature [Figs. 4(a) and 4(c)]. An endothermic glass transition is manifested by the change in the slope of the evolving heat monitored by the pyrometer, $t \approx 390\ \text{ms}$, $T \approx 750\ \text{K}$, for the $\text{Cu}_{47.5}\text{Zr}_{47.5}\text{Al}_{4.0}\text{Co}_{0.5}$ ribbon [Figs. 4(a)] and, $t \approx 3850\ \text{ms}$, $T \approx 745\ \text{K}$, for the $\text{Cu}_{44}\text{Zr}_{44}\text{Al}_8\text{Hf}_2\text{Co}_2$ BMG [Fig. 4(c)]. A sharp drop in the resistance, at $t_x \approx 625\ \text{ms}$, $T_x \approx 890\ \text{K}$ [Fig. 4(a)] and at $t_x \approx 4950\ \text{ms}$, $T_x \approx 910\ \text{K}$ [Fig. 4(c)], marks the onset of crystallization of the $\text{Cu}_{47.5}\text{Zr}_{47.5}\text{Al}_{4.0}\text{Co}_{0.5}$ ribbon and that of the $\text{Cu}_{44}\text{Zr}_{44}\text{Al}_8\text{Hf}_2\text{Co}_2$ BMG, respectively. There are limited studies of independent measurements of T_g and T_x at such high heating rates. Cheng *et al.*³⁵ measured T_g and T_x for $\text{Cu}_{47.5}\text{Zr}_{47.5}\text{Al}_{5.0}$ alloy by ultra-fast scanning calorimetry. For the present heating at $\Phi \approx 950\ \text{K s}^{-1}$ [Fig. 4(a)], T_g and T_x conform to $T_g = 770\ \text{K}$ and $T_x = 900\ \text{K}$ reported at $\Phi = 1000\ \text{K s}^{-1}$.³⁵ Although the composition studied by Cheng *et al.*³⁵ differs from the present study, Miao *et al.*³⁶ have shown that for the equimolar CuZr, calorimetric T_g and T_x are nearly unchanged when the glass is alloyed with 5 at. % of Co; measured by ultra-fast heating calorimetry at $\Phi = 3000\text{--}4000\ \text{K s}^{-1}$. For bulk $\text{Cu}_{44}\text{Zr}_{44}\text{Al}_8\text{Hf}_2\text{Co}_2$, the measured T_g and T_x are in good agreement with the results published on the same alloy in Refs. 6 and 13.

For the ribbon, the use of the voltage divider results in larger noise level during resistance monitoring measurements by passing small test currents prior and posterior to the annealing process [see Fig. 4(a) after 800 ms]. For the BMGs-heating setup, the sample resistance has much weaker temperature dependence than the heated components. The temporal evolution of resistance, giving an upward slope in the temperature-dependent resistance at the early stages of heating, is mainly dominated by the resistance change in the heated electrodes and sample mounting. Taking the linear part of the temperature-dependent resistance in Fig. 4(a), before T_x , gives

FIG. 4. Time-resolved *in situ* x-ray diffraction data of [(a) and (b)] the $\text{Cu}_{47.5}\text{Zr}_{47.5}\text{Al}_{4.0}\text{Co}_{0.5}$ glassy ribbon collected at 250 Hz sampling rate at the P21.1 beamline and those of [(c) and (d)] the $\text{Cu}_{44}\text{Zr}_{44}\text{Al}_8\text{Hf}_2\text{Co}_2$ BMG collected at 100 Hz at the P02.1 beamline on heating in a vacuum of $\sim 10^{-4}$ mbar. [(a) and (c)] The crystallization onset is detected as the drop and the recalcence event on the time-dependent resistivity and pyrometer temperature, respectively. [(b) and (d)] The integrated intensities of a phase evolution on heating the glass show the existence of three distinct states: (i) the glass, (ii) the supercooled liquid, and (iii) the crystalline state (the red arrows evidence the existence of the B2–CuZr phase, and the minor presence of $\text{Cu}_{10}\text{Zr}_7$ phase is indicated by the black arrows—only the most significant peaks are labeled for clarity).

a temperature coefficient of resistance of about $4.1 \times 10^{-5} \text{ K}^{-1}$ for the ribbon. This is two orders of magnitude lower than that for pure copper for which the coefficient is $3.93 \times 10^{-3} \text{ K}^{-1}$.³⁷ The resistance of the bulk-metallic glass given in Fig. 4(c) was processed by a Savitzky–Golay method using Origin 2020.

Due to the linear thermal expansion, bending of ribbon in the direction of the x-ray beam occurs upon heating. This results in changing the sample-to-detector distance as well as peak position on measured XRD patterns. For example, a ribbon movement of 5 mm, overestimated value, would cause a peak shift of about 0.015 Å^{-1} in the Q -space by measurements at a sample-to-detector distance of 1021 mm as in the present work. This effect should be kept in mind when interpreting the diffraction data, but it does not obstruct qualitative and quantitative phase analysis.

The temporal evolution of integrated intensities reveals phase transformations on heating for the $\text{Cu}_{47.5}\text{Zr}_{47.5}\text{Al}_{4.0}\text{Co}_{0.5}$ glassy ribbon and for the $\text{Cu}_{44}\text{Zr}_{44}\text{Al}_8\text{Hf}_2\text{Co}_2$ BMG, as shown in Figs. 4(b) and 4(d), respectively. The time-dependent resistance and temperature, measured simultaneously with the x-ray diffraction, are shown in the upper panels of the corresponding parts. The existence of three distinct states can be recognized from the *in situ* experiments: (i) the glassy state ranging from 0 ms to 380 ms, from room temperature up to 750 K, for the $\text{Cu}_{47.5}\text{Zr}_{47.5}\text{Al}_{4.0}\text{Co}_{0.5}$ glassy ribbon and from 0 ms to 3850 ms, from room temperature up to 745 K, for the $\text{Cu}_{44}\text{Zr}_{44}\text{Al}_8\text{Hf}_2\text{Co}_2$ BMG; (ii) the supercooled liquid ranging between 380 ms and 652 ms, 750–890 K, for the $\text{Cu}_{47.5}\text{Zr}_{47.5}\text{Al}_{4.0}\text{Co}_{0.5}$ glassy ribbon and 3850–4950 ms,

745–910 K, for the $\text{Cu}_{44}\text{Zr}_{44}\text{Al}_8\text{Hf}_2\text{Co}_2$ BMG; and (iii) the crystalline state for $t \geq 625$ ms, $T \geq 890$ K, for the $\text{Cu}_{47.5}\text{Zr}_{47.5}\text{Al}_{4.0}\text{Co}_{0.5}$ glassy ribbon and $t \geq 4950$ ms, $T \geq 910$ K, for the $\text{Cu}_{44}\text{Zr}_{44}\text{Al}_8\text{Hf}_2\text{Co}_2$ BMG until melting is reached (not shown here).

The crystallization of both samples is dominated by the formation of the B2–CuZr phase [indicated by the red arrows in Figs. 4(b) and 4(d) for the $\text{Cu}_{47.5}\text{Zr}_{47.5}\text{Al}_{4.0}\text{Co}_{0.5}$ glassy ribbon and $\text{Cu}_{44}\text{Zr}_{44}\text{Al}_8\text{Hf}_2\text{Co}_2$ BMG, respectively] accompanied by the formation of the low-temperature $\text{Cu}_{10}\text{Zr}_7$ phase [highlighted by the black arrows in Figs. 4(b) and 4(d) for ribbons and BMGs, respectively]. Note that only the most prominent diffraction peaks of both identified phases are marked in Fig. 4. It is the B2 phase that is beneficial to the plasticity of metallic-glass–crystal composites.³⁸ For the selected samples studied here, the applied heating rates are sufficiently high to suppress crystallization of the brittle low-temperature phases, such as commonly observed CuZr_2 , with the minor formation of $\text{Cu}_{10}\text{Zr}_7$.¹³ Even with this minor content of the low-temperature $\text{Cu}_{10}\text{Zr}_7$ phase, the glass–crystal composite may show considerable amount of ductility.⁷

Because of the controlled heating, glass–crystal composites containing dominantly the B2 phase can be made (Fig. 5). Figure 5(b) shows the integrated intensities of a final glass–crystal composite formed on heating the ribbon in a chamber flushed with He, which gives a higher initial cooling rate of about 1100 K s^{-1} , unlike $200\text{--}300 \text{ K s}^{-1}$ in vacuum. To form a composite, the heating must be stopped just before T_x is reached—which is monitored by the resistivity and pyrometer readings [Fig. 5(a)]. When the glass is

FIG. 5. (a) Temperature evolution (*left abscissa*) and time-dependent resistivity (*right abscissa*) of the $\text{Cu}_{47.5}\text{Zr}_{48}\text{Al}_{4.0}\text{Co}_{0.5}$ metallic-glass ribbon heated in a chamber flushed with He to form a glass–crystal composite. (b) *Ex situ* diffractogram derived from the Dectris PILATUS3 X CdTe 2M detector, collected at 1 Hz sampling rate, showing the final glass–crystal composite containing the B2–CuZr phase (red arrows; only a few peaks are labeled) measured at the P21.1 beamline. The inset shows part of the 2D recorded pattern by the detector.

heated at or above T_x , fast crystallization takes place resulting in fully crystalline samples. A composite composed of the parent glass and dominantly B2 phase [marked by the red arrows in Fig. 5(b)] can readily be resolved. Part of the 2D scattered pattern is also shown as the inset in Fig. 5(b).

IV. CONCLUSIONS

Two devices, developed and custom built at the Leibniz Institute for Solid State and Materials Research Dresden, were presented for studying phase transformations in ribbons and bulk-metallic glasses at controlled sample temperature, in terms of heating/cooling rate and ambient atmosphere, by *in situ* high-energy x-ray diffraction. The case studies were carried out at the beamlines P21.1 and P02.1 at PETRA III, DESY. Both devices are interchangeable at both beamlines. It was demonstrated that the crystallization mechanism on heating can readily be controlled, with typical heating rates up to the range of $\sim 10^3 \text{ K s}^{-1}$ relevant for composite formation, and related to the formation of metallic-glass–crystal composites with enhanced plasticity. The fast-current-heating devices also allow for other fundamental properties of glass-forming liquids to be studied, such as phase transformation diagrams on heating and cooling, crystallization kinetics, *in situ* structural changes, and relaxation/rejuvenation by thermal cycling through supercooled liquid.

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DATA AVAILABILITY

Raw data were generated at the Deutsches Elektronen-Synchrotron (DESY) large scale facility. The data that support the findings of this study are available from the corresponding author upon reasonable request.

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