



Novel Soft Magnetic Co-Based Ternary Co–Er–B Bulk Metallic Glasses

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Abstract

In this work, a series of Co-based ternary Co–Er–B bulk metallic glasses (BMGs) with excellent soft magnetic properties and high strength were developed, and the local atomic structure of a typical Co_{71.5}Er_{3.5}B₂₅ metallic glass was studied through in situ high-energy synchrotron X-ray diffraction and ab initio molecular dynamics simulations. The results reveal that the BMG samples can be obtained in a composition region of Co_{68.5–71.5}Er_{3.5–4}B_{25–27.5} by a conventional copper-mold casting method. The Co–Er–B metallic glasses possess stronger atomic bond strengths and denser local atomic packing structure composed of a higher fraction of icosahedral-like clusters but fewer deformed body-centered cubic and crystal-like polyhedrons, and they exhibit slower atomic diffusion behaviors during solidification, as compared to Co–Y–B counterparts. The enhancement in structural stability and the retardation of atomic-ordered diffusion lead to the better glass-forming ability of the Co–Er–B alloys. The smaller magnetic anisotropy energy in the Co–Er–B metallic glasses results in a lower coercivity of less than 1.3 A/m. The Co–Er–B BMGs exhibit high-yield strength of 3560–3969 MPa along with distinct plasticity of around 0.50%.

Keywords Co-based bulk metallic glass · Glass-forming ability · Soft magnetic property · Ab initio molecular dynamics simulation · Local atomic structure

1 Introduction

Since Duwez first prepared Au–Si amorphous alloys by melt quenching in 1960 [1], such materials with a distinctive structure have captivated people's attention. The long-range disordered atomic arrangement inherent in the

amorphous alloys (or called metallic glasses) gives them unique mechanical, physical, and chemical properties that cannot be achieved in crystalline counterparts [2–4]. The early developed metallic glasses commonly exist in the forms of ribbons, wires, or films due to their low glass-forming ability (GFA) [5]. Through rational compositional design strategies, such as Inoue's three empirical rules [2], eutectic criteria [6], minor alloying [7], and so forth, the GFA of the alloys gets enhanced, and the glassy samples in bulk form have been successively discovered. Bulk metallic glasses (BMGs), typically defined for the alloys with a critical sample size of ≥ 1 mm, have been developed in Pd/Pt-based [8, 9], Zr/Ti/Cu-based [10–12], Mg/Ca/Ce/La-based [13–16], and Fe/Co/Ni-based [17–19] alloy systems. Although multi-component-alloyed alloys might possess higher GFA, it is important and valuable to develop binary or ternary BMGs. The long-range disorder atomic structure characteristic of the BMGs makes it challenging to analyze structural information, crucial for comprehending glass formation, while the BMGs with fewer types of components might offer convenience. For instance, the local atomic structure of the binary/ternary BMGs [20] can be analyzed through both

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experiments and simulations; nevertheless, the complexity dramatically increases when dealing with multi-component BMGs [21]. In addition, the binary or ternary BMGs can also serve as base alloys for developing BMGs with further enhanced GFA and other properties.

The Co-based BMGs can be roughly divided into two categories: One category possesses ultrahigh strength. For example, Co-based Co–Ta–B ternary BMGs possess fracture strength of over 6000 MPa, setting the highest record among all bulk alloys [22]. The other category exhibits excellent soft magnetic properties. Compared to Fe-based metallic glasses, the Co-based metallic glasses typically exhibit lower coercivity (H_c), higher permeability, and near zero saturation magnetostriction coefficient (λ_s), which make them more suitable for high-frequency applications. For example, Co-based Co–Y–B metallic glasses [23] possess lower H_c than Fe-based Fe–Y–B metallic glasses [24]. An amorphous Co-based Co–Fe–Si–B–Cr alloy has much lower λ_s and H_c than amorphous Fe–Ni–Si–B–C alloys [25]. In addition, the Co-based metallic glasses exhibit better corrosion resistance than the Fe-based alloys [26]. However, due to that the Co-based alloys suffer from weaker GFA than the Fe-based alloys, the Co-based BMGs usually feature low Co contents and/or composed of four or more elements with complex compositions. The low Co contents reduce ferromagnetic characteristic, and hence, most of the soft magnetic Co-based BMGs are multi-component with alloying Fe. The reported soft magnetic Co-based BMGs are typically found in Co–Fe–TM–B (TM: Transition Metal) [27, 28], Co–(Fe)–RE–(TM)–B (RE: Rare Earth) [23, 29], Co–Fe–TM–Si–B [30], Co–(Fe)–TM–P–B [31, 32], and Co–Fe–B–Si–P [33] systems. Although the B_s of the Co-based BMGs can be enhanced by alloying Fe, the λ_s is increased inevitably [29]. The binary or ternary Fe-free Co-based BMGs with soft magnetic properties have not been reported yet.

The GFA and thermal/mechanical/magnetic properties of the metallic glasses are closely correlated to their local atomic structure. Through ab initio molecular dynamics (AIMD) simulations, Jiang et al. studied the structure of Co-based Co–(P, C, B) amorphous alloys and found that the alloy with stronger atomic bonding and more icosahedral-like (ico-like) polyhedrons exhibits higher GFA [34]. Han et al. found that alloying an appropriate amount of Y into a Fe-based Fe–B alloy increases the fraction of stable atomic local packing and suppresses the formation of deformed body centered cubic (bcc) clusters, leading to enhanced GFA [35]. It is anticipated that alloying RE elements having strong chemical affinities with the constituents into Co-based Co–B alloys might generate more significant effect on enhancing GFA, benefiting from the potential improvements in structural stability and atomic packing density. We have confirmed that minor alloying Y into a $\text{Co}_{75}\text{B}_{25}$ alloy

indeed improves the GFA and magnetic softness; however, obtaining the BMG samples remains a challenge [23]. In this work, a RE element Er was selected to add in the Co–B alloy due to its more negative mixing enthalpies with Co or B compared to other RE elements [36], and the GFA and thermal, magnetic, and mechanical properties of ternary Co–Er–B alloys were studied. Combining in situ high-energy synchrotron X-ray diffraction (HEXRD) with AIMD simulations, the local atomic structure of a $\text{Co}_{71.5}\text{Er}_{3.5}\text{B}_{25}$ BMG was analyzed. For comparison, the GFA and thermal and magnetic properties of $\text{Co}_{71.5}\text{RE}_{3.5}\text{B}_{25}$ (RE = Y, Sm, Gd) alloys were investigated, and the local atomic structure of a $\text{Co}_{71.5}\text{Y}_{3.5}\text{B}_{25}$ counterpart was also studied to clarify the underlying reason of the different GFAs.

2 Materials and Methods

2.1 Experimental Procedure

Master alloy ingots with nominal compositions of $\text{Co}_{62.5-78}\text{Er}_{2-5}\text{B}_{20-32.5}$ and $\text{Co}_{71.5}\text{RE}_{3.5}\text{B}_{25}$ (RE = Y, Sm, Gd) were prepared by arc melting the mixtures of Co (99.98 wt%), RE (99.9 wt%), and B (99.5 wt%) under an argon atmosphere. The alloy ingots were re-melted four times to ensure chemical homogeneity. Alloy ribbons with a thickness of 20 μm and width of 1.5 mm were produced by melt spinning, and cylindrical rods with diameters of 1.0 and 1.5 mm, respectively, and a length of around 20 mm were prepared by copper-mold casting under the argon atmosphere. Structure of the samples was characterized by X-ray diffraction (XRD, Bruker D8 Focus) with $\text{Cu-K}\alpha$ radiation and transmission electron microscopy (TEM, JEOL JEM-2010). A cross-section of the as-cast rods was etched and subsequently observed by optical microscopy (OM, Zeiss Primotech). The largest diameter of the XRD-detected glassy rod sample was determined as the critical diameter for glass formation (d_c). When the d_c was less than 1.0 mm, series of alloy ribbons with a thickness interval of 20 μm were produced, and the largest thickness of the glassy ribbons was set as the critical thickness for glass formation (t_c). The in situ HEXRD experiments at room temperature (300 K) were conducted using the beam line 11-ID-C in the advanced photon source (APS), Argonne national laboratory (ANL), USA, to analyze the local atomic structure. The photon energy was 105.1 keV corresponding to an X-ray wavelength of 0.11798 Å, and the beam size was $0.5 \times 0.5 \text{ mm}^2$. The resultant 2D image files were integrated using the Fit2D program to obtain 1D intensity distributions $I(q)$ as a function of the wavevector q [37], from which the $S(q)$ and the $G(r)$ were derived using the PDFgetX2 program [38]. Glass transition temperature (T_g) and the onset temperature of crystallization (T_x) of the metallic glasses were detected

by differential scanning calorimetry (DSC, TA Ins. Q20) at a heating rate of 0.67 K/s. Liquidus temperature (T_l) was measured by a differential thermal analyzer (DTA, TA Ins. SDT650) under a heating rate of 0.33 K/s. Saturation magnetic flux density (B_s) and H_c were measured by a vibrating sample magnetometer (VSM, LakeShore-7400S) under a maximum applied field of 750 kA/m, and DC B - H loop tracer (Linkjoin MATS-2010SD), respectively. Before the magnetic properties measurements, the ribbons were vacuum-annealed for 300 s at temperatures of ($T_x - 60$) K to release internal stress. Mechanical properties of the BMGs were examined by uniaxial compressive testing using an Instron 5582 mechanical testing machine. The gauge dimension of specimens was 1.0 mm in diameter and 2.0 mm in height, and strain rate was fixed as $5 \times 10^{-4} \text{ s}^{-1}$. The lateral and fracture morphology of the compressed specimens was observed by scanning electron microscopy (SEM, JEOL IT-5600LV). Mass densities of the metallic glasses were determined by an Archimedes method.

2.2 AIMD Simulations

AIMD simulations for $\text{Co}_{71.5}\text{RE}_{3.5}\text{B}_{25}$ (RE = Er, Y) metallic glasses were performed based on density functional theory (DFT) by using the Vienna Ab initio Simulation package [39], combined with canonical NVT ensemble and Nosé thermostat [40]. The cubic simulation boxes with periodic boundary conditions contain 200 atoms, and the box size was determined by the experimental mass densities of the alloys at room temperature. Only the Γ point was adopted for the Brillouin zone sampling. All alloys were melted and equilibrated at 3000 K for 5000 AIMD steps to remove the memory from the initial configurations, after being relaxed for 10 ps, the alloys were sequentially quenched to 2000, 1500, 1100, 800, and 300 K, respectively, at a cooling rate

of $1.67 \times 10^{14} \text{ K/s}$ to produce glassy structure. At each temperature, the equilibrium volume of the supercell was relaxed by approximately keeping the average internal pressure at $\pm 0.5 \text{ kBar}$, and the last 2000 configurations were used for statistical sampling. Pair distribution functions (PDFs) [41] and Voronoi tessellation analysis [42] were conducted by using VMD and OVITO software packages, respectively.

3 Results and Discussion

3.1 GFA and Thermal Stability

Figure 1a illustrates the compositional dependence of the GFA in Co-based ternary Co–Er–B alloys. The alloys within a $\text{Co}_{68.5-71.5}\text{Er}_{3.5-4}\text{B}_{25-27.5}$ region (highlighted in orange) possess a d_c of 1.0 mm, indicating the formation of the BMGs, while the remaining alloys exhibit a lower GFA with d_c values below 1.0 mm. Figure 1b illustrates the XRD patterns of as-cast BMG rods. All exhibit a broad diffraction feature suggesting a single glassy phase. The inset-shown $\text{Co}_{71.5}\text{Er}_{3.5}\text{B}_{25}$ rod sample displays a smooth and lustrous outer surface, which is typical appearance of the BMGs. The homogeneous optical morphology of the transverse cross-section (Fig. 1b(i)) and bright-field TEM image along with a diffuse selected-area electron diffraction (SAED) halo (Fig. 1b(ii)) further confirm the glassy structure in the entire $\text{Co}_{71.5}\text{Er}_{3.5}\text{B}_{25}$ BMG.

The DSC curves of the Co–Er–B BMGs all exhibit a distinct endothermic event corresponding to glass transition, followed by a supercooled liquid region and exothermic reactions caused by crystallization (Fig. 2a). The T_g and T_x roughly increase with lowering the Co content, ranging in 807–855 K and 832–882 K, respectively. The ΔT_x

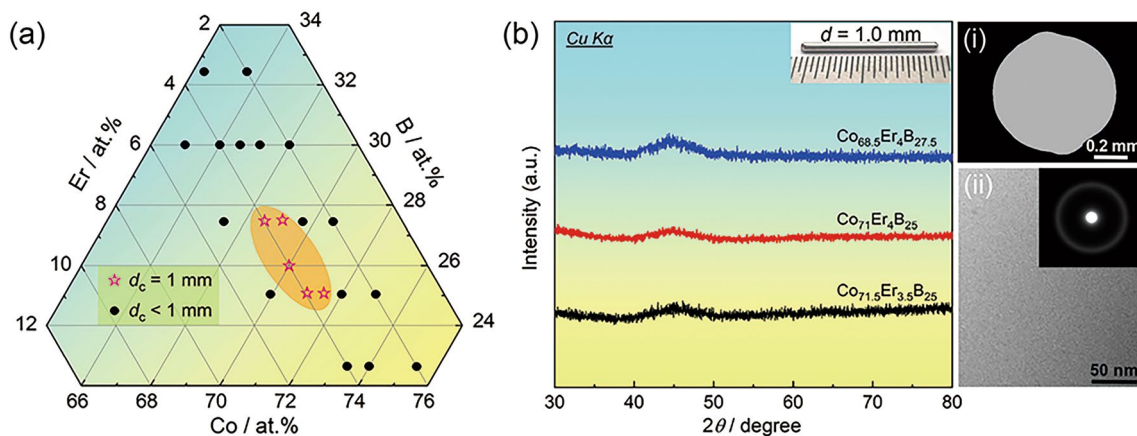


Fig. 1 **a** Compositional dependence of GFA in Co-based Co–Er–B metallic glasses and **b** XRD patterns of as-cast Co–Er–B BMG rods with a diameter of 1.0 mm inset with outer appearance, **i** cross-sectional optical morphology, and **ii** bright-field TEM image along with SAED pattern of a $\text{Co}_{71.5}\text{Er}_{3.5}\text{B}_{25}$ BMG

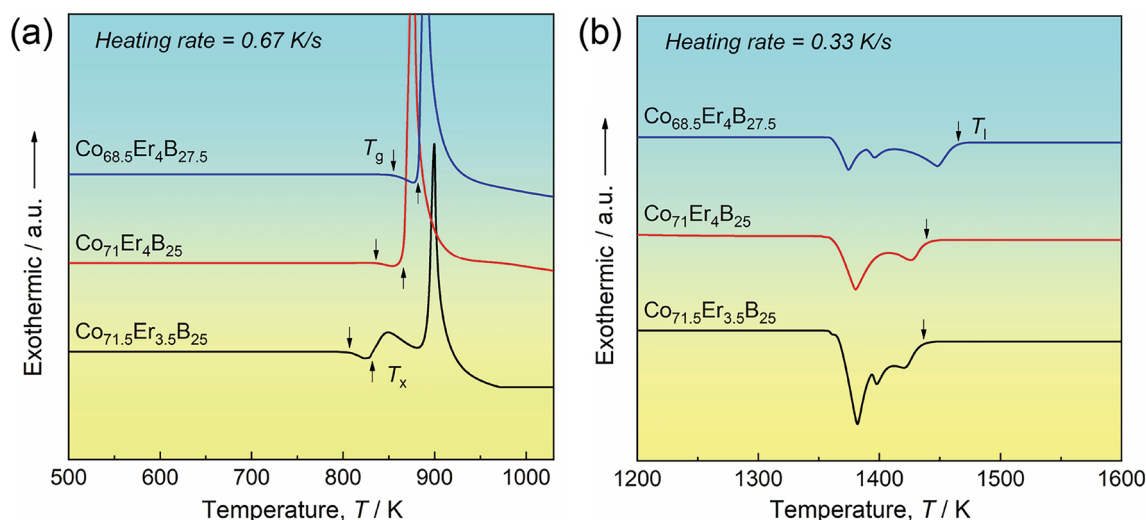


Fig. 2 **a** DSC and **b** DTA curves of Co-based Co–Er–B metallic glasses

($=T_x - T_g$) fluctuates within 25–30 K. After detecting the T_l of the alloys in DTA curves (Fig. 2b), a GFA evaluating parameter T_{rg} ($=T_g/T_l$) [6] was calculated, which ranges in 0.561–0.582. The XRD patterns and DSC curves of $\text{Co}_{71.5}\text{RE}_{3.5}\text{B}_{25}$ (RE = Y, Sm, Gd) counterpart alloys can be seen in Fig. S1 (Supplementary Materials). The T_g , ΔT_x , T_l , T_{rg} , and d_c (or t_c) of the Co–Er–B BMGs and $\text{Co}_{71.5}\text{RE}_{3.5}\text{B}_{25}$ (RE = Y, Sm, Gd) metallic glasses are listed in Table 1. It is seen that the GFA of the $\text{Co}_{71.5}\text{RE}_{3.5}\text{B}_{25}$ (RE = Y, Sm, Gd) alloys is inferior ($t_c = 0.06$ – 0.24 mm), and their T_{rg} values are also lower than those of the Co–Er–B BMGs. As estimated from $T = 10/R^2$ [43], where T (in K/s) is critical cooling rate for glass formation, and R (in cm) refers to d_c or t_c , the T of the Co–Er–B alloys is of the order of 10^3 K/s, much smaller than 10^4 – 10^5 K/s for the $\text{Co}_{71.5}\text{RE}_{3.5}\text{B}_{25}$ (RE = Y, Sm, Gd) alloys.

3.2 Local Atomic Structures

The experimental results demonstrate that the Co–Er–B alloys have higher GFA than the Co–RE–B (RE = Y, Sm, Gd) counterparts. The local atomic structures of the

$\text{Co}_{71.5}\text{RE}_{3.5}\text{B}_{25}$ (RE = Er, Y) metallic glasses were studied to elaborate the mechanism behind it. The $I(q)$ of the two alloys obtained from the HEXRD tests are plotted in Fig. S2 (Supplementary Materials), and the deduced structure factors $S(q)$ are displayed in Fig. 3a, where the simulated results are also shown for comparison. The diffuse HEXRD synchrotron patterns (insets in Fig. 3a) confirm the amorphous feature of the two alloys. The shape and position of each peak in the simulated $S(q)$ essentially align with the experimental results, revealing that the simulations can provide relatively accurate local atomic structures. The principle peaks in $S(q)$ are located at 3.19 and $3.09 \text{ \AA}^{-1}$ for the $\text{Co}_{71.5}\text{Y}_{3.5}\text{B}_{25}$ and $\text{Co}_{71.5}\text{Er}_{3.5}\text{B}_{25}$ alloys, respectively. Reduced total pair distribution function $G(r)$ transformed from the HEXRD results are shown in Fig. 3b. Upon examining the partially enlarged $G(r)$ curves near the first main peak, it is evident that the peak position of the $\text{Co}_{71.5}\text{Er}_{3.5}\text{B}_{25}$ metallic glass is $2.49 \text{ \AA}$, smaller than $2.52 \text{ \AA}$ for the $\text{Co}_{71.5}\text{Y}_{3.5}\text{B}_{25}$, indicating that the Er-bearing alloy possesses a higher atomic packing density as compared to the Y-containing alloy.

The simulated PDFs, coordination numbers (CNs), and chemical short-range order of the $\text{Co}_{71.5}\text{RE}_{3.5}\text{B}_{25}$ (RE = Er,

Table 1 T_g , ΔT_x , T_l , T_{rg} , d_c or t_c , H_c , B_s , σ_y , and ϵ_p of Co-based Co–RE–B (RE = Er, Y, Sm, Gd) metallic glasses

Alloys	T_g (K)	ΔT_x (K)	T_l (K)	T_{rg}	d_c/t_c (mm)	H_c (A/m)	B_s (T)	σ_y (MPa)	ϵ_p (%)
$\text{Co}_{71.5}\text{Er}_{3.5}\text{B}_{25}$	807	25	1438	0.561	1.0	1.3	0.68	3560	0.12
$\text{Co}_{71}\text{Er}_4\text{B}_{25}$	836	30	1439	0.581	1.0	1.2	0.65	3821	0.50
$\text{Co}_{70}\text{Er}_4\text{B}_{26}$	841	30	1452	0.579	1.0	1.2	0.61	3875	0.32
$\text{Co}_{69}\text{Er}_{3.5}\text{B}_{27.5}$	850	25	1486	0.572	1.0	1.3	0.56	3754	0.16
$\text{Co}_{68.5}\text{Er}_4\text{B}_{27.5}$	855	27	1469	0.582	1.0	1.3	0.53	3969	0.17
$\text{Co}_{71.5}\text{Y}_{3.5}\text{B}_{25}$	822	33	1472	0.558	0.24	1.5	0.73	–	–
$\text{Co}_{71.5}\text{Sm}_{3.5}\text{B}_{25}$	821	24	1556	0.528	0.06	2.9	0.71	–	–
$\text{Co}_{71.5}\text{Gd}_{3.5}\text{B}_{25}$	822	25	1525	0.540	0.08	2.0	0.62	–	–

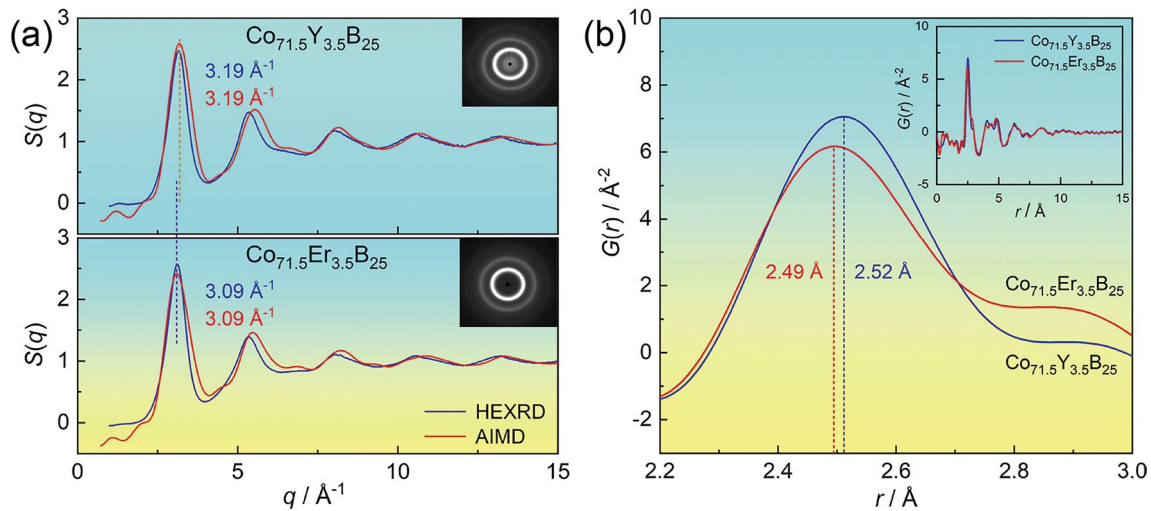


Fig. 3 **a** $S(q)$ curves of $\text{Co}_{71.5}\text{RE}_{3.5}\text{B}_{25}$ ($\text{RE}=\text{Er}, \text{Y}$) metallic glasses at 300 K obtained by HEXRD tests and AIMD simulations inset with synchrotron patterns and **b** partially enlarged $G(r)$ curves transformed from the HEXRD results of the alloys inset with total $G(r)$

Y) metallic glasses were further analyzed to reflect the interactions and chemical affinities between different types of atoms. The PDFs $g(r)$, which describe the probability of finding another atom at a certain distance (r) from the chosen atom, provide the atomic short-range ordering (SRO)

of the metallic glasses [41]. Figure 4 shows the partial and total PDFs of different atomic pairs, and the positions of the first peak in $g(r)$ curves representing the bond lengths of the atomic pairs are marked. The bond lengths of Co–B and Co–Co pairs are 2.04 and 2.45 Å, respectively, which

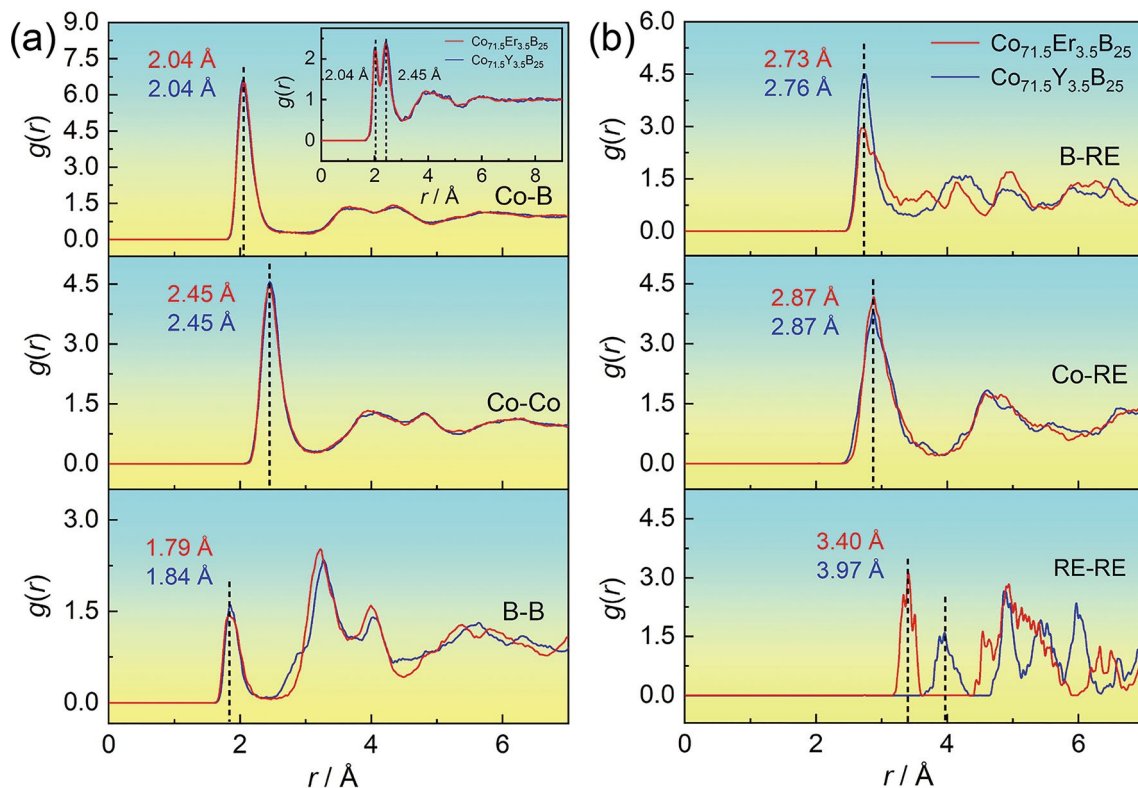


Fig. 4 Partial PDFs of **a** Co–B, Co–Co, and B–B, and **b** B–RE, Co–RE, and RE–RE pairs in $\text{Co}_{71.5}\text{RE}_{3.5}\text{B}_{25}$ ($\text{RE}=\text{Er}, \text{Y}$) metallic glasses at 300 K. Inset in **a** shows total PDF of the two alloys

correspond to the positions of the two sub-peaks in the first peak of the total PDFs (Inset in Fig. 4a), indicating that the SRO structures of the two alloys are mainly composed of metal-metalloid-type Co–B bond and metal–metal-type Co–Co bond. Although the bond lengths of Co–B, Co–RE, and Co–Co pairs are the same in the two alloys: the bond lengths of B–RE, B–B, and RE–RE in the $\text{Co}_{71.5}\text{Er}_{3.5}\text{B}_{25}$ alloy are all shorter than those in the $\text{Co}_{71.5}\text{Y}_{3.5}\text{B}_{25}$. The shorter bond lengths suggest a higher level of compact packing of the atoms. The total CNs were calculated by summing the partial CNs, which were determined by integrating over the first peak of the respective partial PDF $g(r)$ [41]. The calculated total CNs of Co, RE, and B atoms in the two alloys are quite similar, which are around 13, 21, and 9, respectively (Fig. 5a). Warren–Cowley parameters reveal that the chemical affinities between each atom pair in the $\text{Co}_{71.5}\text{Er}_{3.5}\text{B}_{25}$ alloy are stronger than $\text{Co}_{71.5}\text{Y}_{3.5}\text{B}_{25}$ (Fig. 5b). Noting that the reductions of the Warren–Cowley parameters for the B–RE, RE–RE, and B–B atom pairs are more significant than those of the Co–B and Co–Co pairs, which is consistent with the shortened bond lengths. The findings demonstrate that the Er-bearing metallic glass possesses a more densely packed structure and strengthened atomic interactions as compared to the Y-bearing alloy, arising from the crucial role of the Er element [44].

Voronoi polyhedron (VP) analysis was conducted to study the local atomic packing of the $\text{Co}_{71.5}\text{RE}_{3.5}\text{B}_{25}$ (RE = Er, Y) metallic glasses. The VP can be indexed as $\langle n_3, n_4, n_5, n_6 \rangle$ to describe the arrangements of the nearest-neighbor atoms around the center atom, where n_i represents the number of i -edge faces on the VP [45]. Figure 6a and b shows the major VPs centered by Co and B atoms in the two alloys, respectively. The two alloys have similar configurations of the main VPs, i.e., the VPs centered by Co

atom are composed of ico-like ($\langle 0, 1, 10, 2 \rangle, \langle 0, 0, 12, 0 \rangle, \langle 0, 1, 10, 3 \rangle, \langle 0, 1, 10, 4 \rangle$) and deformed bcc ($\langle 0, 3, 6, 4 \rangle, \langle 0, 3, 6, 5 \rangle$) polyhedrons, while those centered by B atom are mainly trigonal prisms (TP) ($\langle 0, 3, 6, 0 \rangle, \langle 0, 2, 8, 0 \rangle, \langle 0, 3, 6, 1 \rangle$) and crystal-like structures ($\langle 0, 4, 4, 0 \rangle, \langle 0, 4, 4, 1 \rangle$). As determined from the fractions of the VPs, both the alloys are dominated by B-centered TP-type clusters ($> 50\%$). It should be noted that the $\text{Co}_{71.5}\text{Er}_{3.5}\text{B}_{25}$ alloy contains a significantly higher fraction of ico-like clusters but fewer deformed bcc and crystal-like VPs, as compared to the $\text{Co}_{71.5}\text{Y}_{3.5}\text{B}_{25}$. The ico-like cluster, characterized by fivefold symmetry, is favorable for amorphous formation due to its incompatibility with periodic arrangement [46]. In contrast, the deformed-bcc and crystal-like VPs exhibit crystal symmetry, making them more prone to transforming into crystalline phases and hindering the formation of the amorphous phase [47, 48]. Consequently, the $\text{Co}_{71.5}\text{Er}_{3.5}\text{B}_{25}$ alloy with more ico-like clusters and fewer deformed-bcc and crystal-like VPs exhibits superior GFA than the $\text{Co}_{71.5}\text{Y}_{3.5}\text{B}_{25}$.

3.3 Dynamics Behaviors

Time-dependent mean square displacement (MSD) was calculated to study the dynamic behaviors of the $\text{Co}_{71.5}\text{RE}_{3.5}\text{B}_{25}$ (RE = Y, Er) alloys at different temperatures. According to Einstein's diffusion equation, a smaller slope of the MSD curve indicates a lower diffusivity of the atoms [46]. Figure 7a presents the MSD curves versus time of the two alloys at different temperatures. As the temperature decreases, the slopes of the curves monotonically decrease, indicating a gradual increase in viscosity and a simultaneous reduction in atomic diffusion coefficient of the alloys. Below 1100 K, it is hardly to observe long-range diffusion behavior. Noting

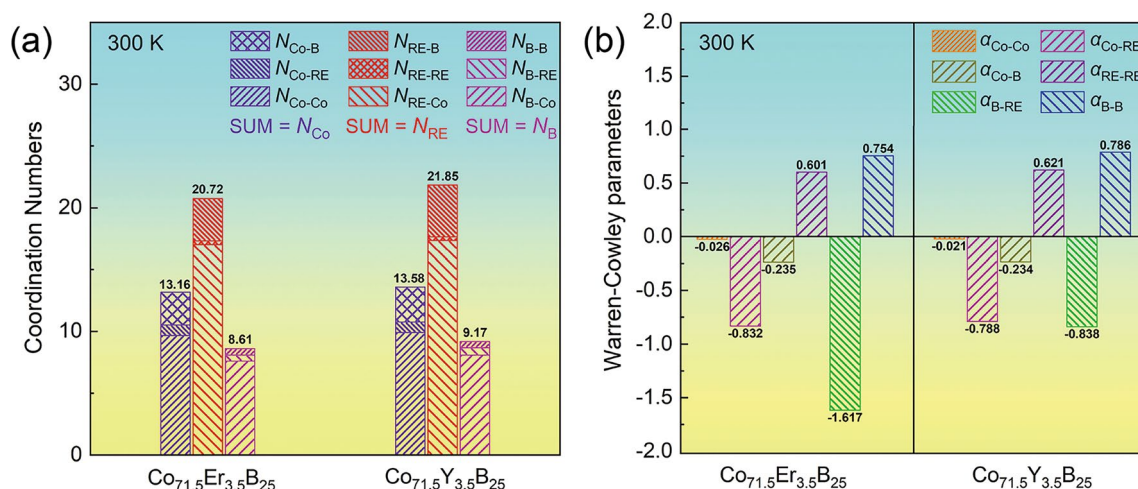


Fig. 5 **a** Coordination numbers of Co, RE, and B atoms and **b** Warren–Cowley parameters between Co, RE, and B atom pairs in $\text{Co}_{71.5}\text{RE}_{3.5}\text{B}_{25}$ (RE = Er, Y) metallic glasses at 300 K

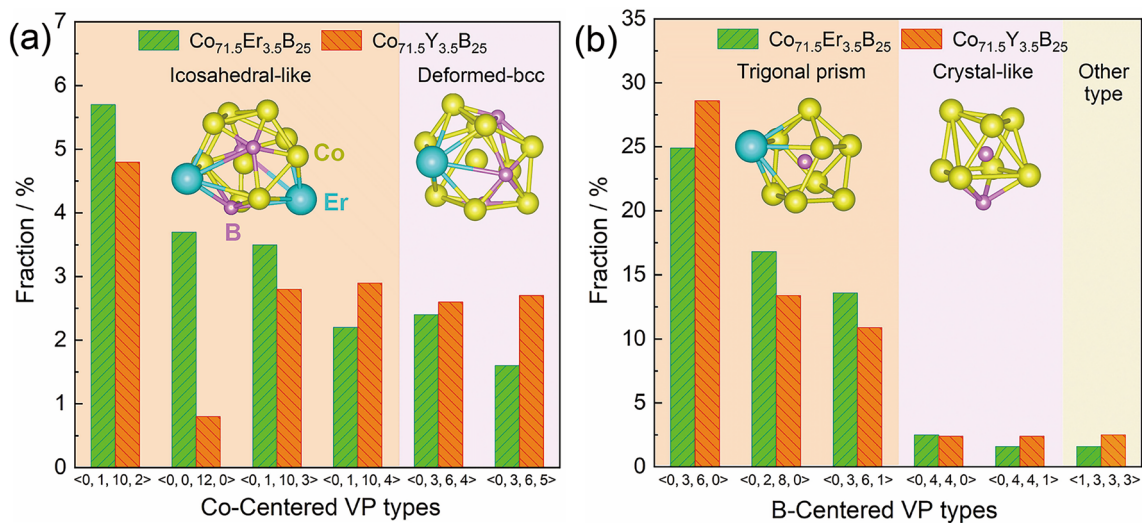


Fig. 6 Fractions of major VPs centered by **a** Co and **b** B atoms of $\text{Co}_{71.5}\text{RE}_{3.5}\text{B}_{25}$ (RE=Er, Y) metallic glasses at 300 K inset with typical VP structures

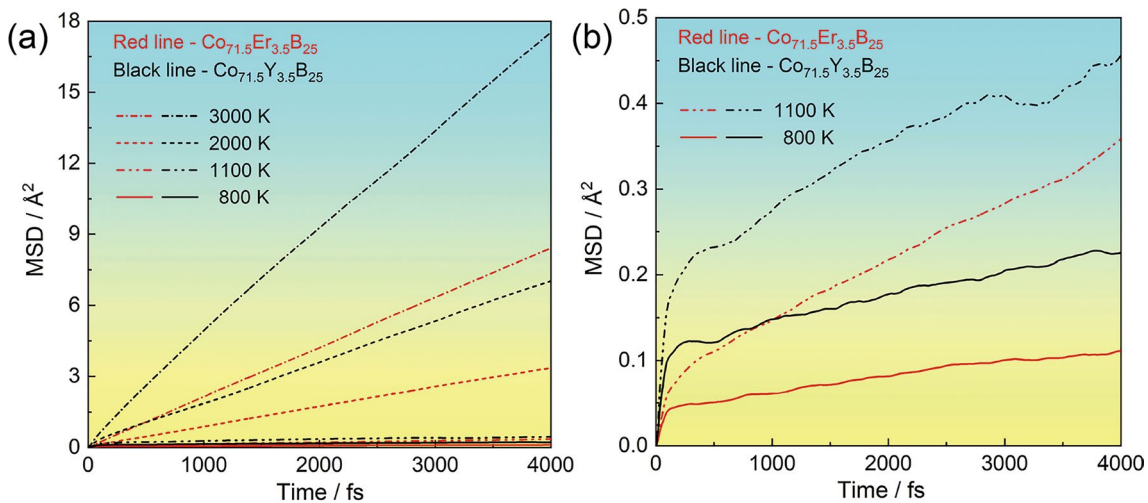


Fig. 7 **a** MSD curves of $\text{Co}_{71.5}\text{RE}_{3.5}\text{B}_{25}$ (RE=Er, Y) alloys at 800–3000 K and **b** corresponding partially enlarged curves at 800 K and 1100 K

that the slopes for the $\text{Co}_{71.5}\text{Er}_{3.5}\text{B}_{25}$ alloy are consistently smaller than those for the $\text{Co}_{71.5}\text{Y}_{3.5}\text{B}_{25}$ alloy throughout the entire cooling process (Fig. 7a and b). The MSD results suggest that the $\text{Co}_{71.5}\text{Er}_{3.5}\text{B}_{25}$ alloy has higher alloy melt viscosity and lower atomic diffusion capacity, which are consistent with its stronger bond strengths and denser local atomic packing structure. These can hinder the long-range diffusion of atoms during solidification and lead to a deceleration of crystallization, corresponding to its better GFA.

3.4 Magnetic and Mechanical Properties

The static magnetic properties tests reveal that the Co–Er–B metallic glasses exhibit a typical soft magnetic characteristic

with quite low H_c values of around 1.3 A/m, and the B_s gradually decreases from 0.68 to 0.53 T with the enrichment of non-magnetic B and Er. The detailed values of the Co–Er–B alloys along with the data for $\text{Co}_{71.5}\text{RE}_{3.5}\text{B}_{25}$ (RE= Y, Sm, Gd) alloys are listed in Table 1. Figure 8a compares the hysteresis loops inset with partially enlarged B - H curves near zero applied field of the $\text{Co}_{71.5}\text{RE}_{3.5}\text{B}_{25}$ (RE=Er, Y) metallic glasses. The hysteresis loops of the $\text{Co}_{71.5}\text{RE}_{3.5}\text{B}_{25}$ (RE= Y, Sm, Gd) metallic glasses can be seen in Fig. S3 (Supplementary Materials). Noting that the Co–Er–B metallic glasses have lower H_c than the $\text{Co}_{71.5}\text{RE}_{3.5}\text{B}_{25}$ (RE= Y, Sm, Gd) alloys. Since the metallic glasses are structurally isotropic and free of crystalline defects like grain boundaries, the H_c is closely related to the magnetic anisotropy

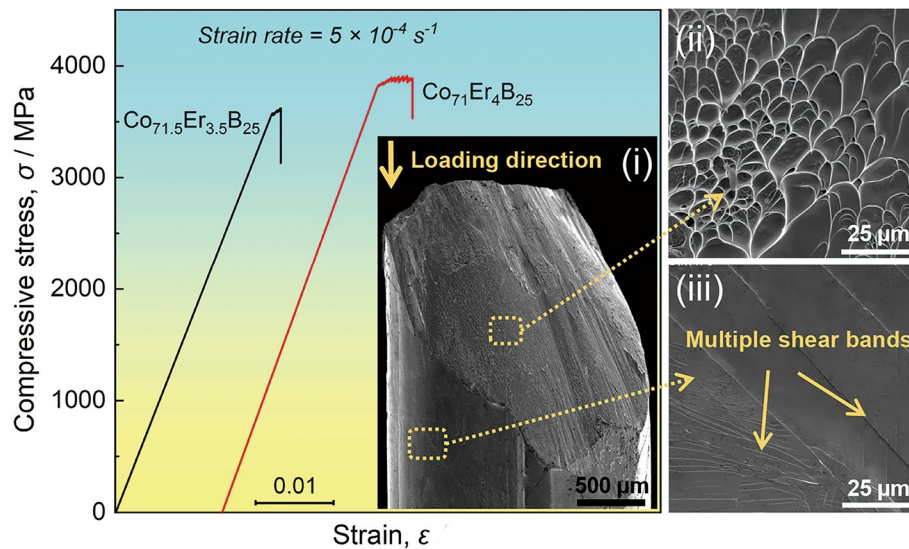


Fig. 9 Compressive stress–strain curves of the Co–Er–B BMGs rods inset with SEM images showing **i** total, **ii** fracture, and **iii** lateral surfaces morphology of the cracked $\text{Co}_{71.5}\text{Er}_{3.5}\text{B}_{25}$ BMG

structure characterized by a higher proportion of ico-like clusters but fewer deformed-bcc and crystal-like VPs, leading to enhanced structural stability and impeded ordered diffusion of atoms during solidification, which are the key factors contributing to the better GFA. The Co–Er–B BMGs exhibit excellent soft magnetic properties featuring low H_c of around 1.2 A/m and good mechanical properties with high σ_y of 3560–3969 MPa and distinct ϵ_p up to 0.50%. The exceptionally low H_c of the Co–Er–B metallic glasses can be attributed to their minimized MAE. The obtained ternary Co–Er–B BMGs can serve as foundational alloys for advancing the development of Co-based BMGs with further enhanced GFA and excellent soft magnetic properties.

Supplementary Information The online version contains supplementary material available at <https://doi.org/10.1007/s40195-024-01722-z>.

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Declarations

Conflict of interest The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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