A lightweight strain glass alloy showing nearly temperature-independent low modulus and high strength

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Fast development of space technologies poses a strong challenge for elastic materials, which need to be not only lightweight, strong and compliant, but also able to maintain stable elasticity over a wide temperature range. Here we report a lightweight magnesium-scandium strain glass alloy (Mg with 21.3 at.% Sc) that meets this challenge. This alloy is as light (density ~2 g cm$^{-3}$) and compliant as organic-based materials, but in contrast with those materials, it possesses a nearly temperature-independent (or Elinvar-type), ultralow elastic energy density of ~0.5 kJ kg$^{-1}$ and high yield strength of ~200–270 MPa; and a long fatigue life of over one million cycles. As a result, it exhibits a relatively high, temperature-independent elastic energy density of ~0.5 kJ kg$^{-1}$ over a wide temperature range from room temperature down to 123 K; a higher yield strength of ~200–270 MPa; and a long fatigue life of over one million cycles. As a result, it exhibits a relatively high, temperature-independent elastic energy density of ~0.5 kJ kg$^{-1}$ over a wide temperature range from room temperature down to 123 K; a higher yield strength of ~200–270 MPa; and a long fatigue life of over one million cycles. Therefore, they have the potential to be a solution to the need for elastic materials (Fig. 1) and aerospace applications. Here we report a surprising finding that with slightly higher Sc doping (by 0.8 at.%), a Mg-21.3Sc alloy shows a vastly different elastic behaviour from that of a Mg-20.5Sc SMA. This alloy exhibits the desired properties of low density (~2 g cm$^{-3}$), nearly temperature-independent (Elinvar-type), low Young’s modulus (~20–23 GPa) and high yield strength (~200–270 MPa; Fig. 1), and such properties persist over a wide temperature range from room temperature (298 K) down to cryogenic temperatures (123 K; Fig. 2). Thus, it possesses a high elastic energy density (~0.5 kJ kg$^{-1}$) at a moderate stress level of 200 MPa relative to known engineering elastic materials (Fig. 1a and Fig. 2c) as a result of overcoming the trade-off relation between low modulus and high strength (Fig. 1b). Furthermore, this lightweight elastic material has a long fatigue life of over one million cycles (Fig. 1c), which is superior to that of various Mg alloys, GFRP and high-strength aluminium alloys (for example, 2024Al T3) as a result of overcoming the trade-off relation between low modulus and high strength (Fig. 1b). Such a performance makes it a promising material for lightweight elastic components in space and aerospace applications.

In the following, we shall first show the mechanical properties of the Mg-21.3Sc alloy and then reveal their relation with a strain glass transition, which explains why the elastic properties change dramatically with such a small change in Sc concentration from Mg-20.5Sc to Mg-21.3Sc. In the present study we have studied...
shows an Elinvar-type low modulus being the same as the SQ sample, suggesting this property is unaffected by cold-rolling. 298–123 K, which contrasts with the Mg-19.5Sc martensitic alloy and conventional Mg alloy AZ91. Supplementary Fig. 3 shows that the CR sample also exhibits temperature-independent, high elastic energy density (calculated from the shaded area in c), Mg-21.3Sc strain glass alloy (SQ) shows a temperature-insensitive elastic deformation behaviour, contrasting with the strongly temperature-dependent elastic hardening of non-transforming Mg alloys (AZ91 and LA141) and the elastic softening of the Mg-19.5Sc martensitic alloy. a temperature-independent (Elinvar-type) low modulus over a wide temperature range of 298–123 K as indicated by the yellow shading, a behaviour seen later and in the Supplementary Information, cold-rolled alloys (abbreviated as CR) after the SQ treatment. As shown later and in the Supplementary Information, cold-rolling does not qualitatively change the unique elastic properties and strain glass nature of the alloy, except for increasing the strength. Therefore, unless otherwise specified, the terms ‘Mg-21.3Sc alloy’ and ‘Mg-21.3Sc strain glass alloy’ mean both the SQ and CR alloys throughout our paper, and we shall not distinguish the two in the discussion of physical mechanism.

Figure 1a shows that at room temperature, the Mg-21.3Sc strain glass alloy exhibits the highest elastic energy density among typical structural materials including organic-based GFRP and carbon fibre reinforced plastics (CFRP) and conventional Mg alloys, Al alloys, TiNi-based SMAs, Ti alloys (Gum metal) and steels. As shown in the inset of Fig. 1a, this value results from its very low Young’s modulus (~20–23 GPa) and high yield strength (~200–270 MPa), which produce a large elastic strain of ~1% even at a moderate stress level of 200 MPa. Owing to the high strength and low density of this alloy (~2 g cm⁻³), a record-high weight-specific elastic energy density, \( U = 0.5 \text{ kJ kg}^{-1} \) (measured by the shaded area), is achieved at a moderate stress level of 200 MPa. The superior elastic energy storage ability at 200 MPa for the strain glass Mg alloy is better seen when compared with that of a high-performance Ti alloy (Gum metal), which shows both solution-treated-and-quenched alloys (abbreviated as SQ) and cold-rolled alloys (abbreviated as CR) after the SQ treatment. As shown later and in the Supplementary Information, cold-rolling does not qualitatively change the unique elastic properties and strain glass nature of the alloy, except for increasing the strength. Therefore, unless otherwise specified, the terms ‘Mg-21.3Sc alloy’ and ‘Mg-21.3Sc strain glass alloy’ mean both the SQ and CR alloys throughout our paper, and we shall not distinguish the two in the discussion of physical mechanism.

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a much smaller elastic energy storage capacity (much smaller shaded area).

Figure 1b shows that the combination of low Young’s modulus (~20–23 GPa) and high yield strength (~200–270 MPa) in the Mg-21.3Sc strain glass alloy is unusual as it overcomes the commonly observed trade-off relation between low modulus and high strength; that is, high strength is usually accompanied by high modulus. Supplementary Fig. 2a further shows that this strain glass Mg alloy has a higher elastic strain (that is, more compliant) than conventional Mg alloys, being similar to that of bones. The combination of low density, low Young’s modulus and high yield strength of the Mg-21.3Sc strain glass alloy makes it comparable with many organic-based natural and artificial materials such as human bones, hard wood and GFRP, a state that other metallic alloys can hardly achieve (Supplementary Fig. 2b).

Figure 1c shows that the Mg-21.3Sc strain glass alloy demonstrates a long fatigue life of one million cycles even at high stress/strain amplitude (~90% of its yield strength), which is superior to that of conventional Mg alloys, GFRP and high-strength aluminium alloys (2024Al T3)30–32.

In combination with the excellent room-temperature properties, an outstanding feature of the Mg-21.3Sc strain glass alloy is its temperature insensitivity in both the low Young’s modulus (Fig. 2a and Supplementary Fig. 3a) and yield strength (Fig. 2b and Supplementary Fig. 3b), as well as in the elastic energy density (Fig. 2c). Such an unusual feature is technologically desired but has been physically challenging so far, as it is not possessed by either conventional Mg alloys or martensitic Mg alloys. The Mg-21.3Sc strain glass alloy exhibits an almost temperature-independent low modulus over a wide temperature range from 298 K down to a cryogenic temperature of 123 K (the low temperature limit of our equipment). Such an unusual temperature-independent elasticity is known as the Elinvar phenomenon and was previously reported only in a special class of iron-based alloys33. By comparison, commercial non-martensitic Mg alloys (LA141 and AZ91) exhibit a normal elastic hardening behaviour (also shown in Supplementary Fig. 1), and the Mg-19.5Sc martensitic alloy exhibits a normal elastic softening behaviour, a common feature of many martensitic alloys25. As a result of the Elinvar-type soft elasticity in the Mg-21.3Sc strain glass alloy, the large elastic energy density remains unchanged over a wide temperature range of ~298–123 K (Fig. 2c). This remarkable property is crucial for elastic applications in temperature-unstable environments like space.

Now we show that the Mg-21.3Sc alloy is not a martensitic alloy, but a strain glass alloy. Four common signatures of strain glass are revealed for the SQ sample: (1) invariance of average structure with temperature (Fig. 3a); (2) non-ergodicity as revealed by zero-field-cool/field-cool (ZFC/FC) experiments (Fig. 3d); and (4) local symmetry breaking as revealed by nanodomains (Figs. 4 and 5). The evidence for strain glass in the CR sample is given in Supplementary Fig. 4, which shows that cold-rolling (higher dislocation density) to the SQ sample does not qualitatively change its strain glass nature, agreeing with previous study34.
First, both differential scanning calorimetry (Fig. 3a) and in situ X-ray diffraction (Fig. 3b) reveal no martensitic transformation in the Mg-21.3Sc alloy, and the alloy remains a body-centred cubic (bcc, or $\beta$) structure over the entire temperature range from 350 to 123 K. However, dynamical mechanical analysis shows typical strain glass freezing signatures\(^34\) in this seemingly ‘non-transforming’ alloy, as revealed by a frequency-dependent anomaly around the glass transition temperature, $T_g \approx 210$ K in both the storage modulus and internal friction (Fig. 3c); this anomaly follows the Vogel–Fulcher relation $\omega = \omega_0 \exp(-E_a/k_{\text{B}}(T_g - T_0))$, where $\omega$ is the frequency, $\omega_0$ is the frequency prefactor, $E_a$ is the activation energy, $k_{\text{B}}$ is the Boltzmann constant and $T_0 \approx 198$ K is the ideal freezing temperature (determined in the inset of Fig. 3c). The above features are a typical signature of a strain glass transition\(^4\).

Figure 3d shows the history dependence of the lattice strain state as manifested by a large deviation in the ZFC/FC curves below $T_g$ (the peak temperature in the ZFC curve). This is another important signature of a strain glass transition\(^4\).

Figure 4 shows microscopic signatures of a strain glass transition—local symmetry breaking as revealed by the formation of orthorhombic martensitic nanodomains in the Mg-21.3Sc alloy. At room temperature, a tweed-like microstructure was observed (Fig. 4a (parallel to [110]$\parallel$ zone axis) and Fig. 4b (parallel to [111]$\parallel$ zone axis)). The corresponding diffraction pattern (insets of Fig. 4a,b) shows diffuse superlattice spots at 1/2[112]$_{\beta}$ and 1/2[011]$_{\beta}$ (yellow triangles), being the same positions as those of the reported Mg–Sc martensite\(^34,35\) and our Mg-19.5Sc martensite (Supplementary Fig. 6).

This indicates that the strain glass breaks the local symmetry of the cubic parent phase into orthorhombic symmetry, while maintaining an average bcc symmetry as shown in the X-ray diffraction profiles (Fig. 3b). The high-resolution transmission electron microscopy (TEM) images in Fig. 4b,c further show local distortion of the lattice, confirming the breaking of the local cubic symmetry of the parent phase. The inverse fast Fourier transform image (Fig. 4d) reveals that the strain glass is characterized by randomly distributed orthorhombic nanodomains of ~10 nm in size.

In situ TEM observations in Fig. 5a,b further show that the orthorhombic nanodomains of the Mg-21.3Sc strain glass evolve smoothly with temperature. At 298 K ($> T_g$), the nanodomains are sparse and tiny (~10 nm), which is consistent with the inverse fast Fourier transform image shown in Fig. 4d. Upon cooling to 123 K ($< T_g$), the nanodomains grow in both size (~25 nm) and volume fraction, as shown in Fig. 5b; but these nanodomains are frozen at low temperatures (Fig. 3c) and do not further grow into large martensite domains. Such evolution is also revealed by the increasing intensity in the diffuse 1/2[112] superlattice spots (insets of Fig. 5a,b). The smooth evolution of nanodomains during the strain glass transition contrasts with the martensitic transformation, which undergoes an abrupt appearance of large martensite domains at its transition start temperature. It is the smoothness of the strain glass transition that is responsible for the remarkable temperature insensitivity of properties in Mg-21.3Sc strain glass alloys (Fig. 2).

Now we show why the strain glass nature of the Mg-21.3Sc alloy leads to the remarkable temperature-independent or Elinvar-type low modulus, high yield strength, high elastic energy density at a moderate stress level, and high fatigue strength. First, strain glass is a martensite-derived nanoscale phase, or a frozen nano-martensite\(^34\) formed by doping an excess amount of point defects (Sc here) into an alloy with martensitic instability. These point defects act as a random field to prohibit long-range strain ordering (that is, martensitic transformation), and thus a frozen nanoscale martensite phase, or strain glass, is formed. This is why Mg-19.5Sc and Mg-20.5Sc are martensitic alloys but Mg-21.3Sc becomes a strain glass alloy. Because of the existence of martensitic instability even in strain glass compositions (Mg-21.3Sc here), the low elastic modulus feature of a martensitic alloy will persist in a strain glass alloy, which is also seen in other strain glass systems\(^34,36\). This is why the Mg-21.3Sc strain glass alloy has a lower Young’s modulus when compared with non-transforming Mg alloys like LA141 and AZ91 (Fig. 2a) or pure Mg, even though it does not have a martensitic transformation.

Nevertheless, when compared with the Mg-19.5Sc martensitic alloy, which shows a strong elastic softening effect due to strong lattice instability with lowering temperature (Fig. 2a, Mg-19.5Sc), the Mg-21.3Sc strain glass alloy possesses a weaker elastic softening effect and appears ‘harder’ (Fig. 2a, Mg-21.3Sc) due to its weaker lattice instability. The weaker lattice instability (or weaker softening) of the strain glass alloy is experimentally evidenced by the cooling-induced growth of martensite nanodomains (Fig. 5) but without a global martensitic transformation (Fig. 3a,b), and is also predicted by theories\(^4\). This weaker elastic softening effect just offsets the ever-present elastic hardening trend of the otherwise non-transforming Mg alloys (Fig. 2a, LA141 and AZ91), and consequently leads to the desired temperature-independent low elastic modulus, or Elinvar-type low modulus. A schematic illustration of the origin of the Elinvar effect is given in Supplementary Fig. 7.

In addition to the Elinvar-type low modulus, the Mg-21.3Sc strain glass alloy also shows a high yield strength (>200 MPa) down to cryogenic temperatures, contrasting with the drastic lowering of yield strength in the martensitic composition of Mg-19.5Sc (Fig. 2b). This characteristic results from the absence of the martensitic transformation in the Mg-21.3Sc alloy and the strengthening effect of Sc. The excellent fatigue resistance of the Mg-21.3Sc alloy is also due to the absence of the martensitic transformation, as such a transformation

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**Fig. 4 | Evidence for local symmetry breaking in Mg-21.3Sc strain glass alloy (SQ) a.** Tweed-like morphology at room temperature with [110]$_{\beta}$ zone axis. The inset shows the diffraction pattern, with diffuse 1/2[112]$_{\beta}$ spots (yellow triangles) corresponding to local orthorhombic martensitic symmetry and 1/2[002]$_{\beta}$ superlattice reflections corresponding to local B2 short-range ordering (SRO B2) in the parent bcc matrix according to the equilibrium phase diagram of the Mg-Sc alloy\(^5\). b, Bright-field image and corresponding diffraction pattern (inset) with [111]$_{\beta}$ zone axes. c, Enlarged tweed-like region in a shows local lattice distortion of the bcc lattice. d, Inverse fast Fourier transform image of c, obtained through selecting all 1/2[112]$_{\beta}$ superlattice reflections, shows a distribution of nanosized orthorhombic domains (bright regions) in the bcc matrix (dark matrix).
would cause dislocation generation\textsuperscript{40} and thus reduce fatigue life. The combination of the Elinvar-type low Young’s modulus and the maintaining of a high yield strength down to low temperatures leads to the desired property of a high and temperature-independent elastic energy density for a strain glass alloy.

In conclusion, a Mg-21.3Sc strain glass alloy is found to exhibit an Elinvar-type low modulus, high yield strength and long fatigue life. As a result, it exhibits a temperature-independent elastic energy density, \( \sim 0.5 \) kJ kg\(^{-1}\), that is high among known engineering materials under a moderate stress level of 200 MPa. The unique temperature-insensitive elasticity may make this lightweight alloy an ideal elastic material in temperature-changing environments like space and aerospace, as well as a promising implant material in orthopaedic applications due to it having a modulus close to that of human bones\textsuperscript{41–43}.

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**Methods**

**Sample preparation.** Mg-21.3Sc, Mg-19.5Sc and Mg-18.5Sc alloys were fabricated in an induction furnace under Ar atmosphere using pure Mg and Sc metals as starting materials (99.99%). The cast ingots (~15 mm) were hot-rolled at 600 °C into a thickness of 1.5 mm. Then specimens of different shapes were cut from the hot-rolled plates. They were further solution-treated at 690 °C for 0.5 h, followed by cold water quenching (termed SQ) to obtain a bcc (β) phase. The cold-rolled sample (termed CR) was made by cold-rolling the 1.5-mm-thick SQ sample to 1 mm.

Cold-rolling further increases the yield strength of the alloy (Fig. 1b) but without changing its strain glass nature (Supplementary Fig. 4) and its Elinvar elasticity property (Supplementary Fig. 3a).

**Composition analysis and element distribution mapping.** Chemical compositions were determined by energy dispersive spectrometry with a Quanta 250 field-emission gun (FEI) at 20 kV and by chemical analysis. Energy dispersive spectrometry mapping shows that the Mg and Sc distribution in the sample is homogeneous. Detailed composition analysis and mapping results are shown in Supplementary Fig. 8.

**Mechanical testing.** The stress–strain curves of the SQ and CR samples were examined by a Shimadzu AG-IS tensile machine. A temperature chamber (Shimadzu TCLN-220P) was used for testing the stress–strain curves over a temperature range from 298 to 123 K. An axial extensometer (Epsilon Technology 3442–005M-020M-LHT) was used for reliable strain reading. Young’s modulus was calculated from the elastic regime in the tensile stress–strain curves by the secant modulus method or ‘apparent elastic modulus method’40,41, as it yields a more accurate evaluation of elastic energy within the elastic limit. Samples for tensile testing were cut from the hot-rolled and cold-rolled plates, each with a gauge length of 20 mm and width of 1.5 mm. Prior to mechanical testing, all the specimens were mechanically polished to 1–1.3 mm in thickness using fine sandpapers and diamond paste to remove a possible oxide layer on the surface. Cyclic tensile testing was performed at 123, 173, 213, 273 and 298 K with a cross-head speed of 0.3 mm min⁻¹. At each temperature, the tensile test was performed after 10 min of isothermal holding to ensure temperature stability and homogeneity within the specimen. Sample temperature was monitored by a T-type thermocouple attached to the sample.

Fatigue tests were performed on a fatigue test machine (TA 3330 Series III) at room temperature in a displacement-controlled three-point bending mode at 2 Hz. The dynamic flexural stress and flexural strain of the sample (Fig. 1c) were calculated from a dynamic force load and displacement following the ASTM D790-17 standard. The dynamic flexural modulus calculated from the slope of the dynamic flexural stress and flexural strain curve can differ substantially from Young’s modulus (determined by static tensile stress–strain curves in Fig. 1a), as shown in Supplementary Fig. 9.

**Structural determination.** The crystal structures at different temperatures were determined by X-ray diffraction (Shimadzu 7000 XRD) with a Cu Kα source at 40 kV and 40 mA. The microstructural observations at different temperatures were done on a JEM 2100F TEM instrument, which is equipped with a field-emission gun and a cooling holder. The data were recorded using a GATAN CCD (charge-coupled device) slow scan camera and analysed by the DigitalMicrograph software.

The TEM samples were made by mechanical polishing an alloy plate down to about 100 μm, followed by punching the thin sheet into ~3 mm discs. The thin disc samples were further thinned by a dimpler, followed by Ar-ion milling at 4–5 keV.

**Characterization of strain glass transition.** Heat flow was analysed with a Q200 differential scanning calorimetry instrument from TA Instruments at a heating/cooling rate of 10 K min⁻¹. A dynamical mechanical analyser (TA, Q800) was employed to measure the storage modulus and internal friction as a function of temperature at different frequencies (0.2, 0.4, 2, 4, 10 and 20 Hz) with three-point-bending mode at a constant amplitude of 3 mm and a cooling/heating rate of 2 K min⁻¹. ZFC/FC experiments were performed on the same dynamical mechanical analysis equipment with a three-point-bending mode under a stress of 40 MPa. Details of the experimental procedure for ZFC/FC experiments are given in Supplementary Fig. 5.

**Data availability**

All data generated or analysed during this study are included in the published article and Supplementary Information and are available from the corresponding authors upon request.

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**Author contributions**

Y.J. and X.R. conceived the idea. C.L. and Y.J. designed the project. C.L., J.T., M.H. and T.M. fabricated the samples. C.L., J.T. and P.L. performed experiments, and C.L. analysed the results with all the authors. D.W. helped analyse the mechanism of the Elinvar effect. C.L., Y.J. and X.R. wrote the manuscript with input from all the authors.

**Competing interests**

The authors declare no competing interests.

**Additional information**

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