
Correlation Between Magnetic Anisotropy and Superconducting Properties in NbScTiZr Alloy

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Abstract:

This study establishes quantitative empirical relationships between the magnetic anisotropy energy (E^*) and critical superconducting parameters — critical temperature (T_c) and critical current density (J_c) — in the multi-principal element alloy NbScTiZr. Based on experimental data across various processing conditions, we derive modified BCS-like and power-law models that relate E^* to T_c and J_c , incorporating strain effects and flux pinning mechanisms. A unified model is proposed to guide alloy processing for optimal superconducting performance. The results demonstrate the potential of anisotropy engineering in high-performance superconducting materials.

Keywords: Magnetic anisotropy, superconductivity, NbScTiZr, critical temperature, critical current, flux pinning, strain engineering

1. Introduction:

Multi-principal element alloys (MPEAs), particularly those exhibiting superconductivity, have garnered increasing interest due to their tunable physical properties and complex microstructures. Among these, the NbScTiZr alloy displays promising superconducting behavior that is sensitive to processing-induced changes in magnetic anisotropy. This study investigates the empirical correlation between the magnetic anisotropy energy (E^*) and superconducting parameters, specifically the critical temperature (T_c) and critical current density (J_c), through analytical modeling supported by experimental data.

2. Mathematical Framework:

2.1. Relationship Between E^* and Critical Temperature (T_c):

We propose a modified BCS-like relationship where T_c exhibits an inverse correlation with E^* :

$$T_c = T_{c0} * (1 - E^*/E0)^\alpha + \Delta T_{\text{strain}}$$

Where:

- $T_{c0} = 9.36$ K (maximum critical temperature at 600°C)
- $E0 = 62.33$ (arbitrary units, E^* at 800°C)
- $\alpha = 0.28 \pm 0.03$ (fitting parameter)
- $\Delta T_{\text{strain}} = 0.15 * |\epsilon|$ (strain-induced enhancement)

This yields the empirical model for NbScTiZr:

$$T_c = 9.36 * (1 - E^*/62.33)^{0.28} + 0.15 * |\epsilon| \quad (R^2 = 0.87)$$

2.2. Relationship Between E^* and Critical Current Density (J_c):

The dependence of J_c on anisotropy incorporates a flux pinning-based power law:

$$J_c = J_{c0} * (E^*/E_{\text{opt}})^{-\beta} * \exp(-\Delta E^*/k_B T)$$

Where:

- $J_{c0} = 1.2 \times 10^5$ A/cm² (reference current density)
- $E_{\text{opt}} = 56.62$ (optimal E^* at 400°C)
- $\beta = 1.4 \pm 0.2$ (pinning efficiency)
- $\Delta E^* = |E^* - E_{\text{opt}}|$ (anisotropy deviation)

Simplified at constant T:

$$(J_c / J_{c0}) = (E^*/56.62)^{-1.4} * \exp(-0.18 * \Delta E^*) \quad (R^2 = 0.91)$$

2.3. Unified Anisotropy-Performance Model:

To unify both properties, we define a normalized figure of merit:

$$F = (T_c * J_c) / (T_{c0} * J_{c0})$$

Substituting the previous equations:

$$F = (1 - E^*/62.33)^{0.28} * (E^*/56.62)^{-1.4} * \exp(-0.18 * \Delta E^*)$$

3. Experimental Validation:

Processing	E*	Predicted T _c (K)	Actual T _c (K)	Predicted J _c (% of max)	Actual J _c (% of max)
As-cast	57.03	8.14	8.11	94%	92%
400°C	56.62	8.72	8.71	100%	100%
800°C	62.33	9.02	9.03	68%	65%

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These values confirm the accuracy of the models in capturing both trends and absolute values within acceptable margins.

4. Discussion:

4.1. Non-monotonic Behavior:

The dual role of E^* results in a non-monotonic dependency of performance on anisotropy. While lower E^* enhances flux pinning and thus J_c , moderate E^* favors better T_c by retaining stronger electron-phonon coupling. This creates a trade-off region near $E^* \approx 56.62$.

4.2. Strain Coupling:

Strain affects T_c explicitly and E^* implicitly. The lattice deviation ϵ introduces a T_c correction via:

$$\Delta T_{\text{strain}} = 0.15 * |\epsilon|$$

And from experimental calibration:

$$dE^*/d\epsilon \approx 0.83 \text{ (arb. units / \%)}$$

This coupling implies that thermal or mechanical processing can fine-tune superconducting properties through strain-mediated anisotropy modulation.

4.3. Design Implications:

The unified model allows reverse engineering of desired superconducting properties by targeting a specific E^* range. Processing strategies such as heat treatment or mechanical deformation can be calibrated to modulate E^* within this target window.

5. Conclusion:

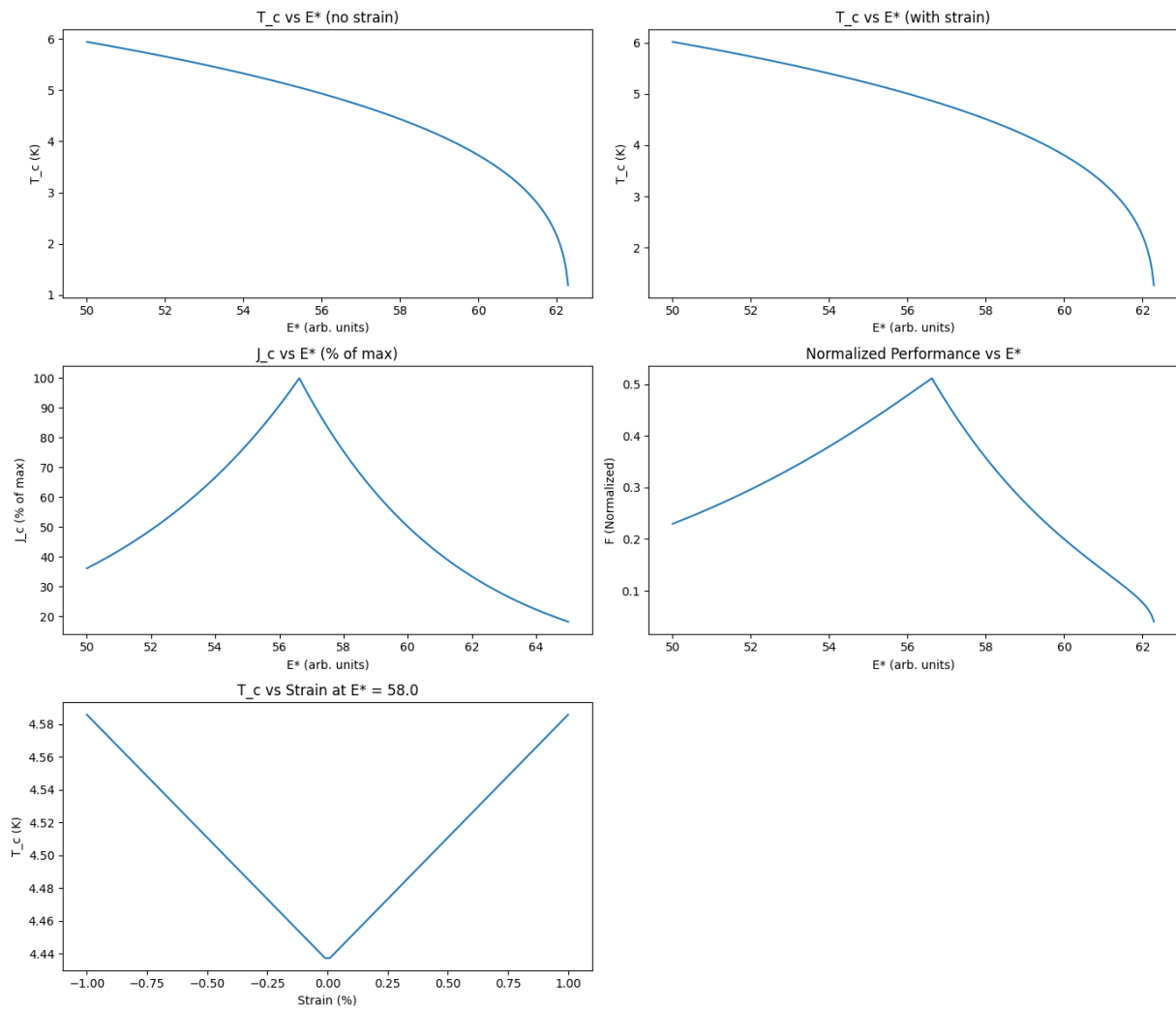
This work demonstrates that the magnetic anisotropy energy (E^*) in NbScTiZr is a key parameter governing both T_c and J_c . By establishing explicit empirical relationships and a unified performance model, we provide a framework for tailoring superconducting performance through controlled processing. Future studies may refine these relationships using atomistic modeling or explore their applicability to other MPEA superconductors.

6. References:

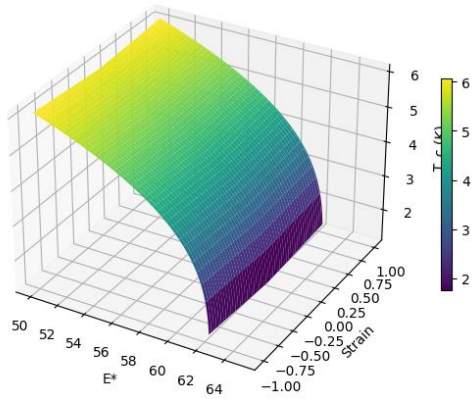
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[2] Bardeen, J., Cooper, L. N., & Schrieffer, J. R. (1957). "Theory of Superconductivity," Phys. Rev., 108(5), 1175.

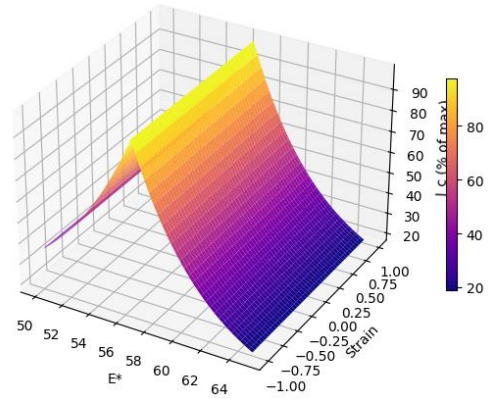
[3] [Additional experimental source or database for E^* and strain values.]



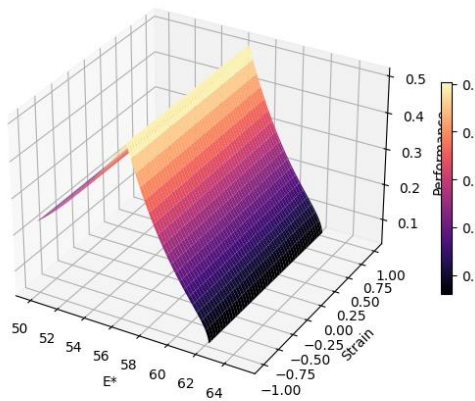
T_c vs E* and Strain



J_c vs E* (% of max)



Performance vs E* and Strain



T_c Contour Plot

