Interplay Between Magnetism and Short-Range Order in High-Entropy Alloys

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What is a high-entropy alloy?

Medium- and High-entropy alloys:

– First examples synthesised in 2004 (1, 2).

– Multiple metals combined in roughly equal ratios.

– Simple, close-packed structures: fcc, bcc, hcp.

– Single-phase solid solution stabilised by configurational entropy:

$$-\beta^{-1}\sum_{i\alpha} c_{i\alpha}\log c_{i\alpha} \tag{1}$$

Why are we interested?

Increased understanding of how to control atomic arrangements in these alloys may allow for improvement of advanced magnetic materials performance. In particular, for control of anisotropy and resistivity in soft magnetic materials. (Transformer alloys, for example). Advanced processing approaches could exert this control, could support advanced manufacturing.

What is the challenge for modellers?

Modelling atomic arrangements in these materials and, more generally, multicomponent alloys is difficult on account of the vast space of potential atomic configurations.

How do *we* model multicomponent alloys?

Linear Response

– Mean-field free energy based on partial atomic occupancies of lattice sites, $\{c_{i\alpha}\}$(3, 4, 5):

$$\Omega = -\beta^{-1}\sum_{i\alpha} c_{i\alpha}\log c_{i\alpha} - \sum_{i\alpha}{}' \nu_{i\alpha}c_{i\alpha} + \langle\Omega_{\mathsf{el}}\rangle_0[\{c_{i\alpha}\}] \tag{2}$$

– Impose perturbation about homogeneous (disordered) alloy, $c_{i\alpha} = c_\alpha + \Delta c_{i\alpha}$.

– Change in free energy due to perturbation written:

$$\delta\Omega = \frac{1}{2}\sum_{i,j}\sum_{\alpha,\alpha'}\Delta c_{i\alpha}[\beta^{-1}C^{-1}_{\alpha,\alpha'} - S^{(2)}_{i\alpha;j\alpha'}]\Delta c_{j\alpha'}, \quad \text{where} \quad C^{-1}_{\alpha\alpha'} = \frac{\delta_{\alpha\alpha'}}{c_\alpha}, \quad -\frac{\partial^2\langle\Omega_{\mathsf{el}}\rangle_0}{\partial c_{i\alpha}\partial c_{j\alpha'}} \equiv S^{(2)}_{i\alpha;j\alpha'}. \tag{3}$$

Term in square brackets referred to as 'chemical stability matrix'.

– Assess which perturbations are energetically favourable to find dominant correlations.

– Convenient to perform analysis in reciprocal space, writing $\Delta c_\alpha(\mathbf{k})$.

– Derivatives of internal energy, $S^{(2)}_{i\alpha;j\alpha'}$, and description of atomic short-range order come from *ab initio* DFT analysis (3): can compare different magnetic states.

Atomistic Modelling

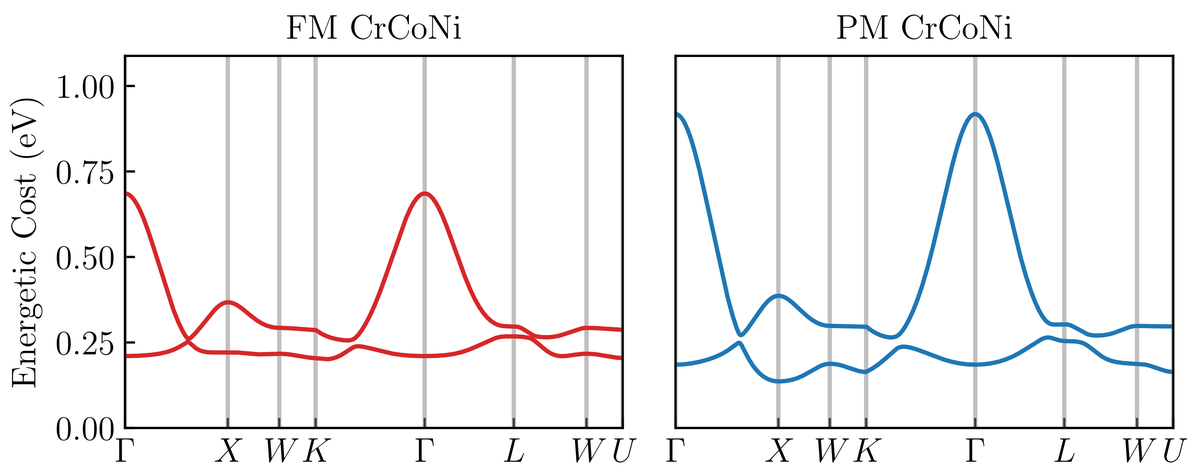
– Fit to a Bragg-Williams Hamiltonian for atomistic modelling:

$$H(\{\xi_{i\alpha}\}) = \sum_{i,j}\sum_{\alpha,\alpha'} V_{i\alpha;j\alpha'}\xi_{i\alpha}\xi_{j\alpha'} \tag{4}$$

$\xi_{i\alpha}$ - does site i contain atom of species α? $V_{i\alpha;j\alpha'}$ - interaction between atoms.

How does the Magnetic State Affect Atomic Ordering?

Superb test case is given by ternary 'medium-entropy' alloy CrCoNi.



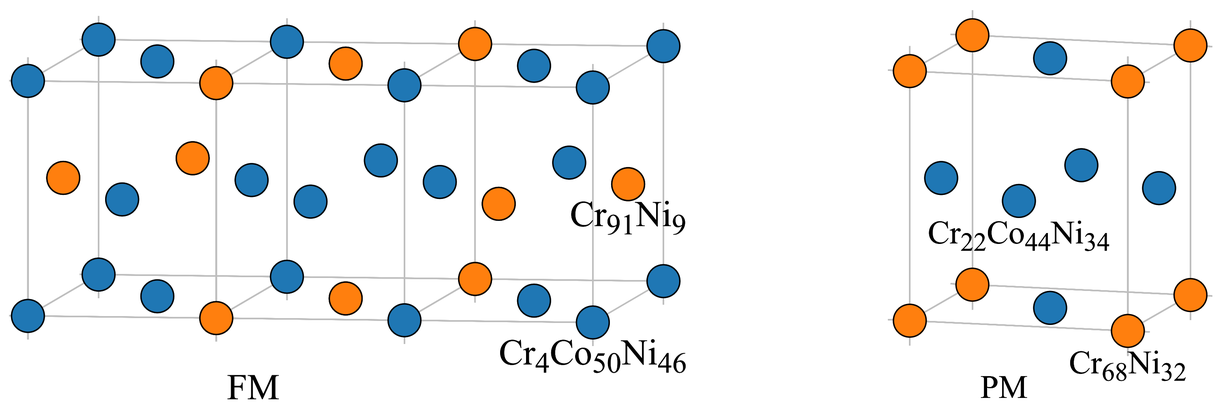
Eigenvalues of the chemical stability matrix around the irreducible Brillouin zone for CrCoNi in its ferrimagnetic ('FM') and paramagnetic ('PM') states, evaluated at T=1000 K. There is clear competition between minima at k = (0, 0, 1) and k = (0, 2/3, 2/3)

Ordering Temperatures

Magnetic State	T_{ord} (K)	k_{ord} $(2\pi/a)$	Δ Cr	Δ Co	Δ Ni
FM	252	(0, 0, 1)	0.813	−0.468	−0.345
PM	606	(0, 2/3, 2/3)	0.724	−0.689	−0.035

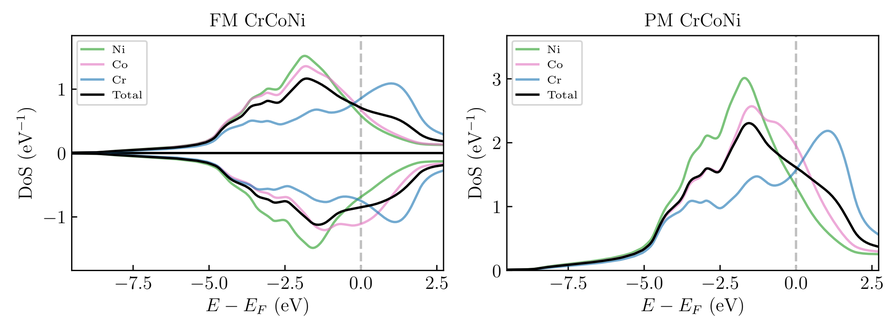
Predicted chemical ordering assuming a *ferrimagnetic* state is the $MoPt_2$ structure, versus $L1_2$ structure for paramagnetic state. Ordering temperature also changes dramatically.

Orderings Visualised



Visualisations of the predicted (partially) chemically ordered structures for both magnetic states. The nature of chemical order is unequivocally connected to the magnetic state of the material. This has significant implications for materials modelling.

Electronic Origins



All three of Ni, Co, and Cr, acquire magnetic moments, and this affects electronic structure, *i.e.* the 'glue' which drives chemical ordering.

Conclusions

– Correct treatment of magnetic state essential to modelling atomic arrangements and materials properties.

– Annealing some alloys in an applied magnetic field could alter nature of atomic arrangements.

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