**Direct observation and impact of co-segregated atoms in magnesium containing multiple alloying elements**

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All modern engineering alloys, including magnesium, aluminium, steels and super-alloys, contain multiple alloying elements, but the precise atomistic roles of these alloying elements remain unclear. A key reason is that direct observation of these alloying elements segregated at the atomic scale is challenging, because the segregation in these materials is prone to electron beam damage. Beam damage is most severe for magnesium alloys and its effect is particularly an issue when the segregated solute atoms become a single atomic column. Here we show that it is possible to solve this difficulty in magnesium by using atomic-resolution energy dispersive X-ray spectroscopy at a much lower electron voltage. With this opportunity, we discover a new pattern of solute segregation in twin boundaries in a magnesium alloy having both larger and smaller solutes: alloying elements co-segregate, forming alternating columns that fully occupy the twin boundary, in contrast to the previous observations of half occupancy of the boundary where mixed-solute columns alternate with magnesium. We further discover that the co-segregation of solutes switches the migration mechanism of the twin boundary from the commonly accepted mode to a new one and increases the boundary pinning effect by over 30 times. Our work demonstrates that atomic-scale analysis of both the structure and chemistry of solute segregation in metallic alloys with complex compositions is now possible. Our findings also provide new insights into the precise role of segregated atoms in interface mobility that dictates mechanical behaviour and properties.