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Nano-oxides boost aluminium heat resistance

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News & views

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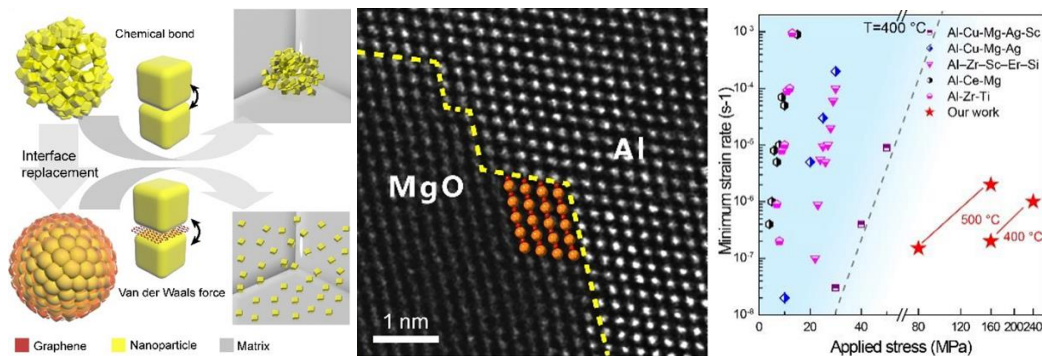
Metals are widely used for structural applications because they combine good strength and some ductility, permitted by the movement of dislocations through a lattice of simple structure. Improving the strength while preventing excessive brittleness is the daily challenge of physical metallurgists who tailor the nature and spatial distribution of defects to dislocation motion. However, it is extremely difficult to maintain high strength in metals at high temperatures for long service times, although it is highly desirable in extreme environments such as jet engines or next generation high temperature nuclear power plants. Such a property requires both sufficiently strong obstacles so that they cannot be easily overcome by thermal activation or dislocation climb, and sufficiently stable obstacles so that they do not undergo fast coarsening in service.

Decades of research have resulted in highly optimized superalloys whose properties depend essentially on the presence of a high volume fraction of an ordered intermetallic phase and a highly coherent interface with the matrix. Steels have also been extensively studied to increase their high temperature properties. The development of Oxide Dispersion Strengthened (ODS) steels, largely driven by the nuclear industry, has led to fascinating materials where a dense distribution of extremely small (few nm) (Y,Ti) oxides is achieved, permitted by ball milling and powder metallurgy. These materials possess very good creep resistance up to 650°C and do not recrystallize nor undergo significant precipitate coarsening until very close to their melting point ^{1,2}.

In light alloys, especially Aluminium, there has been in recent years also a race for raising the high temperature properties, which were notoriously disappointing. As was highlighted in a recent paper by Xue *et al.*³, Aluminium alloys are usually strengthened by precipitates, but one has to choose between high solubility solutes (Cu, Zn, Mg, ...) providing high strength but low thermal stability and low diffusivity solutes (Fe, Zr, Ti, ...) providing high thermal stability but low strength. To date two strategies have been pursued to overcome this dilemma: either to associate by specific compositions and multi-stage heat treatments these different chemical species³ or to use out-of-equilibrium processing such as additive manufacturing to obtain a high solubility of low diffusivity elements⁴⁻⁶. These two strategies have resulted in alloys capable of sustaining significant stresses up to 400°C.

Now, writing in *Nature Materials*, Bai *et al.*

[Bai,X.*etal.Nat.Mater.*[https://doi.org/10.1038/s41563-024-01884-2\(2024\)](https://doi.org/10.1038/s41563-024-01884-2(2024))] propose a third strategy, consisting of introducing in an Al matrix MgO nanoparticles to create an ODS Aluminium alloy. Similarly to the processing of ODS steels, these ODS Aluminium alloys are obtained by ball milling of Al and nanoparticles followed by extrusion, but this strategy was until now unsuccessful due to the excessive surface energy of the nanoparticles which caused them to remain agglomerated during the ball milling process. Bai *et al.* show that this issue can be overcome by coating the nanoparticles by a graphene-like layer which drastically decreases their surface energy (reduction estimated by a factor of several hundreds). After ball milling and consolidation, they obtain a homogeneous distribution (almost 10^{24} m^{-3}) of oxide nanoparticles ~ 5 nm in size, fully coherent with the matrix thanks to the similarity of the lattice parameters of Al and MgO. After the consolidation process, they show that the carbon layer initially present has migrated to form isolated carbides.



This material shows truly outstanding properties: at room temperature, when 5% fraction oxides are mixed with a high strength 7000 series Al alloy, a strength of ~ 850 MPa is reached, and at 500°C the MgO/Al alloy remains at a tensile strength of 200 MPa and has very impressive creep properties, which clearly overrides the state of the art. The mechanical properties of these alloys are not affected by holding 10h at 600°C , almost at the melting point, demonstrating an outstanding thermal stability of these embedded nanoparticles. All this comes together with some ductility, and they demonstrate the feasibility of this strategy with other oxide types (La, Y, Ce, Ti), although MgO gives the best results.

These developments open a new field for application of Aluminium alloys in high temperature environments, where it could compete, at lower weight, with some Ti alloys. Obviously practical challenges remain to upscale the production process of such materials, since ball milling is not a highly productive process.

In terms of unveiling the mechanisms behind these outstanding properties, Bai et al. have carried out detailed electron microscopy as well as some atom probe tomography, together with density functional theory (DFT) calculations. They clearly demonstrate the highly coherent nature of the oxide / Al interface, and their calculations indicate that the cost of vacancies at the interface is extremely high. The coherence and associated elastic strains help understanding the high temperature strength and low creep rate, while vacancies avoiding the precipitate interface are probably an important ingredient to understand the extreme coarsening resistance of this material, together with the high thermodynamic stability of MgO and the low oxygen solubility in Al. More work is needed to understand quantitatively the observed mechanical properties at high temperature ; this will require combining advanced microscopy and multi-scale simulations.

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