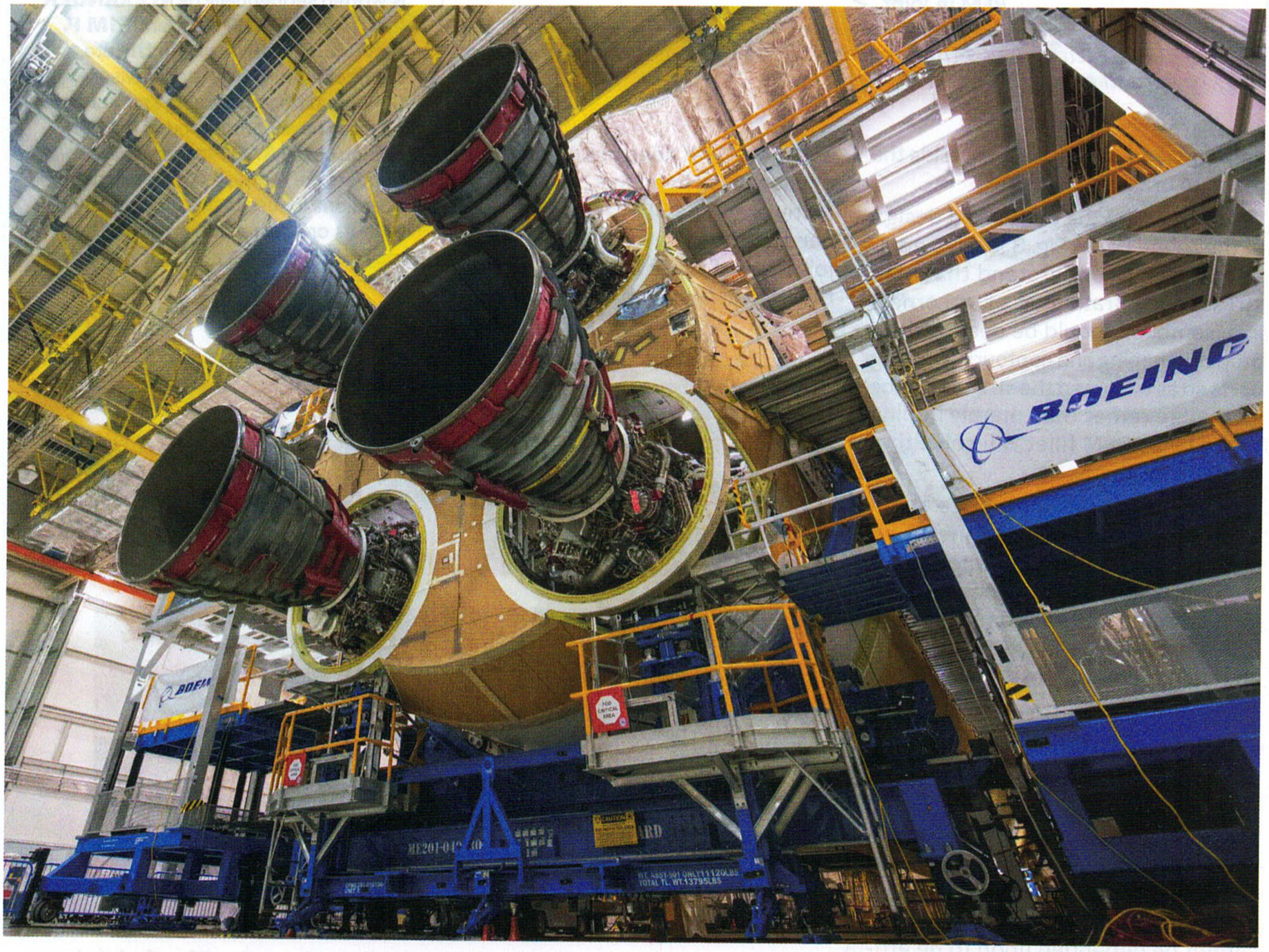
BY NIGEL SCOTCHMER, JIHUI YAN, AND KAIPING ZHANG

Bespoke Materials Made to Order

High-entropy alloys are being produced with specific properties



"Bespoke" is defined as a product or service that is specially made for a particular person, organization, or service. For example, a bespoke suit made by a tailor is a suit specially made to a customer's needs. One day soon, industry will be able to produce bespoke high-entropy alloys (HEAs) that will permit customers to order materials with specific properties.

But what is a HEA? A traditional alloy has one large component and small amounts of other elements. Steel, for example, is mostly iron with small amounts of other elements to improve its overall performance. Figure 1A shows a conventional alloy.

HEAs, on the other hand, generally have five or more elements in relatively equal percentages (Refs. 1, 2). Entropy means "disordered," and thus the internal structure of a HEA could be as shown in Fig. 1B.

Some HEAs have considerably better strength-to-weight ratios, more fracture resistance, better high-temperature performance, superior tensile strength, and better corrosion and oxidation resistance than conventional alloys.

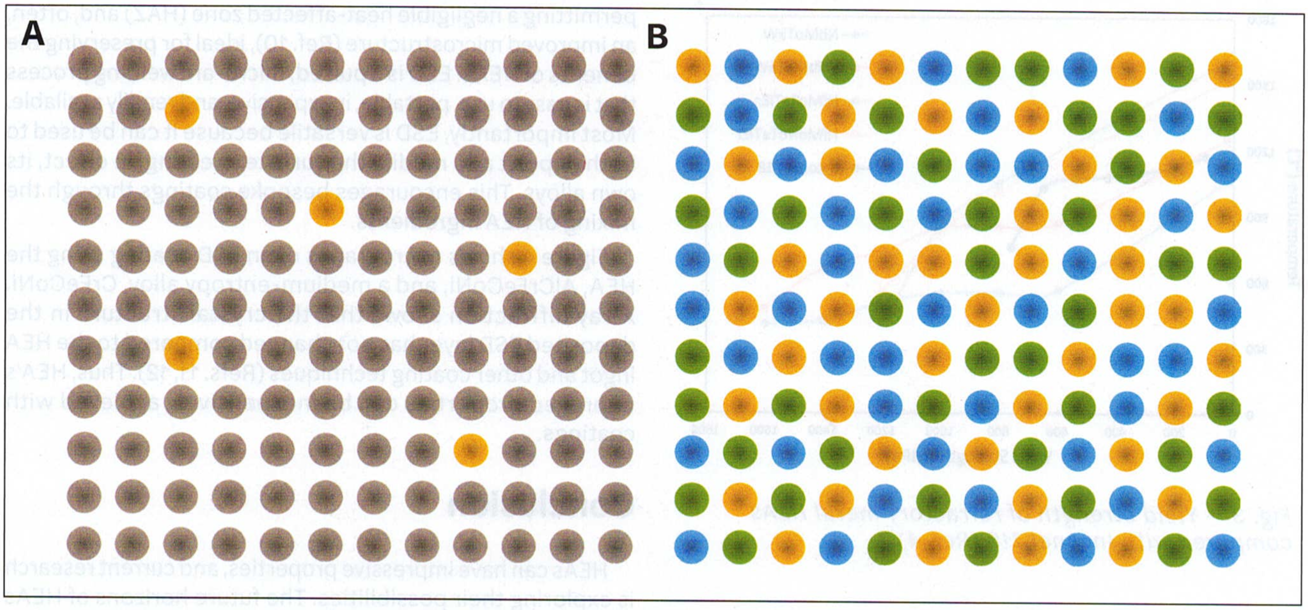


Fig. 1 — Two-dimensional schematic: A — Conventional alloy; B — HEA (Ref. 3).

Four Key Traits of HEAs

HEAs have four key characteristics (Refs. 3–5).

▪ The first is that the sum of the matter's internal energy and the product of its pressure and volume (enthalpy) will increase at higher temperatures, and a higher entropy (disordered structure) greatly stabilizes the matter (Ref. 5). This means there is an unexpected result of improved performance when more elements are in the alloy. This unexpected result is called the **high-entropy effect**.

▪ The second is the **sluggish-diffusion effect**. Due to the disordered and confused atomic configuration inside the alloy, there are different diffusion rates in the alloy. This means there is a slower rate of distributing energy in the alloy, and this helps the alloy maintain its superior performance.

▪ The third effect is the **lattice distortion effect** because different elements have different sizes and different bonding energies between elements, and the crystal structure is reflected in the lattice distortion, as shown in Fig. 2.

▪ The last is the **empirical effect**, as different factors occur simultaneously — such as the number, size, shape, and distribution of phases; the basic properties of elements; mutual interactions; etc. — all of which lead to unpredictable results.

Figure 3 illustrates the higher properties of some HEAs compared to Inconel® 718, showing their potential in

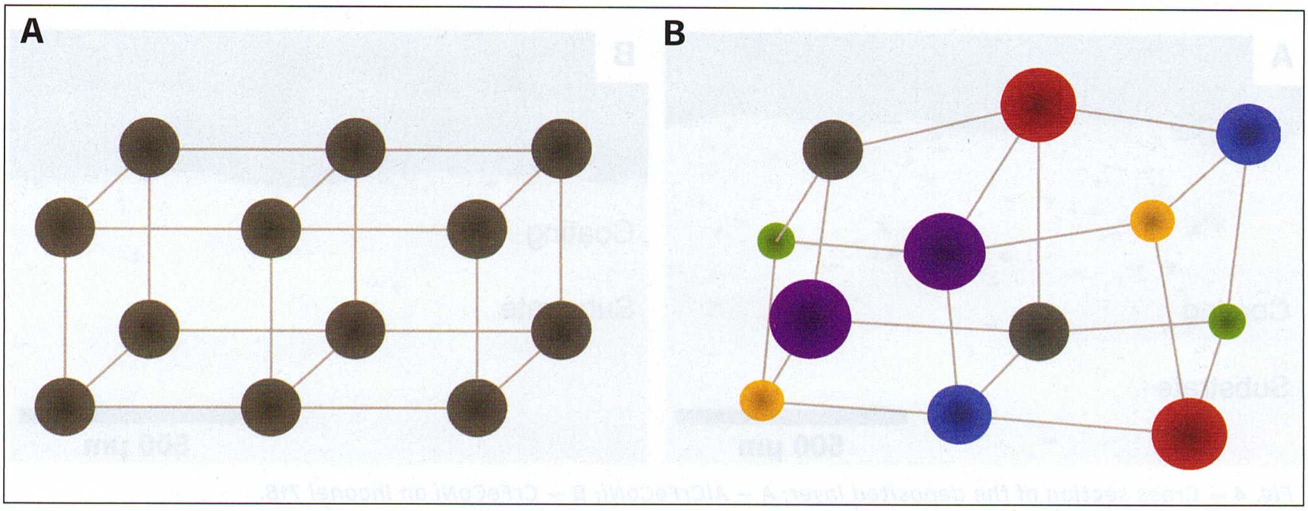


Fig. 2 — Schematic crystal structure: A — Simple one-component alloy; B — HEA with lattice distortion (Ref. 6).

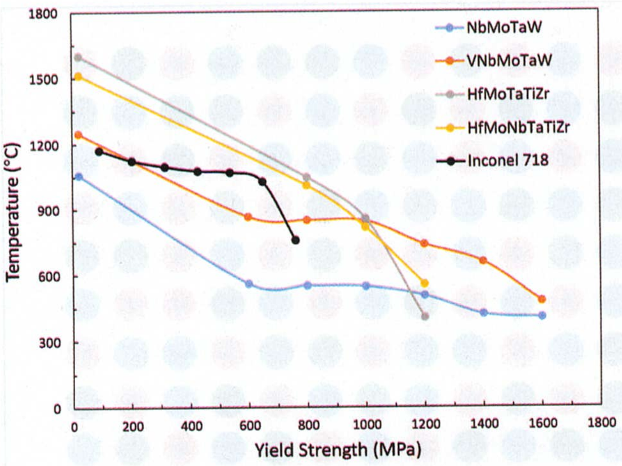


Fig. 3 — Yield strength of refractory metal HEAs compared with Inconel 718 (Ref. 4).

applications such as turbine blades, impellers for pumps, etc. To obtain low-density alloys, researchers are replacing heavy metals, such as Ta and W, with Al, Cr, and Ti (Ref. 7).

Effects of Electrospark Deposition Coating on HEAs

Of course, the manufacture of HEAs is in its infancy, and costs are very high. Because the surface of a material is often the most important (Ref. 8), less-expensive coatings and surface-modification technologies, such as laser cladding, thermal spraying, cold spraying, and electrospark deposition (ESD), can address this issue (Ref. 9).

There are several reasons ESD is one of the best processes. First, ESD has excellent metallurgical bonding. Uniquely, ESD also has a very low heat input and exceptionally rapid cooling, permitting a negligible heat-affected zone (HAZ) and, often, an improved microstructure (Ref. 10), ideal for preserving the benefits of HEAs. ESD is a pulsed, micro-arc welding process that is easy to use, portable, inexpensive, and readily available. Most importantly, ESD is versatile because it can be used to both deposit and modify the surface, creating, in effect, its own alloys. This encourages bespoke coatings through the mixing of HEA ingredients.

Figure 4 shows micrographs of an ESD coating using the HEA, AlCrFeCoNi, and a medium-entropy alloy, CrFeCoNi. X-ray diffraction shows that the crystal structure in the deposited ESD layer has not changed compared to the HEA ingot and other coating techniques (Refs. 11, 12). Thus, HEA's improved properties can be inexpensively achieved with coatings.

Conclusion

HEAs can have impressive properties, and current research is exploring their possibilities. The future horizons of HEAs will spread in unexpected ways. However, costs to manufacture HEAs will be higher than for regular alloys, and as a result, enhanced surfaces using processes such as ESD will increasingly be used to reduce wear and corrosion as well as for other purposes, such as dimensional repair, without incurring the full costs of manufacturing HEAs.

The almost infinite possibilities of different elements chosen for their properties and used in HEAs make the future exciting. WJ

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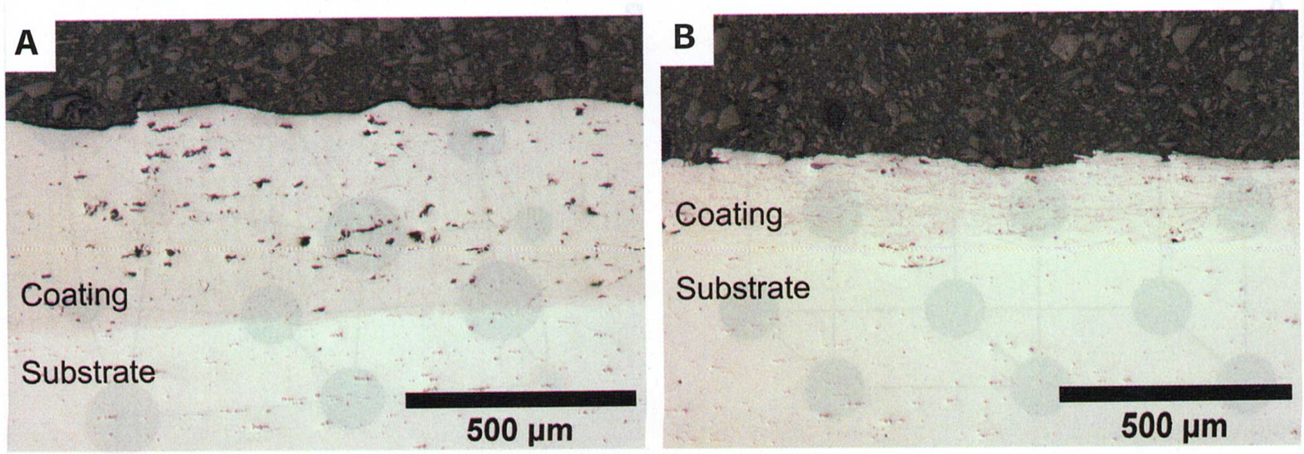

Fig. 4 — Cross section of the deposited layer: A — AlCrFeCoNi; B — CrFeCoNi on Inconel 718.

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