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Review Article

High Entropy Alloys: Materials Discovery for Aero Gear Applications

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Abstract

In this review, the current literature on a relatively new type of material, High Entropy Alloys (HEAs), has been examined to identify whether they are for aero-gear equipment and has been evaluated, in part, by a literature survey and in part through discussion to deal with the current state of art in landing gear application. On the basis of both reviews a number of problems have been identified which require further study by future researchers in order to fill the gap with possible solutions and possible HEA systems for the use of landing gear components has also suggested.

Introduction

With new materials and techniques constantly being developed in order to meet both the requirements of passengers and government regulations, the aero equipment industry is always changing. The majority of conventional landing gear alloys are based on one main element. The main element, which is an alloy family based on the main element, is complemented by various kinds of alloying elements. Steel is based, for example, on Iron (Fe) and aluminum (Al) alloys. The number of elements in the periodic table is, however, limited, so that the alloy families we can develop are also limited. If we don't think about one or two base elements, but about multiple factors outside the conventional box and design alloys, what are we going to get? A high-entropy alloy (HEA) [1,2], that is known as five or more main elemental alloys. This novel definition was first introduced in 1995 [3]. A concentration of between 5 and 35 at each major element. In addition to the main elements, HEAs may contain minor elements, each below 5 at.%. Such alloys are known as HEAs because they have substantially higher mixing entropies than those in standard alloys in liquid or random solid solution states. The effect of entropy in HEAs is therefore far more marked. Existing physical metallurgy and binary/ternary phase diagrams indicate these multi-elements may generate several dozen kinds of phases and compounds, which lead to complicated and brittle, hard to analyze and engineered microstructures and possibly have very limited practical value [4]. Nevertheless, the experimental findings, as compared to such assumptions, show that greater entropy in such alloys allows it possible for a solid solution phase to form with simple structures and decreases the number of phases. These characters are of vital importance in developing and applying these alloys, given that the higher entropy is available. These alloys were also called alloys with high entropy. Due to the unique composition of the multi-principal element, HEA can have special characteristics. These include high resistance/hardness, outstanding wear resistance, exceptional resistance to high temperatures, good structural stability, good corrosion and oxidation resistance. For typical alloys, some of these features are not seen, making HEA desirable in many places. It can also expand its range of applications even further by being used at high temperatures. Moreover, the manufacture of HEAs does not require special processing or machinery, which ensures that current facilities and technology can easily introduce the mass production of HEAs. In preparation of more than 300 study HEAs, over 30 elements have been employed to develop an exciting new area of metallic materials. This results in many promising properties, mainly based on so-called four core effects. These main effects are a high mixing entropy, a slower diffusion than in standard alloy systems, an increase in the strain of the gate (due to several different sizes) and a cocktail effect, which may contribute to characteristics that seem unintuitive at first [5]. This paper examines some key aspects of today's HEAs and potential proposals for aero gear applications,

Processing of HEAS

The most common method for melting and casting the alloy is the various processing methods available for HEAs. The fusion is done mainly through vacuum arc fusion, but sometimes by vacuum induction fusion, followed by the casting, often by copper mold casting [6]. The report was published. The reliance on process conditions, such as the cooling rate [7], heat treatment [8] and forging [9], should be noted. The increased cooling rate in AlCoCrFeNi was shown to increase plasticity and strength because of grain refine and a decrease in Cr-segregation [10], while the change in the cooling rate was achieved by casting alloys of various sizes which also show that size would have a slight impact on properties. Both samples had the same step constitution, however, it should be said. A contrast between AlCoCrCuFeNi natural and splat quenching showed that faster cooling suppresses the growth of other phases and consists only of an imperfectly structured Body Centered Cubic (BCC) phase compared to several BCC phases and Face Centered Cubic (FCC) phase as-cast [11]. This metastable phase is then sensitive to refining which is most likely to lead to further phases that have been eliminated during rapid cooling. It was observed that the dendrite changes in equiaxed grains using AlCoCrFeNi Bridgman solidification method, which is attributed to the high ratio between temperature gradient and growth rate of this technique [7]. Such reliance on processing conditions not only increases the difficulty of HEAs, but also enables the products to be modified more effectively. It is exciting to produce potential alloys because other HEAs have been shown to be forgeable. Another way to synthesize the HEAs is to use mechanical alloy (MA) as a Powder Metallurgy (PM) process, followed by consolidation (mostly spark plasma sintering), rather than moving from a liquid to a solid state, it starts with solid state constituents. In contrast with the separated microstructure of melted and cast HEAs, which often exhibit dendrites and inter-dendrite regions that can be hard to extract with homogenizing due to the slow spread of HEAs, prepared by PM often show greater homogeneity within their microstructures. In addition, MA might be desirable for elements with a large range of evaporation temperatures that may dissolve elements before other elements melt. This could be avoided during melting of the arc by placing the elements underneath the other elements at an early stage, but this is far from method of foolproof, and MA is the best choice. However, it is worth pointing out that the lighter elements have been shown to have a lower concentration than the ones loaded in the system, attributed to the lighter elements attached to the walls during friction, and also to difficulties with absolute homogeneity [4,12]. PM is typically a successful manufacturing route with

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an increased chance of homogeneity as well as the ability to process fairly large parts nowadays.

In various manners coatings and thin HEAs films have been produced. The most commonly prepared from the vapor state is by magnetron or plasma sputtering, while they were prepared from the liquid state by inert tungsten gas/gas arc welding or laser-coated (mainly on steel substrate in both scenarios). Some minor work has also been performed on the additive development of HEAs, where synthesize of FeCoCrNi, by Y *Brif et al.* [13] has used Selective Laser Melting (SLM). Only one FCC stage was shown to be contained if a series of processing parameters were synthesized. As a result of a fine microstructure achieved with SLM, the tensile properties are enhanced by the as-cast condition. For a layer thickness of 20µm the tensile yield power was 600MPa compared to the as-cast condition of 181MPa. The FCC process was also very ductile as anticipated.

Materials Drives for using HEAs as Aero Gear Application

HEAs can be favorably compared with many commercial alloys, particularly at high temperatures. That is good by itself but the possibility to reduce the overall density of the alloy and to add more lighter elements is another major factor for the potential use of HEA in aero-gear generation materials. For example, nickel-based super alloys are highly Ni-dependent (8.908g/cm^3 [14]). Inconel 718 is the most popular nickel-based alloy, with a density of 8.19g/cm^3, whereas the $AlMo_{0.5}NbTa_{0.5}TiZr$ aluminum contains a density of 7.4g/cm$^{3.}$ With increasing amounts of aluminum, it is very enticing to decrease the density with a density of only 2.7g/cm^3 [14]. The density can be determined according to the rule of mixtures for a single-phase solid solution in Equation 1

$$\rho_{mix} = \frac{\sum_i X_i A_i}{\sum_i \frac{X_i A_i}{\rho_i}} \quad \ldots\ldots\ldots\ldots (1)$$

Where Ai = atomic weight,
ρi and i = density

The equiatomic AlCoCrCuFeNi density (Ai and ρi [14]) can then be calculated to 7.1g/cm^3. The values used in the ρi are based on the structure of the pure element of the room temperature crystal, which may not be the same as the alloy's crystal structure. The density can then be used to calculate the Specific Yield Strength (SYS), which is the yield force σy divided by the material's density. For a range of temperatures the Device can be compared to the values of other superalloys with certain HEA ($AlCoCrFeNi_{2.1}$ (7.28g/cm^3) [15], $AlMo_{0.5}NbTa_{0.5}TiZr$ (7.2g/cm^3) [16] CrNbTiVZr (6.57g/cm^3) [17] $Al_{20}Li_{20}Mg_{10}Sc_{20}Ti_{30}$ (2.67g/cm^3) [18]). When only these values are considered, HEAs are clearly very promised to reduce their weight. In aerospace industry, such a lower weight reduction is highly desirable, because lower density means a lower gear weight, which in turn lowers the demand for landing gear-carrying aircraft and can result in more total weight reduction which means a lesser amount of fuel required in total. Therefore, it is a successful way to achieve potential climate targets to find alloys capable of preserving their properties at high temperatures. The slow diffusion effect for HEAs shows that at such high temperatures, HEAs could be good candidates for use.

1. Linking Gap

With the many promising features and an interesting new kind of HEA material. Nevertheless, as these types of materials can still be used in aero-gear, problems still have to be solved. A quite dispersed investigation has been carried out so far, with different properties investigated in different processing conditions for different systems. The number of potential alloys that the high entropy principle gives is understandable. 7099 possible alloys [2] have an equi atomic ratio of between 5 and 13 elements and there is far more possible combination with the varying concentrations inside those systems. It was actually just the system Al-Co-Cr-Cu-Fe-Ni that was studied under various conditions and much remains to be found. The cocktail effect also gives some fear, although one may foresee some similarities in characteristics between HEAs from high mixing entropy, lattice distortion and slow diffusion. Also, these more complex alloys are expected to have quite different properties/problems, including the optimized strength versus ductility, lack of creep and fatigue tests, problems with the thermal expansion coefficient and the lack of machining information, given the range of properties shown by conventional alloys.

2. Creep and fatigue resistance

Creep and fatigue resistance are the most significant material properties. $Al_{0.5}CoCrCuFeNi$ [19] and the $Al_{0.3}CoCrFeNi$ [20,21] fatigue possession has provided a dispersion of results, but the findings were encouraging for potential materials at the moment. The research also focused on High-Cycle Fatigue (HCF), whereas Low Cycle Fatigue (LCF) is the most important property for the requested sections. It was noted that the FCC-orientated alloy, $Al_{0.5}CoCrCuFeNi$, showed the greatest fatigue strength instead of the alloy consisting mainly of a BCC but also some phases of the FCC. Although these findings are not sufficient to show the general trend, fatigue-resistant alloys on FCC-based HEAs are a strong starting point [22]. More work will also benefit from the creeping properties of HEAs. Nonetheless, due to the typical mechanism for strengthening solution hardening and the slow diffusion in HEAs with diffusion deformity at elevated temperatures, good properties may be expected. Though promising, they are not yet mapped, and this is important before these alloys are applied to aero gear. In the event that the creep properties are not good enough for the desired material, a typical effective way to improve creep resistance is to coarsen the grain size, for example by measuring the cooling rate of the liner after casting. However, this could be problematic as many HEAs are getting their good strength from their nanoscale grains [17,23] and their coarsier could affect their strength negatively.

3. Corrosion resistance

For the aero gear and its specific parts, the resistance to oxidation is important, but the alloys often have good oxidation at the beginning, which is seldom a limiting factor. However, more research may be required for HEAs with the resistance to oxidation still being an unknown area. A good oxidation resistance is expected to occur in the alloys containing either aluminum, chromium, or both in rather large concentrations due to the creation of a protective layer, so the alloys based on Al-Co-Cr-Fe-Ni could possibly be of good oxidation resistance. Refractory HEAs are more interesting in further studies because of their low oxidation resistance of refractory elements. Aluminum is also contained in the refractory alloys with the best mechanical features, and the protective Al_2O_3 layer is therefore possible but further research is required (as with the simpler Al-Co-Cr-Fe-Ni system). In summary, aluminum and/or chromium, for HEAs that have to be able to demonstrate oxidation resistance, are good candidates for the formation of elements [24].

4. Thermal characteristics

HEAs have already been shown to be of good strength at high temperatures. However, an increase in Coefficient of Thermal Expansion (CTE) at higher temperatures that are higher than that for traditional superalloys is a potential problem for high temperature uses. This may cause problems when components made from these alloys are combined with components made from conventional superalloys. If during a change in temperature they expand and contract different quantities. CTE for HEAs has been measured for the AlxCoCrFeNi system and may be different for other systems [25]. For HEAs considered to be used as coatings when it needs to match/complement the substratum material, the CTE 's behavior is particularly critical. It may not necessarily become a problem, but researchers will have to be aware of the stresses resulting from thermal expansion/contraction. The thermal stability of HEAs is another possible issue which must be investigated. As previously mentioned, several cast HEAs occur in metastable states, in particular in high-speed cooling systems. As materials are served for a long period at elevated temperatures, there is a risk that the balance process can shift. Although this may be hindered by the slow diffusion effect, the conduct of HEAs in high temperatures over long periods of time is still to be investigated because thermal stability of the alloy is a requirement.

Alloy and Property Optimization

In the competition between strength and ductility, the need for HEA properties optimization is best described with changes in composition and microstructure. When changing the composition for an alloy framework, the strength may be increased/decreased at the expense of ductility if the compositional phases modified. There may be a relatively small but ductile phase of FCC for certain compositions but changing it might add a stronger property but brittle BCC or even a more brittle ordered phase. There will then be a kind of rivalry between strength and ductility, in which the properties for the correct use must be optimized. Not only is this a matter of strength and ductility since the other characteristics depend on the microstructure and phase constitution, but the need to combine them is most easily illustrated by combining strength with ductility. Moreover, most recognized strength is measured under compressive stress, and just a few under the most important tensile loads for engineering. Extensive research will have to be undertaken to optimize properties, but the crystal structure, the phase constitution and the previously laid down empirical rules should be decided on less extensively (that would be if precipitation should be strengthened and so on). In addition to considering their effect upon improving properties, it is important to know which elements to be used. Using rare or simply very costly materials will make the new alloy too costly. For example, the low density HEA $Al_{20}Li_{20}Mg_{10}Sc_{20}Ti_{30}$ [18] contains a large proportion of scandium, which is a rare and costly element and alloy of low industrial value. This is significant, however, for example.

Production Output

The ability to form and connect to other materials is another important feature of a material. If greater sections are produced than experimental samples, it will also change the properties, and shows that this is the case. Since the HEAs remain a rather new type of material it is understandable for other research to take precedence, such as understanding the composition or processing conditions that will take them to what stage or phase, that the process of manufacturing and shaping for industrial use was not one priority [26]. HEAs were manufactured in various ways, primarily through casting, but also through powder metallurgy and various coating technologies. Some HEAs were formed as well, which promises to be further processed, but factors such as weldability remain unknown. To date, there has been a certain dispersion of material properties. This dispersion was due to material defects, which are necessary to eliminate or at least reduce the number of defects. The articles in which the compressive yield forces of the AlCoCrFeNi [10] were calculated in addition to Si [27], Mo [28], Ti [29], and Nb [30] are another example of the property scattering. In all four cases the room temperature efficiency was measured, and when you compare the result strength, you can see that they are [28]:1051MPa, [30]:1373MPa, [27]:1110MPa and [29]:1500MPa. All of these without additional elements are for AlCoCrFeNi, to be sure. The four had melted their components on a water-cooled copper hearth, and all four had a single copper melting process. In order to produce reproductive performance, tighter control of the processing properties is required. For HEAs with more than a step, it is even more necessary as the microstructure can be relatively varied.

Future Prospects for Components Structure

As described before, HEAs are new and their properties are not adequately mapped to be used industrially. The following section is however going to attempt to indicate those systems for further possible use studies in the above listed aero gear sections. LCF properties, followed by strength, steepness, mechanical fatigue creep/thermo, good oxidation properties were the key limit properties for the Load Carrying Structure (LCS). Neither of these properties is especially well examined and the scheme proposed would depend on very vague terminology. The good fatigue features of the investigated systems have been identified for FCC-based systems and not too far behind the other more complicated systems. As regards creep, it has not been deeply studied, but HEA generally has good resistance to creep, and if not, the grains may be ground. On the other hand, fine grains, solid solutions and precipitation hardening will provide a high degree of strength. Aluminum and chromium have been suggested as valuable compounds in the system in order to increase the probability of good oxidation resistance. A good candidate material for the LCS will then have a single FCC phase to produce best fatigue characteristics, which would then be reinforced with solid solutions and nanograins (if the creep characteristics allow). To increasing the oxidation power, it should contain both aluminium and chromium. If the creeping properties of nanograins are not strong enough, a certain force can be sacrificed by coarsening the grains. On the basis of this, AlCoCrFeNiMo will be a possible candidate method. Preferably with an Al sufficiently low concentration to only have FCC phase and a sufficiently low Mo concentration that the α phase will not form and Mo atoms will help strengthen solid solution. It is possible that before the α phase the alloy is produced using MA rather than casting, larger amounts of Mo may be possible to increase the homogeneity of the alloy. If there is not enough strength obtained from the strengthening of solid solution and fine grain measurements, the Mo-containment can be increased to enable α precipitates to be achieved without losing too much of LCF. Another important parameter is the Valence Electron Concentration (VEC), which indicates which structure will have the shaped phase, for example, the VEC in the AlxCoCrFeNiMoz system vary with the aluminum and molybdenum concentration. Due to the low VEC the empirical limit of Al and Mo concentration for FCC phases has been reported to be VEC≥8 [31] and both of them have below these values for the BCC phase with Al and Mo. Adding higher VEC elements or that the nickel or cobalt ratio of elements with high VEC may then stabilize the FCC process, provided that these elements are not mixed in too high/low enthalpies with other elements and the atomic measurements are not much different. Temperature stability, strong creeping and formability, LCF and oxidation were the limiting characteristics for the heat shields. Again, while it is obviously simpler than how to achieve LCSs, it is somewhat unclear how such properties can be accomplished. It is still uncertain how to achieve good thermal stability, but traditional systems with simple phases have a greater chance of being improved by solid solutions.

The thermal shield material should be a one-phase solid solution to achieve the best temperature stability, according to conventional experience. The creep-resistance of ground grains would benefit, and the resistance to oxidation would benefit from Al and Cr being included. The thermal conductivity may be decreased if needed and if possible, by fine grains, but the creep properties are given priority. This could probably be done with the AlCoCrFeNi system, which only has FCC step with a low Al material. This system has been shown to be forgiving and is also promising. Again, many of the proposals are based on existing research that is by no means considered extensive. The fatigue property is one example where two alloys, one structured by FCC and one structured by BCC have been compared. The significantly improved, but not by much, characteristic of the FCC standardized alloy is the one FCC step proposal. There was not just one FCC phase in the post, there were two FCC phases, one of which in Cu was nice. It is because the variations of AlCoCrCuFeNi-X without Cu showed generally better propensities than those with Cu that the suggestions disregard this. If the above-mentioned problems can be solved, they could very well be good candidates for the possible use of aeronautical systems in future, thereby reducing the weight of the landing gear that could lead to substantial improvements in fuel efficiency, as discussed above.

Conclusion and Recommendation

HEAs are a new concept for materials based on metal alloys that contain five or more major components. This also contributes to the so called four core effects, high mixing entropy, distortion of the lattice, slow diffusion and cocktail effects. The fact that they consist of very high concentrations of several different elements means that alloys with densities lower than, for example, iron and nickel-based alloys can be produced by adding some lightweight elements.

HEA is more likely, because of its high mixing entropy and the slow diffusion effect, to create simple, solid solutions than was intuitively believed. Various empirical rules have been formulated to decide whether or not a HEA is a reasonable solution based primarily on the Hume-Rothery law, and although they are very useful, other problems continue to exist. An empirical rule has also been proposed to determine whether the phase is FCC or BCC based on the concentration of valence electron. Most HEA work has centered on several variations of the system TiAlVCoCrCuFeNi, and the majority of synthesized characteristics for this system are given. However, some properties, particularly those based on the grid distortion and slow diffusion, are expected to be more general. Many HEAs display a high strength, partly because of the lattice distortion; in part due to the solid solution strengthening and partly because of the slower diffusion mechanism, the high strength can be retained even at high temperatures. You may adjust the strength by changing the composition of the alloy, which changes the alloy phase(s). The system of TiVCrCoFeNi, for example, can be changed by adding Al from FCC to BCC. Additional alloys can add phases even more complex, often at the expense of ductility, that can reinforce the alloy. Nevertheless, mixing elements does not only produce new phases, because they can also extend into existing phases and improve the solution.

HEAs also demonstrated good softening strength and good wear properties. Contrary to the conventional scenario in which longevity and wear strength are linear, there is not always such a dependency on HEAs. The type of wear has been showing a shift between delamination and oxidation, depending on the concentration of different alloying elements. There have been several studies on the fatigue characteristics of HEAs and the few findings seem promising, but more remains to be done. The resistance to corrosion is different from the composition of the alloy, but overall does not appear to be as strong as nickel-based alloys. Some oxidation studies were carried out and promising results were obtained. Another positive aspect is that many HEAs contain relatively large quantities of aluminum and chromium, which improve the resistance to oxidation. For corrosion properties, chromium should also be fine. The thermal conductivity for pure metals is lower than that, and this is due to the effect of the lattice distortion. The conductivity is reduced by precipitation and a large number of grain limits. The thermal expansion coefficient for the HEA studied increases with temperature to the same degree as common superalloys, which can be difficult to unite. Differently, but primarily through melt and casting, HEAs have been handled. There is some dispersion of materials, and this is due in some ways to the presence of defects in the cast alloys, indicating that if you want to use HEAs in aero-gear, they should be reduced. HEAs have one of the benefits of being fairly similar to superalloys, demonstrating that the methods used to create and form today's superalloys may also create and form tomorrow's HEAs. If this is possible, HEAs are a cheaper solution since the majority of the necessary structure already exists.

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