

High Temperature Aluminum Alloys for Cast Iron and Titanium Applications

Objective

To develop and optimize aluminum alloys for use in automotive and aerospace applications by improving their strength and high-temperature creep. The use of aluminum will decrease the weight of automotive and aerospace components that currently use cast iron and titanium, leading to decreases in production costs and significant gains in fuel efficiency.

Background

Al-Sc-based alloys have been the subject of extensive research in the Seidman-Dunand groups; they have been the subject of 6 PhD theses and have been in over 30 peer-reviewed publications. The reason for this is that even trace amounts of scandium (<1 at. %) serve to greatly increase the strength and high temperature creep resistance of aluminum alloys.

It has previously been found that Al-Sc-Zr alloys have outstanding high-temperature creep resistance due to precipitation strengthening provided by an $L1_2$ ordered $Al_3(Sc_{1-x}Zr_x)$ phase [2]. Their strengthening is due primarily to the precipitation of a fine dispersion of Sc-enriched precipitates. These precipitates are protected from coarsening at high temperature by a Zr-enriched shell, a result of the comparatively low diffusivity of Zr with respect to Al and Sc [1-4]. Although Al-Sc-Zr alloys demonstrate good strength, they are not commercially viable due to the fact that scandium is 3 orders of magnitude more expensive than the other metals. To help counter this, a heavy rare-earth element (RE) can replace a fraction of the much more expensive scandium, as the RE elements enhance the elastic interactions with dislocations, and improve the creep resistance of the alloys [5-6]. Of the heavy rare-earth elements, erbium is chosen for this work because it is the cheapest of the RE elements that form stable $L1_2$ precipitates in aluminum. Erbium, however, diffuses at a faster rate than scandium, and thus without proper alloy design may increase the coarsening kinetics of the $Al_3(Sc_{1-x}Zr_x)$ precipitates in aluminum alloys. The final goal is to form precipitates with an erbium core, followed by a shell of scandium and an outer layer of zirconium, shown schematically in figure 1. As erbium has the highest diffusion rate, it precipitates first in the aluminum alloy, forming the core. Scandium precipitates next, and as zirconium is the slowest-diffusing element, it forms the outer shell. Through this process the strength is maintained at high temperatures, as the increased resistance of the precipitates to coarsening prevents dislocation motion [7]. With this in mind, the Seidman-Dunand research groups are working in collaboration with Ford and Boeing to develop and optimize an Al-Sc-Er-Zr alloy which exhibits strength and creep resistance at temperatures up to 500°C using the conventional casting and heat-treatment.

A first generation of Al-Sc-Zr-Er alloys has already been cast and analyzed. Significant precipitation is observed, along with the slowing of coarsening at temperatures of 400-475°C for all alloys, due to the presence of the outer Zr-enriched shell. When 0.02 at.% Er was substituted for 0.02 at.% Sc forming Al-0.06Zr-0.04Sc-0.02Er, the alloy strength is lowered by approximately 20%, while lowering the cost of the alloy by 30%, as shown in figure 2.

High resolution imaging of Al-0.06Sc-0.06Zr at.% alloy employing atom-probe tomography (APT) [14-16] revealed a Zr shell surrounding the Sc core of the precipitates. When the 0.02 at.% Er is substituted in, the APT shows an Er core surrounded by a Sc shell and then a Zr shell, shown on figure 3. However, the precipitate density dropped from approximately $3.8 \times 10^{22} \text{ m}^{-3}$ to $2.8 \times 10^{22} \text{ m}^{-3}$, explaining the 20% decrease in strength. Overall, the results show that the desired nanostructure has been achieved, but requires further tailoring in order to optimize the high-temperature strength of the Al-Sc-Zr-Er alloys.

The next step in the research project is confirm the structure and composition of the strengthening precipitates, which will explain the difference in the strength between the Al-Sc-Zr and Al-Sc-Zr-Er alloys. This information will be used to design a second generation of alloys, which will have an optimized composition and processing cycle in order to maximize the high-temperature properties of the material. They must be cast and analyzed chemically, and from there the isochronal/isothermal aging of the samples can begin.

My work research will be focused on the addition of a trace amount of silicon, 0.025 at%, which is anticipated to substantially increase the high-temperature strength of the alloy [8]. Previous research has shown that silicon atoms serve as nucleation sites for the Al-Sc-based precipitates, leading to a significant increase in the precipitate number density, and corresponding to a 40% increase in strength [8]. My task will be to quantify the effect of silicon on the nanostructure and mechanical properties of the Al-Sc-Zr-Er-Si second generation of alloys.

Significance of Research Project

The increased strength and creep resistance of the alloys at high temperatures are extremely vital for both Ford and Boeing. Traditional aluminum alloys such as 319 begin to melt at 500°C, yet the brake rotors of a car must function at temperatures up to 480°C, and the structure near the auxiliary power units of an airplane must run continuously at 350°C. Furthermore, from a business perspective, cast aluminum brake rotors in a Ford vehicle would reduce the vehicle's weight by approximately 40-50 lbs. Their decrease in weight would make the cars more environmentally friendly by increasing their fuel efficiency. The brake rotors represent the automotive component with the greatest potential for weight savings For Boeing, using the Al-Sc-Zr-Er-Si alloy instead of titanium would reduce the weight by about 25%, and the cost by 50%.

I will begin work on this project in March, and continue through the summer. My work will begin with the casting of the second generation of alloys; and as such, I will be involved at every phase of the project, from manufacturing to processing to testing and data analysis. The results from the second generation of Al-Sc-Zr-Er-Si alloys will bring us a step closer to optimizing these alloys to meet the economic and fuel-efficiency goals set by Ford and Boeing.

Preparation

My relevant class-work to the topic includes Introduction to Material Science and Engineering (MSE 301), Thermodynamics for Material Scientists (MSE 314), and Phase Transformations and Diffusion (MSE 315), and am taking Microstructural Dynamics (MSE 316-1) in the spring. All of these are valuable in understanding the principles governing the formation of the precipitates and their requisite properties bestowed upon the alloy. I am also taking Mechanics of Materials I (CIV ENG 216) in the spring, which should let me better understand the behavior of materials when subjected to mechanical stress, similar to the hardness testing undergone by the samples. This project is the first to study Al-Sc-Er-Zr alloys; as such, once a suitable alloy has been found and submitted to Ford and Boeing, they will be amongst the first to use the design in their vehicles.

Academic Credit

As this is my first research project, I hope that this is the beginning of a long line of research in this field for me. I will initially count this class as a credit for Special Problems in Material Science (MSE 399), although in the fall quarter of next year I plan to make this research project my Senior Project (MSE 396 1-2). I hope that I will be able to contribute and further the project as much as it will further my knowledge in actual research.

Appendix A: References

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Appendix B: Graphs and Figures

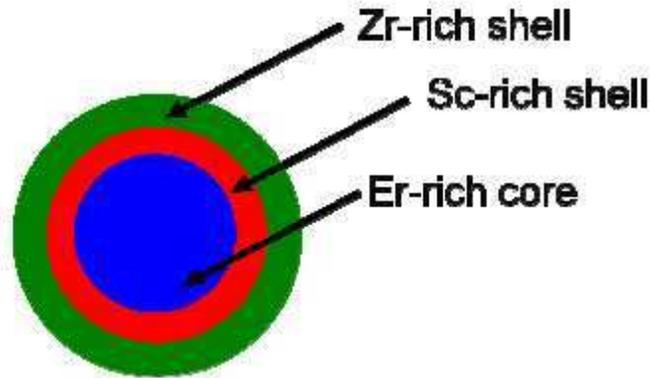


Figure 1. Schematic of the Er-rich core / Sc-rich shell / Zr-rich shell precipitate structure that leads to the high-temperature strength in the Al-Sc-Zr-Er alloys.

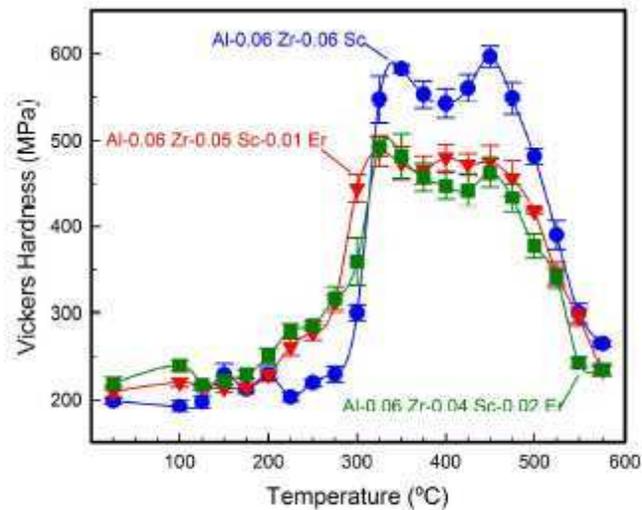


Figure 2. The Vickers Hardness, a measure of alloy strength, as a function of temperature. Significant precipitation hardening is observed in all alloys at temperatures above 200 °C. The substitution of 0.02 Er for 0.02 Sc at.% lowers alloy strength by 20%, while lowering alloy cost by 30 %. Precipitate coarsening is terminated between 400-475°C for all alloys by the addition of a Zr shell, leading to a peak in the Al-0.06 Sc-0.06 Zr at.% alloy strength at 450°C, and a plateau in the strength of the Er containing alloys. Optimization of alloy design is anticipated to lead to increases in the strength of the Al-Sc-Er-Zr alloys.

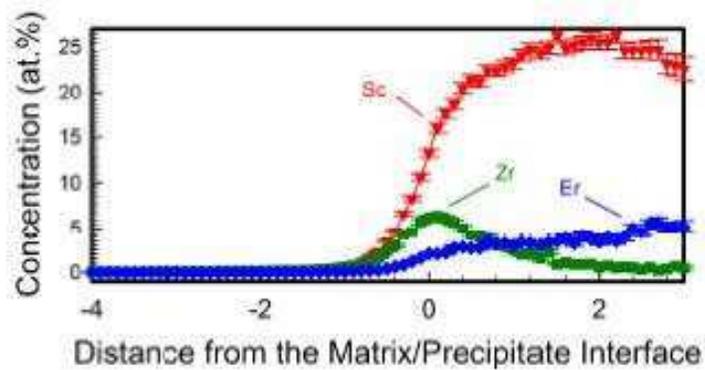
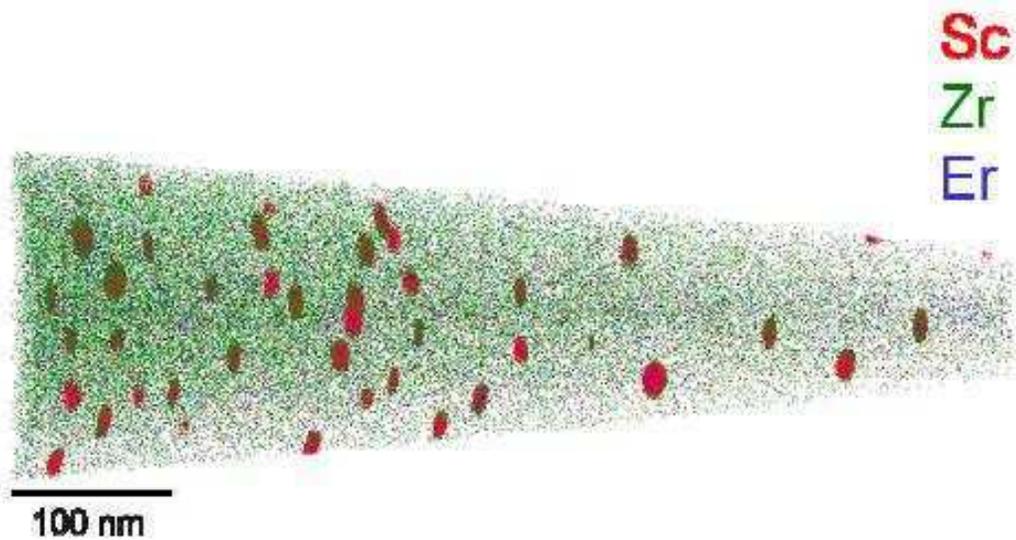


Figure 3. A high-resolution atom-probe tomographic image of an Al-0.04 Sc-0.02 Er-0.06 Zr at.% alloy aged at 450°C. An Er-rich core is surrounded first by a Sc-rich shell, then by a Zr-rich shell, as illustrated in the average composition profile across the matrix/precipitate interface. Once optimized, this nanostructure will lead to improved high-temperature properties, and allow these alloys to replace heavier and more expensive titanium and cast iron alloys in aerospace and automotive components.