Designing Cast Al-Fe-Based Eutectic Alloy Through Zr Additions for Powertrain Applications

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Introduction

Aluminium-silicon (Al-Si) alloys are widely used in automotive engines due to their lightweight, high strength, heat resistance, and suitability for die and squeeze casting. However, current alloys tend to lose strength at elevated temperatures (~250°C) due to precipitate coarsening, limiting their long-term performance in high-temperature applications such as pistons, rotors, and jet engine parts.

This study focuses on developing a thermally stable Al-Fe-Zr eutectic alloy, engineered to resist precipitate coarsening and maintain strength after prolonged exposure at elevated temperatures.

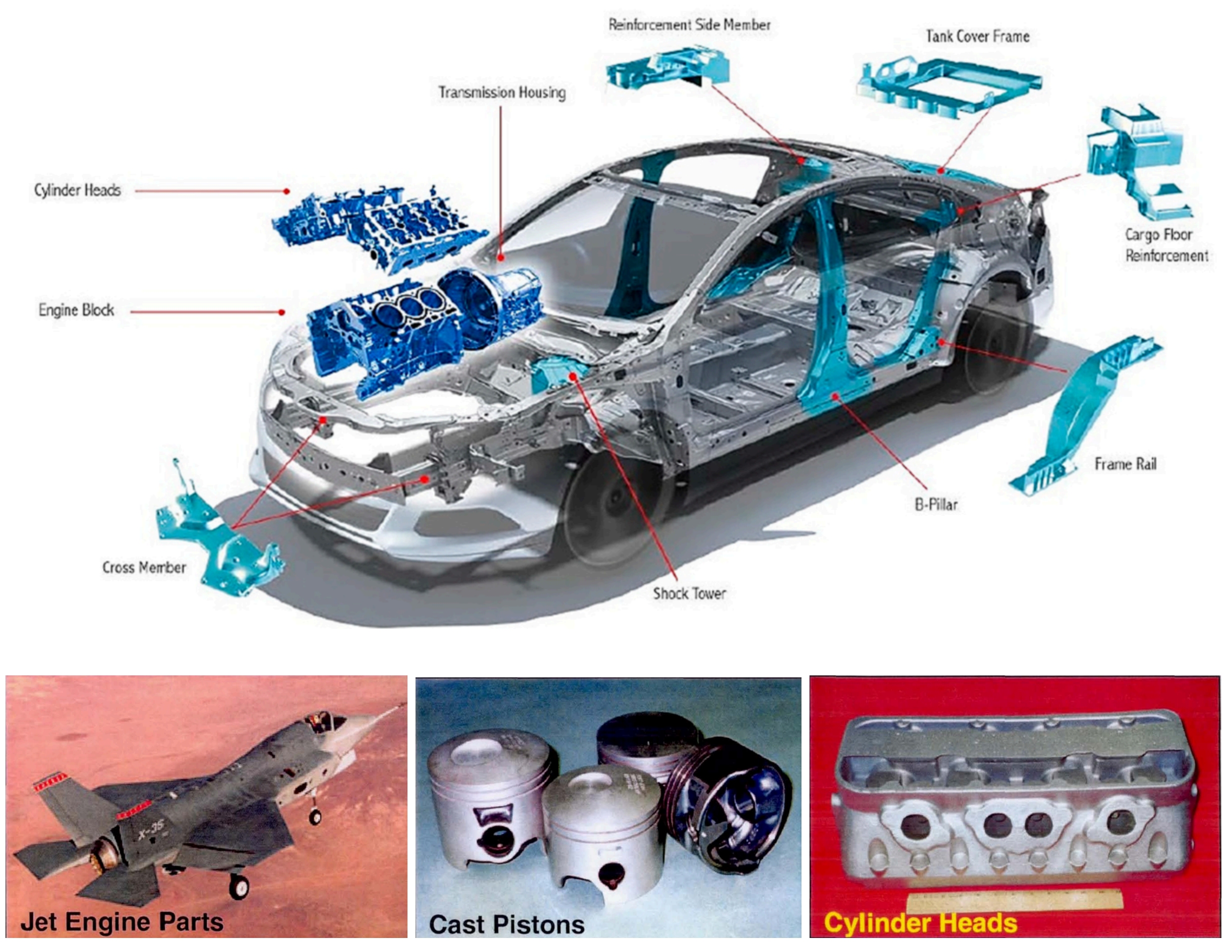


Fig 1. Components made up of AL-Si alloy

Background

- **Current Alloys:** NASA-developed Al alloys (Al398, Al388) are standard for high-temperature engine components, operating reliably between 232°C and 400°C.

- **Problem:** Conventional alloys lose mechanical strength at ~250°C due to the coarsening of strengthening precipitates.

- **Proposed Solution:** Introduce Zr to Al-Fe alloys to form stable L12-Al3Zr nano-precipitates, enhancing thermal stability and mechanical strength.

Rockwell Hardness of NASA alloy		
Temperature (°C)	NASA 398 hypereutectic alloy (16% w. Si)	NASA 388 eutectic alloy (<13% wt. Si)
25	71	72
260	55	53
370	33	31

Table 1. Hardness value of NASA alloy at different temperatures

Objectives:

- Design and synthesise a cast Al-Fe-Zr eutectic alloy.
- Achieve resistance to precipitate coarsening at high temperatures and ensuring microstructure stability after long duration of exposer at that high temperature .
- Ensure strength retention after 1,000 hours at 250°C.

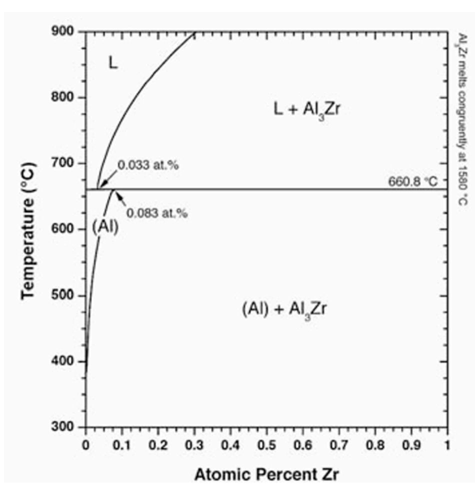


Fig 2. Phase diagram of Zr

Methodology:

1. **Alloy Composition:** Al-2.7Fe and Al-2.7Fe-0.15Zr.
2. **Processing Steps:**
   - Arc melting and chill casting.
   - Heat treatment at 400°C for 10 hours.
   - Aging at 250°C for various durations.
3. **Characterization:**
   - Microstructural analysis (SEM, TEM planned for future work).
   - Mechanical testing (hardness, yield strength).
   - X-ray diffraction for phase identification.

Results:

Microstructure:

- **Al-Fe Alloy:** Exhibited a eutectic microstructure with Al and Al-AlFe phases.
- **Al-Fe-Zr Alloy:** Presence of fine, coherent L12-Al3Zr particles in the α-Al matrix after ageing.

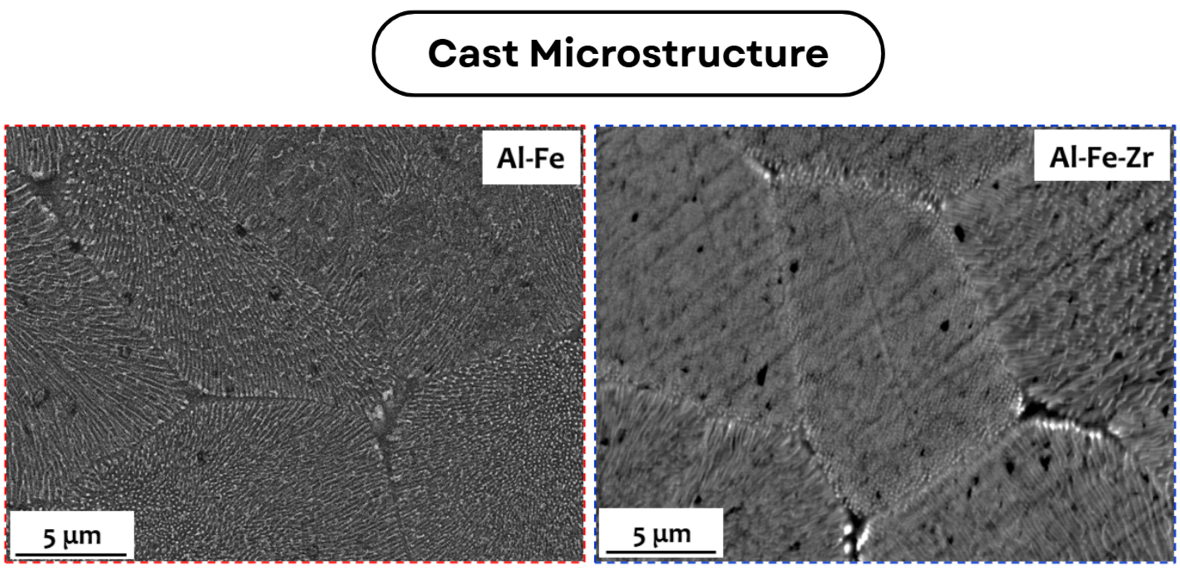


Fig 3. Cast microstructure of AlFe and AlFeZr alloy

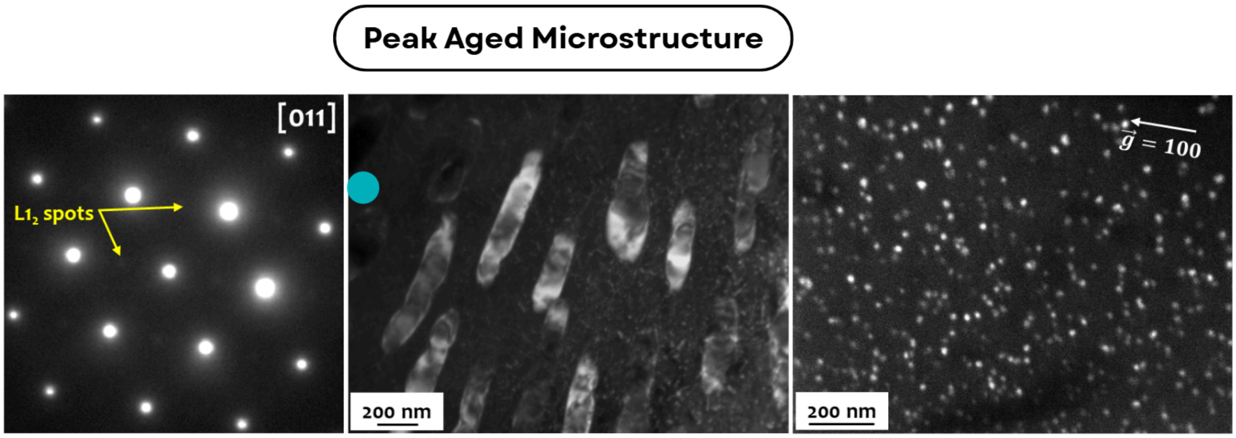


Fig 4. TEM images of peaked aged sample at 400°C after 10hr of aging

TEM images shows the presence of Al_3Zr presences after aging AlFeZr at 400° C. After 10 hr of exposing we get the maximum hardness beyond that the hardness starts geting almost constant you can see hardness evolution in figure 6.

X-RAY Diffraction Pattern:

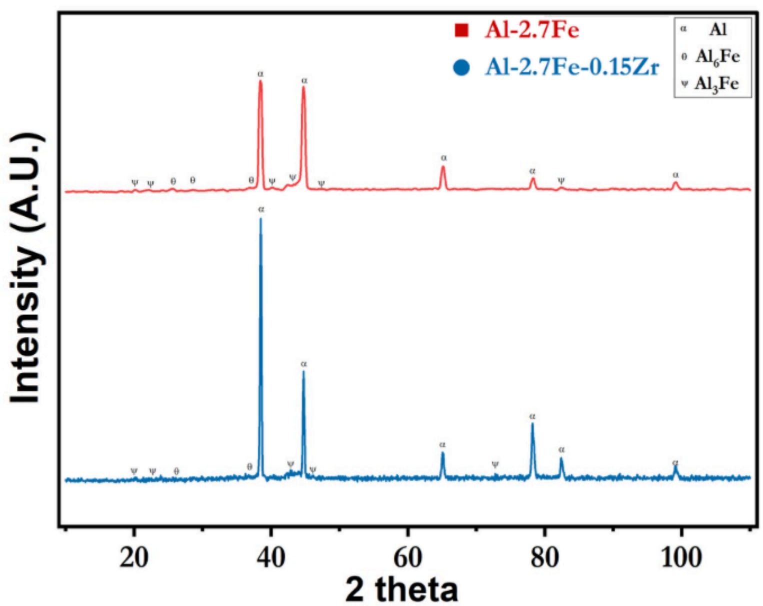


Fig 5. XRD plot of aloys to see the phases

Hardness Evolution at 400 °C:

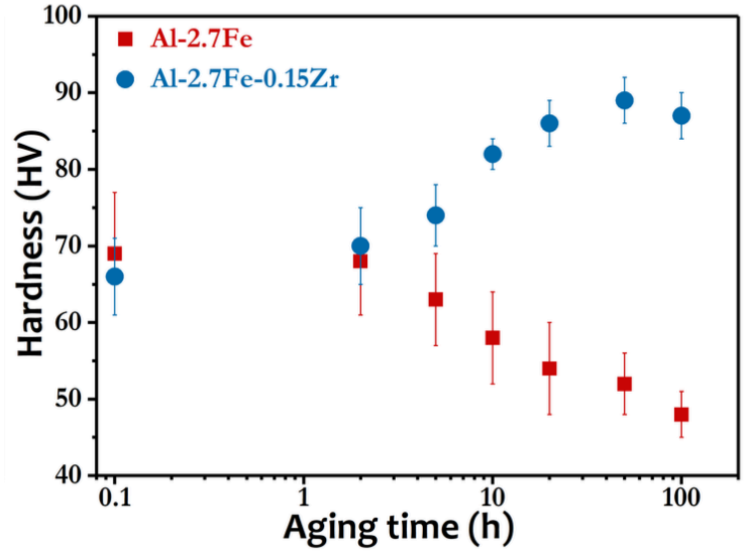
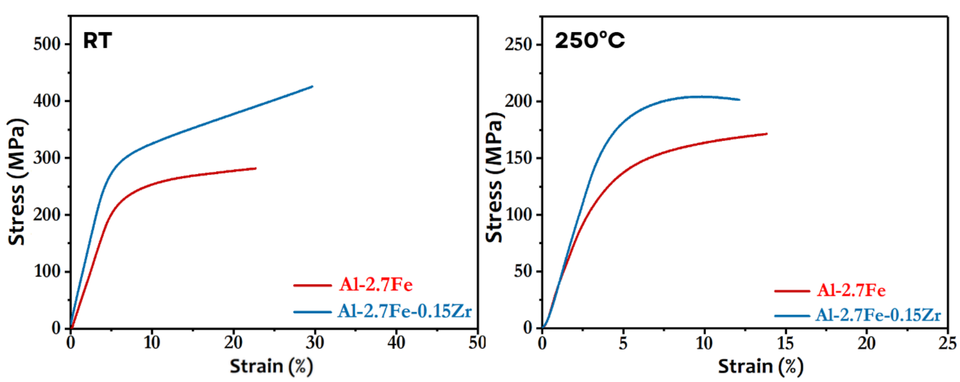


Fig 6. Hardness evolution plot of alloys aging at 400°C

Mechanical Properties:



Yield strength of the alloy		
Alloys	**25 °C (MPa)**	**250 °C (MPa)**
Al-Fe	195 ± 15	123 ± 18
Al-Fe-Zr	261 ± 4	160 ± 10

Fig 7. Strength plot of alloys

Graph shows that the yield strength for both peak aged alloys at room temperature and at 250°C. The Al-Fe-Zr alloy consistently outperforms the Al-Fe alloy in both properties, confirming the beneficial effect of Zr additions.

Hardness Evolution:

Al-Fe-Zr alloy maintained higher hardness and better stability during prolonged aging at 250°C compared to Al-Fe.

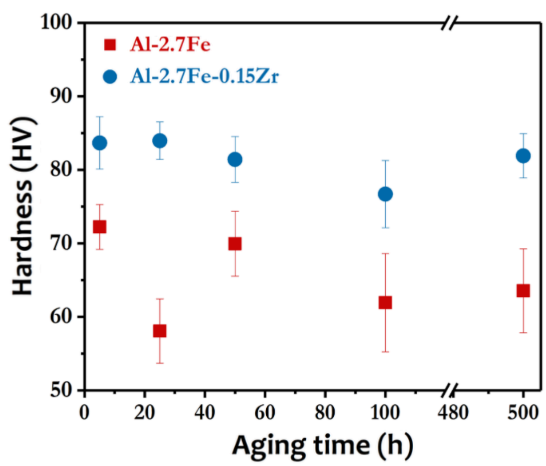


Fig 8. Hardness plot of aging peak aged sample at 250°C for different duration

Long-Term Stability: The Al-Fe-Zr alloy demonstrated good mechanical and microstructural stability at 250°C for up to 500 hours.

Microstructure Evolution after ageing at 250 °C:

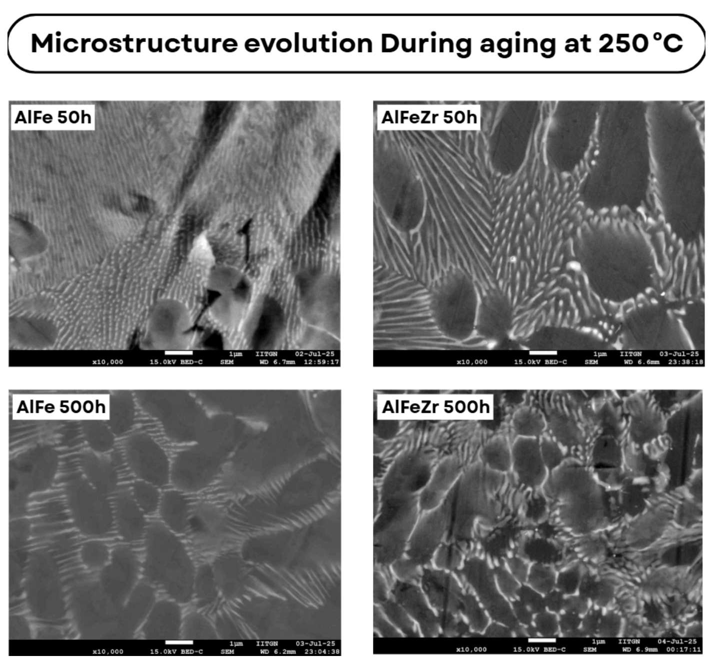


Fig 9. SEM images of Alloys to see the micrstructural changes

Discussion

- **Zr Additions:** Zr stabilizes the L12-Al3Zr precipitates, which resist coarsening and contribute to the retention of mechanical properties at elevated temperatures.
- **Performance:** The Al-Fe-Zr alloy outperforms conventional Al-Fe alloys in terms of both hardness and yield strength after thermal exposure, making it a promising candidate for high-temperature automotive and aerospace applications.

Conclusions

- A cast Al-Fe-Zr alloy with a eutectic microstructure was successfully designed and synthesized.
- The incorporation of Zr led to the formation of thermally stable nano-precipitates, resulting in superior mechanical properties and long-term stability at elevated temperatures.
- The Al-Fe-Zr alloy achieved a peak hardness of 89 HV at 400°C and retained high yield strength after aging at 250°C.

Future Work

- Conduct detailed SEM and TEM analyses at multiple temperatures to further understand microstructural changes.
- Perform additional mechanical property evaluations.
- Test electrical conductivity to assess suitability for electrical applications.

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- J. A. Lee, "Commercialization of NASA's high strength cast aluminum alloy for high temperature applications," Proceedings of the 28th Annual Conference on Composites, Materials and Structures, NASA Marshall Space Flight Center, 2004. [Online]. Available: Aluminum-Silicon (Al-Si) alloys are widely used in the automotive industry for engine components due to their lightweight, high strength, excellent high-temperature performance, good wear resistance, and compatibility with high-pressure die casting and squeeze casting processes.

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