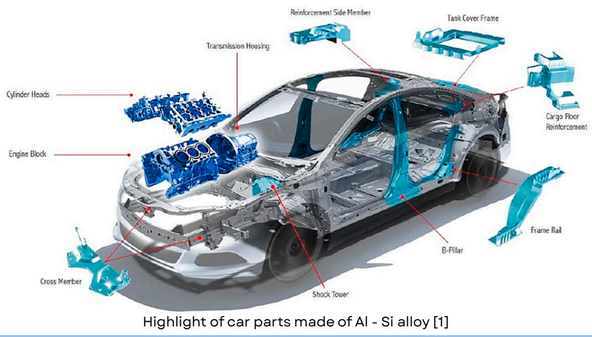
Designing cast Al-Fe-based eutectic alloy through Zr additions for powertrain applications

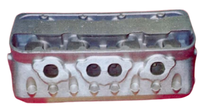
Pawan Seth, Rishabh Dwivedi, K Vardhrajan, Prafull Pandey
Materials Engineering Department
Indian Institute of Technology Gandhinagar
pawan.seth@iitgn.ac.in

Background

- Al-Si alloys are used in automotive engines for their light weight, high strength, heat resistance, and suitability for die and squeeze casting.
- NASA-developed Al alloys such as Al398 and Al388 are commonly used in critical components like pistons and rotors, reliable in high-temperature applications ranging from 232 °C to 400 °C.

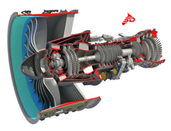


Highlight of car parts made of Al - Si alloy [1]


Cylinder Head [2]


Jet Engine Parts [2]


Cast Pistons [2]


Gas Turbine [3]

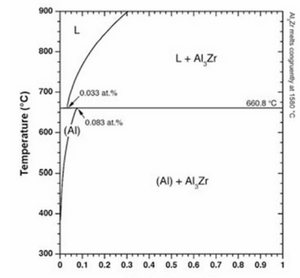
Literature

Table 1: Hardness of T5 Al-Si Alloy (Permanent Mold Cast) After 100-Hour Heat Treatment at Testing Temperatures [3][4]

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

Motivation

- Current alloys lose strength over time at ~250°C due to precipitate coarsening.
- We introduce a thermally stable Al-Fe-Zr eutectic alloy engineered to:
  - Fe is a common impurity in Al and has good alloying properties
  - Resist precipitate coarsening through Zr-stabilized $L1_2$ nano-precipitates
  - Maintain strength retention after 1,000 hours at 250°C



Cast Pistons [5]

Methodology

Composition → Arc Melting → Chill Cast → Heat Treatment 400°C / 10hr → Aging at 250°C

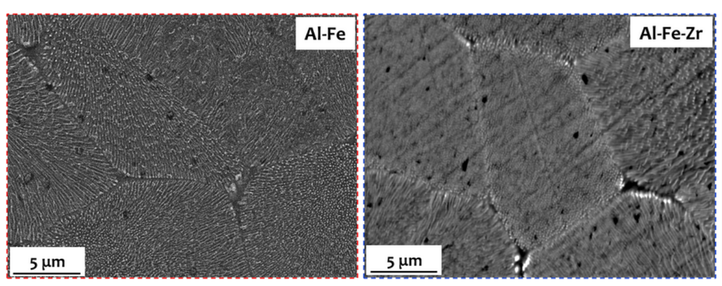

Arc Melting

Arc Melter with Suction Casting Unit

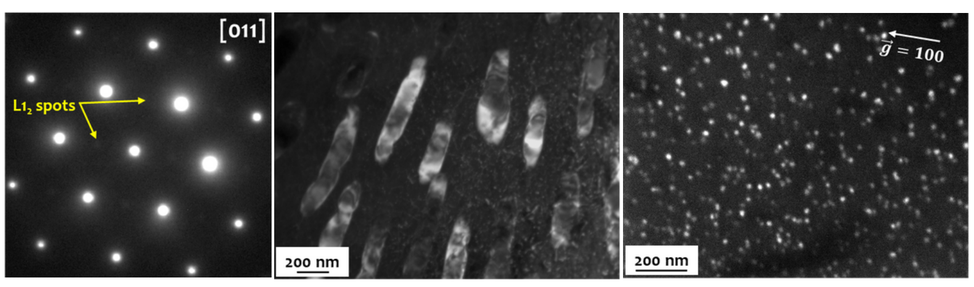

Oven (Used to aging sample at 250°C)

Result

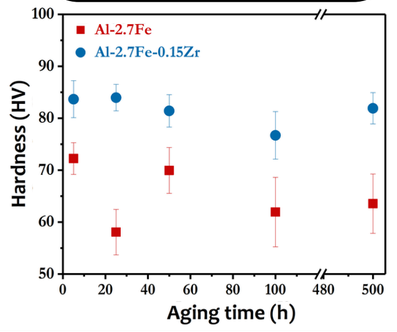
Cast Microstructure



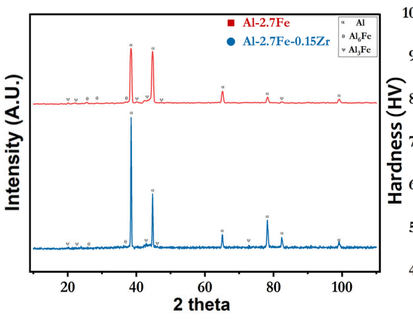
Peak Aged Microstructure



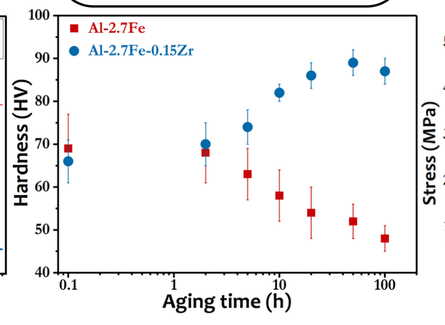
Hardness Evolution During aging at 250 °C



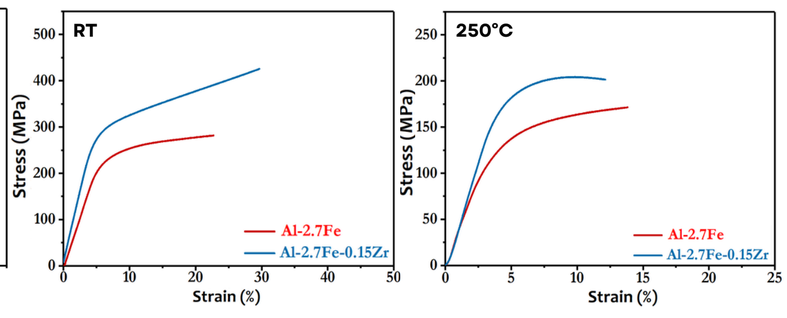
X-Rays Analysis



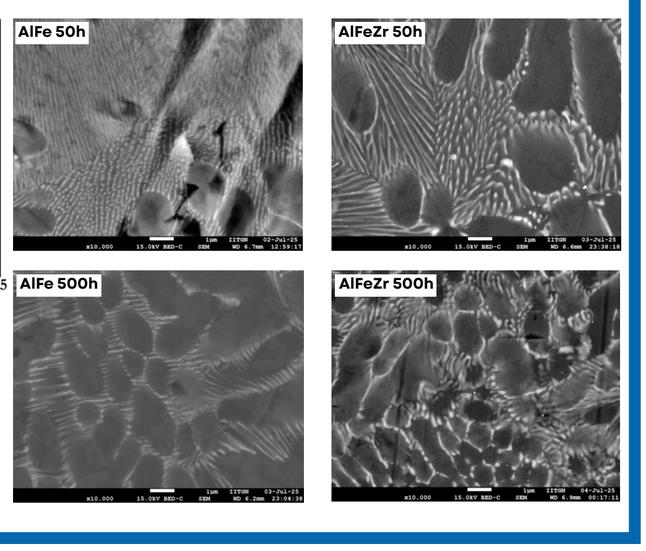
Hardness Evolution During Aging at 400 °C



Mechanical Testing



Microstructure evolution During aging at 250 °C



Vickers Hardness Measurements at 250 °C for Different Aging Times					
Alloys	5	25	50	100	500
Al-Fe	72.25	58.08	69.95	61.94	63.56
Al-Fe-Zr	83.67	83.97	81.42	76.71	81.92

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

Conclusion

- A cast Al-Fe-Zr alloy was designed, exhibiting a eutectic microstructure consisting of Al–Al_3Fe/Al_6Fe phases.
- Aging at 400°C resulted in increased hardness due to the precipitation of coherent $L1_2$-Al_3Zr particles in the α-Al matrix.
- The alloy AlFeZr shows peak hardness of 89 HV at 400 °C.
- The peak-aged Al-Fe-Zr alloy exhibited yield strength values of 261 ± 4 MPa at 25 °C and 160 ± 10 MPa at 250 °C.
- The peak-aged Al-Fe-Zr alloy demonstrated good mechanical and microstructural stability at 250 °C for up to 500 hours.

Future Work

- Measure hardness after exposure at 250°C for 1000hr.
- Conduct SEM and TEM analysis at three different temperatures to observe microstructural changes.
- Perform mechanical testing to evaluate additional mechanical properties.
- Test electrical conductivity to assess suitability for electrical applications.

Acknowledge

- I would like to thank my SRIP advisor Prof. Prafull Pandey.
- To all Lab Staff and instrument TAs at IIT Gandhinagar,
- I would like to thank my research group colleagues Rishabh Dwivedi and K Vardhrajan for their help.

Refrences

1. J. Liu, W. Wang, X. Zhang, Y. Zhang, and Y. Wang, "Effect of Zr Addition on Microstructure and Mechanical Properties of Al–Si–Cu–Mg Cast Aluminum Alloy," Coatings, vol. 13, no. 5, p. 958, May 2023. [Online]. Available: https://www.mdpi.com/2079-6412/13/5/958
2. 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].https://ntrs.nasa.gov/api/citations/20040035597/downloads/20040035597.pdf
3. NASA Marshall Space Flight Center, "NASA 388 Material Properties Data Sheet," Huntsville, AL, USA, Apr. 20, 2001. [Online]. Available: https://pacmaterials.com/data/NASA_388_Data_Sheet.pdf
4. NASA Marshall Space Flight Center, "NASA 398 Material Properties Data Sheet," Huntsville, AL, USA, Apr. 20, 2001. [Online]. Available: https://pacmaterials.com/data/NASA_398_Data_Sheet.pdf
5. K. E. Knipling, D. C. Dunand, and D. N. Seidman, "Criteria for developing castable, creep-resistant aluminum-based alloys – A review," Int. J. Mater. Res., vol. 97, no. 3, pp. 246–265, 2006. [Online]. Available: https://dunand.northwestern.edu/pdf/Knipling2006.pdf
6. MRF Furnaces, "Arc Melt Furnace ABJ-900," MRF Products, Jun. 30, 2025 [Online]. Available: https://mrf-furnaces.com/products/arc-melting-furnaces/arc-melt-furnace-abj-900/.
7. I. R. Hughes and H. Jones, "Coupled eutectic growth in Al-Fe alloys. Part 1: Effects of high-growth velocity," Journal of Materials Science, vol. 11, no. 11, pp. 1781–1793, 1976.
8. I. R. Hughes and H. Jones, "Coupled eutectic growth in Al-Fe alloys. Part 2 Thermal stability of the Al-Al_6Fe eutectic," Journal of Materials Science, vol. 12, no. 2, pp. 323–333, 1977.